THE WILD GOOSE ASSOCIATION

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The International Loran Radionavigation Forum

Proceedings of the Twenty-Third Annual Technical Symposium

November 1 - 3, 1994

Newport, Rhode Island

Published by
The Wild Goose Association
P.O. Box 556
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Proceedings of the Twenty-Third Annual Technical Symposium

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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.

Proceedings of the 23rd Annual Convention and Technical Symposium

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International Loran Association

(Formerly The Wild Goose Association)

November 15, 1994
For immediate release:

Loran Association renamed

At its 23rd Annual Convention and Technical Symposium held in Newport, Rhode Island, the loran advocacy group's president, Dale Johnson, announced that the membership voted overwhelmingly in favor of a name change from the **Wild Goose Asssociation** to the **International Loran Association**. The new name will become effective immediately, subject only to completion of administrative procedures in Massachusetts, where the group is incorporated.

"The name change reflects the growing international involvement and expansion of Loran-C worldwide," President Johnson said. It will facilitate the efforts of the group's Committee for a Balanced Radionavigation Policy, which is carrying out a multi-faceted campaign to reverse U. S. Coast Guard initiatives for an early termination of Loran-C.

The Convention adopted a Resolution to capture the sense of the meeting:

Resolved:

a. that the United States Department of Transportation be urged to endorse a policy for providing a mix of dissimilar wide-area terrestrial and satellite systems.

b. that Loran-C continue as the major terrestrial component of that mix.

The International Loran Association is a non-profit organization whose members are drawn from government, industry, academia and the user community throughout the world. The next meeting is planned for **June 26-30 in Moscow, Russia** (see enclosed brochure).

ILA Operations, 150 S. Plains Rd., The Plains, OH 45701, USA
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Wild Goose Association (International Loran Association)
23rd Annual Convention and Technical Symposium
Newport, Rhode Island, USA
Tuesday, November 1, 1994

Opening Remarks

by Dale E. Johnson, President

Welcome to the 23rd Annual Convention and Technical Symposium of the Wild Goose Association.

For anyone who is not aware of it, we are in the process of changing the name of this organization and hereafter we will be known as the International Loran Association. I know this change may give some of you a little discomfort, but the change is appropriate at this time. The international scope of the organization is growing and will continue to grow as position referenced navigation becomes business-as-usual worldwide. As you know, Loran coverage is being expanded under local control in Europe, Asia and the Far East.

The word Loran is included in the new logo to clearly state the association's primary focus on Loran as a valuable component in the mix of radionavigation and positioning systems to people who are not familiar with the organization's work. You will notice that the Wild Goose will remain at the center of the logo and the familiar goose call will still be a part of our meetings.

This has been a challenging year full of opportunities and hard work for many members of the association. With mixed emotions, I think the next year promises to be the same.

I have been asked many times, "Isn't GPS going to replace Loran?" A quick answer to that question is, Loran will be around for a long time because it still has the largest user base of any positioning system in the world. As satellite positioning systems reach maturity it is expected that these systems will have an even larger user base, and Loran will take on a redefined role as an excellent partner with satellite positioning systems. The key point being, both systems have limitations, but the two systems share no common limitations. I don't know of any captain that doesn't want at least two equally capable navigation systems in the cockpit or on the bridge.

As we discuss these issues, we must be careful to always be positive in our approach. I fear that we are often perceived as taking a negative approach when we point out the limitations of any other system. In fact we know that all navigation systems, including Loran, have some limitations. The important point to focus on is that the partner systems must not have any common limitations if they are to be fully capable partners.

It seems to be a fact-of-life that as huge programs are presented to government for development, they are always oversold, promising a panacea of capability and value, in order to get Congress to fund the program. It has taken a huge amount of time and money to put the Global Positioning System in place; and it does have limitations, but satellite positioning will probably become a utility as commonly used as the telephone by the turn of the century.

As we transition from all the past methods of navigation to a seamless Global Navigation System that will serve all users worldwide, we must keep safety and the needs of all users clearly in focus as the system is developed. No single failure, or even a second failure, should be allowed to seriously degrade the system.

Let us remember that if we are to be of any real value to the world, we must first be a servant. We must always keep the needs of the users in mind in every decision that we make. In the past year this organization has expanded its activities by taking a strong position as a user advocacy group to speak on behalf of 1.3 million Loran owners to keep the Loran system in operation. We have seen a strong response from both marine and aviation users and it has become apparent that there are a significant number of users who depend on Loran for precise timing and other functions.

You won't want to miss the panel discussion on Wednesday afternoon. Mike Moroney has assembled a distinguished panel of speakers to engage in a lively discussion on policy issues.

Wild Goose Association (International Loran Association)
23rd Annual Convention and Technical Symposium
Newport, Rhode Island, USA
Tuesday, November 1, 1994

Luncheon Remarks

by Randall J. Stevens

Mr. Stevens is the FAA Program Manager for the National Simulation Capability. He is with the FAA's Operations Research Service in Washington, D.C.

Before I begin, I think it's only fair to tell you that about two weeks ago, I called John Illgen and tried to duck out of making this presentation. I did so because we are reorganizing the aquisition group at the FAA and when that reorganization takes place, I will no longer be the National Simulation Capability Program Manager and, quite frankly, I wasn't sure whether John's invitation was still good under these altered circumstances. He said it was, so I'm here to speak and you're here to listen to what may well be my swan song.

Today, I would like to focus this presentation on three areas, geese, the National Airspace System, and finally the National Simulation Capability Program.

My understanding is that others have stood before you and made presentations on geese. I'm also going to do that but hopefully with a different slant.

You are already aware that geese are web-footed birds, closely related to ducks and swans. They range in size from 20 to 40 inches long which puts them between ducks and swans. There are 13 kinds of wild geese in the US and Canada of which Canada Geese are the best known type. Others include snow geese, blue geese, and brants. All are migratory birds, with habitats ranging from the Arctic Circle in the north to Mexico in the south. They may reach 30 yrs of age. They are superb aviators, flying with their companions in tight V-formations, rapidly honking loudly. Remember "honking loudly," you'll need to know that later. They climb as high as 29,000 ft. Remember that also for later.

In addition to being good aviators, geese are good navigators. I'm from the Washington, DC, area and we have thousands of geese that winter in our area, many on the eastern shore of Maryland, along the inlets and bays to the east of Chesapeake Bay. They come there from the Ungava Peninsula in northern Quebec, an area bordered on the west by Hudson Bay, on the north by the Hudson Strait, and on the east by Ungava Bay. This gives them a one way commute of 1800 miles. And I complain about my 13-mile commute to work in the morning.

Interestingly, while wild geese are born with navigation sensors and computers already installed, they are not born with a nav data base. That data base is acquired and loaded into their system only when they complete their first migration in company with older, more experienced birds. However, once they have completed their first migration and learned the route, they are capable of completing the trip on their own. Their system is programmed for life although they generally fly only between the same two areas.

Within the borders of the United States, geese are using and sharing the US National Airspace System with other aircraft. They are doing so without the benefit of:

- radios

- other required equipment such as transponders and altitude encoders
- pilot certificates, or
- aircraft registration

and they routinely flaunt airspace restrictions and violate Federal Air Regulations in a manner that would result in loss of certificate, steep fines, and perhaps imprisonment for other pilots.

If geese would voluntarily restrict their flights to airspace other than category A, B, C, or D airspace, they would be exempt from all those requirements. Since that is not always the case, then they must comply. By the way, category A airspace is all that airspace above 18,000 feet and to operate there requires a clearance from air traffic control.

Most recently, I had the personal experience of observing a gaggle of geese violating the Manassas, VA airport class D airspace. I observed them from the cockpit of my airplane and knew that they were operating without benefit of a clearance and were not communicating with the tower.

As a consequence of this natural but still disruptive behavior, geese, along with other migratory birds are a recognized hazard to aviation. Enough so that the FAA has a form, Form 5200-7, Bird Strike Incident/Ingestion Report to document the hazard. Additionally, advisories are issued to pilots for known hazards associated migratory birds.

The point is all this is that to legally use all the airspace in which they are currently operating, geese, in addition to their on board navigational systems, would require transponders, communication radios, and other instrumentation as necessary to comply with the FARs and with air traffic control clearances. Only when this is done, will geese cease to be a hazard to other aircraft. However, installation of these systems in your average goose would render that bird unairworthy. In fact, the goose is incapable of generating sufficient lift to get it all off the ground. And even if geese were transponder equipped, you could never get them to squawk "IDENT" since geese don't squawk, they honk.

Clearly, the possession of only superior navigational capabilities and piloting skills is not sufficient if you are going to operate in all the airspace of the NAS and avail yourself of all the services offered. You will need other things. You need procedures that are understood, in common, by both pilots and controllers; you need a communication system to transmit information; you need a surveillance system to help keep track of who's where; and more. Again, no single component is, by itself, sufficient. It is only when all these things are integrated into a coherent system that safe, efficient use is made of the airspace.

The questions becomes one of how you integrate any one or all these "apparent" stand-alone capabilities into an effective national airspace system? For example, how do you take advantage of the capabilities and potential inherent in a system like LORAN? Just having LORAN isn't enough. You also modify existing procedures or create new ones to use the potential. You likewise modify or add new ground based ATC components as necessary to accomodate the changes in procedures. And you decide what set of changes provides the best mix of capability. Just adding LORAN is not enough.

In past years this was more easily done. Traffic density was lower and ATC domains were only loosely coupled. These domains such as en route, terminal, and tower operated as separate fiefdoms where only borders were shared and procedures existed that controlled border crossings. Change could be instituted in one domain and have negligble impact on other domains. Individual programs were relatively independent of one another. Aircraft and their onboard systems were significantly less capable than today.

But that world is rapidly disappearing. By the year 2010, more people will be flying more often to more places than ever before. US airlines will carry more than one billion passenters and operations of general aviation aircraft will increase by 43% to 43 million flight hours annually. The demand for FAA-provided services will increase dramatically. The challenge of 2010 will be to assure that these flights are conducted with unprecedented levels of safety, security, and efficiency; that the environmental consequences will be acceptable; and that natural resources will be conserved.

With this increasing demand comes the technological revolutions that will enable those demands to be met. Proposed technologies such as LORAN span all the domains. But ultimately, at the core of the revolution stands increased automation; automation that is being installed on the aircraft and automation that is planned for ground-based systems. From advanced computers and next generation flight management systems for new aircraft to advanced computers and air traffic control systems on the ground.

One of the effects of this increased use of automation is that air traffic control domains are migrating from the loosely coupled system of the past to a more tightly coupled system of the future. It is serving to blur the lines of distinction between air traffic control domains and provide opportunities to challenge the traditional roles of the pilot and the air traffic controller. This technology is providing new ways of looking at air traffic control that can shatter the boundaries.

But with this opportunity comes the realization that building this tightly coupled system of the future is more difficult. It is harder to predict, through classic analysis or simulations of individual stovepipe components, what the system effects are going to be.

We have a sense of how an individual program will work and we can project how it will work in the context of today's system. This ability to project begins to break down when we try to project how many individual programs will work with each other, making up an entirely new system of the future.

To help bridge this gap, the FAA created the National Simulation Capability program four years ago to develop a capability to link simulation of individual components into larger systems simulations. The FAA has long used simulation as a tool in building individual components of the NAS for all the reasons you would expect. These include HCI development, requirements validation, operational concept development and performance analysis among others. There was a strong desire and perceived need to extend these same types of benefits for developing the overall system. Benefits would include early program evaluation, future concepts definition, functional allocation and evaluation across subsystems among others. National Simulation capability was intended to be a doorway to the future.

National Simulation Capability, or NSC, provides a complete, real-time virtual representation of air traffic control and flight operations in the future. It involves human controllers making decisions at consoles, and human aircrew making decisions in cockpits using completely integrated and fully interactive system components of the future.

We use large-scale simulation as a tool to examine, assess and evaluate system-wide effects, providing a consistent perspective across all components, visualizing how they fit together as the National Airspace System evolves and matures.

And by keeping humans in the loop, we keep the focus on the overall implications for controllers and aircrews and for the procedures both will use. These real time simulations include even the most subtle details of the real world such as severe weather or an unscheduled runway closure but do so in a safe, consequence free environment.

Today, we can link multiple, individual component simulations. Many of these are operating at the Integration and Interaction Laboratory (or I-Lab) in McLean, VA. We have linked multiple simulation Laboratories at the FAA Technical Center in Atlantic City, NJ. And, as we recently demonstrated at the Air Traffic Control Convention in September, we can link these two activities with each other. At both these locations, we have the capability of putting pilots in low to medium fidelity cockpits, controllers at workstations representative of future systems or at workstations identical to today's system, and we generate and control the hundreds of other aircraft required for a robust ATC simulation. In addition, we have the capability of linking with multiple high fidelity flight simulators located around the country whenever we have the need for pilots operating in an environment and with systems that most closely replicates the real world.

We can perform rapid, flexible prototyping involving controllers and pilots right from the start, we can increase the range of alternative technologies and operational concepts that can be evaluated and we can help stabilize requirements early in the development cycle before large resources are committed to creating expensive hardware and software for field testing.

There are tangible bottom-line benefits: systems can be field faster, at lower cost and with greater confidence that they will perform efficiently and safely within the total system and can be used by real people in the real world.

If this sounds like just so much hype, believe me, it isn't. Let's look at an example of how NSC was used to do just the things I've described.

In June of last year, under the sponsorship of the FAA's Office of System Capacity, a TCAS Separation Assistance Working Group, or SAWG, met to explore uses of the TCAS system beyond its original purpose and that would have the benefit of increasing overall system capacity.

TCAS is the Traffic Alerting and Collision Avoidance System, now installed in all large aircraft. In its primary role, it alerts the cockpit crew of potential threats and provides advisories on recommended avoidance manuevers.

The SAWG is composed of representatives from the airlines, the pilot's unions, the FAA, the National Air Traffic Controllers Association, and industry.

In a meeting in May of last year, a proposal was made to that group by United Airlines for an oceanic in-trail climb procedure. This procedure, based upon use of TCAS's range display would allow aircraft to climb to more fuel efficient altitudes under circumstances where previouly, in this non-radar enviornment, they would have been stuck at the lower altitude.

In July ,we brought together controllers, pilots and representatives from the airlines to participate in the first NSC simulations of this procedure in the I-Lab. We continued to run simulations in the I-Lab during the remainder of the summer and into the early fall as we evaluated and refined the procedure. These exercises were accomplished at a fairly low level of fidelity.

By late fall, the procedure was refined sufficiently that it could be evaluated in high-fidelity flight simulators with airline crews. The purpose of these exercises was to evaluate and assess the suitability of the procedure under varying environmental and aircraft conditions including various failure modes. They were the first exercises conducted involving line pilots. These evaluations were conducted by the two participating airlines, United and Delta, and the FAA in Oklahoma City. These exercises also assisted the airlines in developing the necessary training bulletins that would be used by their flight crews.

Finally, high fidelity simulations were run at the FAA Technical Center in the Oceanic Development Facility. Conducted shortly after the first of the year, these high fidelity exercises provided air traffic controllers with an operating environment that very closely replicated their real one and served the same purposes as previous evaluations: could the procedure be safely executed by field controllers. These evaluations resulted in the final refinements to the in-trail climb procedures.

Ten months after the procedure was first proposed on 8 1/2 x 11 paper, flight trials, involving United Airlines in one exercise and Delta Airlines in another, were conducted in April and May of this year. The procedure was approved this past summer for use on routes between the US mainland and Hawaii and its implementation is pending the completion of controller training at the Oakland En Route Traffic Control Center.

Implementation of this procedure has been called by others as the first major improvement in oceanic air traffic control in 30 years.

National Simulation Capability is not somebody's promise. It exists and it is providing the virtual environment to represent and envision today the National Airspace System of tomorrow.

But we still can't do anything about those geese.

Wild Goose Association (International Loran Association)
23rd Annual Convention and Technical Symposium
Newport, Rhode Island, USA
Luncheon Address, Thursday, November 3, 1994

Institutional Inertia

by John M. Beukers

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 Institute of Navigation's (ION) 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 senior member of the Institute of Electrical and Electronics Engineers, a member of the Institute of Navigation, a Director of the International Navigation Association, and a Director of the International Loran Association (formally the Wild Goose Association).

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

ABSTRACT

This address was given at the 23rd Annual Convention and Technical Symposium of the Wild Goose Association, now renamed, the International Loran Association. First, the address considers the integrity of the United States' Federal Radionavigation Plan suggesting that a clear, unambiguous statement of policy and a consistent, stable long-term plan is essential for the document to have credibility. The presentation goes on to describe the *Institutional Inertia* facing global acceptance of satellite navigation technology suggesting that an international initiative is required to nominate a single organization to provide leadership. A number of options are described. It is noted that Inmarsat already has the charter to fill the role if the Parties to the Inmarsat Convention will accept modifications to Inmarsat's internal structure and method of revenue generation.

FEDERAL RADIONAVIGATION PLAN

Those of us who make it our business to follow the development of United States radionavigation policy and plans can only describe the past 12 months as being frustrating and lacking in substance. Other than the user conferences last year, the process to produce the 1994 Federal Radionavigation Plan is being conducted in secrecy behind closed doors. To an outside observer the snippets of information that leak out give the impression that the planning process is confused, lacks coordination and is out of touch with the real world. Yet our government is spending more money on radionavigation today than at any time in the past, so why is it that we don't seem to be able to establish a rational policy and stick with it?

Perhaps the fundamental reason lies in our way of introducing new technologies without giving due consideration to what already exists and works. We practice a policy of all or nothing. Under the pretext of creating savings, and, in order to justify huge amounts of taxpayer's money being poured into a new technology, we go out of our way to disrupt what is useful and economic. Add to this our impatience for results; our excitement of the new; our throw-away culture that compels us to cast off the old; and we end up in a quagmire of indecision, confusion and excessive cost. To the nation's users this is not helpful. The international community might be amused if it were not for the fact that U.S. radionavigation planning has a direct financial and social impact on much of the rest of the world. Perhaps this fact is lost on Washington or our planners don't even care.

This all-or-nothing rush to new technology disrupts the present. Hundreds of thousands of current users become confused; industry is decimated, and proven technologies are denied to potential users. I know of no better example of this than by referring to a General Accounting Office (GAO) report issued well over a decade ago. The report has the title DOT Should Terminate Loran-C Development And Modernization And Exploit the Potential of the NAVSTAR/Global Positioning System. The report recommended that the phase out of Loran-C should commence in 1983; a ten year transition period be allowed; and that final termination of Loran-C service should occur by 1993. That was last year! DOT not only ignored the recommendation but responded by having the FAA fund a program to provide Loran-C coverage of the mid-continent. However, the image of Loran-C as a secure and valuable asset suffered and has never fully recovered. Are we seeing a repeat performance of this today?

Let's take a look at the record. With the signature of the Secretary of Transportation in 1974, Loran-C was adopted as the navigation system for the U.S. Coastal Confluence Zone. Just four years later GAO was calling for Loran-C termination and in 1981 recommended a phase out period of 10 years with final termination in 1993. The 1992 Federal Radionavigation Plan called for a 10-15 year transition period for Loran-C with a termination of 2015. Last year, at the FRP user conferences, the U.S. Coast Guard flew trial balloons suggesting that Loran-C could be removed from the budget by 1996. We hear that drafts of the 1994 FRP suggest termination of Loran-C in the 2003-2005 time frame with a "reasonable" transition period. Now we are told that Loran-C is to be removed from the Coast Guard budget in 2000 no matter what the 1994 FRP says.

Mr. President, I have difficulty in describing the conduct of our Government on this issue in polite terms but will settle for arbitrary and irresponsible. Our newly named International Loran Association is the only independent organization that represents the interests of well over a million U.S. users, the growing international user community and the supporting industry. As a watchdog the Association performs a unique and essential service, and I would like to take this opportunity to acknowledge the fine work of our Association's *Committee For a Balanced Radionavigation Policy* whose efforts are directed towards resolving the Government's indecision and the confusion it creates.

Today the U.S. has an opportunity, in the publication of the 1994 issue of the Federal Radionavigation Plan, to regain its authoritative leadership by providing a clear, long-term, unambiguous statement of radionavigation plans and policy. We sincerely hope that those who are responsible for the document see it this way, even if it means withholding publication to provide time for a thorough review for consistency and the policies contained therein.

ACCEPTING NEW TECHNOLOGIES

When John F. Kennedy set the goal of placing a man on the moon he did so with little risk that his objective would not be achieved. Few would question the magnitude of the technical challenge, but there were virtually no other obstacles. This was virgin territory. No agreements to be made; no international compromises to be reached; no legal barriers to hurdle; no existing systems or technologies to supplant - just plain technological innovation that money and time could, and did, buy.

But, by making the assumption that we are faced with purely technical challenges, we are attempting to apply the same approach to introduce satellite technology for global radionavigation; however, this is not a virgin environment. After many years of development and fine tuning we have built a worldwide decentralized infrastructure of reliable radionavigation systems that serve a large and diverse user-base covering a broad range of applications. These users must be recognized. As we convert to a centralized satellite-based system we are confronted with a host of new institutional, safety and certification issues that cannot be ignored or bypassed. The technical challenge can be likened to the childhood excitement of reaching the seaside and running over the sand to the sea. The moment we reach water, however, our headway is slowed and our ultimate speed in the deep water is determined by the environment not our own strength and agility. Institutional issues are found in this deep water which is the reason why those that give serious and responsible consideration to the introduction of satellite technology put sole-means certification out 10 or 20 years.

Yes, today we do have 24 Block II and the last of the Block I GPS satellites in the sky, but I would suggest that this is just the beginning of a long and tortuous path for satellite positioning and navigation technology to be *accepted* worldwide. Already GPS is being *used* by many throughout the world, but we must be careful not to confuse GPS's general use with acceptance of satellite technology. Acceptance has the much broader meaning of approval, authorization and certification, and all that lies beyond these words, while use is simply a statement of application. The hiker does not require GPS's acceptance to use a hand-held unit, but, under no circumstances would a responsible airline take the risk of landing an aircraft without full authorization and certification of its radionavigation equipment and acceptance of the signals that are employed. This is where we run into *Institutional Inertia*, and it is one of the main reasons why our projections, based on advances in technology, are frequently off by decades.

Can the politicians of a single State overcome this inertia by issuing policy, passing laws or making appropriations? It is improbable. Acceptance of systems for global radionavigation has to be the prerogative of the Special Agencies of the United Nations for these are the only institutions where the States of the world meet to reach a consensus. A single State may be the catalyst for action, but the rate of progress to reach the end goal faces the natural inertia of these international bodies over which we have little influence.

To speed up the acceptance of global radionavigation systems, their multimodal use must be recognized and appropriate action taken. Aviation interests through ICAO with substantial resources are leading the charge but represent the smallest user base. The mariners represented by IMO and IALA with limited resources are the next largest community but are barely heard. The largest segment of users is comprised of those on land, but it is fragmented and without a single voice. Others like the World Meteorological Organization (WMO), are on the outside looking in.

INSTITUTIONAL ISSUES

In virtually every report on global radionavigation system acceptance, the schedule for implementation is conditioned upon resolving Institutional Issues, but little of substance has been accomplished. What are these issues? Let me take a moment to remind you of some:

1. Ownership and Control - *Who, how, backup.*
2. Universal Access - *Availability to all.*
3. Source of Long-Term Funding - *Implementation of cost recovery methods, Contributions.*
4. System Longevity - *20, 30, 40 or more years.*
5. State Participation with System Implementation and Operation - *States need to participate.*
6. User Interfaces - *Organized centers and communications.*
7. Development of Legal Infrastructure - *Service provider binding agreements.*
8. Determination of Insurers' Exposure and Liabilities - *Insurance premiums.*
9. Compatibility with State Laws - *Modification and acceptance of new laws.*
10. Frequency Spectrum Allocation - *Worldwide navigation and communication frequencies.*
11. Interference from Registered Sources of Electromagnetic Radiation - *Working with interference lists.*
12. Security and Military Restrictions - *Agreements, if still applicable.*
13. Misuse by Renegade Parties - *U.N. Security Council issue.*
14. Unfriendly Jamming, Interference and Spoofing - *U.N. Security Council issue, National Security issue.*
15. Markets and Market Share - *Level playing field for competitive products.*
16. Global Trading Inequalities, Commodity Profitability - *Agriculture - sharing technological advances.*

So how do we go about reaching a consensus on how to deal with these issues in a multimodal, multinational user community? It is unlikely that a single State or one sector of the user community will be successful. For some time now I have advocated that a single organization under the auspices of the United Nations should be created and charged with the responsibility. However, this approach has not met with much enthusiasm and is usually dismissed as being too cumbersome and would take too long to set up. But two and a half years have gone by since the original proposal was made at the International Space Year Conference in Munich, and, to my knowledge, no viable alternative has been provided or accepted.

SOME OPTIONS

The procedure to get things moving is relatively simple and has precedence. The organization of Inmarsat was created out of a Convention made at a Conference resulting from a resolution passed by the Council of the International Maritime Organization. It would be a simple matter for the ICAO Council, for example, to pass a similar resolution if it was so disposed. Attendance at the Conference would be multinational representing multimodal interests and would involve the Special Agencies of the United Nations and other international organizations. The objective would be to formulate a Convention on Global Radionavigation.

If IMO, representing marine, and ICAO, representing aviation interests, fail to take the initiative, and in the absence of an organization representing land use, there is an alternative, perhaps simpler and more direct, approach whose success depends largely on acceptance by the communications and navigation community rather than consent by established international organizations. In his keynote address to the ION GPS meeting in Salt Lake City a few weeks ago, Olof Lundberg, Director General of Inmarsat, made it quite clear that his organization stood ready to add radiodetermination (i.e. positioning for navigation) to its global communications services, as permitted under Article 3 of the Inmarsat Convention of 1979.

Despite the competence granted under Article 3, actual implementation of this major new service would predictably require structural changes within the Inmarsat organization and a different method of funding. The administrative procedure for making these changes is contained in the Inmarsat Convention and subsequent amendments. Briefly, the procedure goes like this: The Director General, or one of the 75 Inmarsat Parties, places a proposal on the agenda for a regular session of the Inmarsat Assembly that meets regularly every two years. At the commencement of the Assembly a simple majority votes in favor of the agenda. The proposal is discussed and voted upon. Assuming adoption, Inmarsat would then be able to provide radiodetermination-navigation services in accordance with the new structure and procedures.

It sounds too simple: so what are the hurdles? Inmarsat's current corporate structure and cost recovery methods for its communication services are not compatible with radiodetermination services. The Parties to the Inmarsat Convention will have to agree to an alternate or augmented internal institutional arrangement which will permit State contribution of components for the satellite service and State funding on a worldwide basis. Whether an agreement can be reached will depend upon the financial integrity of the proposal; the willingness of States to contribute; and the success of convincing the communication-oriented Parties that it is in their best interests to offer the new service. The complementary nature and advantages of offering both services will have to be promoted and sold to the Parties' that are essentially Post and Telegraph organizations.

There are those within the Inmarsat organization who are optimistic that an agreement can be reached but recognize that success will rest on creating an acceptable proposal. With the Parties concurrence it will then remain up to the radionavigation community to participate and to be sufficiently broadminded to endorse Inmarsat as the provider of a civil global service.

FUTURE MEETINGS

It is no secret that the organizers of the 1995 Moscow Conference have it in mind to bring together a multinational, multimodal cross section of radionavigation interests. The Conference format has been designed to encourage discussion and debate of institutional, policy and management issues. At the final session of the Conference it is expected that a Resolution concerning global radionavigation will be passed to reflect the consensus of those attending. Perhaps the Moscow Conference may act as a stepping stone and the resolution serve as a catalyst for further action.

With a similar objective in mind, IALA is to conduct a Seminar and Workshop in Cape Town, South Africa on November 13-15, 1995. This seminar will address planning and coordination of intermodal radionavigation services as they affect central and southern regions of Africa. The agenda and cast of characters for this meeting have much in common with that of the Moscow Conference.

My concluding words must be a plug for Moscow 95. What better incentive is there for you to be with us in Moscow on this unique and potentially historic occasion to help reach a radionavigation consensus that could be taken forward to the IALA Seminar, passed to the IMO and ICAO Councils for consideration, and submitted to Inmarsat for distribution to its Parties.

Thank you for your attention. If there is time Mr. President, I would be pleased to address comments or questions from the floor.

John M. Beukers

September 30, 1994

Symposium Papers

Session I

Systems Development

THE DEVELOPMENT OF LORAN C AND CHAYKA COVERAGE IN THE WORLD

N. WARD

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Abstract

The developments in Loran C and Chayka worldwide are discussed. New agreements to support Loran C and form links with Chayka chains are considered and the status and future of existing systems are reported. The standardisation of coverage prediction methods is discussed and overall world coverage reviewed.

Introduction

The intention of the U.S. Authorities to withdraw from overseas Loran C chains has initiated considerable activity to arrange for the continuation of these services. Changes which have led to the establishment of the Commonwealth of Independent States have enabled greater co-operation with other administrations, leading to the development of joint Loran C/Chayka chains in several regions.

Two areas of the world, North West Europe and the Far East have signed agreements on the provision of radionavigation services using Loran C and Loran C/Chayka respectively.

India has replaced its Decca Navigator chains with Loran C and other countries are considering similar moves. It can be seen that Loran C/Chayka coverage is greater and is expanding at a greater rate than ever before.

Existing Systems

North America
The status and future prospects of the continental U.S. Loran C system will be covered in detail by other speakers. The international community is aware of the internal U.S. discussions on funding, but takes as the official position that set out in the 1992 Federal Radionavigation Plan, that the existing 8 chains will continue in operation until at least 2015.
Canada's Loran C stations remain part of two chains on the West Coast (Canadian West Coast and North Central U.S). The Canadian East Coast chain includes the secondaries at Cape Race and Fox Harbour. The Labrador Sea chain will be decommissioned at the end of November, with the impending closure of Angissoq. It will be replaced on Dec. 1st by a new chain: Newfoundland East Coast (GRI 7270) with, as its master, a new station at Comfort Cove (Newfoundland) and secondaries at Fox Harbour and Cape Race. Coverage is shown in Fig. 1. There are no plans to discontinue the Canadian Loran C service.

Commonwealth of Independent States
The four Chayka chains continue to operate and their coverage maps are shown in Figs. 2 - 4. The European chain consists of 5 stations with the master located at Bryansk (Russian Federation) and secondaries at Petropavlovsk (RF), Slonim (Byelorussia), Simferopol (Ukraine), Syzran (RF).

The East chain of 5 stations, all in the Russian Federation, has the master at Aleksandrovsk - Sakhalinsky and secondaries at Petropavlovsk - Kamchatsky, Ussuriysk, Kurilsk and Okhotsk.

The North chain of 4 stations has the master at Dudinka, secondaries at Taimylar, Pankratyer and Inta. The North-West chain of 3 stations uses Inta as the master, with Pankratyer and Tumanny as secondaries.

The system provides an accuracy of 120 - 1500m (RMS) over an area of approximately 20m km^2 and is planned to remain in use until 2015.

Saudi Arabia
The two chains, North and South, have been re-configured with masters Afif and Al Khamasin respectively. Secondaries are Saliwa, Ash Shaykh Humayd, Al Mumassam (North) and Saliwa, Afif, Al Mumassam (South).

India
Two Loran C chains have been established in India. East coast (Fig 5) with the master at Balasore and secondaries at Patpur and Diamond Harbour; West coast (Fig 6) with the master at Dhranghadhra and secondaries at Veraval and Billimora. These replaced the Bombay and Calcutta Decca Navigator chains. There is a proposal to add a transmitter to the West coast chain, at Mandin, thus replacing the remaining (Salaya) Decca Navigator chain. Further Loran C coverage may be planned for other parts of India.

Europe
The Mediterranean chain is operating without the Kargabarun (Turkey), secondary at present due to mast failure, but it is hoped to restore this with support from the European Union and the C.I.S. The stations at Sellia Marina and Lampedusa (Italy) and Estartit (Spain) continue to operate and negotiations for their takeover by the host countries are well advanced.

The Norwegian and Icelandic chains continue in their present form until at least the end of 1994, when the new North-West European Loran C System (NELS) comes into being.

Developing Systems
NELS:
NELS will include all the stations in the present Norwegian chain, with the exception of Sandur in Iceland. The stations will be re-grouped, together with three new stations in Norway and Ireland and the two existing French stations, to form four new chains, Lessay, Bo, Sylt and Ejde.
The present expectation is that the overall coverage shown in Fig. 7 will be in place by mid-1995.
FERNS:
The Far East Radio Navigation System (FERNS) is well advanced, with the revised North West Pacific chain (Master Niijima) expected to start operating on 1st October 1994. The East Asian chain began joint operation in July 1993. The powers of the Korean stations at Pohang and Kwangju are expected to be increased to 150kW and 50kW respectively by the end of 1994. The joint Russian/American Chain in the Bering Sea is now operational. The China North Sea and China East Sea chains are in trial operation. The China South Sea chain has been in operation for some time. The coverage from the whole system will be as indicated in Fig. 8 and there is potential for further expansion to link up with the Indian chains.

Systems Under Consideration

Iberian/Mediterranean/Black Sea
Various developments of the Mediterranean chain are being discussed. A system covering the Iberian peninsula, including the Azores and the Canary Islands is being considered by the countries concerned. This would possibly share stations with both the Mediterranean chain (Estartit) and NELS (Soustons).
Various proposals have been made to cover the eastern end of the Mediterranean and the Black Sea. These include a new chain with Kargabarun as the Master, Sellia Marina and Simferopol (Ukraine) as secondaries together with Ash Shaykh Humayd (S. Arabia), or a new station in Crete or Egypt.

Barents Sea
Norway and Russia are discussing a joint chain covering the Barents Sea, with links to NELS Boe chain and the North West Chayka chain. In the short term, it is proposed to add the Chayka station at Tumanny to the Boe chain as an additional secondary. This is planned before the end of 1996.

Baltic Sea
Russia, Germany and Norway are engaged in discussions on a joint chain to cover the Baltic. This would use existing stations at Sylt (NELS) and in the European Chayka chain. A new station would be required, possibly at Kaliningrad.

South Africa
The proposals for a Loran C system in South Africa have not been finalised, because of the change in Government earlier this year. A radionavigation policy for South Africa has been prepared for consideration by the Government.

Coverage Prediction Methods

Various coverage diagrams have been presented. Not all of these have been derived using the same methods or criteria.

Comparing coverage predictions from two sources for one particular chain, would show that they can be quite different. This is not because one is right and one is wrong. They are both right, but use different criteria and include or exclude some factors. This can lead to confusion for both the planner and the user. There is a good case for standardising on one method, but which should we choose?

The most widely used method has been that developed by the U.S. Coast Guard. However, in the development of NELS, it was found that interference could be the limiting factor and this was not included in the U.S.C.G. model. It was therefore decided to develop a modelling system which took account of this. It is suggested that the coverage model developed for the NELS should be adopted as the standard method. It has been described in papers presented at previous WGA Conventions and is now freely available to any authority or administration wishing to use it. Enquiries should be addressed to the NELS Co-ordinating Agency in Oslo or to IALA in Paris. Worldwide databases of ground conductivity, atmospheric noise and interference sources will need to be developed and a programme of work to achieve this needs to be planned.

Conclusions

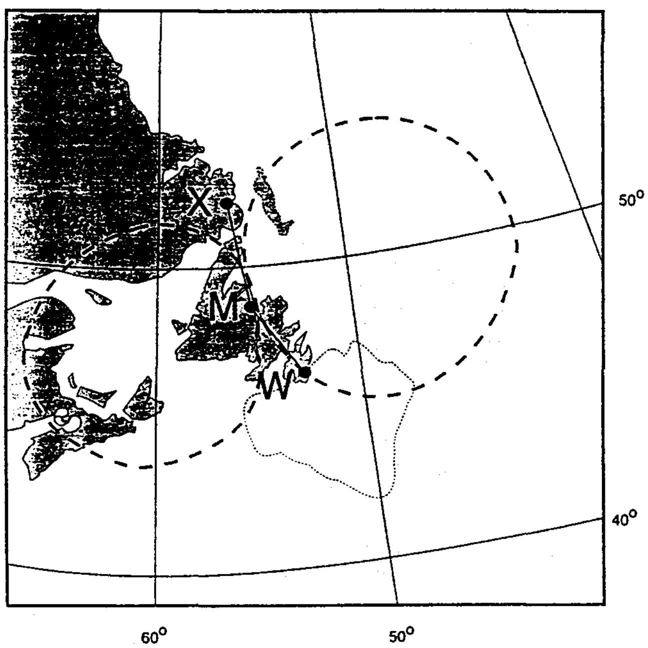
Coverage of Loran C/Chayka is greater than it has ever been before. If we compare the coverage when the U.S.C.G. announced its withdrawal (Fig. 9) with present coverage (Fig. 10) and projected coverage, if current plans are fulfilled (Fig. 11), we can see that Loran C/Chayka has the potential to provide coverage over a large proportion of the world's surface. It is clearly the only viable terrestrial system which can provide a complementary service to future global satellite navigation systems.

Biography

Nick Ward is Principal Development Engineer with Trinity House Lighthouse Service, responsible for the R & D Program of the three General Lighthouse Authorities in the U.K. and Ireland. He is a member and past secretary of the IALA Radionavigation Committee and was closely involved with the development of the North West European Loran C System.

LORAN - C COVERAGE (PREDICTED)
NEWFOUNDLAND EAST COAST CHAIN (7270)

FIGURE.1

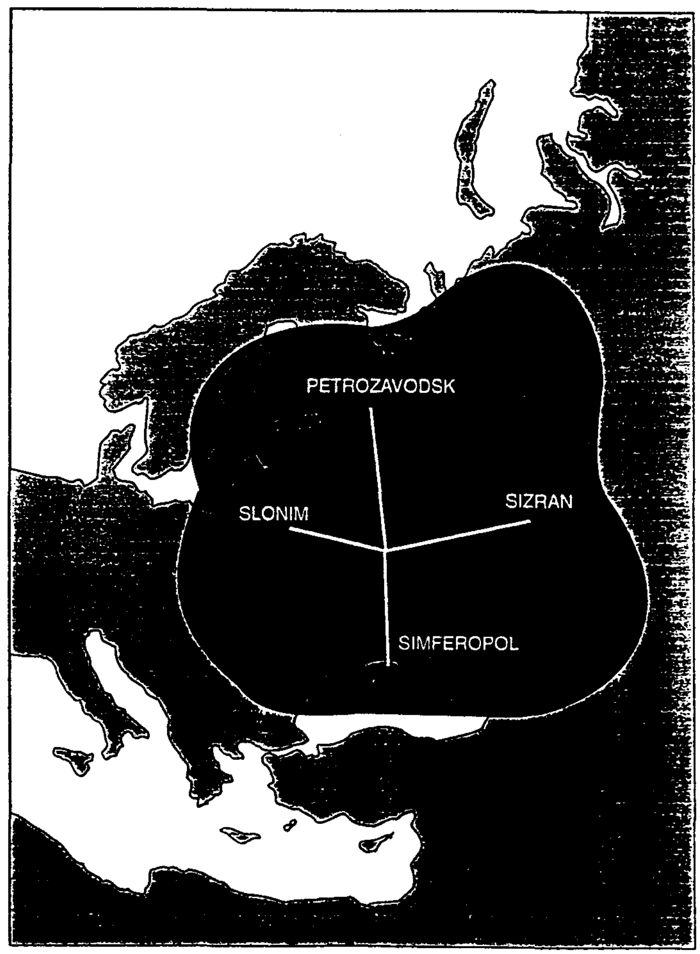


M - COMFORT COVE
W - CAPE RACE
X - FOX HARBOUR

APPROXIMATE LIMITS OF COVERAGE - 1:3 SNR AND 1/4 N.M. REPEATABLE FIX ACCURACY (95% 2dRMS)

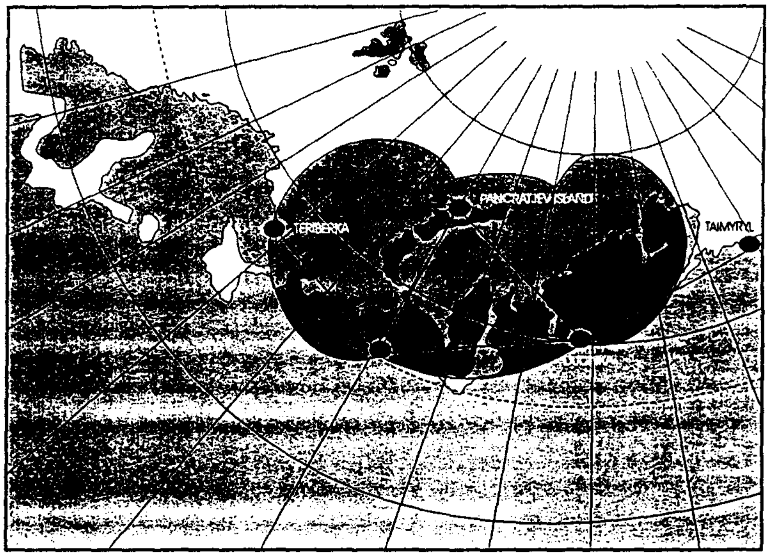
CHAYKA EUROPEAN CHAIN COVERAGE AREA

FIGURE 2



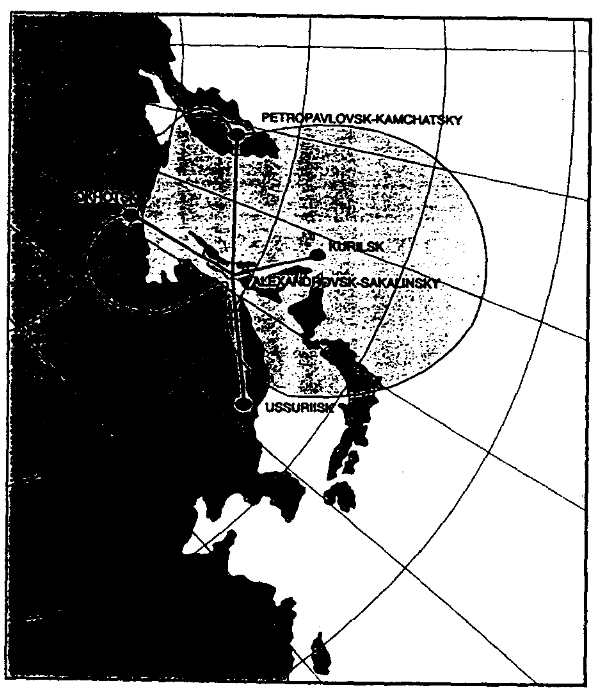
CHAYKA COVERAGE AREA
OF NORTH-WEST AND NORTH CHAIN

FIGURE 3



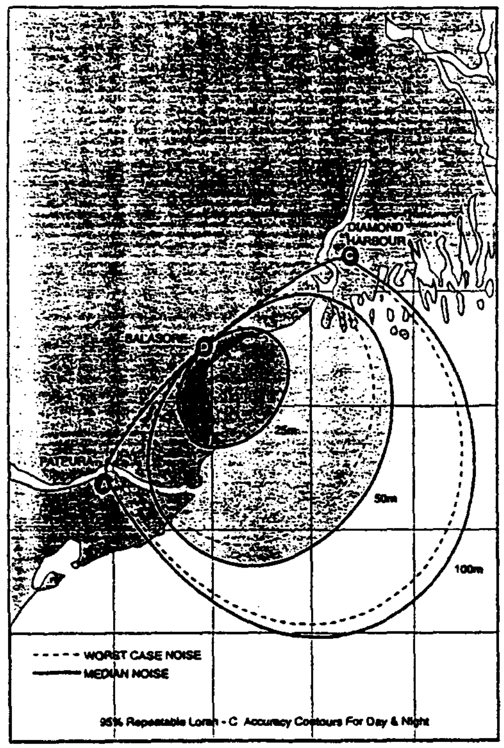
CHAYKA EAST CHAIN COVERAGE AREA

FIGURE 4



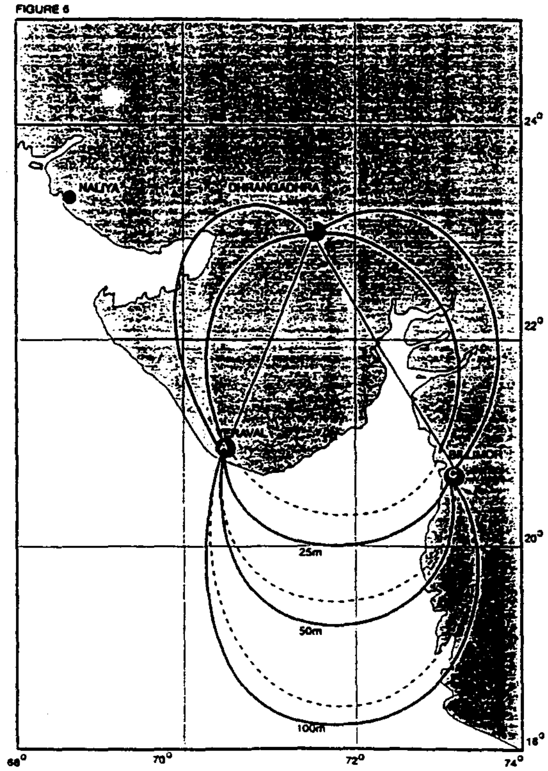
CALCUTTA LORAN - C CHAIN

FIGURE 5



BOMBAY LORAN - C CHAIN

FIGURE 6



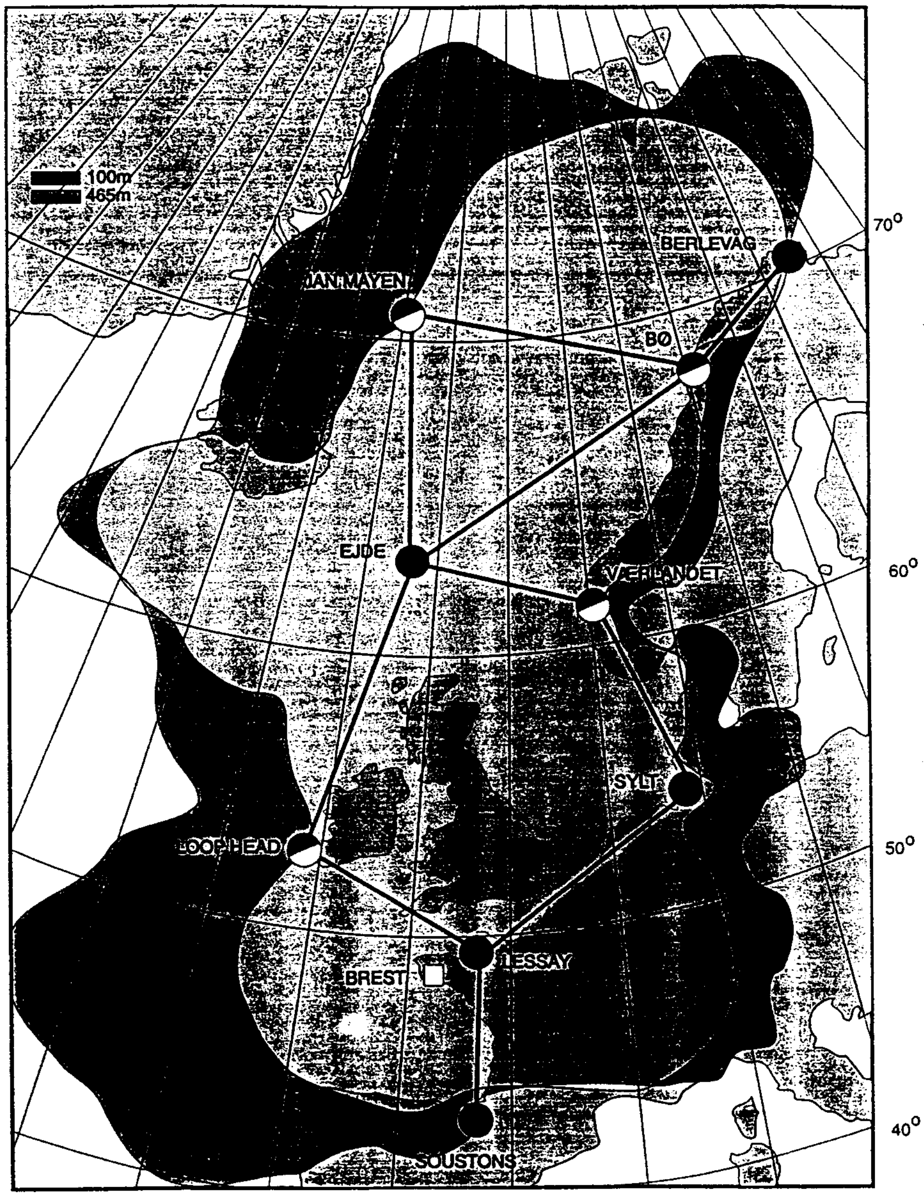
95% REPEATABLE LORAN - C ACCURACY CONTOURS FOR DAY & NIGHT

- - - - - - - - WORST CASE NOISE

———————— MEDIAN NOISE

PREDICTED COVERAGE OF THE NORTHWEST EUROPEAN LORAN - C SYSTEM (NELS)

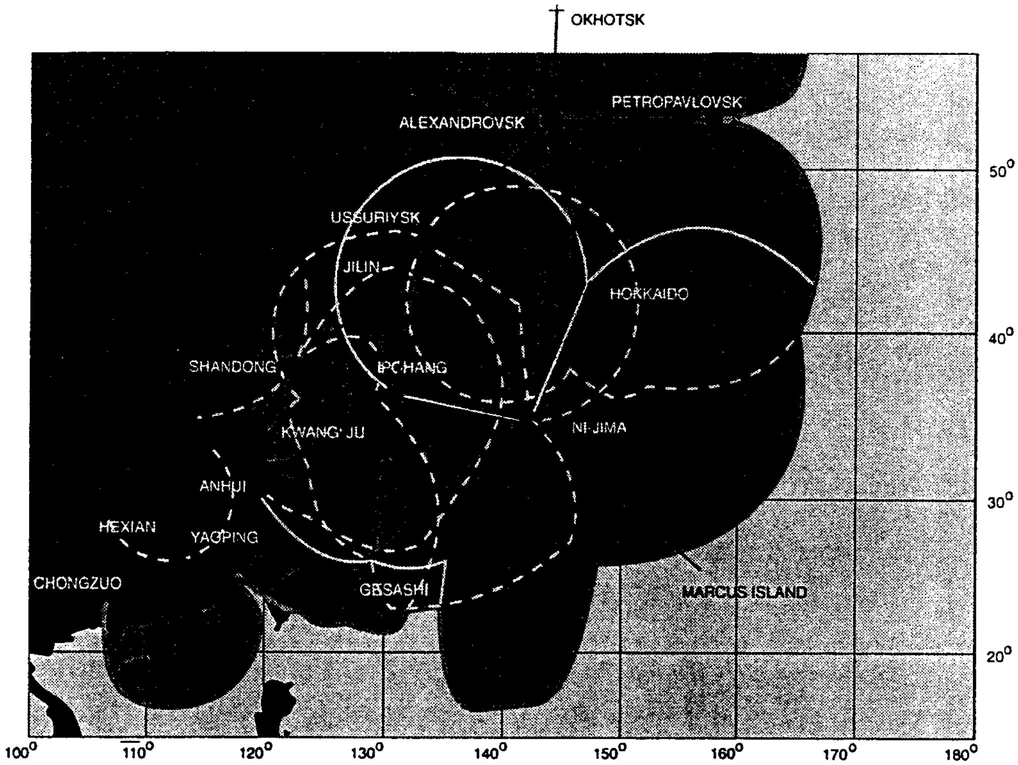
FIGURE 7



○ SINGLE RATE
◐ DUAL RATE
□ CONTROL CENTRE

FIGURE 8

FERNS COVERAGE



Loran - C Coverage Diagram 1990

FIGURE 9

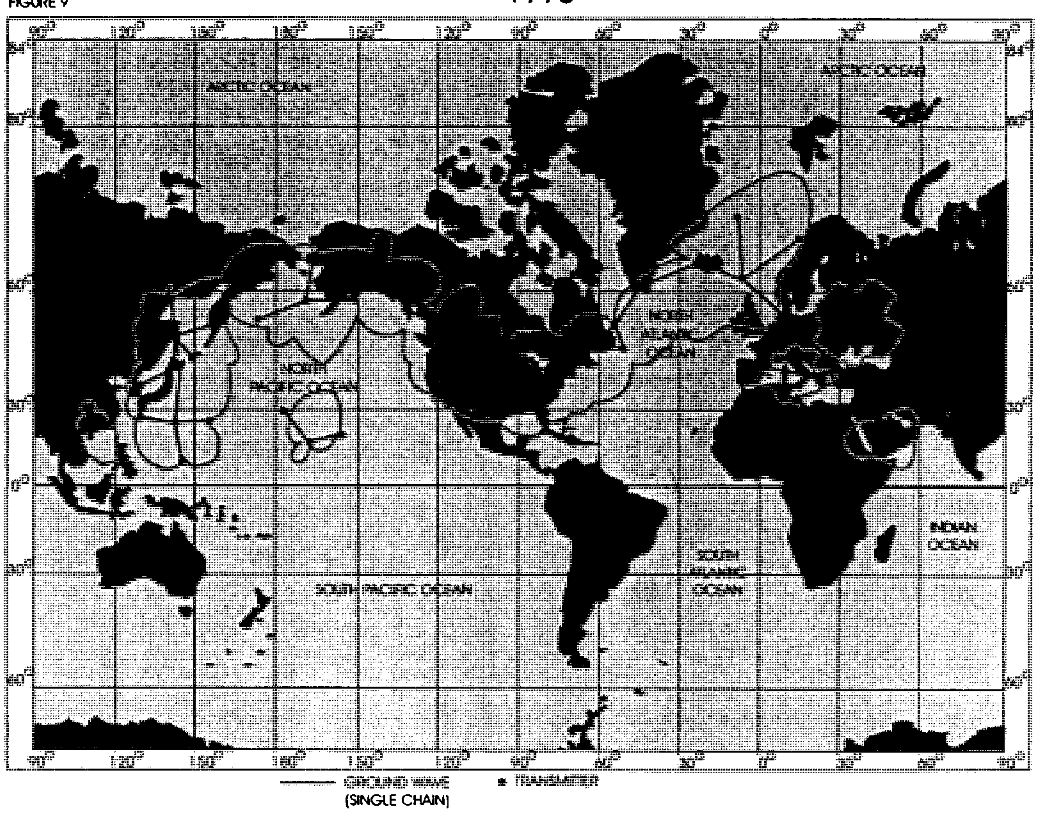


Figure 10

Loran - C Coverage Diagram
1995

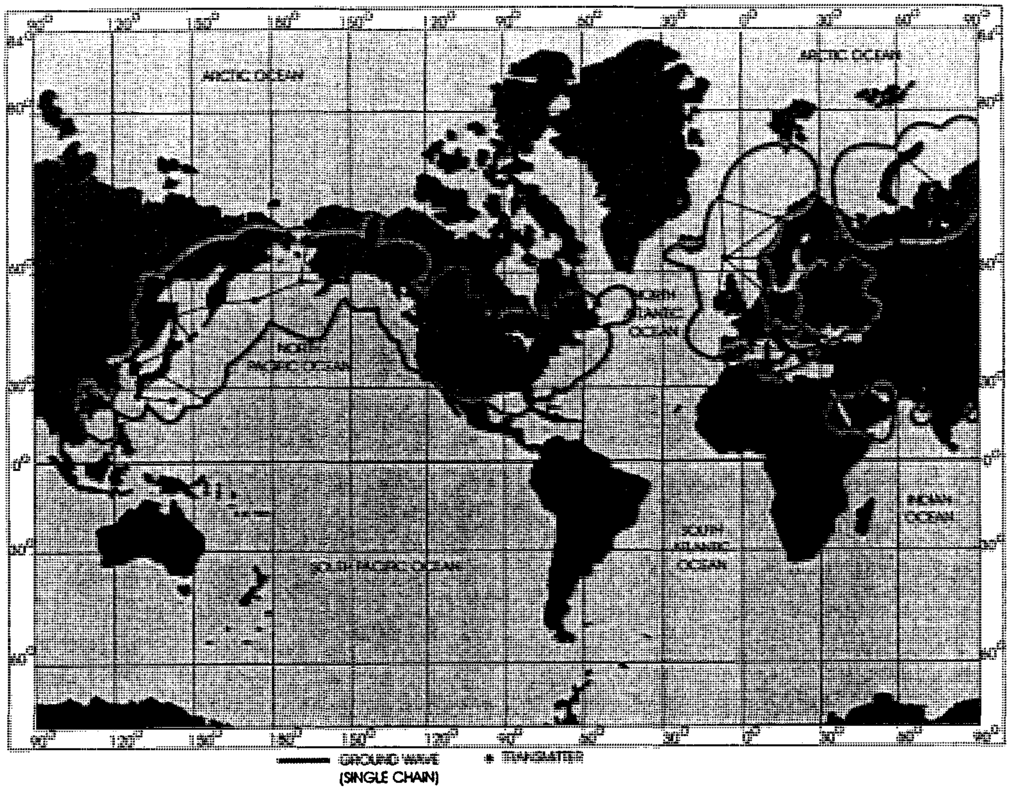
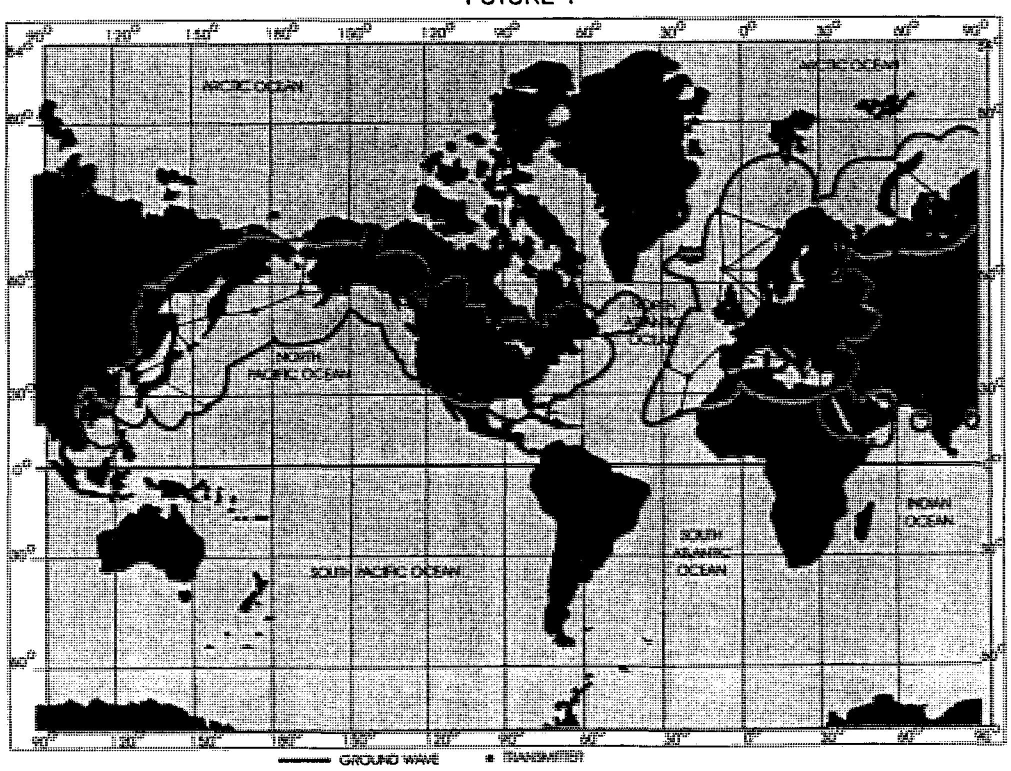


Figure 11

Loran - C Coverage Diagram
FUTURE ?



CO-ORDINATION OF LORAN-C/CHAYKA G.R.I's BY IALA

N. Ward (International Association of Lighthouse Authorities)

Introduction

The United States Coast Guard (USCG) will cease operating Loran-C in the international arena, with effect from 1st January 1995. The USCG has advised on GRI selection in the past. In a letter dated 20th August 1993, the Chief, Office of Navigation Safety and Waterway Services requested that IALA should take over the role of international co-ordinator for Loran-C Group Repetition Intervals (GRI).

Loran-C and Chayka systems are still developing worldwide. GRI assignments must be co-ordinated in order to avoid Cross-Rate Interference or duplication of GRI use and to optimise performance. GRI affects tracking error, susceptibility to Carrier Wave Interference, blanking periods for dual-rate stations and effective range, as well as incidence of Cross-Rate Interference.

Selection of good GRIs can significantly affect coverage and the processes and criteria involved in GRI selection and coverage prediction are inter-related.

The IALA Radionavigation Committee has been tasked with recommending a procedure for co-ordinating GRIs.

Proposed Procedure

Organisations wishing to establish a new Loran-C, Chayka or Loran-C/Chayka radionavigation network or alter an existing network would obtain clearance for the use of the proposed GRI from IALA.

A request for clearance to use a specific GRI would be made in writing to IALA accompanied by a report demonstrating compliance with the criteria for establishing GRI's as defined in the Annex to this paper.

Upon receipt of the request accompanied by the Compliance Report, IALA would establish that the GRI is not already in use or previously assigned, by reference to the master GRI list held by IALA.

IALA would undertake to notify all current IALA members and current providers of Loran-C and Chayka services of the request, thereby providing an opportunity to comment. Providers of Loran-C and Chayka services would be sent a copy of the Compliance Report for review and would submit their response within a stipulated period.

IALA would notify the requesting Organisation of the results of consultations and clear the proposed GRI for use, or provide reasons for not clearing the request within a stipulated period. Copies of the Compliance Report and IALA notification would be made available to other organisations upon written request to IALA.

To avoid requesting an unsuitable GRI, IALA would provide, upon written request a list of Loran-C/Chayka transmitting stations, their locations, power and GRIs in use and GRIs previously assigned.

Timescale

This proposed procedure is to be considered further by a meeting of the IALA Radionavigation Committee in March 1995 and the criteria for selection will be finalised at that time.

ANNEX

CRITERIA TO BE USED FOR LORAN-C/CHAYKA COVERAGE PREDICTIONS AND GRI SELECTION

Parameter Value/Source

Field Strength
Ground conductivity Bangor map 3 Jan 91
Attenuation curves CCIR Rep. 717-2

Atmospheric Noise
Source of data CCIR Rep. 322-3
Calculation Method COMDTINST 16562.4
Element size 10° x 10° lat/lon

Carrier-wave interference (CWI)
Source of data IFRB
Band omitted 90-110 kHz
Modification Decca stations
Propagation modes Groundwave, Skywave
Summing rule RSS

Notch filters used to calculate CWI strengths
Number 3 + 3
Tuning ranges 50-100/100-150 kHz
Notch filter model Triangular
Centre depth 30 dB
Width +/-1 kHz
Tuning Strategy Select worst after receiver filters

Receiver filters
Bandpass filter Butterworth 5th order
Tracking loop bandwidth +/-0,1 Hz

Geometrical limit
Accuracy contours
463 m (1/4 NM) 2σ
TD standard deviation based on SNR and SIR

ECD Limit
Source of data Sherman's curve
Limiting ECD values +/- 2.4 μs

Skywave interference limit
Skywave delay data USCG
Skywave field strength USCG/Decca (99% ile)
Time Period Winter Day
Operating limits RTCM70, IEC80

GRI Criteria

- The interval should be long enough to accommodate the Time Differences of the secondaries, but should be minimised to increase effective power.
- Prime numbers should be used if possible.
- Existing GRIs should not be used.
- Free timeslots should be allowed for TOE control, if required.
- Tracking errors should be minimised.
- Cross-rate interference should be minimised.
- Blanking periods should be minimised.

THE CONCEPT OF APPLICATION OF THE CHAYKA/LORAN-C RNS FOR RADIONAVIGATION SUPPORT OF MARINE, AIR AND LAND USERS

Vladimir Demisov
Internavigation Committee

Presently Russia has established and operates a well-developed navigation support infrastructure based on ground radionavigation systems, space navigation systems and various special short-range radionavigation systems. The basic trends in developing radionavigation aids are stated in the Russian Radionavigation Plan and the Intergovernmental Radionavigation Program of the member states of the Commonwealth of Independent States.

The existing radionavigation systems have various coverage areas depending on their designation - from local to global - and meet user requirements to various extent. Chayka/Loran-C radionavigation systems meet marine, air and land user requirements in short-range and remote navigation areas for aircraft flight, sailing and land en route transportation support in all aspects except availability.

Excellent technical characteristics of Chayka/Loran-C RNS, adequate number of air and marine users and relatively low operational costs predetermine their efficient application in the near future.

Chayka and Loran-C systems are used and will be used in the following areas:

- continued self-contained utilization;
- joint operation of Chayka/Loran-C RNS when establishing international chains;
- integration of Chayka and Loran-C RNS with GLONASS/GPS.

Continued self-contained operation of Chayka and Loran-C RNS is stipulated by possible improvements in their coverage areas and position accuracies via application of receivers operating with two or more different chains.

Integration of Chayka/Loran-C RNS when establishing joint international chains is being implemented. In compliance with the Agreement between Russia and the USA as of May 31, 1988, a joint Russian-American Chayka/Loran-C chain has been established comprising of two

Russian stations (in Aleksandrovsk-on-Sakhalin and Petropavlovsk-on-Kamchatka) and one American station in Attu which significantly increased their radionavigation field (by 25%).

Establishing of similar joint chains is covered by a number of agreements:

- in the East-Asian region between Japan, China, the Republic of Korea and Russia;
- in the Mediterranean and the Black Sea region between France, Italy, Turkey, Egypt, Spain, Greece, Russia, Tunisia, Algeria and Morocco;
- in the North-West and the Baltic Sea region between Denmark, France, Germany, Netherlands, Russia, Norway and Iceland.

Integration of Chayka and Loran-C radionavigation systems will significantly improve the efficiency of their combined application. For their integration it is necessary:

- to select a common coordinate system for their stations and insert it into user receivers;
- to select a common time scale for accurate timing of transmissions from their stations;
- to develop integrated user equipment with additional non-standard modes of operation.

Integration of ground-based and space RNS has allowed to produce an integrated radionavigation system which outperforms each of its components used separately. As in the case of integrating space systems integration of ground-based and space RNS navigation support is 0.997 to 0.998 for each of them, their integration characteristics will in practice approach unity.

Chayka (Loran-C) and GLONASS (GPS) radionavigation systems being integrated can be used in future as principal navigation aids on all stages of navigation except categorized approach and landing and maneuvering in harbors.

Integration of radionavigation systems facilitates establishing of the concept of a unified radionavigation field. The unified radionavigation field is a totality of integrated radionavigation fields of ground- and space-based RNS which have a common (matched) coordinate and time systems and a coordinated signal structure. Such coordinate-time basis and matched navigation signal structure allows to develop a unified family of integrated receivers.

Combined processing of navigation parameters on the basis of measurements from three arbitrary radionavigation signals (one satellite and two ground stations, two satellites and one ground station, etc.) will improve navigation determination robustness. Redundancy of measurements in a single radionavigation field will allow to monitor radionavigation system quality practically in real time.

For instance, with GLONASS SNS orbital block having 12 satellites position determination probability in the coverage area of a ground-based RNS improves from 0.68 to 0.82 and to 0.99 with additional one or two ground stations.

Combination of ground system functions with those of "pseudolites" and realization of differential GLONASS (GPS) subsystems can improve accuracy to units of meters (centimeters with carrier phase measurements) with simultaneous improvement of navigation support availability and integrity in regions equipped with ground-based stations. Such a united radionavigation field can be based on the GLONASS/GPS radionavigation field.

Application of a united radionavigation field will allow to meet requirements of main user groups, as well as to increase the probability of continuous navigation support and mutual monitoring of space- and ground-based RNS.

Formal Verification in Navigation System Design

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Abstract

Correctness of design is becoming more of an issue as complexity and size of electronic systems increases. To overcome this problem, formal verfication can be applied to observe the behaviour of the design on various levels of abstraction. This method is based on an analysis of the transition graph of a model of the system under design. As has been shown in real life examples, formal verification can be used as an additonal powerful tool the designer can use to tackle the increased complexity of todays systems. The paper describes the benefits and drawbacks of this method, and illustrates it with the application to a real time navigation system.

1 Introduction

Verification of navigation systems has always been an issue, especially for airborne receivers. Exhaustive test were developed to verify if a receiver performed according to its specifications. In the era of mainly analog circuitry with its susceptibility to temperature, humidity, vibrations and power levels of signals, these tests were quite acceptable to verify correct behavior of receivers. With advancing technology in areas of design and fabrication, receivers grow in complexity and capabilities, and rely more and more on software and digital hardware. Where simulation was traditionally suitable for checking proper operation, it is now overtaken by the increase in complexity of today's systems. The number of states a receiver can remain in and the number of transitions possible from all these states is that high, that exhaustive simulation is not feasible anymore due to the length of the test. This carries the increasing risk of detecting errors only late in the design cycle, or worst case, after the product is out on the market.

New ways of exploring the state space are required to handle the increase in complexity in an efficient way. Preferably, one would like to detect possible design flaws in an early stage. I.e. it should be possible to check abstract models of the functions to be implemented on consistency and unwanted behavior. In this way, models for different parts on different levels of design can be verified before a refinement in the design is made. After these models passed the test, a more detailed model of a smaller part of the system can be verified, and is followed finally by the actual implementation of the system. This verification process is called Formal Verification, since the verification is based on formally (mathematically) proving that a certain implementation satisfies a specification, or that a specification excludes certain undesired behavior. The next section will describe in more detail the basics of verification. Section 3 presents an example to illustrate this verification process. Section 4 presents the application of this method for more complex systems. Section 5 discusses the current developments in the software used for verification and the implication and usability of Formal Verification in the design of navigation systems.

2 Formal Verification

The previous section already mentioned that Formal Verification exists of formally checking an implementation against its specification. That is, proving formally, with the aid of mathematics, that a certain implementation satisfies a specification. To perform this check, a formal semantics has been defined to describe a system and a specification. The proof methods are based on operations within the boundaries of these semantics, hence its name *Formal* Verification.

The main strength of this method is that it operates on sets of states instead of on each state individually. Input variables cause the system to transfer from one set of states to another set. By coding the sets of states by Boolean functions, and by coding these functions in an efficient and canonical way, operations on the state space can be easily implemented/performed [1]. E.g if the Boolean functions are represented by Binary Decision Diagrams (BDD's), equivalence checking is reduced to a comparison of two binary tree-structures. Furthermore, it opens a whole range of algorithms to manipulate these BDD's.

There are several flavors of Formal Verification:

1. Theorem proving
2. Equivalence Checking
3. Model Checking
4. Language Containment

Theorem proving is based on reasoning with sets of axioms and assumptions over a relation between an implementation and a specification. The software, guided by the user, checks the consistency between the specified relations. The main problem is that there is still quite some input required from the user, which makes it difficult to expand this system to handle more complex and larger designs. Equivalence checking is used to prove that two models are logically the same under a set of constraints. E.g. to prove that an implementation which is optimized by using the don't care conditions of some input variables is logically equivalent to the original specification. This method is very useful in checking the correctness of the implementation with a higher level description, but less practical for checking (un-)desired behavior. Model Checking relies on the explicit state transition graph representation of the system to be verified. The main problem in this approach is the dependency on the number of states of the system. This number generally increases exponentially with the number of components (latches/variables), which limits the use of this approach to smaller circuits. With language containment, the system to be verified is described as an automaton, over which a certain language is defined. This language is a set of strings of input characters accepted by this automaton. In general, the system to be verified as well the properties to be verified are modelled as finite state machines (FSM's), each accepting a certain language. The properties are used to specify a certain correctness of the operation. E.g functional (the operation does what it is intended to do), safety (nothing 'bad' happens) and liveness (finally something 'good' will happen).

If all the sets of input strings of the automaton to be verified can not bring the property automaton into its final state, this system does not exhibit this (undesired) property. The check whether the property can reach the dead state or not is performed by taking the intersection of the languages (hence its name language containment). If this intersection is empty, there is no common input sequence between the bad property and the system, hence it is not possible for the system to exhibit this undesirable property.

This latter method is the basis of the Berkeley developed software for verification HSIS (Hierarchical Interactive Sequential System)[2].

For a detailed introduction into various aspects and backgrounds of Formal Verification, the reader is referred to [3].

3 Example

The first step in design is to develop a global model of the system. Before this model is refined and implemented, one would like to verify that this model is correct, that is, shows correct behavior with respect to all possible inputs. This global model expresses only part of the functionality, e.g. one could describe a handshaking protocol in a communication system, without modeling all the inner details of the functional blocks. The behavior of this conceptual model can be verified to find possible design flaws in this protocol.

A small example is worked through to illustrate the modelling and verification process. Imagine two functional units (FU's) which are both able to access a common bus. Depending on external inputs, both FU's can write data to this bus (see figure 1). In this particular example, FU 1 is able to either write the data directly to the bus or perform an operation on it before writing, depending on the actual value of the external data. FU 2 always processes the external data before writing it on the bus.

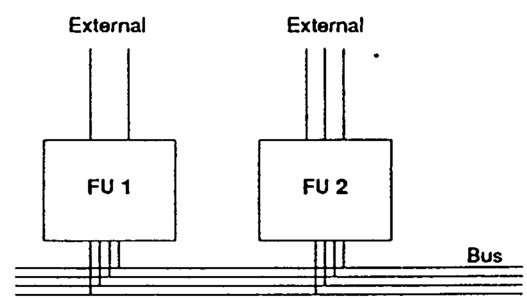

Figure 1: Bus with two Functional Units

If we abstract this system, the global behavior can be modelled as two finite state machines (FSM's) which cycle through 3 states each (see figure 2). FSM 1 transfers from state A to state B or C nondeterministically, FSM 2 always cycles through state B before going to state C. Since 'C' models the state in which the FU's write to the bus, the property to be verified is that FSM 1 and 2 are never be in state C simultaneously. In this particularly simple example, it is easy to see that both systems can be in the critical state C at the same time. This problem is not so trivial in general, and the aid of software tools is of great use.

The next step in the verification process is to describe the obtained model in a compilable hardware description language like VHDL or Verilog[4], and to model the property to be verified as yet another

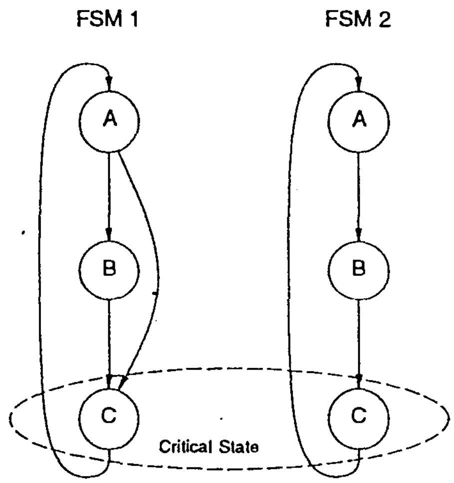

Figure 2: Model with Finite State Machines

FSM. The property FSM consists of a two-state machine with a 'good' state and a 'bad' state. In case both FU's are in the critical state 'C' at the same time, this property FSM goes into the bad state and stays there forever. This will be detected by the verification software, and an error trace will be generated. The Verilog description of the FU's and the property FSM are listed in the appendices, as is the error trace generated by the verification software HSIS[2].

Note that in the modelling phase, successful use can be made of the following lemma (1):

Lemma 1 *Data can be regarded as distinguishable abstract objects, if the precise value of the data is of no importance to the properties to be verified.*

Proof: As long as the value of the data has no influence on the behavior of a system, it does not matter what the actual size of this data is. This implies that theb number of bits (thus variables) can be drastically reduced without affecting the accuracy of the results.

This lemma is extremely useful in data-flow oriented systems, where data is moved around and operations are performed on it. Data should be distinguishable, to verify that all data is processed in the right order, and no objects disappear or are overwritten. Only on a very detailed level of the design, the range of values the data can take will be important, to verify data dependent properties like overflow detection. On the level of abstraction above this one, it is sufficient to verify that e.g. the exception generated as a result of this overflow is handled correctly.

4 Verification strategy

The verification methodology as explained in the previous section can be expanded to larger designs as well. To illustrate this process on a large scale design, the verification approach is applied to a part of the Gollum Navigation system.
The Gollum system is a multi system navigation receiver, based on a core processor with a few dedicated functional units for high speed signal processing tasks[5]. The control of these dedicated units as well as the slower data processing tasks are performed in software running on the core processor.

At the highest level of abstraction, the Gollum system can be modelled as a set of communicating processes. On this level, high level properties like global timing constraints, correct data exchange, fairness etc. can be verified against the estimated run-times of several tasks (see figure 3). Among the tasks to be verified are the ones with hard real time constraints. E.g. if it can not be guaranteed that all data is read before it is overwritten by newer data, than there is no implementation satisfying the design objectives, and either the hardware platform needs to be expanded, or the objectives should be reduced. The tasks with soft real time requirements, like the processing of the filtered data should run within their time limits as well, but the runtime of these tasks depend heavily on the actual implementation of modules lower in the hierarchy. Assumptions for run time can be used, but these assumptions need to be validated during the verification process, and no final answer can be given until a the assumptions on which this failure is based are validated.

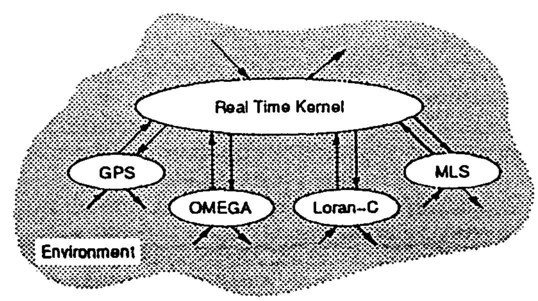

Figure 3: Top level model for verification

Thereafter, each module is separated from the total system, refined and verified (see figure 4). The global behavior of the refined/more detailed system should be within the behavior of its more global representation. That is, the refined module should always satisfy the properties of the module before the refinement took place.

By hiding internal peculiarities and separating modules from other modules, it is possible to verify a wide range of properties for each module without

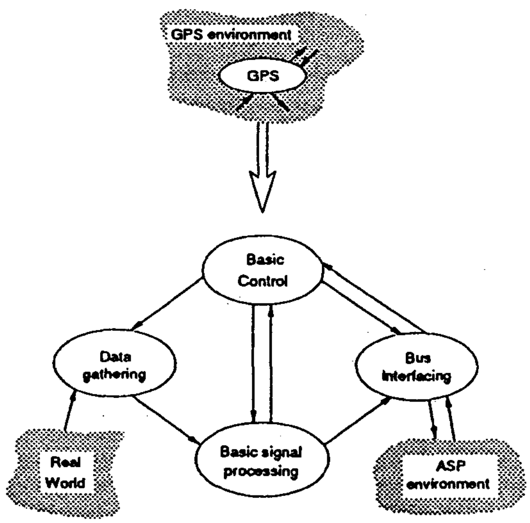

Figure 4: Refined model for verification

the state-space explosion which would occur if all modules were verified as one set of interacting finite state machines (FSMs). The caveat is however that each module operates within an environment, and that this environment depends on the behavior of all modules together. E.g, if all subsystems use all functional units in a more or less equal way the total system might satisfy certain timing properties. However, as some subsystems suddenly expose an extreme desire for the same basic operation, the subsystem might violate the timing constraints which were satisfied before. The solution to this problem is to add additional hardware, to satisfy the need for this sparse resource. After the modification, a new round of verification takes place until the designer is satisfied with the results. This iterative approach might span several levels of abstraction. E.g. the success or failure to meet real-time requirements is influenced by the way the operations are scheduled. Adding extra resources, might lead to different schedules (different environment) which eliminates these property violations.

The previous section indicated that the modelling of the environment needs to be done with great care. It should be part of the iterative approach and assumptions made to model the environment should be checked on their validity. Preferably, the possible input/output behavior of all other modules on a similar level of abstraction is conjuncted into a single representation of the environment of the module to be verified, using bounded non-determinism in time and control. By merging only the input/output behavior of the other modules the internal complexity of these modules are hidden for the rest of the system. However, as a result the environment might include output combinations which are impossible for certain input conditions. Nevertheless, if the verification succeeds, one can be sure that the properties hold. If it the verification fails, it might be the case that the error is caused by the to restricted model of the environment. In this case, the environment needs to be enhanced to exclude this unrealistic behavior.
In the same manner as the abstraction of the environment is handled, the control and data path can be abstracted. Not only is the model easier to handle this way, it is easier to interpret the error trace as well since there are less states involved.

5 Developments

When new tools are developed, the question arises how it will influence the way design is typically performed. Though no one can tell the future, one can expect that formal verification will not make certification tests obsolete. First of all because the subject of verification is a model of the system, secondly, because verification software itself is not verified. Besides, if language containment is used, unspecified errors are not found since the test is defined between specified unwanted behavior and the system.
However, applying Formal Verification to the design of large systems introduces the possibility of finding design flaws early in the design cycle. These errors would not have been detected when no formal verification was used. Furthermore, it leads to a more structured way of design, in which several levels of design are interleaved. Due to the more structured design approach, there are less problems which otherwise would have originated from the more add-hoc design style. When short design cycles become of increasing importance, using formal verification will pay off by the reduction in re-design time of navigation systems.

At this moment, the Berkeley verification software is being extended by adding the ability to handle timing constraints[6]. As soon as timing constraints can be handled by the verification software, the spectrum of real-time systems is opened for the application formal verification.
Other developments currently going on, is the development of an assertion language, called TESLA, which significantly expands the expressiveness of the Verilog hardware description language [7]. By using TESLA, proper behavior of a system can be specified by means of compact sequence specification inside the file specifying the system to be verified. Since these sequences directly specify (un-) desired behavior, this way of specifying is a lot closer to the designer itself. Furthermore, these assertions, are automatically translated into sets of finite state machines, representing the properties to be verified. Especially when timed properties are concerned, this way of specifying takes away a large part of the modelling and specification by the designer.

Appendix A

Verilog description of FU-example

```
typedef enum (A,B,C) possibstates;

module both (clk);
input clk;

possibstates wire mm1,mm2;

  m1(clk,mm1);
  m2(clk,mm2);

endmodule


module m1 (clk,mstate);
input clk;
output mstate;

possibstates reg mstate;
initial mstate = A;

always @(posedge clk) begin
   case (mstate)
       A: begin
                mstate <= B;
                mstate <= C;
          end
       B: mstate <= C;
       C: mstate <= A;
    endcase;
  end
endmodule


module m2 (clk,mstate);
input clk;
output mstate;

possibstates reg mstate;

initial mstate = B;

always @(posedge clk) begin
   case (mstate)
       A: mstate <= B;
       B: mstate <= C;
       C: mstate <= A;
    endcase;
  end
endmodule
```

Appendix B

Verilog description of property checking automaton

```
typedef enum (good, bad) test_states;
typedef enum (A,B,C) possibstates;

module check_status(a,b);
input a,b;

possibstates wire a,b;

test_states reg check_state;

initial check_state = good;

always @(posedge clk)
  begin
   if ((a==C) && (b==C))
     check_state = bad;
  end
endmodule
```

Appendix C

Error trace of verification of FU-example

```
########################################
########## Begin Error Trace ###########
############## Variables ###############
STATE:   mm1    mm2    check_state

CL Outs:


########## PATH to Bad Cycle ###########
ST:    mm1=A    mm2=B    check_state=good
ST:    mm1=C    mm2=C
ST:    mm1=A    mm2=A    check_state=bad

############ Bad Cycle #################
ST:    mm1=A    mm2=A    check_state=bad
ST:    mm1=B    mm2=B
ST:    mm1=C    mm2=C
ST:    mm1=A    mm2=A

############ End Error Trace ###########
########################################
```

Note that since the mutual exclusion property is specified using a synchronous automaton, the variable check_state moves to the 'bad' state the cycle after the violation occurs. The bad cycle given, represents a loop in the system in which the property violation occurs.

Appendix D Verification Software

The Berkeley verification software can be retrieved by anonymus ftp from ic.eecs.berkeley.edu.
The tarred and compressed file is located at "pub/hsis/hsis.tar.Z".

Acknowledgements

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Biography

André K. 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 Circuits and Systems 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 and Saudi Chains.
From September 1993 untill May 1994, he worked at the University of California, Berkeley, to research the use of formal verification in the design of the Gollum integrated navigation receiver.

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LORAN-C STATIONS - AN ELECTROMAGNETIC RADIATION HAZARD?

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ABSTRACT

The growing public sensitivity to questions of electromagnetic radiation is beginning to affect the expansion of Loran-C systems. The development of the station at Loop Head, Ireland, a key element of the new North-West European Loran system, has become embroiled in a planning approval process. A principal objection of the opponents to the station is that its transmissions will present a health hazard to local residents.

Loran-C planners need to ensure that stations meet national and international guidelines in respect of the intensities of the electric and magnetic fields to be radiated. They must also avoid electric shock hazards close to the station. Calculating the values of these parameters so that non-specialists may clearly see that they fall within the guidelines is not straightforward. In particular, the pulsed nature of the Loran transmission both complicates the design process and raises additional objections to the electromagnetic fields.

The paper presents calculations and arguments prepared for the documentation and the public hearings in connection with the Loop Head station. It is intended to be of value to members of the Loran-C community and others who seek to understand the electromagnetic radiation and associated planning approval aspects of Loran-C stations.

INTRODUCTION

The Loran-C station planned for Loop Head in the West of Ireland is a key element of the new North-West European Loran-C System (NELS). It will operate as a secondary in both the Lessay and Ejde chains (Fig. 1). Its location was selected in a uniquely detailed planning process in which some 100 different configurations were studied using a computer-based coverage and performance prediction model [1]. Providing high-quality Loran coverage off the west coast of Ireland was a specific objective - and a considerable challenge. In the configuration chosen, three triads cover each other's base-line extension areas.

Loran-C is especially important here since an important fishing industry operates in an oceanic area of very hostile climate. The performance of the existing Decca Navigator system, is hampered by the geography: it is always difficult to provide maritime coverage from stations of a hyperbolic terrestrial system installed on an island. The Decca winter night 95% repeatable accuracy deteriorates to some 11 km in certain inshore areas where there are Decca baseline extensions. In contrast, the new Loran-C system is expected to provide the full 95% confidence repeatable accuracy of 463m (0.25 nm) out to at least 200 NM offshore, and better than 200m accuracy in all inshore waters.

The coverage studies showed the need for a 250 kW Loran station to be located in South-West Ireland, in either the north of County Kerry or the south-west of County Clare (Fig. 2). A desk study identified some 40 candidate sites. The site selection process studied, ***inter alia***: the local topography; ground conductivity; access; services; freedom from LF interference, power lines and large structures; distance from airfields, railways, major roads, oil and gas installations; and absence of features of special historical or archaeological interest. The USCG Loran-C Site Selection Criteria [2] played an important role in this study. A site at Feeard, in the west of County Clare, was selected; this is the site known as 'Loop Head' since it lies just inland from the headland of that name, on the Loop Head Peninsula which juts out into the Atlantic Ocean.

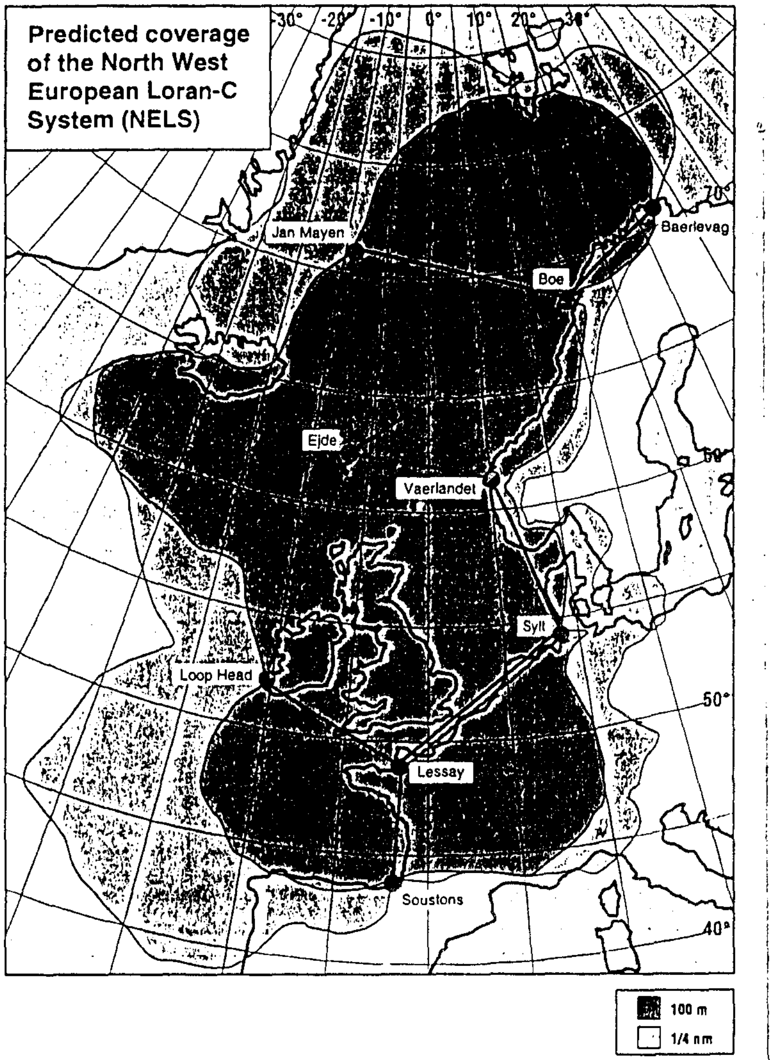

Fig. 1: Loop Head station is a dual-rated secondary station in the Ejde and Lessay chains of the North-West European Loran-C system.

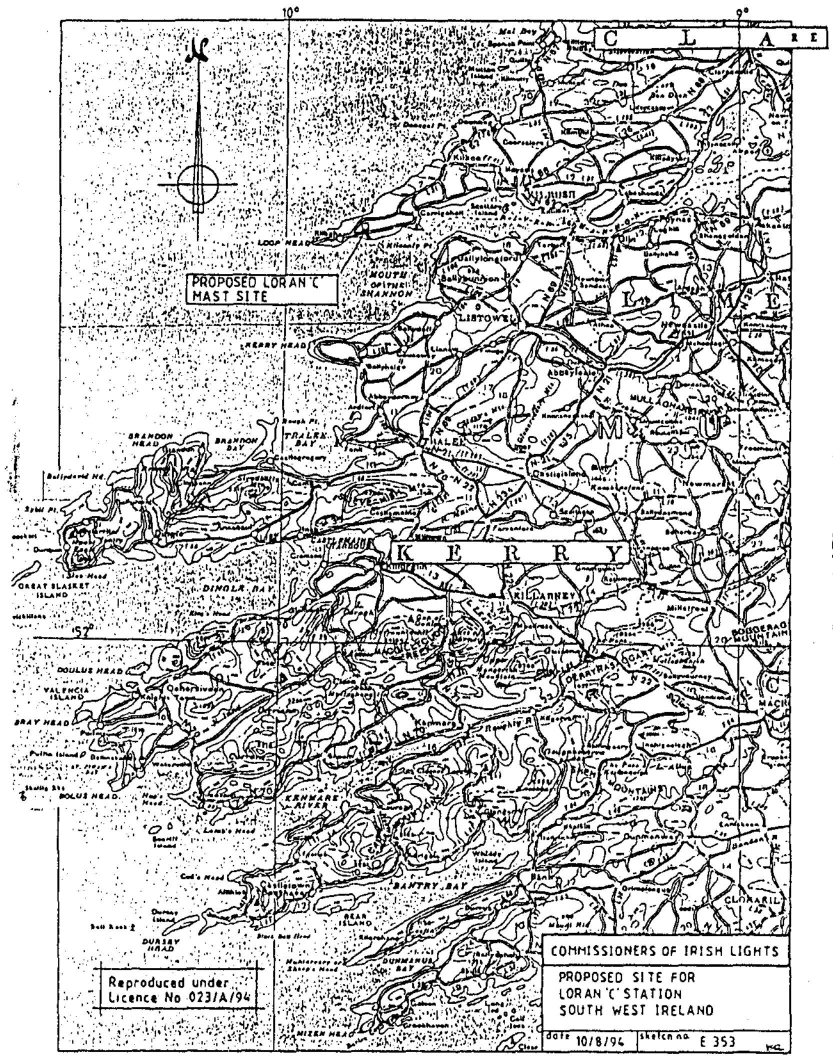

Fig. 2: The station is located on the Loop Head Peninsula which juts out into the Atlantic Ocean (Map courtesy of CIL)

The station is to be built by the Commissioners of Irish Lights, the General Lighthouse Authority for the island of Ireland, acting as agents for the Irish Department of the Marine. In 1992, the Commissioners held a Public Information Meeting and published an Environmental Impact Statement describing the station. The Chief Technical Adviser of the Department of Transport, Energy and Communications also prepared a report on EM aspects of the development [3]. Following local opposition to the station, the Irish Government required the Commissioners to apply for Planning Permission for the station. Clare County Council refused their application. The Commissioners appealed and a public hearing was held by An Bord Pleanála, the Irish National Planning Board.

One of the major grounds of the opposition to the plan, and a specific reason for the refusal of Planning Permission, was that: 'The proposed development may be prejudicial to public health' and 'may endanger the health of those occupying or employed in adjoining structures' 'due to the impact which the electromagnetic fields produced by the development may have on the population in the vicinity'.

This is believed to be the first time that a planned Loran-C station has been delayed because of apprehension about electromagnetic radiation. However, such concerns are not new: the US Coast Guard has investigated the strengths of fields around all stations in the US [4] and the fields within, and adjacent to, their masts [5]. Other investigations have focused on the pulsed nature of the Loran transmissions; the literature has been well summarised by [3]. In general, public anxiety about electromagnetic fields is increasing and an enormous scientific research effort is being devoted to the subject.

CONCERNS ABOUT ELECTROMAGNETIC RADIATION

Objectors to the Loop Head Loran station raised specific concerns about electromagnetic (EM) fields. The Senior Executive Planner of Clare County Council claimed that; 'the proposed development will involve the transmission of a radio frequency carrier modulated in the extremely low frequency range' and that 'it is generally accepted that fields associated with extremely low frequency transmission produce noticeable effects in human tissue'. A report commissioned by objectors stated that 'the still poor state of scientific knowledge about low frequency radiation effects on organic health, together with an increasing level of anecdotal evidence that such radiations may be responsible for psychofunctional near-disease states and other more serious teratological and immunoregulatory effects, taken together provide sufficient grounds for recommending that the installation is not approved' [6].

There are objections to the transmissions on the grounds that they are 'low frequency' (and often, incorrectly, that they are 'extremely low frequency (ELF)', or that they are pulsed, or (again incorrectly) 'pulsed at ELF' frequencies.

Those concerned about the effects of EM radiation fall broadly into two camps. Let us call them the 'scientific' and the 'non-scientific' groups. The scientific group believe that the hazards of exposure to excessive radiation should be investigated, guidelines drawn up in the light of the results, and radio transmitting installations required to conform to those guidelines. In fact this process has been under way for many years: a massive scientific research effort has been devoted to investigating the effects of EM fields on human beings, especially at 50 Hz and 60 Hz. Both *in vitro* studies (on cell cultures or pieces of tissue) and *in vivo* studies (on whole organisms or populations) have been conducted. One organisation claims to hold a database of some 4,000 scientific papers. The results of the work are studied continually by international bodies such as the International Commission on Non-Ionising Radiation Protection (ICNIRP) of the International Radiation Protection Association (IRPA), and by their national counterparts. Their independent experts, drawn from medicine, physics, bio-chemistry, physiology, dermatology and other disciplines, review the literature and, from time to time, recommend guidelines. This work is conducted in association with the World Health Organisation (WHO) and the International Labour Organisation (ILO). Responsible engineers then design radio transmitters in accordance with the standards published by these bodies.

The 'non-scientific' camp take the view that our knowledge of the field is inadequate and incomplete. 'Scientists', they say, 'disagree about these matters, so who knows what's safe?' The most extreme advocates of this approach regard all scientists as knaves or fools, and those who would erect radio stations as immoral people who do not flinch to experiment on their children, born or unborn. They condemn not just Loran-C stations but, directly or indirectly, all radio transmitters. Between the supporters

Prediction/standard	Electric field strength (V/m)	Magnetic field strength (A/m)
	..	
IRPA occupational exposure	614	16.0
IRPA public exposure	87	0.730
EC occupational exposure	614	16.3
Canada occupational exposure	600	4.9
Canada public exposure	280	2.19
NRPB former occupational expos	614	48.9
NRPB former public exposure	205	48.9
NRPB occupational exposure	1000	64.0
NRPB public exposure	1000	64.0
ACGIH occupational exposure	614	1.63
ANSI occupational exposure	614	163.0
ANSI public exposure	614	163.0
US EPA option 1	87	0.23
US EPA option 2	275	0.73
US EPA option 3	614	1.63
Austria public exposure	275	40.0
Germany public exposure	300	16.0
Japan Public exposure	275	22.0
Loop Head, 10m from antenna	34.2	0.374
Loop Head, 300m from antenna	2.6	0.007
Loop Head, 2km from antenna	0.4	0.001

Table 1: International and national standards, plus Loop Head field strengths (after McManus [3])

of the 'scientific' and 'non-scientific' approaches there is great mutual suspicion and even hostility. Public hearings, such as the Loop Head Loran-C one, seek to reduce this antagonism and find rational solutions to the problem.

The approach of the scientific group is to calculate and measure the EM fields that a proposed station will generate, and demonstrate that they fall within appropriate national and international guidelines. This paper will show how that has been done in the case of Loop Head.

STANDARDS

National and international EM radiation standards at the Loran-C frequency of 100 kHz generally consider three factors: the electric field (or 'E-field) strength, the magnetic field (or 'H-field') strength and the 'contact current'. The approach adopted by the United Kingdom's National Radiological Protection Board (NRPB) will be cited here as an example. The NRPB set 'investigation levels'; these are not limits but rather values 'provided for the purpose of comparison with measured field quantities for investigating whether compliance with basic restrictions is achieved'.

In respect of the strength of the E-field, the Loran-C frequency lies on a boundary. Below 100 kHz the investigation level is based on 'the avoidance of electrical stimulation effects'. Above, it also takes into account thermal effects (at much higher frequencies thermal effects become dominant). The investigation level is 1000 V/m RMS.

The magnetic field investigation level is based on induced current density. It is expressed either as a magnetic field strength, 64 A/m, or in terms of the corresponding magnetic flux density, 80 μTeslas.

Thirdly, a current can flow between a person in a strong electric field and a sufficiently large ungrounded conducting object (such as a large vehicle) with which they may come into contact and experience an electric shock or burn. The NRPB investigation level of this contact current is 20 mA.

With increasing Loran-C field strength, the electric field reaches its investigation value well before the magnetic field. If very large ungrounded metal objects are present in high-field areas, however, the dominant hazard may be the contact current.

Table 1 compares these NRPB investigation levels with the figures employed by other authorities. Note that many guidelines do not specify the contact current separately but specify an E-field limit which takes this hazard into account. Also, some authorities distinguish between 'occupational exposure' limits and those to which the public may be exposed. Ireland does not set its own standards for non-ionising radiation but customarily has regard to IRPA, UK and EC norms.

The values shown in Table 1 are the average, or root-mean-square (RMS), values which are applicable directly to a transmitter of constant power output. Because a Loran-C transmission is pulsed, however, its average power is much less than its peak power. The IRPA recommend that, when dealing with pulsed transmissions,

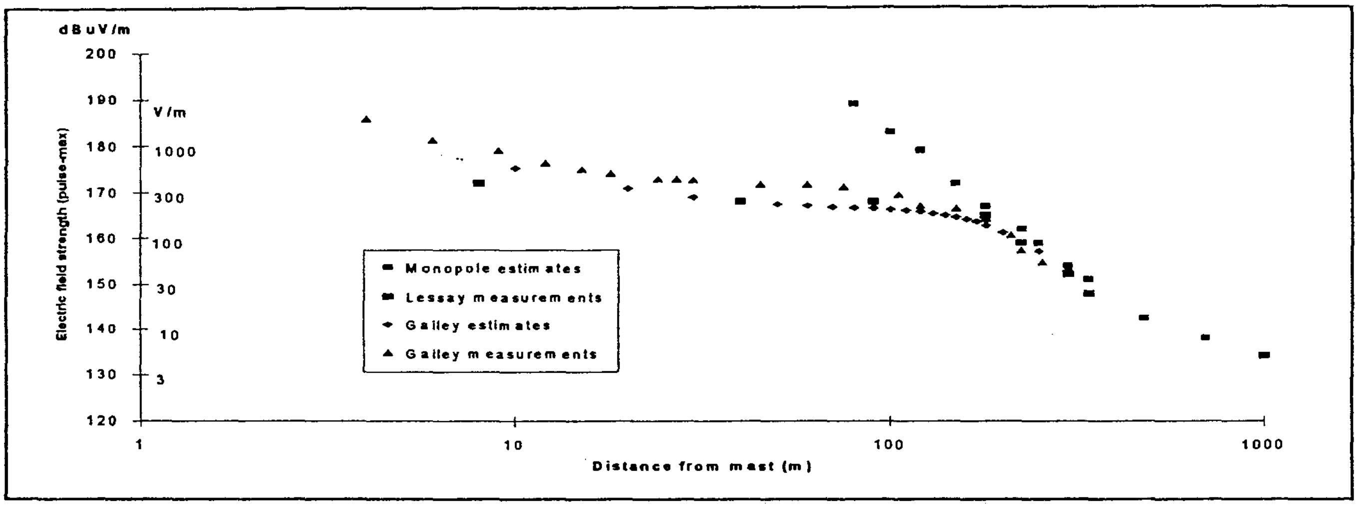

Fig. 3: Estimated and measured values of pulse-maximum E-fields

the RMS values should be applied, but that the field strengths at the peaks of the pulses should not exceed 32 times the RMS values: that is, 2784 V/m or 23.4 A/m. The IRPA also set limits on the rate of change of the magnetic field strength; however, these are inappropriate to Loran-C signals whose rate of change is dominated by that of the carrier rather than by the slowly-rising pulse envelope.

THE LOOP HEAD LORAN-C STATION

The debate over the proposed Loop Head installation revealed extensive mis-understanding of the nature of Loran-C transmissions among those objecting to the development. To clarify the situation: all Loran-C stations transmit signals centred on the frequency of 100 kHz, 99% of the energy being confined to the band 90-110 kHz. The transmission has a complex line spectrum, with the spectral lines spaced at approximately 5 Hz. Loran-C is a low-frequency (LF) transmission, not an ELF (30-300 Hz) transmission. The modulation of the Loop Head station will consist of groups of 8 pulses transmitted at the Group Repetition Intervals (GRIs) of the two chains in which it operates as a secondary station: 67310 and 90070 μs. During the transmission of each of these pulse groups, pulses will be radiated at the rate of 1000 per second; at other times the station will be silent. The modulation of a Loran-C station such as Loop Head is not, therefore, ELF modulation, even though the station transmits approximately 208 individual pulses in each second.

The power rating of the Loop Head transmitter will be 250 kW. This is the power radiated along the surface of the earth, at the *maximum* of each pulse. It is equivalent to the power radiated by a loss-less, electrically-short, monopole antenna fed by a transmitter of 250 kW output power or by a loss-less isotropic radiator fed with a power of approximately 750 kW. The *average* power of this station will be 3.51 kW (see below).

The antenna will consist of a 219 m (720 ft) vertical radiator with a capacity hat formed by the inner sections of the top guy wires. The radius of the guying system will be 300 m and the capacity hat approximately 130 m. A buried 300 m-radius earth mat will also be provided.

ESTIMATED FIELD STRENGTH VALUES

In assessing the EM acceptability of the proposed station the electric field intensity is the key factor. It must be compared with its investigation level; the E-field is also the source of the contact current hazard. A simple approach to estimating how the intensity of the electric field varies with range from the mast is to regard the antenna as an electrically-short monopole. The field at 1 km from a station of 1 kW radiated power is then 0.3 V/m (110 dBμV/m) [7]. The corresponding figure for the 250 kW Loop Head station is 5.0 V/m (134 dBμV/m). This 1 km range lies in the 'near far-field', where the intensity falls with increasing range with a slope of -20 dB per decade.

Fig. 3 shows that, at ranges of more than a few kilometres, ground losses may become significant and cause the slope to increase. Closer to the antenna, in the 'near' field, the slope increases to -60 dB per decade because of the dominance of the electrostatic term in the electric field equation [8]. The -20 dB and -60 dB asymptotes intercept 477 m from the antenna, at the boundary between the near field and near far-field. The magnetic field strength in the near far-field is related to the electric field strength by the 377 ohm factor. Closer to the mast than 477 m, however, the H-field slope is only -40 dB/decade, so the E-field becomes even more dominant.

Under the capacity hat this simple monopole model should over-estimate the electric field strength. This is confirmed by Gailey's work [4]. Gailey has estimated the E-fields (and the H-fields) close to the mast. Both he and McKaughan [5] have employed the Lawrence Livermore National Laboratory Electromagnetic Code (the 'NEC' model). Fig. 3 shows Gailey's E-field estimates for the Seneca, NY, station which has an antenna similar to that to be used at Loop Head; the results have been scaled to the Loop Head power level. The Gailey and monopole estimates agree well outside the capacity hat of the antenna.

ELECTRIC FIELD MEASUREMENTS

Electric field strengths have been measured at the Loran station at Lessay, France, which radiates the same power from the same type of antenna as will Loop Head. For near far-field measurements, a Rohde & Schwarz Field Strength Meter Type ESH2 and Loop Antenna Type HFH2-Z2 were used. This calibrated measurement set-up is traceable to reference standards. In order to measure the fields at the maxima of the Loran-C pulses, correction factors were applied which allow for the limited bandwidth of the measurement system. The result was a measurement of 5 V/m (134 dBμV/m) at 1 km.

The result was then checked (and the bandwidth correction avoided) by measuring the voltage from the calibrated loop antenna directly on an oscilloscope. The measured field strength was 5.1 V/m (134 dBμV/m).

For the near-field measurements a specialised electric field strength meter, Instruments for Industry Type EFS-1, was employed. This small, portable, battery-powered instrument employs short monopole antennas to measure field intensities up to 1000 V/m (180 dBμV/m). It was supported at a standard height of 1 m on a block of insulating material. The meter was calibrated to measure the Loran pulse-maximum values by operating it alongside the calibrated loop and oscilloscope at 1 km. Thereafter it was employed as a transfer standard to compare the measured fields with this reference value. The closest approach to the mast permitted by this equipment was 8 m.

The results are shown in Fig. 3. Agreement with the monopole estimates is excellent from 1 km down to 200 m range, when the over-estimates of this model become apparent. Gailey's NEC-program estimates lie even closer to the Lessay measurements.

Gailey also measured the electric and magnetic field strengths at Seneca; his measured E-field values, shown in Fig. 3, are a little higher than his estimates.

PULSE-MAXIMUM & RMS VALUES

Loran-C transmissions consist of sets of rounded pulses whose maximum values we have estimated and measured so far. However, national and international E-field and H-field standards are almost always RMS values, measured over long periods compared to the duration of a Loran pulse. We should therefore consider how to compute these long-term RMS values. The term 'pulse-maximum', rather than 'peak', will continue to be used here to avoid confusion between the peaks of the pulses and the peaks of the individual cycles.

The analysis is complicated by the lack of a universal 'standard' Loran-C pulse. Although the leading edges of Loran pulses are very precisely defined, their trailing edges are simply 'controlled in order to meet spectrum requirements' and so 'may differ significantly in appearance and characteristics' between sites and equipment [9]. From oscilloscope photographs of pulses from solid-state transmitters of the type to be used at Loop Head, the average power over the period 0-250 μs is found to be 0.27 times the pulse-maximum power and the average voltage 0.40 times (Fig. 4). The long-term RMS power of the station may then be calculated from the following formula:

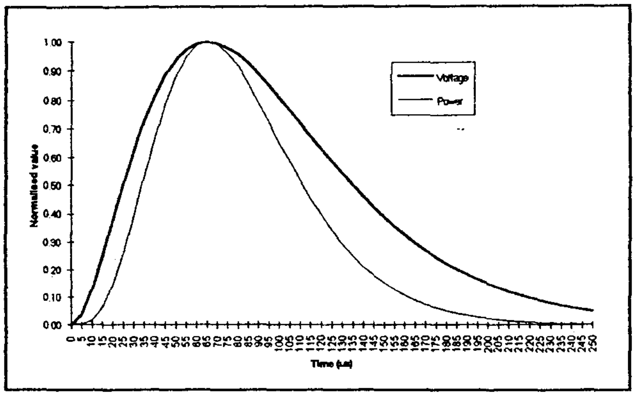

Fig. 4: Normalised Loran-C signal voltage and power. The figure is drawn using eqn. (2) and does not include the effect of the tail-biter.

$$P_{av} = 6.75\frac{nP}{G} \quad kW \qquad (1)$$

where P is the nominal power in kW,
n=8 for a secondary and 9 for a master station,
and G=the GRI in the 4-figure form.

If the station is dual-rated, the powers of the two rates are summed (ignoring the effect of blanking). Thus, for Loop Head which will be a secondary of two chains with GRIs of 6731 and 9007, the powers will be 2.01 and 1.50 kW, a total of 3.51 kW. Thus the average power will be 0.014 times the maximum. The RMS values of the E- and H-fields will be approximately 0.09 times the pulse-maximum values.

The energy in each Loran-C pulse has been estimated as 0.0675P Joules.

Gailey has also analysed this problem mathematically. He assumed a pulse of the form shown in eqn(2):

$$A(t) = A_p[(\frac{t}{t_p})\exp(1-\frac{t}{t_p})]^2 \sin(wt) \qquad (2)$$

This ignores the effect of the tail-biter in the transmitter and so slightly over-estimates the average values. Allowing for this, there is good agreement with the results of my analysis above.

COMPARISON WITH STANDARDS

The measured and estimated values will now be compared with the current standards of the UK NRPB. The magnetic field investigation level is 64 A/m RMS. The highest H-field value recorded by Gailey at Seneca equates to approximately 1.26 A/m. Even at the pulse maximum the H-field only reaches 14 A/m.

The E-field investigation level is 1000 V/m. The measured value 8 m from the Lessay mast was 38 V/m RMS. Gailey at 4 m measured a field equivalent to 126 V/m. The pulse-maximum values very close to the base of the mast may exceed the investigation level, but the RMS values are well below it.

In dealing with contact currents the pulse maximum value should be employed. Further, one cannot employ measurements made at other stations since the contact current depends on the size and nature of the 'ungrounded conducting object'. It is customary to consider each case individually.

At the outer edge of the antenna structure, 300 m from the mast, the pulse-maximum electric field has fallen to approximately 45 V/m and the RMS to 4 V/m. These values are well below any national or international limits for public exposure. The site boundary will, of course, be even further from the mast than this.

McManus independently noted that: 'there are many Loran-C stations in existence' (some have operated of more than 30 years), 'most of them significantly more powerful than the one being proposed for Loop Head'; and that: 'the peak power output ... is of the same order of magnitude as that of many long wave and medium wave transmitters' and while they 'have 100% duty cycle ... the Loran station is "on" for only 12.5% of the time'. He concluded: 'It has not been possible to identify any grounds for supporting a belief that the operation of the proposed station presents a hazard to health' [3].

CONCLUSIONS

In assessing the electromagnetic acceptability of a Loran-C station, one must estimate the electric and magnetic fields and compare them with limits or investigation levels set by competent authorities. At Loran frequencies the E-field is more significant than the H-field and the contact current limit is also important. The E-field values at the site boundary and beyond may be estimated using a monopole model; theory and measurement agree well. Within the aerial structure, that is below the capacity hat, a fuller model such as the NEC program is required. The RMS values of the fields must be calculated from the pulse-maxima predicted and measured; the equations presented above allow this to be done.

The paper has demonstrated that the RMS E-fields and H-fields, not only at the site boundary and beyond, but to within metres of the mast, fall well within the relevant national and international standards. It recommends that potential contact current hazards be investigated individually.

ACKNOWLEDGEMENTS

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BIOGRAPHY

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Loran Augmented GPS/Eurofix Preliminary Demonstration

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I. Summary

A. Background

This is a discussion of the test procedure and initial results of experiments conducted for the Volpe National Transportation Systems Center, to determine the most effective modulation and coding schemes for transmission of differential GPS using the Loran-C signal. The Eurofix methods proposed in [1] form the bsis for the coding schemes tested. The detection scheme is a result of independent development at Maegpulse, Inc. The resulting system should be able to provide coverage of the entire land area of the continental US. This sets the minimum detection range at 850 km from a 400kW peak power Loran-C transmitter. This range is simulated by the 1100 km range to Carolina Beach from Bedford, MA. In the following discussion, the level of 25 dB below the Nantucket Loran-C signal is equivalent to the Carolina Beach signal. Further since Nantucket is dual-rated, and the experiments were conducted on their low rate (9960), Nantucket provided a very high level cross rate signal on its high rate (5930). Cross rate interference is the primary limitation on the range of the Loran-C communications service, and so was strongly considered in these tests. It should be noted however that normally, the users of such service would choose the closest Loran-C station to minimize spacial decorrelation of the differential corrections, and therefore cross rate interference. Further, it would be expected that a dual rated station transmitting the corrections would use priority blanking favoring the rate carrying the communications signal.

B. Loran-C Communications

1. USCG Interstation Communications

The concept of communications on the Loran-C signal has been with us for some time. The first use was in support of the Office of Civil Defense in 1964, when it was desired to cover the entire US with an easily detected radio signal to alert the population to an aerial attack. This system was never implemented.

Next, during the Vietnam war, a chain of Loran-C stations was established in Thailand and Vietnam. As there was no landline communications between the sites, and HF radio was unreliable, a system of modulation of the Loran-C signals, using pulse position modulation was developed. This was implemented in 1966, and used for several years until better alternative communications was developed by US forces. However, it did confirm the use of pulse position modulation as a viable communications means, and proved its effectiveness.

2. Clarinet Pilgrim

Clarinet Pilgrim was a joint USN & USCG program to retransmit USN Fleet Broadcasts on Loran-C for those users which were unable to receive the direct broadcasts reliably. This service was implemented in the Northwest Pacific chain in the mid-1970's.

3. Decca Navigator Skyfix

Decca Survey has implemented a method of pulse position modulation to some of its Pulse 8 stations, and uses the capability for differential GPS. This is being replaced by a satellite communications link.

C. Potential for Loran-C & GPS Integration

1. DGPS Communications

As described above, there is a communications capability inherent in the Loran-C signal. The modulation scheme, as described by van Willigen [1] provides only a modest 15 to 30 bps data rate. The full text of the RTCM SC-104 messages requires greater bandwidth, but inserts more information than would be necessary in Loran Comm based DGPS. First, the source stations are identified by the GRI, phase code, and coding delay of the stations, making identification within the message text redundant. Secondly, the very precise timing of the signals from the Loran station make full regular transmision of Z-Count unnecessary. Asynchronous transmission of satellite data is also possible with the precise timing of the Loran signal.

2. Loran-C Grid Calibration in Real Time

The concept of Loran-C grid calibration in real time offers the potential of using the Loran-C signal to determine vehicle position between DGPS updates, making the requirement for continuous DGPS updates less stringent. This process might be described as DGPS based relative Loran-C positioning, and allows best use of the energy in a Loran-C pulse.

3. Elimination of temporal decorrelation

Extending the thought further, current DGPS data, derived from signals received earlier at the

DGPS base station can be applied to the user's observed GPS pseudoranges at that same earlier time, eliminating temporal decorrelation. The old position is then updated to the current position, using the change of position as determined from relative Loran-Cdescribed above. There is then no temporal decorrelation of the DGPS fix, and the accuracy of the present position is limited to the temporal and spacial decorrelation of the Loran-C over the update time (10 to 60 seconds), and the measurement accuracy of the Loran-C set, potentially 2 to 4 meters.

Actually, the Loran-C signals' temporal and spacial decorrelation are such that a much longer interval between DGPS updates could be tolerated, such as might occur should there be insufficient satellites above the horizon, or a tracked satellite be declared unhealthy.

4. System Back-up

Should either system be unable to provide its share of the total navigation data capability of the LAGPS/Eurofix system, the system performance is only degraded to the nominal performance of either radionavigation service alone. This soft fail capability greatly eases the concerns over a single system radionavigation service.

II. Loran Communications Signal Characteristics

A. Modulation

1. Pulse Position Modulation and Word Encoding

Each transmitting station transmits a group of eight pulses (plus the master station's ninth pulse, not used for navigation). The first two secondary station pulses and the master station ninth pulse are used for communicating transmitting station faults (blink). The pulses 3 through 8 are always on air, and are not used for other purposes. It is these six pulses which are used for LAGPS/Eurofix data communications. Each pulse is either advanced or retarded to represent a one or zero respectively. To ensure and equal number of advances and retards for each stations signal, each bit pattern is repeated four times, and the sense of the one and zero shift is reversed in the second and fourth transmission of each bit pattern. For integrity and sync messages the balancing pattern is reversed in the third and fourth, and in the second and third pulse groups respectively. This makes these special messages uncorrelated with the message, and therefore uniquely detectable.

The bit pattern in the current experiment is six bits long, so four consecutive pulse groups (two PCI's) are used for each bit pattern. The number of bits in the bit pattern may be a multiple of six bits, and the choice of six, twelve, or eighteen bits (2, 4, or 6 PCI's) is yet to be made. It will be based on the impact of the cross rate interference effects, which have not yet been fully analyzed to determine the optimum arrangement. The following paper [1] offers a complete discussion of the alternatives in this choice.

B. Data Coding

1. RTCM SC-104 Message Type & Efficient Coding

It is essential that no redundant data be sent, and that information available from another sources be eliminated from the DGPS messages. For example, the station identification requirement in RTCM SC-104 format is available from the selection of GRI, phase code, and coding delay in the Loran-C section of the LAGPS/Eurofix receiver, hence need not be sent in the LAGPS/Eurofix message. Also the Z-count can be derived from relatively infrequent actual transmissions, for synchronization checks. Between these confirmations, the Z-count can be precisely determined from its fixed relationship to the Loran-C GRI, coding delay, and propagation time computations. Additionally, SV identification, Scale factor and UDRE can be minimized and delta PRC and RRC used to minimize the number of bits in these. Using all of these techniques we project that the mean latency of data can be reduced to less than 10 seconds. In these experiments, the mean latency with data on up to nine SV's is reduced to less than 20 seconds.

2. Integrity Message Encoding:

Special messages are sent in a different modulation format to make them easily dintinguishable, in detection, from the differential data. The modulation pattern is set such that each bit pattern is repeated four times, as before, but the sense of the one and zero shift is reversed in the second and third transmission of each bit pattern. This message then will not correlate with any regular or sync message, and can be inserted in the middle of regular messages, without losing message sync, and providing integrity messages in under two seconds.

III. The Experiment:

A. Bit Error Rate

1. In order to develop confidence in the fundamental concept, first the modulation scheme was developed with canned messages so that the bit error could be easily counted, over a long period. To ensure accurate simulation of the potential

interfering signals, off-air signals from a Loran-C receiving antenna were mixed with simulated signals which were modulated. The level of the simulated signal was set so that a Loran-C receiver saw those signals at the same level as signals from a station 600 miles away. The simulated signals were timed to fall in the EECEN, Wildwood interval of the East Coast Loran-C Chain.

2. Extensive tests were run to determine the error rate versus various signal levels with the existing on-air cross rate interference conditions, which were essentially the 5930 rate signal from Nantucket, 166 km away.

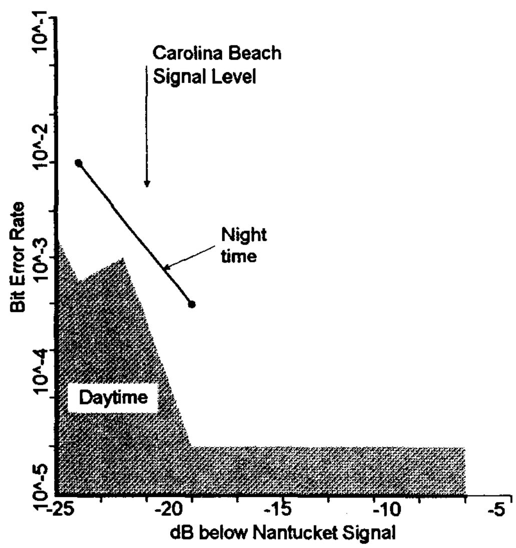

Figure 2. Bit Error Rate, representing over 2 Megabits of data

B. Experimental Coding

1. Word Coding

The compressed RTCM SC-104 message was transmitted in six bit words, as was used for the canned message. Future testing will address 12 and 18 bit words.

2. Data Coding

The DGPS data message consists of data from up to nine SV's. The message consists of a header data set for one SV and eight additional data sets. As shown in Table 1, the first data set is derived from the most recent RTCM SC-104 Type 1 message received from the reference station. The next eight data sets contain less information from the RTCM SC-104 message received immediately before each subsection is transmitted. This is the meaning of asynchronous data transmission. The most recent correction received by the user is only a few seconds old, and the other SV's have progressively older data. Therefore, as each subsection of the message is decoded, it is used in the message formatter of the LAGPS/Eurofix receiver to fabricate a new RTCM SC-104 Type 1 message for the DGPS receiver. The order of SV's in LAGPS/Eurofix message is round-robin, with up to nine satellites.

Data Type	# Bits	Comments
Sync	12	Sync start of D
Message Type	2	Up to 4 distinct
Fill	5	
Modified Z-Count	13	Same as RTCM
Scale Factor	1	"
UDRE	2	"
Satellite ID	5	"
PRC	16	"
RRC	8	"
IOD	8	"
Parity	8	"
Total # of Bits	66	

Table 1 Preliminary Format, 1st Data Set of the LAGPS/Eurofix DGPS Message

Data Type	# Bits	Comments
Scale Factor	1	Same as RTCM
UDRE	2	"
Satellite ID	5	"
PRC	16	"
RRC	8	"
IOD	8	"
Parity	8	"
Total # of Bits	48	

Table 2. Preliminary Format, subsequent Data Sets of the LAGPS/Eurofix DGPS Message

C. Demodulation to reject Cross rate

1. Cross correlation thresholds

Each received pulse is cross correlated with a reference pulse to determine the state of modulation. The cross correlation values are compared, and the most likely state of each data bit is determined. In order to minimize cross rate interference effects, the observed values are compared to mean past values, and outliers are rejected from bit state determination. Bit error rates of less that 0.1% at the equivalent of 600 miles from the Loran-C transmitter have been observed.

2. Parity Checks

Finally, parity checks are used to avoid injection of erroneous data into the navigation solution. Multiple bits are used to minimize false detections. Insufficient data has been gathered to confirm expected message error rates. Also the message format is not yet optimized, so that observed data are not yet meaningful.

IV. Equipment Set-up

A. Message Source:

1. DGPS Base Station

The DGPS base station is a Trimble Model 4000RL II. This receiver is limited to nine SV's (UDRE$\geqq 1$), and is not of appropriate grade for operational use in this application. However it is adequate for initial testing. The receiver is installed atop the Marriott Hotel, in Cambridge, MA, and is an asset of the Volpe National Transportation Systems Center.

2. Data Connection to the Encoder & Modulator

Dial-up service between the data modem at the base station is being used. In later experiments this will be improved with a dedicated line.

3. Encoder & Modulator

A PC is used to receive the RTCM SC-104 type 1 messages from the base station, and parse the data for transmission to the modulator.

The Modulator is a logic board, installed in the simulator or transmitter, which advances or retards the Loran-C pulses by one microsecond depending on the logic state from the PC. With this hardware configuration, any combination of word, data, and forward error correction can be tested without further hardware modification.

B. Signal Source

1. Loran-C Signal Simulator

A Megapulse LSG-5 Loran-C simulator was modified to accept the modulator output, and provide one simulated station group with the ability to modulate the pulses. The LSG-5 was used in the proof of concept tests which preceded development of the encoding schemes.

To simulate on-air conditions of cross rate, CWI, and atmospheric noise, a Loran-C receiving antenna is used to inject all received signals into the receiver along with the simulated signal. The modulated simulator signal is timed to fall in the 'T' slot in the East Coast Chain, which is unused except when the EECEN transmitter is on air.

2. Megapulse 3500 Transmitter & 20' TLM

In order to better examine on air conditions, a 1 watt signal was transmitted from the building, and produced a received signal at a level comparable to the Carolina Beach signal.

3. Megapulse 6500 Transmitter & Dummy Load

To assure compatibility with the solid state transmitter, a production transmitter was modulated while under factory acceptance test. There was sufficient leakage from the dummy load to permit tracking and demodulation with the test receiver.

4. EECEN Wildwood Test Transmitter

With coordination from VNTSC, a temporary modulator was installed at the USCG EECEN, at Wildwood, NJ. During approximately six hours of on air operation with a canned message transmitted, the signal was received and evaluated at Megapulse. The test showed no bit errors in about 100k bits.

C. Receiver

1. Accufix 500 with Correlator Modification

A standard Accufix 500 time difference receiver was modified to provide the sampling process for input to the cross correlation detector, which was implemented in a PC. The receiver was tracking all signals on the East Coast Chain, and providing timing signals for the sampling.

V. Observed Performance

A. Bit Error Rates

Bit errors rates were measured without parity detection, or error correcting codes. The correlation values for each of the four transmissions of each bit were compared, outliers rejected, and the remaining bits voted. Individual bits are then compared to the know transmitted bit pattern. Figure 1 above shows the summarized test results. It appears that further improvement can be achieved by use of alternative correlation patterns.

B. Message error rates

Message errors are defined as parity errors in any sub-section of an LAGPS/Eurofix message. The parity errors effect only the sub-section in which they occur. Hence neither sync timing nor data other than that for the SV in the effected sub-section, are effected.

C. Position Errors, 95% error circle

Lastly, the detected data messages are assembled into RTCM SC-104 type 1 messages for use in the user receiver, a Motorola Model PVT 6, DGPS receiver. The type 1 messages are output each time there is an update of any SV. That is as each sub-section is received, the data on that SV is updated and the new Type1 message is sent to the DGPS receiver at 9600 baud. Figure 2 shows the results achieved with a six satellite DGPS receiver. The corrected data has a 95% error probable radius of 8.8 meters. The message error rate was about 1%.

VI. Continuing Evaluation:

1. Further development required on the data and message encoding. The next paper [1] specifically looks at encoding methods which will minimize cross rate interference, and increase the probability of detection for the data.
2. Additionally, new methods of deriving information needed inthe DGPS solutions have been proposed, and these need to be programmed and tested. With these improvements, it is expected that the mean latency can be reduced to less than 10 seconds, which will result in a 95% error probable of less than 5 meters. Further improvement would then need additional data transmission, such as atmospheric model data.
3. Lastly, longer term testing is required to ensure all potential error sources have been addressed in the system design.

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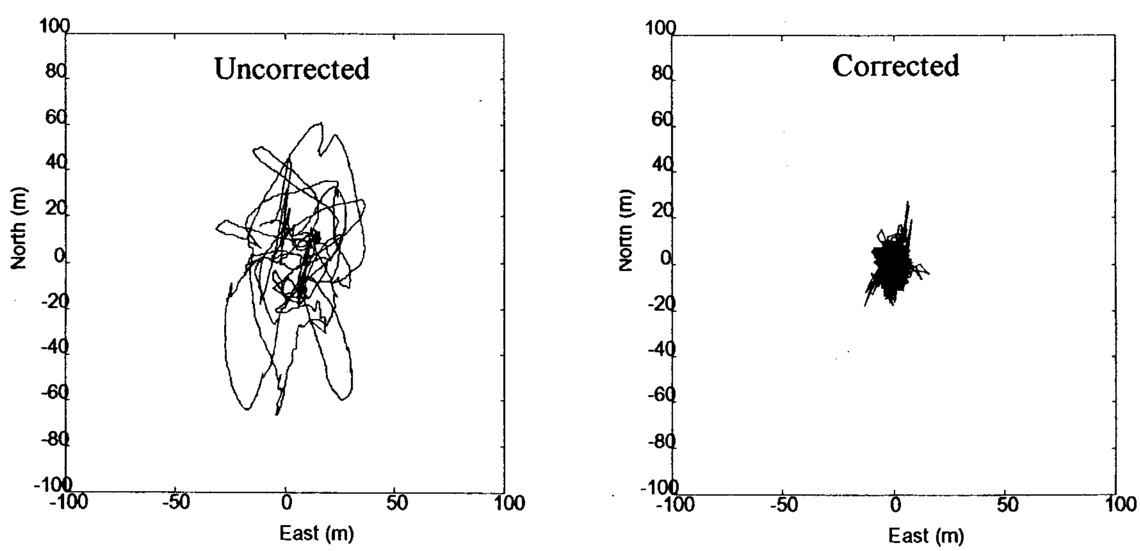

Figure 1. Comparison of uncorrected GPS position fixes, and LAGPS/Eurofix positions for the same time period, 10/26/94.

EUROFIX: Have We Reached the Limit ?

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1 - Abstract

The first on-air field trials with Eurofix have been done with the USCG Loran-C transmitter in Wildwood in September 1994. Megapulse suggested a very efficient detection technique for additionally time-modulated Loran-C pulses. The column-balanced coding scheme, also designed by Megapulse, effectively suppresses cross-rate interference.

This paper discusses the basics of the Eurofix datalink and its influence on the accuracy performance of DGPS, achievable by either synchronous or asynchronous DGPS correction types. The datalink bandwidth and its associated message error rates are the prime parameters to obtain high accuracy levels. Cross-rate interference seems to be one of the most important issues. It is shown how the sub-periodic intervals of the used GRIs control the interference patterns and the message error rates.

To prevent tracking errors in the Loran-C range measurements the modulation is balanced. As the integration window of the collected samples is seldom fully synchronous with the balanced modulation frames, there is always a slight imbalance left. The balancing requirement, however, reduces the datalink bandwidth. By applying nearly-balanced modulation schemes, the data throughput can significantly be improved while keeping the range tracking errors at the same level as with the column-balanced coding technique.

The paper ends with showing the results of the analysis of the range-tracking process in hard limiter receivers. The differences in range tracking unmodulated, fully unbalanced, nearly-balanced and column-balanced are depicted.

2 - Introduction

The original concept of Eurofix, as proposed by Van Willigen in 1989 [1], has been subject to a number of changes to improve the accuracy and integrity performance up to a level where it may meet the FRP standards for harbor approaches. Roland [2] developed an efficient and yet easy to implement demodulation technique for hard-limiter type receivers in which almost all energy of the ground- and skywave of the Loran-C pulse is available for data communication. He also suggested a coding/decoding algorithm which effectively counteracts noise and cross-rate interference. The first on-air demonstrations, carried out by Megapulse Inc., the United States Coast Guard and the Volpe Transportation Center, show the required DGPS accuracy performance feasible, even with the rather slow Loran-C based datalink.

The horizontal error radius for RTCM type 1 DGPS can be approximated by:

$$R = 2 \cdot HDOP \cdot \sqrt{\sigma_{ref}^2 + \sigma_{user}^2 + (f(d))^2 + \left(0.002 \cdot t_{data}^2\right)^2} \quad (1)$$

where

R	=	95% horizontal positioning error [m]
HDOP	=	horizontal dilution of precision (1.5)
σ_{ref}	=	range measurement noise and multipath of GPS reference receiver (0.5 m)
σ_{user}	=	range measurement noise and multipath of GPS user receiver (2.5 m)
f(d)	=	f(d) range measurement errors due to spatial decorrelation. (0.5 - 5 m)
t_{data}	=	correction data latency of RTCM type-1 message [sec]

The function f(d) is rather complex as it depends on a number of factors, such as applied ionospheric models, ephemeris anomalies, local- versus wide-area correction techniques, and mask angles [3,4,5]. The values between brackets give some typical values for current type DGPS receivers. With a data latency of 30 to 60 seconds (RTCM type-1 message, 8 satellites, 15 bps) the 95% horizontal DGPS accuracy amounts to 13 - 24 meters. Analyzing the various parameter influences on accuracy indicates that the quadratic error growth due to data latency is the main error contribution. Therefore, Beekhuis et al [6,7] suggested the highly efficient asynchronous DGPS technique which significantly reduces the temporal decorrelation. Figure 1 shows for two different users the effect of satellite configuration

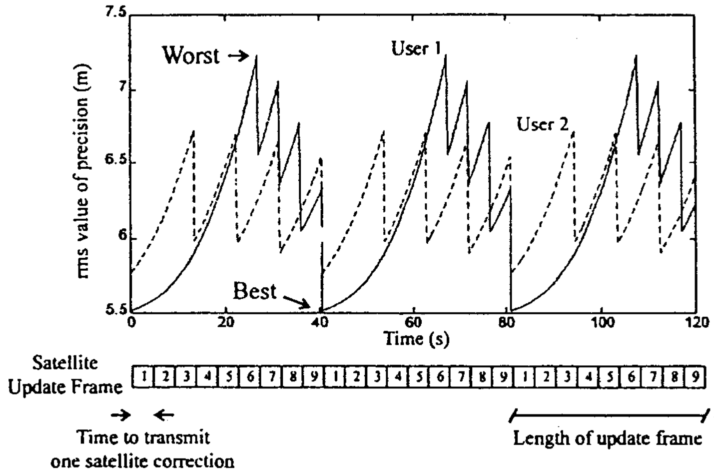

Figure 1. Position error as a function of time for two different satellite configurations.

selection in the asynchronous update frame. The plot shows an asynchronous update frame where 9 satellites are updated in 40 seconds. The vertical axis gives the position error as function of time for two different configurations.

Receiver 1 uses satellites 6, 7, 8, and 9 to calculate its position, receiver 2 uses satellites 3, 5, 7, and 9. Each time a new correction for a used satellite is received the total accuracy is improved (vertical transitions in the picture). Obviously, the different temporal decorrelation of the satellite corrections causes the total accuracy to change so dramatically. Therefore, it is difficult to predict the exact amount of improvement due to different data latencies for different satellite configurations.

Current high-end GPS receivers track satellites with very low errors due to noise and multipath. Noise is largely rejected by carrier-rate-aiding code tracking, while multipath is reduced by narrow-correlator spacing and by Multipath Estimating Delay Lock Loop (MEDLL) techniques [8]. As a result, the temporal and spatial decorrelations become the dominant parts of the total DGPS error. As every Loran-C station may eventually operate as a Eurofix station, the user has the possibility to apply a weighted average from a number of pseudorange corrections from surrounding reference stations. So, the final accuracy is then mainly limited by the amount of temporal decorrelation. Further improvement of the DGPS positioning accuracy can only be accomplished by speeding up the datalink. In other words, the data latency must be minimized which means that the effective datalink bandwidth has to be maximized.

3 - General Eurofix Datalink Model

The purpose of the Eurofix datalink is to transport

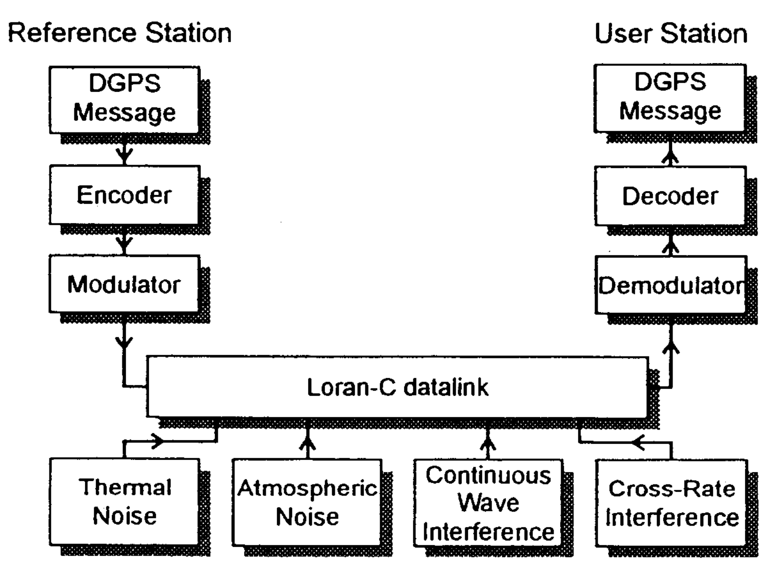

Figure 2. The Eurofix datalink model.

DGPS corrections from reference station to users at distances up to 800 km. Therefore, the Loran-C signal is additionally modulated with small time shifts of the transmitted pulses. Figure 2 indicates that the Eurofix datalink is disturbed by four kinds of interferences: thermal noise, atmospheric noise, continuous wave interference and cross-rate interference. This paper addresses only cross-rate interference, the largest source of interference that may hamper reliable data transmission.

3a - Restrictions on the Eurofix datalink

The design of an appropriate DGPS datalink based on the Loran-C signal is bounded by restrictions from both the DGPS system and the Loran-C system. The temporal decorrelation of the DGPS corrections calls for both a reliable and fast datalink. Obviously, both requirements are conflicting; the more reliable the datalink is made, the slower it becomes. Therefore, the available transmission bandwidth of the Loran-C signal has to be optimally used to satisfy both requirements to some extend.

On the other hand, the Loran-C signal cannot be modified unrestrictedly. Data transmission over the Loran-C signal is only allowed if normal Loran-C operation is not noticeably disturbed. Therefore, the following three issues are taken into account when designing the Eurofix datalink:

a) The first two pulses in each group of eight cannot be used for data transmission since they are reserved for normal Loran-C operation (blinking).

b) To avoid serious tracking errors the modulation should be balanced which means that there should be an equal number of time advances and time delays within a certain modulation block.

c) The loss in navigational power to supply the data signal power should be kept low to maintain good Loran-C positioning performance.

Based on these requirements, a 1 μs time shift modulation is selected yielding a modulation angle φ of 36 °, as can be seen in Figure 3.

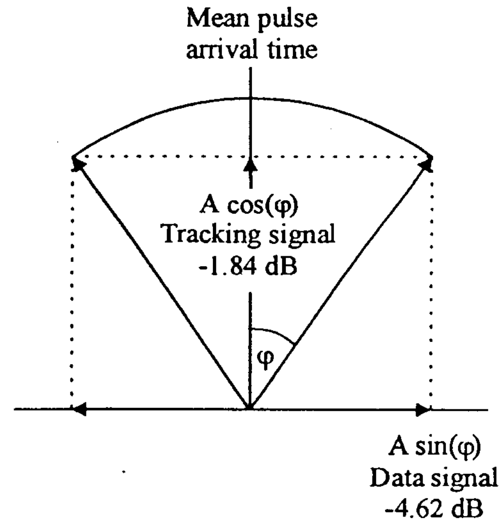

Figure 3. Vector representation of the time shifted Loran-C signal.

The tracking signal is reduced by $-20 \log(\cos(\varphi)) = 1.84$ dB for one modulated pulse. With only six out of eight pulses used for data modulation, the average reduction becomes $6/8 \cdot 1.84 = 1.38$ dB. The available data signal is 4.62 dB below the amplitude of the unmodulated Loran-C pulse.

3b - Cross-rate Interference Susceptibility

As was mentioned earlier, the main source of interference of the Eurofix datalink is cross-rate. During normal Loran-C signal tracking the influence of cross-rate is minimized by integration of the collected signal samples for a longer period of time. With Eurofix, however, each modulated pulse carries a piece of information which we like to recover. Figure 4 shows the concept of cross-rate interference for GRIs 6000 and 8000.

The cross-rate pattern depends highly on the GRIs of

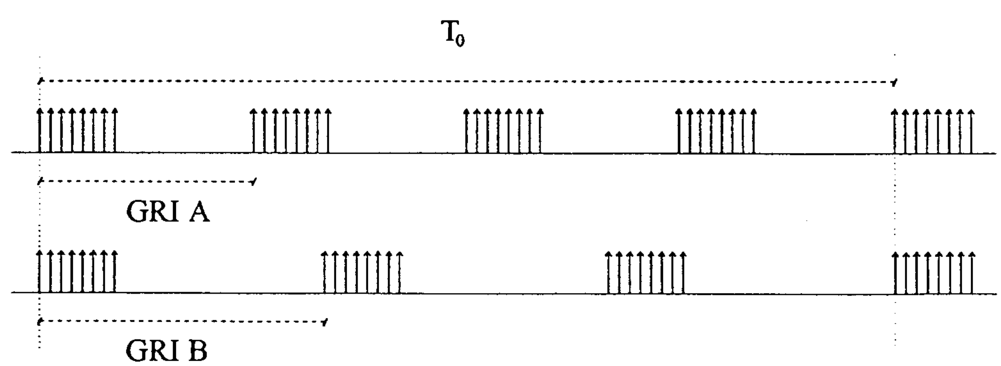

Figure 4. Cross-rate interference for GRIs 6000 and 8000.

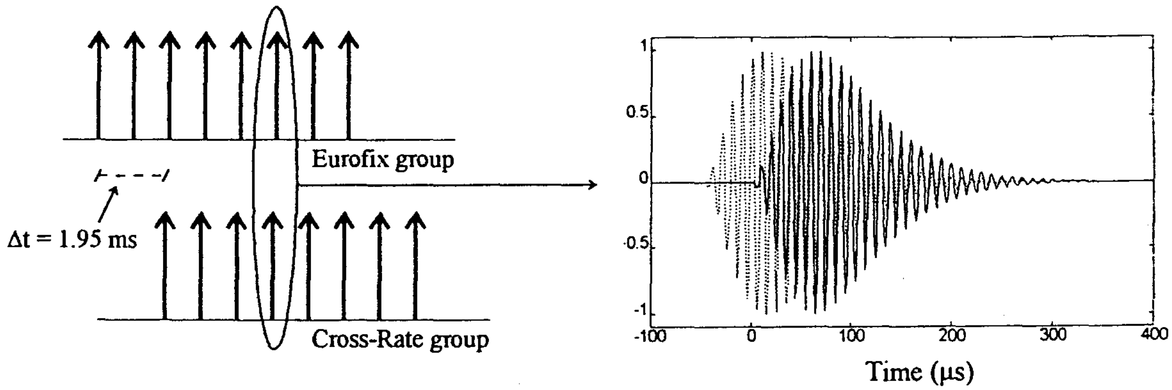

Figure 5. Example of cross-rate alignment, left: group alignment, right: pulse alignment (Eurofix pulse solid and cross-rate pulse dotted).

the two interfering chains. The repetition time T_O, the cross-over period, of this pattern is given by [9]:

$$T_O = \frac{GRI_A \cdot GRI_B}{GCD(GRI_A, GRI_B)} \cdot 10^{-5} \text{ seconds} \qquad (2)$$

where GCD is the greatest common divisor. The alignment of the cross-rating pulse group with respect to the Eurofix pulse group depends on the time difference between the start of both groups which can be calculated with:

$$\Delta t = t_0 + \mathbf{n} \cdot GRI_A + \mathbf{m} \cdot GRI_B \qquad (3)$$

where t_0 is the initial time offset at the user position at some starting point in time, **n** is the number of Eurofix GRIs and **m** the number of cross-rating GRIs. If the time difference Δt lies between -8 ms and 8 ms, the two pulse groups partly overlap. If the ninth Master pulse is taken into account as well, this period will be extended. All is clarified with an example.

Example: Suppose the Eurofix station has GRI_A = 6500 and the cross-rating station has GRI_B = 5005, and initially they were aligned (t_0 = 0). After 30 times GRI_A (1.95 seconds) **m** will be 39 (nearest integer) and the time difference $\Delta t = -1.95$ ms. This means that $group_A$ starts 2 pulses earlier than $group_B$ but the coinciding pulses of $group_A$ start 50 µsec later than those of $group_B$. Further, only pulse 3 through 8 of $group_A$ will be hit by a pulse of $group_B$ with an offset of 50 µsec as shown in Figure 5.

Figure 6 shows the cross-rate patterns of the GRI combination of the 9960 Northeast US chain and the 5930 Canadian East Coast chain. The interaction of the European combination 9007 (Ejde) and 6731 (Lessay) is depicted in Figure 7. The patterns are calculated in accordance with Formula 3. The patterns only indicate whether a group of pulses is hit by cross-rate, relative amplitudes and phases are not considered yet. On the horizontal axis the number of the Eurofix GRI is displayed, on the vertical axis the

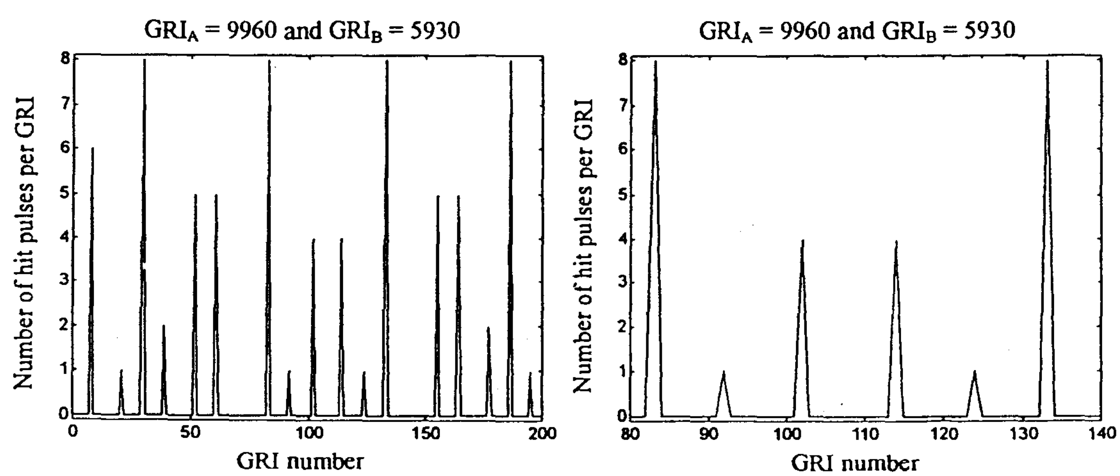

Figure 6 a&b. Cross-rate pattern of the 9960 Northeast US chain (Eurofix) and the 5930 Canadian East Coast chain (cross-rate).

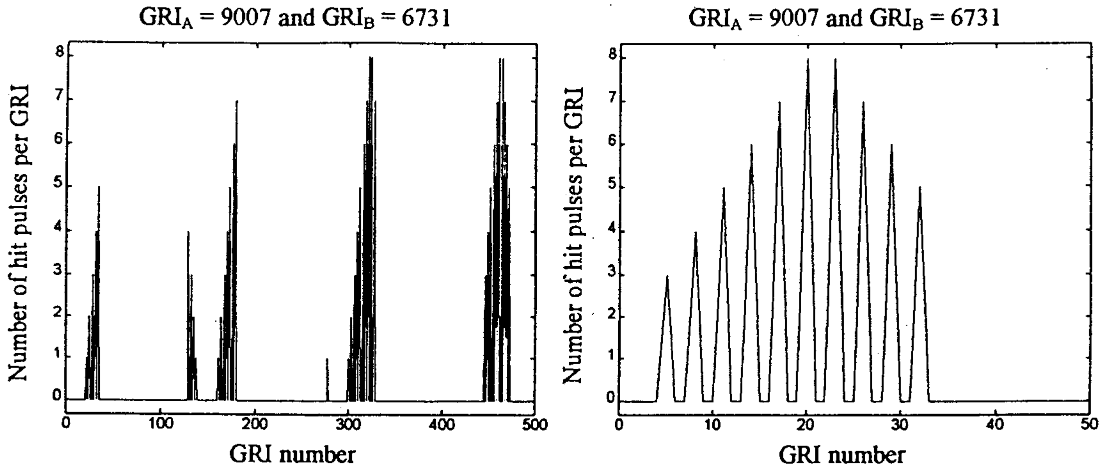

Figure 7 a&b. Cross-rate pattern of two new European Loran-C chains.

number of hit pulses per group is shown.
Both pictures show the cross-rate pattern when only one station interferes with the Eurofix signal. If more interfering stations are received at signal levels comparable to the Eurofix signal, then a combination of more cross-rate patterns results. Figures 6 and 7 indicate that the peaks in the cross-rate patterns are separated at equal distances. This so called sub-periodic interval [9] is due to the fact that the Loran-C pulses are not infinitesimally small but of a certain width (approximately 200 μs which will be lengthened by the reception of skywaves). Especially, cross-rate patterns with small sub-periodic intervals and a large number of hit pulses per group (as in Figure 7) make reliable data transmission a non-trivial issue.

Each pair of Loran-C chains interfering with each other has its own typical cross-rate pattern with its own sub-periodic intervals. Especially, this sub-periodic interval can cause problems when not properly dealt with in the selection of appropriate modulation and coding schemes.

Tables I and II give the sub-periodic intervals of the North American and European Loran-C chains.

		7001	9007	7499	6731
Bø	7001	X	18	1	23 25
Ejde	9007	14 35	X	10 15	**3**
Sylt	7499	1	12 18	X	8 9
Lessay	6731	24 26	**4**	9 10	X

Table I. Sub-periodic cross-rate intervals of the new European Loran-C chains.

Especially, GRI pairs with boldfaced numbers correspond to badly aligned cross-rate patterns. Extra care should be taken in the design of a coding scheme to compensate even for this kind of

		5990	9940	8290	9610	8970	7980	9960	5930
Canadian West Coast Chain	5990	X	15 20	7	24				
US West Coast Chain	9940	9 12	X	**10 15**	30	18 19			
North Central US Chain	8290	5	**12 18**	X	15 22	1 27		**12 18**	
South Central US Chain	9610	15	31	13 19	X	**14**	15	2 27	
Great Lakes Chain	8970		20 21	1 36	**15**	X	16 24	20 30	**4**
Southeast US Chain	7980				18	18 27	X	25	**3**
Northeast US Chain	9960			**10 15**	2 26	18 27	20	X	9
Canadian East Coast Chain	5930					**6**	**4**	15	X

Table II. Sub-periodic cross-rate intervals of the American Loran-C chains

	GRI A	GRI B
GRI 1 & 2	0 0 + + + + + +	0 0 + + + + + +
GRI 3 & 4	0 0 - - - - - -	0 0 - - - - - -
GRI 5 & 6	0 0 + + + + + +	0 0 + + + + + +
GRI 7 & 8	0 0 - - - - - -	0 0 - - - - - -

Code bit
vertically extracted

Figure 8. The column-balanced modulation scheme.

interference.

Whether a cross-rating pulse destroys the Eurofix information completely, depends highly on the signal strength and relative phase of the cross-rate signal with respect to the Eurofix signal. The relative phase depends on user position with respect to both interfering Loran-C stations, phase code of both signals and the actual transmitted Eurofix data.

3c - Revisiting the column-balanced modulation scheme

The first strategy used to counteract the influences of cross-rate interference is the column-balanced modulation scheme developed by Megapulse, Inc. The on-air demonstrations with the experimental transmitter at Wildwood are carried out using this modulation scheme which is shown in Figure 8.

In GRIs 1&2 each data bit is represented by a time shifted pulse. In order to be balanced, the resulting modulation pattern is inverted in the next two GRIs. To provide appropriate protection against the influences of cross-rate interference the four GRI modulation pattern is repeated once again. In this way, each data bit is represented by four modulated pulses in four different GRIs. At the receiving end, the transmitted data is recollected by majority voting over the four corresponding modulated pulses. With this scheme 12 data bits can be transmitted in 8 GRIs which corresponds to an effective data rate of 1.5 bit per GRI (37.5 - 15 bits per second). As was described in Section 2, the DGPS accuracy is bounded by the temporal decorrelating effect of the satellite corrections. Therefore, even slight improvements in effective data rate may have great influence on the final DGPS accuracy.

3d - Sliding window concept.

Although the scheme is balanced at first sight, imbalances may still occur in the received modulation pattern. To compensate for low SNR and

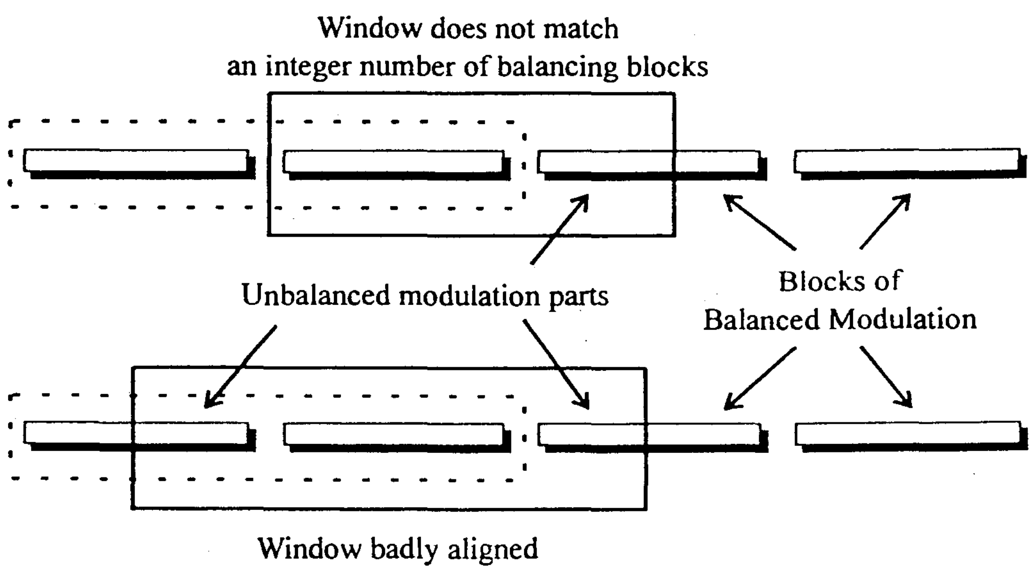

Figure 9. Integration window versus balanced modulation blocks.

influences of cross-rate, each Loran-C receiver takes a number of samples of consecutive pulses before a time measurement is done. Therefore, the sample collection of a Loran-C receiver can be seen as a sliding window over all available pulses in time. No tracking errors are induced by the data modulation as long as the received modulation pattern is balanced within the sliding window of the receiver. Figure 9, however, shows that balanced modulation for one receiver integration window can be unbalanced for another. In general the Loran-C receiver starts the integration of the signal samples at an arbitrary moment in time. If this moment in time does not coincide with the start of a balanced block, the received pulses within the integration window may still be unbalanced after all.

The unbalanced parts in the receiver window will not cause any noticeable tracking errors as long as they remain small with respect to the size of the receiver window. Clearly, Loran-C receivers with larger integration times will notice less influence of imbalances than receivers with smaller integration times.

4 - Nearly-balanced Coding Scheme

To improve the DGPS accuracy within the Eurofix concept, coding schemes have to be designed which yield higher data throughput than the currently used column-balanced technique. On the other hand, the coding scheme should also be able to correct for the influences of cross-rate interference and noise. Especially, the balancing requirement puts large constraints on the design of reliable and yet fast modulation schemes. It is reasonable to assume that the DGPS information source outputs zeros and ones in more or less equal proportions. Therefore, it is also very likely that the majority of the transmitted messages is already balanced to some extent.

Recently, a coding scheme has been developed which uses all available transmission bandwidth within the Loran-C signal. The code is based on a (6,5) odd parity check code concatenated with a Reed Solomon code to compensate for the influences of cross-rate. The (6,5) odd parity code has the advantage that the majority of the possible code words is already balanced which is explained in Figure 10.

Figure 10 shows that 20 out of 32 possible code words are balanced. The remaining 12 words have an imbalance of 4 pulses and can be divided into two groups of 6 with opposite effects on the Loran-C tracking mechanism. A message built up by code words of the (6,5) odd parity code will normally be balanced or show just a slight imbalance. Also, the Loran-C transmitter has the opportunity to check whether the offered modulation pattern may cause unacceptable tracking errors in the Loran-C receivers. The Eurofix transmitter may decide to transmit a DGPS integrity message instead, to notify the DGPS users. The influence of this intentional loss of a DGPS message on the final DGPS accuracy is compensated for by the increased data rate.

The odd parity code by itself is not sufficient to compensate for errors due to cross-rate interference. Therefore, the code is concatenated with a Reed Solomon (RS) code. This code is capable of

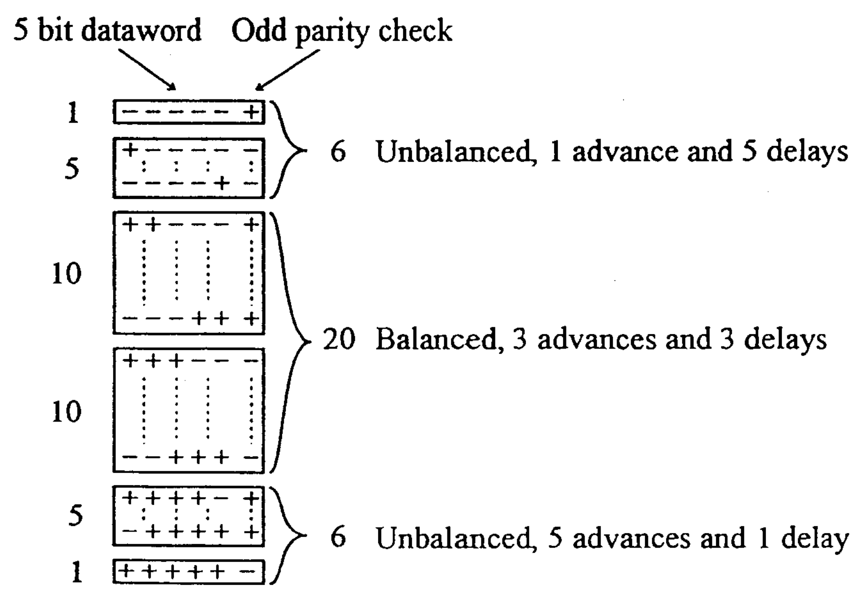

Figure 10. Nearly-balanced scheme using the (6,5) odd parity code.

correcting multiple series of errors and is thus very suitable to correct errors due to cross-rate. The RS code is a symbol-oriented coding scheme in which each modulated GRI represents a 5-bit symbol. The RS encoder adds a number of parity symbols which can be used to correct for symbol errors due to cross-rate. The (6,5) odd parity code can aid in the decoding process by localizing the symbol errors. With the concatenated scheme a 45 bit asynchronous DGPS message can be transmitted in about 15 to 31 GRIs depending on the amount of parity symbols needed to ensure reliable data transmission. What this amount should be is still subject of study. However, the effective data rate will then be increased from 1.5 to at most 3 bits per GRI.

5 - Influence of Data Modulation on the Navigation Performance

In Section 3 the signal loss due to the 1 μs time shift modulation was calculated. In this calculation no timing aspects (tracking errors) were considered. Figure 11 shows the performance of a simulated normal Loran-C hard-limiter receiver for four different Loran-C signal conditions:

1. Unmodulated Loran-C, the present normal Loran-C signal
2. Column-balanced modulation
3. Nearly-balanced modulation
4. Totally unbalanced modulation, the Loran-C pulses are randomly modulated with time advances and delays

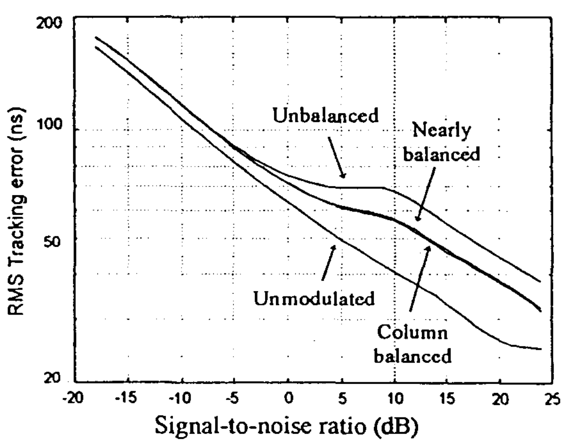

Figure 11. Navigation performance of a normal hard-limiter Loran-C receiver with unmodulated and modulated pulses.

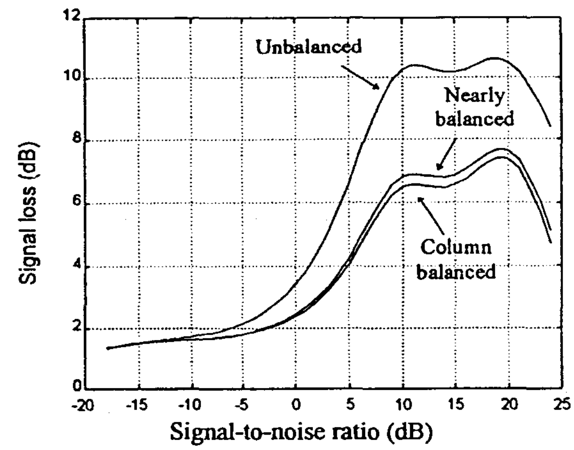

Figure 12. Navigation performance of a normal Loran-C receiver with Eurofix modulated pulses with respect to unmodulated Loran-C reception.

The simulated Loran-C receiver has an integration time of 2 seconds (20 GRIs with a 100 ms GRI) and a tracking stepsize of 50 ns. The signal-to-noise ratio is shown on the horizontal axis while the vertical axis represents the rms value of the tracking error. Figure 12 compares the three modulated cases with respect to the present unmodulated reception of the Loran-C signals. Now, the vertical axis shows the signal loss in dB due to the modulated pulses.

Two remarkable observations can be made from these pictures:

1. At higher SNR the performance of the hard-limiter receiver decreases for Eurofix modulated Loran-C signals compared to the normal unmodulated Loran-C signal. This phenomenon is due to the dead zone in the phase detector of hard-limiter receivers and will not occur with linear Loran-C receivers. Fortunately, the Loran-C tracking loss in accuracy occurs only at high SNRs where tracking is already of high quality.
2. The column-balanced and the nearly-balanced modulation show more or less the same performance. This justifies further research into nearly-balanced coding schemes which can use the available transmission bandwidth more effectively.

6 - Concluding Remarks

It has been shown that the temporal decorrelation of the satellite corrections will be the dominant part in the final DGPS accuracy with current high-end GPS receivers. However, the balancing requirement and the necessity to compensate for cross-rate influences make the Loran-C datalink somewhat slow. The column-balanced modulation scheme developed by Megapulse, Inc. provides a fairly reliable means to transmit DGPS corrections. However, the sliding window concept shows that slight imbalances may occur in the Loran-C receiver even if the transmitted modulation pattern is balanced. A nearly-balanced coding scheme has been designed which is able to transmit DGPS messages reliably at higher data rates and where the imbalance is comparable to the column-balanced modulation. Future experiments have to show what the influence of the higher throughput will be on the final DGPS accuracy.

7 - Acknowledgments

The authors would like to thank Mr. William Roland and Mr. Hein (Jan) Andersen of Megapulse, Inc. for their incredible effort to make the Eurofix project a success. Without their ideas and dedication the Eurofix project would not be where it is today. We would also like to thank Dr. Jos Weber of the Delft University of Technology for his support on the field of error correcting theory. Eurofix, being part of a larger project called 'Integrated Navigation for Traffic and Transportation' is partly funded by the Beek-Committee. Finally, we would like to thank the Dutch Department of Transportation for all the extensive and encouraging help we got. We would like to encourage everyone who has suggestions or comments on the work presented here to contact one of the authors. Any idea for further improvement of the Eurofix navigation system is received with open arms.

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9 - Biographies

Gerard W.A. Offermans received his masters degree in electrical engineering from the Delft University of Technology in 1994. His master thesis research dealt with his invented nearly-balanced coding scheme for the Eurofix datalink. He is now working on GNSS datalinks for aerospace, maritime and land applications in a 4-year Ph.D. research program at the same university.

Dr. Durk van Willigen heads as a professor in radionavigation a research team of staff and Ph.D. and M.Sc. students in the Department of Electrical Engineering at the Delft University of Technology. This group focuses on integrated navigation systems which are based on DGNSS and Loran-C (Eurofix), and on DGNSS and MLS (MIAS - Multi-mode Integrated Approach System). This team puts much effort on man-machine interface aspects in cockpits of aircraft in a 4D ATM environment. As Boardmember of the International Research Center for Simulation, Motion and Navigation (SIMONA) he is responsible for all research on the simulation of complex navigation systems. Finally, Durk van Willigen is the president of Reelektronika, a small privately owned consultancy on radar and radionavigation.

Edward J. Breeuwer received his M.Sc. degree in Electrical Engineering from Delft University of Technology in 1992. He did his master thesis research program on GPS multipath issues at the Avionics Engineering Center of the University of Ohio. He is currently working towards a Ph.D. at the Delft University, where he is studying the potentials of integrated navigation systems for land, sea (Eurofix) and air (MIAS) applications. He is actively involved in foreign contract research programs on GNSS precision approaches.

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STUDY OF LORAN-C TRANSMISSION OF DGPS DATA

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ABSTRACT

There is interest in using the CONUS Loran-C stations to transmit DGPS corrections, specifically to aircraft attempting to use GPS for non-precision apporaches. The transmission technique could consist of pulse-position modulation of the loran pulses, similar to that used in Clarinet Pilgrim. The paper predicts the worst-case atmospheric noise and cross-rate interference to be found, and calculates the bit error rate to be expected under these conditions.

INTRODUCTION

There is much interest in using GPS as a primary navigation system in performing non-precision approaches (NPAs) in the continental U.S. (CONUS). The standard positioning service (SPS), which is available to all, is subject to deliberate position errors which can exceed 100 meters 5% of the time. In order to defeat these errors, a number of systems of differential GPS (DGPS) have been proposed. One of these proposals is to disseminate the DGPS corrections by modulating the data on the transmissions of the 18 Loran-C stations located throughout the CONUS.

This paper presents a brief analysis of the effectiveness of using a system of modulating Loran-C pulses to transmit differential GPS correction information to aircraft in the continental U.S., specifically for assistance in making NPAs. The modulation system under study is pulse-position modulation of the loran pulses, essentially identical to the technique used in the Clarinet Pilgrim (CP) system developed for the U.S. Navy.

CONUS LORAN-C

There are 18 Loran-C transmitting stations in the continental U.S., operating on eight different rates. Figure 1 shows the locations of the transmitters and the chain interconnection. In order to estimate the probable performance of digital communication from the loran stations, it will be assumed that DGPS correction messages will be transmitted from all 18 loran stations. It will also be assumed that the DGPS receiver is able to track at least two GRI simultaneously, and can select the closest loran transmitter to receive the DGPS message. The problems of designing such a receiver and of generating and decoding these messages are not a part of this paper.

It happens that 13 of the 18 stations are dual-rated, which means that they transmit on two different Group repetition Intervals (GRI) from the same antenna. Since the GRI are not synchronous, there is a periodic "crossover" in which both rates should be transmitting nearly simultaneously. The transmitters are not capable of this, so it is necessary that one of the rates be not transmitted. The Coast Guard has two methods of dealing with this, either blanking the shorter GRI whenever coincidence occurs, or alternately blanking first one and then the other. The first method is compatible with the communication requirement, simply putting the modulation on the GRI which is not blanked. The second method interrupts both GRI, and would introduce unnecessary errors, which is not acceptable.

CLARINET PILGRIM

Clarinet Pilgrim is the code name for a system used by the U.S. navy in the 1970s which transmitted coded fleet broadcasts by modulating the transmitted pulses of loran transmitters. Although it performed satisfactorily, it was limited to areas covered by Loran-C. It has since been replaced by newer systems and is no longer in operation.

The data transmitted was a 50 baud binary stream, sent identically from each loran station in the chain. The information was converted into pulse-position modulation of the last six of each eight-pulse loran group. The modulation consisted of a one-microsecond shift of the timing of the pulse, either advance or retard, corresponding to binary data. The first two pulses were not used as they could be switched off and on by the Coast Guard operators in the "blink" mode to indicate station malfunction. In the use of CP in the Pacific, the Northwest Pacific chain, with a GRI of 9970, was used. With six pulses per group modulated, there resulted in about 60.18 pulses per second being available for data. At each transmitter, the 50 baud data stream was separated into 6-bit "words", and a "sync word" was inserted periodically to make up the difference in rates. At the receiver, the sync words were recognized and stripped out

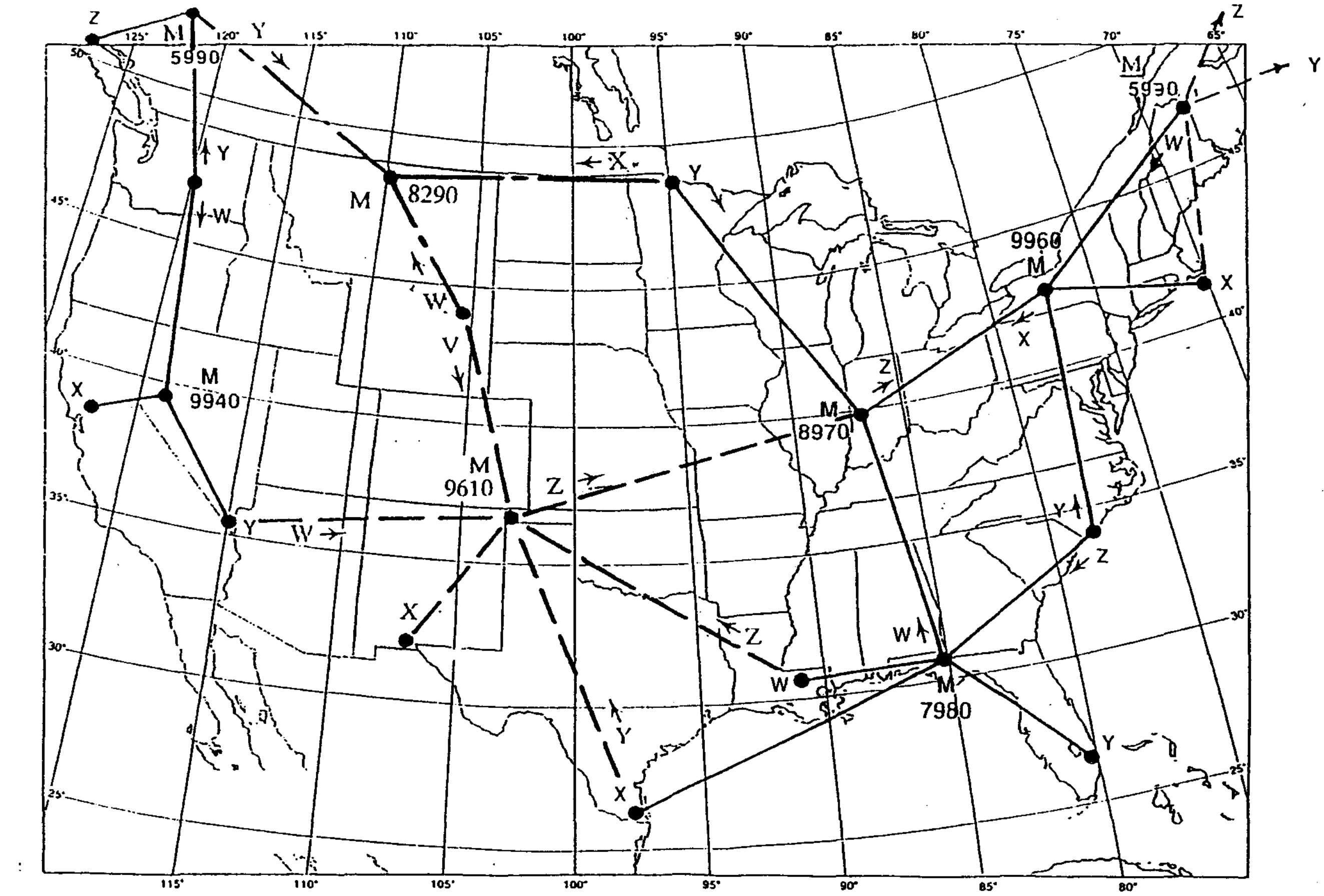

Figure 1. CONUS Loran-C Chains

of the data stream, which was then reconstituted at the 50 baud rate.

Although the data stream was normally pseudo-random, there was the possibility of a series of ones or zeroes being transmitted, so the phase modulation sense was reversed every two GRI, to maintain an average zero modulation offset. The sync words were, of course, balanced in themselves.

Because the system was not bothered by skywave interference, and actually used skywave signals at long distances, the Clarinet Pilgrim receiver used a narrower r-f bandwidth than the loran navigation receiver, approximately 6 kHz, and tracking was done at the peak of the received, filtered pulse. Data were received from three stations, and the resulting data from each were combined bit by bit in a "majority vote" process to reduce the error rate. This was the only error-correcting method used in the system.

During the course of the development and operation program, theoretical and experimental studies were made to determine the error rate of the system resulting from atmospheric noise and crossing rate interference. The results of these studies can be used to predict the error rate of a system used in the CONUS using similar modulation.

NON-PRECISION APPROACHES

The objective of this exercise is to develop a system which can be used to assist aircraft in non-precision approaches. The SPS mode of GPS is available to all, including civilian aircraft. The Selective Availability (SA) introduces errors in the SPS data which can result in position errors which exceed 100 meters 5% of the time. The DGPS system transmits data which can correct most of those errors, the amount of correction depending on the delay between reception of satellite data at the DGPS station and the decoding of the correction data at the receiver.

Figure 2 is an example of field data taken recently (1), and indicates that the SA can result in position changes in the order of 100 meters per minute. This means that to hold errors below, say, 20 meters, the correction information must be compiled, transmitted, received, decoded and acted upon in 12 seconds.

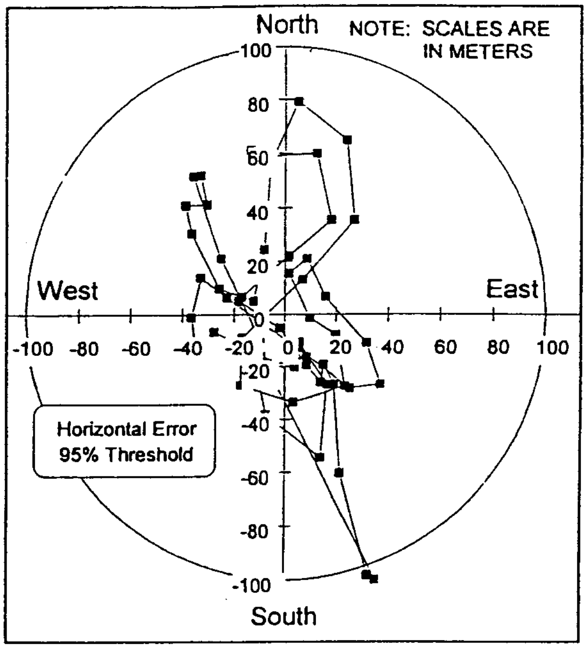

Fig.2—Horizontal Errors over 1 h

DATA FORMAT

The Radio Technical Commission for Marine Services (RTCM) has developed a set of digital data formats for transmission of various types of data, including DGPS. This format is detailed in reference (2). The Type 1 message, which transmits the basic correction information, uses about 50 bits per satellite, or 300 bits for six satellites. The Eurofix system proposes a format which would use 61 bits per satellite, 366 bits for six satellites.

The minimum data rate available from the loran transmitters is 60 baud, so that data from six satellites could be transmitted in five or six seconds. Detailed system design could determine whether all data should be transmitted at the same rate, or tied to the specific loran GRI.

In any case, it is apparent that there will be data capability to provide differential data at a rate sufficient to correct the GPS position information to an accuracy of 25 meters or so, sufficiently accurate for non-precision approaches.

EUROFIX

The idea of using the Loran-C pulses to transmit DGPS corrections has already been suggested by Durk van Willigen, of Delft University of Technology. The proposed system, called Eurofix, would utilize the loran stations now operating in the European area and new stations proposed to be installed in the near future.

As described, the optimal configuration of the Eurofix system would use a 15 baud data rate, transmitting pseudorange and range-rate corrections for six satellites in 28 seconds. Each message would have only parity bits for error detection, so that a parity error would negate the message, requiring a wait for the next message for

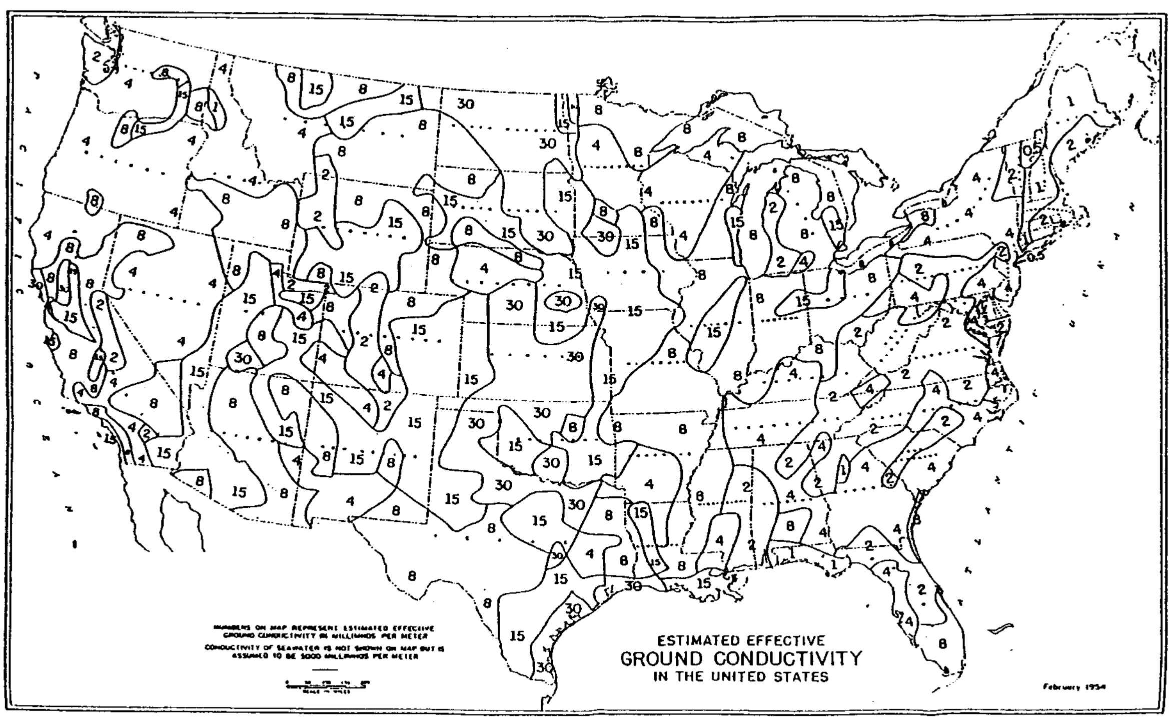

Figure 3.

that satellite, consequentially producing an increase in the rms range error.

SYSTEM PERFORMANCE

The first step in evaluating the performance of the proposed system is to determine the maximum distance between transmitter and receiver, since this determines the received signal strength and other signal characteristics. A study of the CONUS coverage reveals several points 400 nautical miles from the closest loran transmitter. The worst case occurs at a point N36 30, W094 45. The closest airport to this point is 5OK0, at Kansas, Oklahoma, N36 08.7, W94 47.25. This airport is 411 nautical miles from Dana, IN, 380 nm from Grangeville, LA and 394 nm. from Boise City, OK.

The next step is to predict the signal conditions at the worst case location. At a range of 400 nautical miles, the groundwave signal is of sufficient amplitude that it can be the preferred mode even in the presence of skywaves. The conductivity map of the U.S., figure 3, shows that the average ground conductivity for all the paths from the transmitters to the receiver location is at least 10 millimhos per meter, so that the expected signal field strength, derived from figure 4, is 70 dB above one microvolt per meter.

ATMOSPHERIC NOISE

The latest information on atmospheric noise amplitude and characteristics is found in CCIR Report 322-3 (reference 3). It was study of the noise prediction charts in this report which resulted in the selection of Kansas, Oklahoma as the worst location. Two other locations farther north also have a distance of 400 nm. to the nearest loran transmitter, but the noise conditions are more severe in Oklahoma.

CCIR Report 322-3 gives predictions of rms noise amplitude anywhere on the surface of the earth, in four-hour time blocks for each of the four seasons of the year, a total of 24 values. These are mean values, En, rms noise field strengths in dB above one microvolt per meter, exceeded 50% of the time. Also given for each time block is the value of Du, in dB, the ratio of the upper decile of noise voltage, to the mean. In order to establish worst case conditions, each value of En was increased by its corresponding value of Du, giving what will be called Eu, the rms noise level exceeded 10% of the time.

In an effort to get a clearer understanding of the noise situation, the values of Eu at 5OK0 have been plotted for each time block in figure 5. The graph shows clearly that during two of the 24 time blocks, from 1200

GROUNDWAVE FIELD STRENGTH

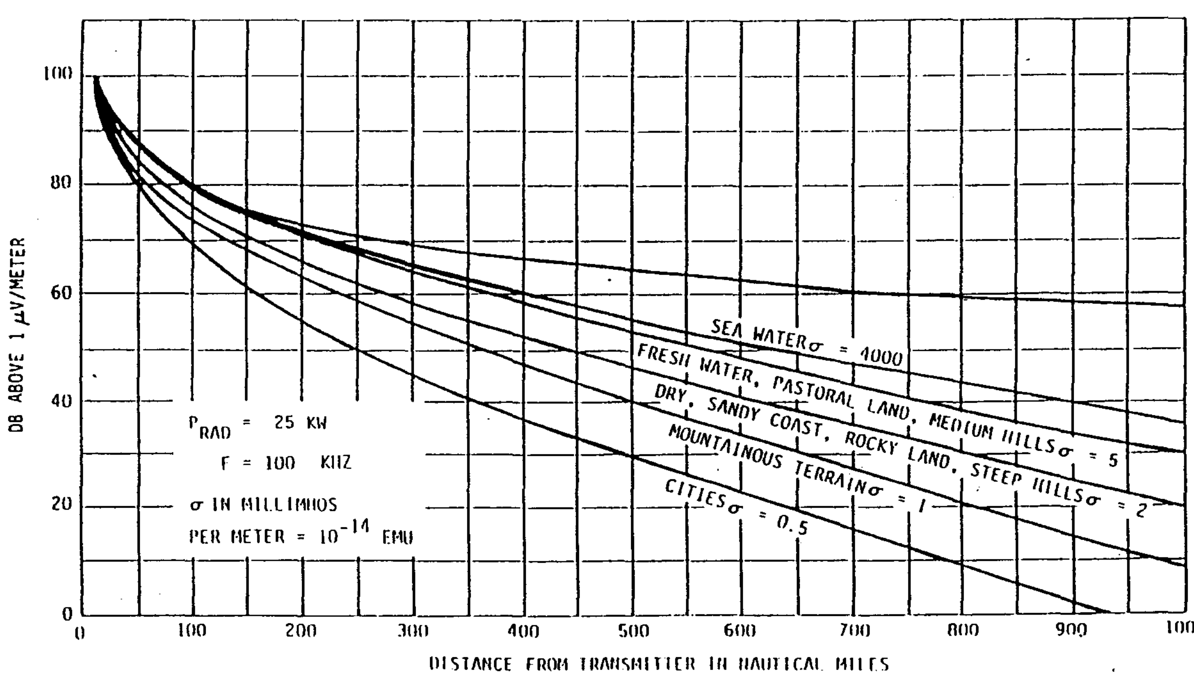

Figure 4.

to 2000 hours local time in the summer, the average rms noise will exceed 73 dB, 10% of the time. This can be regarded as a realistic worst case condition, and since it is the mean value which exceeds 73 dB, then the actual noise value exceeds 73 dB only 5% of the time. The next worst values of Eu are less than 65 dB, at 1600-2000 hours in spring and 2000-2400 hours in summer.

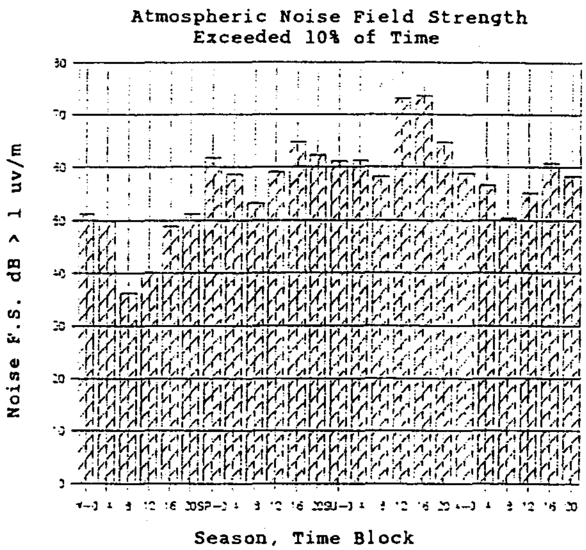

Figure 5. Atmospheric Noise at Kansas, Oklahoma

The issuance of CCIR Report 322-3 revised the worldwide noise maps, the result of collection of additional data. and also corrected the formula for calculating the value of Vd, the amplitude probability of noise, as a function of the receiver bandwidth. The result is that the value of Vd applicable to this system using a 20 kHz bandwidth comes out to be approximately 14 dB. Using this value of Vd results in a curve of noise amplitude probability as shown in figure 6, plotting the probability that the noise will exceed any value relative to the rms value. The curve shows, for example, that the noise voltage will exceed the rms value 2.7% of the time, or a value 2 dB above the rms value 1.9% of the time.

Calculations were made during the Clarinet Pilgrim of the relationship between bit error rate and atmospheric noise level. These were based on the narrow bandwidth used. Using these data, and adjusting for the difference in noise amplitude probability distribution for the wider bandwidth results in the curve of figure 7. From this curve, the bit error rate for SNR of -3 dB is .014.

SKYWAVES

Daytime and night present quite different skywave conditions at 100 kHz. At a range

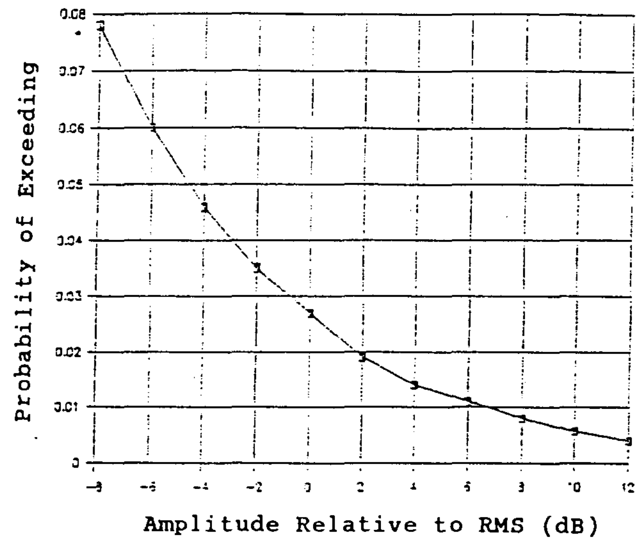

Figure 6. Atmospheric Noise Amplitude Probability Distribution Vd=14 dB

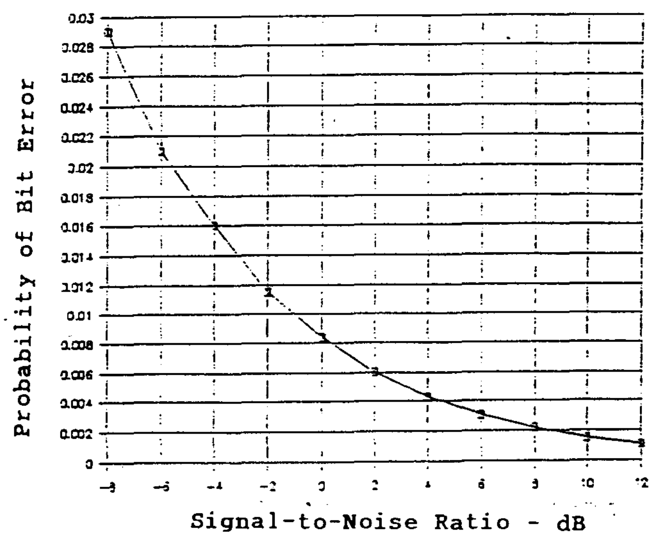

Figure 7. Clarinet Pilgrim Bit Error Rate Atmospheric Noise Vd = 14 dB

of 400 nautical miles, which will be considered the worst case, with the groundwave at an amplitude of 70 dB, the daytime skywave is expected to be 7 dB smaller and have a delay relative to the groundwave of 53 microseconds. At night, the skywave will be 3 dB larger than the groundwave, but the delay will be 84 microseconds. In either case, the peak of the groundwave loran pulse can be used for data sampling, since the skywave will not be of sufficient amplitude to have a meaningful effect on the signal.

The principal effect of skywaves is to bring crossing rates to a higher amplitude at night. The effect of this on the data error rates is evaluated below. It should be noted that the skywave conditions quoted here differ from those specified in the Eurofix papers. This is because the lower latitude of the CONUS enjoys a more benign skywave environment.

CROSSING RATE INTERFERENCE

If the crossing rate signal is considered of constant amplitude and random phase, then the probability of error due to a hit, as a function of signal-to-interference ratio is given in figure 8. When the two are equal, the probability is 0.29, The error probability approaches 0.5 as the SIR gets bad, and drops to zero when the SIR is above 4.6 dB.

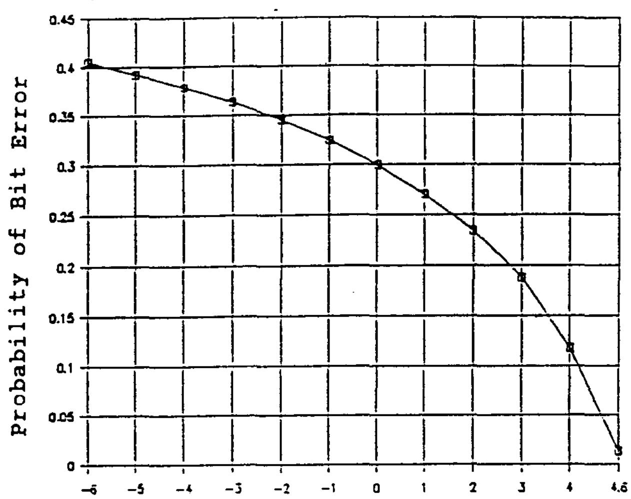

Figure 8. Crossing Rate Error Probability

A BASIC program was written calculating the number of hits crossing between all the rates used in the CONUS with six modulated pulses. The program defines a "hit" as coincidence with a modulated pulse within a 200 microsecond window. This is quite conservative for the proposed configuration using 20 kHz bandwidth which produces relatively short pulses. It should be noted that "hits" do not occur all the time.

The "hit" rates of interest are as follows:

GRI1/GRI2	RATE
9610/9960	.00770
7980/8970	.00891
8970/9610	.00832
7980/9610	.00832
8970/9960	.00802
7980/9960	.01606 ***

The worst "hit" rate, between 9960 and 7980, is .016, but this rate occurs only 1/4 of the time, depending on the location of the receiver. One fourth of the time the hit rate is .0010, and half the time the hit rate is zero. It is assumed that the strongest crossing rate will be the same strength as the signal being used, the location being equidistant (400 nm.) from two stations. This means that the relative amplitude will be 0 dB, resulting in a 0.29 probability of error for each hit. This makes the maximum probability of error due to a single 7980 crossing signal of equal amplitude to be .00466.

EXPECTED BIT ERROR RATE

For the location selected, Kansas. Oklahoma, there is a choice of three stations;

STATION	GRIs
Boise City	9610, 8970
Grangeville	9610, 7980
Dana	9960, 8970

The worst crossing rate error at this location will occur if Dana is used, 9960. In this case, the crossing rates will be 9610 and 8970 from Boise City and 9610 and 7980 from Grangeville, producing the following error rates:

STATION	BIT ERROR RATES
Boise City	.00223+.00233=.00456
Grangeville	.00223+.00466=.00689

In the worst case, these will add linearly, giving an error rate of .01145

At the times of highest atmospheric noise, the worst expected data error rate will be the sum of the error rates contributed by atmospheric noise and crossing rate signals. It should be noted that the worst atmospheric noise occurs during daylight hours, so that At Kansas, Oklahoma, the worst case signal-to-noise ratio will be -3 dB. The worst crossing rate will be on 9960, with three signals at 0 dB relative amplitude. The resulting error rate will be:

Crossing Rates	.0115
Atmospheric Noise	.014

Total Error (sum)	.0255

The means a bit error rate of slightly more than one in 40 can be expected at the worst location, at the time of worst atmospheric noise,

At night, skywaves from other stations can have amplitude as much as 2 dB larger than the desired signal. These are Malone, Raymondville, Carolina Beach and Las Cruces. These will add to the crossing rate error as follows:

STATION	GRI
Malone	7980,8970
Carolina Beach	7980
Raymondville	7980,9610
Las Cruces	9610,8970

The "hit" rate for 9610 and 8970 against 9960 is independent of the relative timing, so the hits can be directly added. For 7980, for a moving vehicle, a more realistic estimate is obtained by averaging the hit rates over the interval, and adding the averages. The hit rates are .00466, .0029, 0, 0, each 1/4 of the period, giving an average of .00189. This results in crossing signals

2 x 9610 = .00524
2 x 8970 = .00546
3 x 7980 = .00567

Total Error = .01637

Total Skywave Error (sum)	.01637
Groundwave Signals Error	.0115

Night Crossrate Error Rate	.0279

Atmospheric noise, according to CCIR 322-3, has a maximum field strength of 65 dB at night, giving a signal-to-noise ratio of +5 dB, which should produce a bit error rate of .003. This, added to the crossing rate errors, produces an error rate of .0309. This is obviously the most serious condition, as a bit error rate in the order of .028 may occur every night, in the worst location.

Examination of the details of the crossing rate interference reveals that, once a "hit" occurs due to a crossing rate, no further hit occurs for at least 25 GRI, with one exception. In the case of 9610 crossing 9960, a "hit" is usually followed by another just two GRI later. In every case, the configuration of the pulses is such that only one of the pulses hit the first time gets hit a second time.

CONCLUSIONS

This brief analysis of the effectiveness of the Clarinet Pilgrim form of modulation of the Loran-C stations to transmit DGPS information shows that, in the worst location, the bit error rate can be as high as .0309. Such an error rate is probably unsatisfactory. Methods of solving this problem include ignoring the worst cases, or correction coding to reduce the error rate. The crossing rate problem can be mitigated by receiver tracking of the crossing rate and identifying errors due to "hits". Analysis of these solutions, or evaluation of the effect of the error rate on the dynamics of data transmission are considered beyond the scope of this study.

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Symposium Papers

Session II

Management and Policy

Signal Availability Requirement for Radionavigation Aids in the National Airspace System

Phase II Study

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Abstract

The FAA has initiated a project to define the availability requirement for radionavigation aids within the National Airspace System (NAS). To date, no rigorous availability standards for navigational aids have been established. In 1993, the Volpe Center conducted a study, Phase I, which was the first step in the determination of the signal availability requirement [1].

The Phase I study compared the availability of two nonprecision approach (NPA) aids: VOR and Loran-C. The results demonstrated that the availability of Loran-C for a nonprecision approach is approximately 99.6%, while VOR is available for an approach 99.99% of the time. However, if a second approach is attempted, the availability of Loran is comparable to VOR. The reason that the availability improves so much on the second approach attempt is that the majority of Loran outages are momentaries (outages lasting less than one minute), whereas VOR outages are typically longer in duration.

The Phase I study was based purely on navigation availability data from the New England region. The objective of the Phase II study was to expand on the previous analysis and validate the results for the entire NAS. As in the Phase I study, the availability performance of VOR was compared with that of Loran-C. An extensive database of VOR outages from the Southwest region and Loran-C outages from ten chains throughout the Conterminous U.S. (CONUS) were compiled and processed at the Volpe Center.

These data were used to derive the input parameters to a Markov model of a nonprecision approach. Applying the Markov model, the availability of the VOR and Loran systems for nonprecision approach was investigated and compared. Momentary outage data for each of the ten Loran chains were examined to determine the most common causes of outages. Loran availability can then be increased by mitigating these problem areas.

Pilot acceptability also needs to be taken into consideration in the development of a signal availability requirement. Pilot acceptability refers to willingness of the pilot to use a particular navigational aid in attempting a nonprecision approach. The Volpe Center is currently preparing to conduct a pilot survey in order to investigate this issue. Tolerance of signal outages needs to be considered from an Air Traffic Control standpoint as well. When fully defined, the signal availability requirement will apply to all current and future nonprecision approach navigational aids.

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]. The FAA is currently in the process of defining a signal availability requirement for all radionavigation systems within the National Airspace System. An availability standard, which is based on extensive analysis, has yet to be established.

The general approach taken in this study was to compare the availability performance of VOR and Loran-C. The rationale for this approach was 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 a significant bearing on the establishment of an availability requirement. It should be emphasized, however, that the availability performance of VOR does not set the requirement for the NAS.

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 could be approved for nonprecision approaches. The nonprecision approach (NPA) phase of flight was chosen for the availability analysis since it is the most stringent (with the exception of precision approach). Therefore, any availability requirement which satisfies NPA also will satisfy other phases of flight as well.

The results of the Phase I study demonstrated that both the VOR and Loran systems achieve an availability of approximately 99.99%, if the pilot attempted a second approach with Loran. The current study took a similar approach to Phase I, but with a much more extensive database of navigation outage data in an attempt to validate the signal availability performance of the two systems.

As in Phase I, a generic nonprecision approach was modeled for this study. The NPA modeled for the analysis is depicted by the scenario in Figure 1. The phases of the approach were simulated as follows:

Final Approach

The final approach stage began at the Final Approach Fix (FAF) and ended at touchdown, which is a distance of approximately five nautical miles. During this phase, if a fault in the navigational signal occurred, the aircraft executed a missed approach. The pilot could then enter a holding pattern and attempt another approach, or head for an alternate airport.

Successful Approach (Landing)

If the navigational signal was available throughout the approach, the aircraft lands. In this study, the airborne navigational equipment was assumed to be operational at all times.

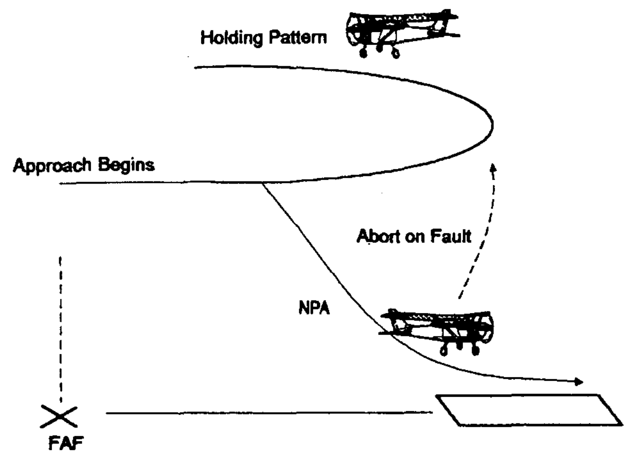

Figure 1 Model of a Nonprecision Approach

Missed Approach

When the airborne navigational equipment detects a fault in the navigation signal and displays a warning to the pilot, current procedures require that the pilot head to the missed approach point (using timing, heading, etc.) and execute a missed approach. In this study, it was assumed that the pilot, following the execution of a missed approach, entered a holding pattern and attempted another landing at the same airport.

Holding Pattern

If a missed approach was executed, the aircraft enters a holding pattern in order to make another approach. During the holding pattern stage, there could be a recovery from the fault in the navigational signal.

The sequence for multiple approaches was:

1) Navigational signals were lost during the approach.

2) The onboard navigation system detected the signal loss and warned the pilot.

3) The pilot executed a missed approach and entered a holding pattern.

4) Another approach was executed provided the navigation signal was available at the FAF.

5) Five approaches were simulated in the model.

The study assumed that the navigation signal always was available at the start of an approach.

Data Collection

The data used in this analysis were based on outage information recorded by the operators of the VOR and Loran systems, the FAA and USCG, respectively.

VOR Data

The FAA does not require its radionavigation facilities to report momentary outages (outages lasting less than one minute). In order to produce an equal comparison between VOR and other navigational aids, information on VOR momentaries had to be obtained. Fortunately, a number of the regional field service centers in the CONUS also are Remote Maintenance and Communications Centers (RMCC), which have autolog systems in operation. These systems automatically log all outages that occur at navigational aid facilities.

As mentioned previously, the Phase I study was based on VOR data from the New England region. In order to evaluate VOR availability for a different portion of the U.S., and remove any potential biases from the Phase I results, this study focused on VORs located in the Southwest region. VOR outage data were obtained from the FAA Southwest region located at the Fort Worth Air Route Traffic Control Center (ARTCC) and Airway Facilities Sector (AFS) Center in Euless, Texas. VORs in Texas, Arkansas, Oklahoma, and Louisiana are monitored by the Southwest Region. VOR data were received on a monthly basis for a one year period (Dec. 1992 - Nov. 1993).

VOR outage data were obtained in the form of log files from the 52 VOR facilities in the Southwest region, as shown in Table 1. This table gives the identifier (ID), the name of the station, the state where the VOR is located, as well as the number of outages for the data collection period.

Each time a VOR facility experiences an outage, a message is generated automatically and forwarded to the RMCC, where it is recorded by a computer into a log file. A second message is sent to the RMCC when the affected facility resumes normal operation. A database was generated from these log files which consisted of:

- Time and date of outage
- Station identification
- Duration of outage

Table 1 Southwest Region VOR Stations

#	ID	NAME	State	No. of Outages
1	ADM	ARDMORE	OK	57
2	AQN	ACTON	TX	9
3	ARG	WALNUT RIDGE	AR	6
4	BFV	BURNSFLAT	OK	26
5	BPR	BRIDGEPORT	TX	153
6	BUJ	BLUE RIDGE	TX	4
7	BVO	BARTLESVILLE	OK	73
8	CDS	CHILDRESS	TX	18
9	DAK	DRAKE (FAYETTEVILLE)	AR	22
10	DFW	DALLAS/FT WORTH	TX	30
11	DTN	SHREVEPORT	LA	12
12	DUC	DUNCAN	OK	13
13	ELD	EL DORADO	AR	12
14	EMG	ELM GROVE	LA	4
15	FLP	FLIPPIN	AR	43
16	FSM	FORT SMITH	AR	13
17	FZT	FRANKSTON	TX	9
18	GAG	GAGE	OK	61
19	GGG	GREGG COUNTY	TX	114
20	GNP	GLENPOOL	OK	36
21	GQE	GILMORE	AR	7
22	GTH	GUTHRIE	TX	9
23	HBR	HOBART	OK	23
24	HOT	HOT SPRINGS	AR	16
25	HRO	HARRISON	AR	77
26	IFI	KINGFISHER	OK	55
27	IRW	WILL ROGERS	OK	35
28	JBR	JONESBORO	AR	105
29	LAW	LAWTON	OK	32
30	LIT	LITTLE ROCK	AR	18
31	MLC	MCALISTER	OK	56
32	MLU	MONROE	LA	16
33	MON	MONTICELLO	AR	21
34	MQP	MILLSAP	TX	18
35	ODG	WOODRING	AR	27
36	OKM	OKMULGEE	OK	59
37	PBF	PINE BLUFF	AR	32
38	PER	PONCA CITY	OK	61
39	PGO	RICH MOUNTAIN	OK	25
40	PRX	PARIS	TX	9
41	PWA	WILLEY POST	OK	36
42	RZC	RAZORBACK	AR	27
43	SCY	SCURRY	TX	37
44	SHV	SHREVEPORT	LA	10
45	SLR	SULPHUR SPRINGS	TX	31
46	SPS	WICHITA FALLS	TX	50
47	SWO	STILLWATER	OK	34
48	SYO	SAYRE	OK	16
49	TUL	TULSA	OK	62
50	TXK	TEXARKANA	OK	12
51	TYR	TYLER	AR	22
52	UIM	QUITMAN	TX	12

The database of VOR outages was compiled at the Volpe Center and later processed using in-house computer programs. A database of 350 days was created from 350 log files accumulated from Dec. 1992 through Nov. 1993. There were fifteen days between February and May that were missing from the log files.

In the raw database there were 1766 recorded outages ranging in duration from several seconds to more than 24 hours. Figure 2 displays a breakdown of outages for the VOR data. Outages were divided into four categories:

Momentary Outage: Less than 1 minute
Short Term Outage: 1 min. $\leq t < 10$ min.
Medium Term Outage: 10 min. $\leq t < 1$ hr.
Long Term Outage: More than an hour

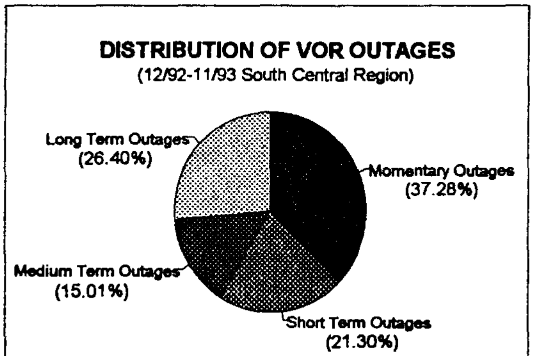

Figure 2 Distribution of VOR Outages

The following points were eliminated from the raw database:

1. The VOR station LUE was decommissioned. Therefore, the outage associated with this facility was removed from the database.
2. Outages lasting longer than 24 hours (163 points) also were purged from the data, since the pilot filing a flight plan would have advance notice about such outages, and would not be expected to attempt a landing at an airport supported by the unavailable VOR.

There were a total of 1602 VOR outages in the final database used in the availability analysis.

Loran-C Data

Loran-C outage data are available from the U.S. Coast Guard (USCG). The Coast Guard control of Loran stations is handled by the Atlantic Area and Pacific Area Commands. Each Command publishes monthly, quarterly and annual reports on the number and duration of outages occurring at transmitter sites under their control. These reports tabulate two types of outages: unusable time (UUT) and momentaries. Unusable time is defined to be any outage lasting one minute or longer. A momentary is any outage lasting less than one minute.

A total of ten Loran chains were evaluated in this analysis: six in the Atlantic Area and four in the Pacific Area. Data for the Atlantic Area chains were collected from January 1989 to June 1993, with the exception of the South Central U.S. (SOCUS) Chain which did not become operational until 1991. Table 2 displays the number of momentary and UUT outages for each Loran chain in the Atlantic Area.

Data for the Pacific Area chains were collected from April 1991 until May-June 1993. Momentary and UUT outage data are provided in Table 3 for the Pacific Area Loran chains.

Table 2 Data Collection for Atlantic Area Loran Chains

Atlantic Area Loran Chains	Number of Stations in Loran Chain	Number of Momentaries	Number of UUT Outages
GRI 9960 Northeast U.S.	5	4741	261
GRI 5930 Canadian East Coast	4	2830	136
GRI 7930 Labrador Sea	3	3041	109
GRI 7980 Southeast U.S.	5	5958	384
GRI 8970 Great Lakes	5	5142	344
GRI 9610 South Central U.S.	6	3810	324

Table 3 Data Collection for Pacific Area Loran Chains

Pacific Area Loran Chains	Number of Stations in Loran Chain	Number of Momentaries	Number of UUT Outages
GRI 7960 Gulf of Alaska	4	2196	596
GRI 8290 North Central U.S.	4	1818	247
GRI 9940 U.S. West Coast	4	3119	171
GRI 9990 North Pacific	4	2032	214

Two databases were obtained from the USCG for each Loran chain. The data fields in the first database consisted of:

- Month and Year
- Number of Momentaries during the Month

In the second database, long term outages were recorded by incident. The data fields consisted of:

- Month and Year
- Duration of Outage

Loran outages traditionally have been characterized by momentaries and account for at least 90% of all Loran outages. A study was performed in 1992 which examined Loran-C outages for both tube type (TTX) and solid state (SSX) transmitters. This study was included as Appendix D of the Phase I report.

The primary contributors of momentary outages are:

- Power failures
- Lightning strikes
- Transmitter overload (TTX)
- Transmitter coupler network switching problems (SSX)
- Operational/maintenance procedures

Markov Model

In order to evaluate availability performance, a Markov model of a generic nonprecision approach was developed. A Markov model is a statistical model which simulates the evolution of a system in time, by means of probabilistic transitions from one state to another. These transition probabilities are computed from historical data. A Markov model only requires knowledge of the current state and the appropriate transition probabilities in order to predict the next state.

The purpose of the Markov model in this analysis was to calculate the probability that an outage in the navigation system will prevent the successful completion of a nonprecision approach. The model assumed that the aircraft had reached the final approach fix (FAF) and the navigation signal was available (probability = 1) at that point. The primary output of the Markov model is the probability of a successful approach versus the number of approaches attempted.

In the model, the approach began at the final approach fix, which is five nautical miles from the touchdown point. If the navigation signal was lost during the approach, the airborne receiver must alert the pilot within ten seconds, and the pilot then executes a missed approach. Following a missed approach, the pilot entered a holding pattern in order to attempt another approach. During this time, a previously unavailable signal could become available, and therefore be reacquired by the airborne navigational equipment. ???

The holding pattern was assumed to be a distance of 19 nmi and was modeled as a time delay. This process accounted for any change in the navigation state which may have taken place during the circling interval. The probability of the signal returning then became an input for evaluating subsequent approach attempts. If there were not any outages during approach, then the pilot lands successfully. This is called the "terminal state" in the vernacular of Markov processes. The model developed for this study assumed that successful completion of the NPA is equivalent to landing successfully. The Markov state diagram for this study is shown in Figure 3.

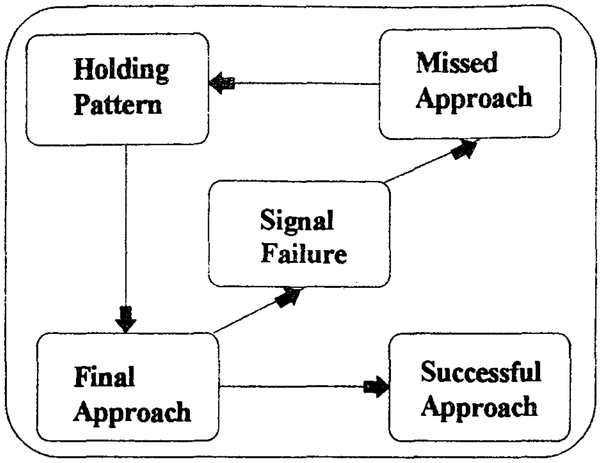

Figure 3 Markov State Diagram

Up to four different fault modes were considered in this analysis.

1. Long Term Outage
2. Medium Term Outage
3. Short Term Outage
4. Momentary Outage

It was assumed that the probability of changing from one state to another was Poisson in nature. Thus, the parameters for change could be defined in terms of mean time to condition change. That is, the change in fault modes could be modeled in terms of Mean Time to Long Term Outage, Mean Time to Momentary Outage, Mean Time to Recovery from a Momentary Outage, etc. "Recovery" means that not only has the navigational signal been fully restored, but that it has been reacquired by the airborne receiver.

The law of rare events guarantees that the Mean Time to Failure is a Poisson distribution. The Mean Time to Recovery data were determined empirically and have an exponential distribution. The clustering of recovery times in the VOR and Loran-C outage databases indicated distinct fault modes. This will be discussed further in the next section.

In the Markov Model used, there were ten possible states that the aircraft could be in:

1. Normal Navigation
2. Long Term Outage, Continue Approach
3. Medium Term Outage, Continue Approach
4. Short Term Outage, Continue Approach
5. Momentary Outage, Continue Approach
6. Holding Pattern after Long Term Outage
7. Holding Pattern after Medium Term Outage
8. Holding Pattern after Short Term Outage
9. Holding Pattern after Momentary Outage
10. Successful Approach

States 2 through 5 were needed to simulate both the pilot and the onboard navigation system reaction to the outage.

Transition Probabilities

The analysis in this study was based on a multistate, first-order Markov process. The probability of transitioning from one state of the model, 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 one state of the model in one interval of time 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 given by: $P_{i+1} = \Phi \cdot P_i$ (1), where Φ is the transition matrix. This matrix is time-invariant in general, but changes as the approach stage or navigation availability change.

The probability of staying in a state is 1 minus the probability of leaving the state. The initial *P* vector is P_0, which contains the steady-state probabilities for normal navigation and the four fault modes.

In the evaluation, Equation (1) was iterated $K = T_1/dt$ times, where T_1 is the duration of the nominal approach and dt is the iteration interval.

Since entering a fault condition is a Poisson process, the probability of experiencing a signal failure was:

$$P_{failure} = 1 - e^{-dt/MeanTimeToFailure} \quad (2),$$

where the Mean Time to Failure is the mean time to a navigation signal outage. There was also the probability that the system will return to normal navigation:

$$P_{recovery} = 1 - e^{-dt/MeanTimeToRecovery} \quad (3),$$

where the Mean Time to Recovery is the mean time until the navigation signal becomes available again.

Applying this methodology, the transition probabilities for the Markov model are:

1. Probability of entering the Long Term Outage state in $dt = 1 - e^{-dt/MTTL}$, where MTTL is the Mean Time to Long Term Outage

2. Probability of regaining navigation in dt after a Long Term Outage = $1 - e^{-dt/MTRL}$, where MTRL is the Mean Time to Recovery from a Long Term Outage

This logic applies to the other fault modes as well.

The Kth iteration of $P_i = \Phi_1 \cdot P_{i-1}$ (4) projected the probability vector, P, to the completion of the approach. The navigation state became the "successful approach", or landing state at the end of the NPA. At this point, the state of the model represented the probability of achieving a successful approach, $P_{SuccessfulApproach} = \Phi_2 \cdot P$ (5).

Holding Pattern

When an outage occurred, the fault states became holding pattern states, which simulates a missed approach at a fixed time before touchdown.

Then the transition matrix for the holding pattern, $\Phi_4 = [\Phi_3]^{Tc/dt}$ (6), was formed representing the state transition over a period T_C, the circling (holding pattern) time. The initial probability state at the start of the second approach attempt is then:

$$P_i = \Phi_4 \cdot P_{SuccessfulApproach} \quad (7)$$

The process of evaluating the probabilities during the second approach attempt was then repeated according to Equation (5). The steady-state probability vector which initiated the process was obtained by iterating Φ_4 until P_i was constant, to some precision. The initial probability vector is then the first column in the resulting matrix.

The algorithm can be summarized with the aid of Figure 4. The initial probability vector for being in any of the various states, P_o, which specifies the navigation, or "no fault" state with probability 1.

That is, fault states were not allowed at the start of the NPA. If the aircraft subsequently entered a fault condition, it was forced to execute a missed approach. This was modeled by adding the probabilities of being in fault states to those of being in the associated holding pattern states.

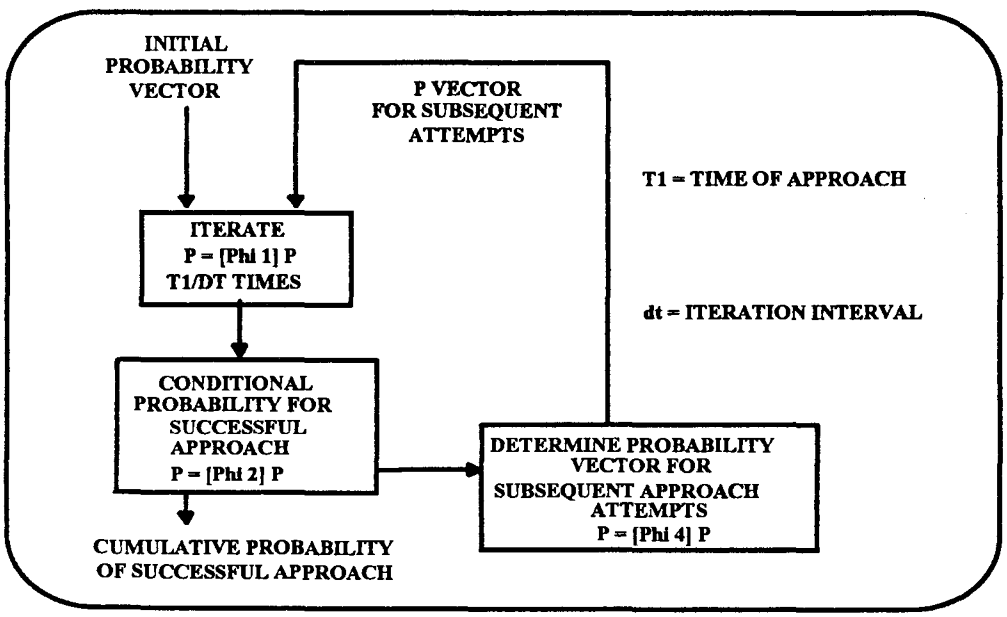

Figure 4 Summary of Markov Algorithm

That is, fault states were not allowed at the start of the NPA. If the aircraft subsequently entered a fault condition, it was forced to execute a missed approach. This was modeled by adding the probabilities of being in fault states to those of being in the associated holding pattern states.

At any time during the NPA, the navigational system availability could be lost. This would cause a transition to a fault state, and the pilot would then initiate a missed approach. As the aircraft circled, the fault state could change to the navigation state. The probability vector after circling was determined from Equation (7). The probability of achieving the successful approach state remained the same, but the result for the other states was now represented by the initial P vector, P_i, at the start of the second approach attempt.

The process then repeats itself from the top. The probability of being in the successful approach state on the second approach attempt is the cumulative probability of achieving a successful approach the first or second time. The process could be repeated a third or more times to model additional attempts. Five approach attempts were modeled in this analysis.

Analysis of Data

In the Markov model, transition from the navigation state to the outage state is dictated by the mean time to signal failure (MTTF) for the various signal failure modes. Transition back from an outage to the navigation state is determined by the mean time to signal recovery (MTTR) for each signal failure mode. The values for MTTF and MTTR were determined from the VOR and Loran-C outage databases discussed in Section II.

The clustering of the recovery times in the outage databases indicated that there were several distinct fault modes. Fitting routines were used on the raw data to identify the number of fault modes and their associated parameters. Each fault mode was characterized by the MTTF and MTTR parameters. This procedure was applied to both the VOR and Loran databases.

The approach taken in this analysis was to use each database to develop a histogram of the number of faults versus the duration of the outage, and then hypothesize the number of fault modes and the anticipated MTTR for each mode. Next, a specialized fitting routine was applied to the histogram to obtain a weighted least-squares fit between a theoretical histogram generated by the algorithm and that generated from the database.

A gradient search technique was used to improve the estimate of the MTTR, and therefore improve the data fit. The result was a coefficient which gave an estimate of the percentage that each fault mode contributes to the total number of outages, as well as an improved estimate of the MTTR for each fault mode.

If the number of fault modes and the initial estimate of the MTTR were reasonably chosen, the sum of the coefficients should be very close to 1.0. The expected MTTR from the model (due to all fault types) should be very close to the MTTR obtained by averaging all the outage duration times listed in the database. Furthermore, the theoretical histogram should closely resemble the histogram generated from the data.

If too few modes were hypothesized, the visual fit to the resulting data would be poor. If too many modes were hypothesized, or if poor initial estimates of the MTTRs were used, negative coefficients would occur in the results. That would indicate that a new starting point (number of faults and initial estimates of MTTRs) should be chosen.

Four fault modes were identified from the VOR data. The analytical results for the Southwest Region VOR stations are summarized in Table 4.

Table 4 Markov Model Parameters for VOR Data

Outage Type	Coefficient	MTTR (min.)	MTTF (min.)
Momentary	0.3729	0.5000	47669.4023
Short Term	0.2473	4.9256	71886.4922
Med. Term	0.3111	60.6815	57141.2188
Long Term	0.1553	1011.6910	114452.6875

These are the parameters which were used in the Markov model analysis. The MTTR for a momentary outage was raised to 30 seconds in order to model the receiver recovery time, although the VOR data itself had a lower MTTR.

The signal failure rate and mean time to signal failure were calculated as follows:

$$\text{Signal Failure Rate} = \frac{\text{total number of VOR outages}}{[(\#\text{minutes in one year})\cdot(\#\text{ VOR stations reporting})\cdot(\text{sum of coefficients})]} \quad (8)$$

$$= \frac{1602}{(350\cdot 24\cdot 60)\cdot(52)\cdot(1.08672)} = 0.00005625$$

$$MTTF = \frac{1}{Coefficient\cdot SignalFailureRate} \quad (9)$$

Four fault modes also were identified for the Loran-C system. The analytical results are shown in Table 5.

Table 5 Markov Model Parameters for Loran-C Data

Outage Type	Coefficient	MTTR (min.)	MTTF (min.)
Momentary	0.9020	1.1000	734.0965
Short Term	0.0525	2.7528	12601.7803
Med. Term	0.0157	10.8617	42194.0977
Long Term	0.0205	102.8440	32256.1562

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 a nonprecision approach. For a signal-to-noise ratio of -6 dB, the average recovery time for airborne receivers was about 40 seconds. This time has been included in the MTTR for Loran-C data.

Failure rates were computed for each Loran chain. In order to compute the signal failure rate of the Loran system over the entire CONUS, an average failure rate of the ten chains considered in this analysis was computed. This failure rate equals 0.0015596.

Signal Availability Results

The results of this study are concerned only with loss of navigation signals during the nonprecision approach, and not with losses which may occur during other phases of flight. The results assume that an approach was not initiated unless there was signal availability and the onboard receiver was properly tracking the signal.

Applying the scenario in Figure 1, the pilot is at the final approach fix with the navigational signal available. The question addressed was: Given that there was navigation at the FAF, what is the probability that the pilot could successfully complete the nonprecision approach? The Markov process shown in Figure 3 was applied to answer this question.

Two approach speeds were simulated in the Markov model: 90 Kt. and 120 Kt. The distance traveled in the holding pattern was assumed to be 19 nmi. For the 90 Kt. scenario, the time to execute the NPA was 3.3 min. and the holding pattern time was 12.7 min. In the 120 Kt. case, the time to execute the NPA was 2.5 min. and the holding pattern duration was 9.5 min. As discussed previously, up to five approaches were attempted. The iteration interval, *dt*, for the Markov Model was chosen to be .25 min.

Both the VOR and Loran-C navigational systems have built-in redundancy. A Loran chain always has three or more stations. So, if one station goes off the air, it would be possible to navigate with another

The total signal failure rate for each Loran chain was determined by:

$$\text{Failure Rate} = \frac{\text{total number of outages in Loran chain}}{[(\#\text{minutes in data collection period})\cdot(\frac{\#\text{ of stations in Loran chain}}{3\text{ stations per approach triad}})\cdot(\text{sum of coefficients})]} \quad (10)$$

triad or even with another chain. At present, however, an NPA at an airport requires a specific triad of stations within a single chain. Therefore, in this model, a navigational fault was declared if the signal from any of the three specified stations was not received properly. Similarly, a VOR NPA at an airport requires the use of a specific VOR. In the study, loss of reception of signals from this VOR resulted in a navigational fault, even though other VORs could be received.

The signal availability of the 52 VOR stations for both approach speeds is shown in Table 6. On the first approach attempt, VOR had an availability of 99.967% for a 90 Kt. approach speed and 99.974% for an approach speed of 120 Kt. This availability is much lower than the 99.993% (120 Kt.) found for the New England region in the Phase I study.

Signal availability was calculated for each of the ten Loran chains, as well as for the overall system. The results for an approach speed of 90 Kt. are shown in Table 7.

Availability ranges from 99.54% for the Canadian East Coast Chain down to 98.9% for the U.S. West Coast Chain on the initial approach attempt. Combining all Loran chains provided an overall system availability of 99.24%.

For an approach speed of 120 Kt., Loran availability varied from 99.13% to 99.64% on the first attempt. The overall system availability was found to be 99.4%. These results are presented in Table 8.

The availability for Loran-C is an order of magnitude lower on the first approach attempt than

Table 6 VOR Availability

Approach Speed	Approach 1	Approach 2	Approach 3	Approach 4	Approach 5
90 Kt.	.9996668	.9998648	.9998886	.9999046	.9999173
120 Kt.	.9997429	.9998897	.9999080	.9999191	.9999280

The number of VOR momentaries increased from 29.36% percent of the outages in the Phase I analysis to 37.29% in the current study. The increase in the number of momentaries meant that there was a greater chance of the signal becoming available on the second and subsequent approaches. For the second approach attempt, VOR signal availability increased to 99.986% and 99.988% for the 90 Kt. and 120 Kt. approach speeds, respectively.

that provided by the VOR system. However, if more than one landing attempt could be made, Loran and VOR provide almost an equivalent probability of having a successful approach. The dramatic improvement in Loran availability results from the fact that the majority of Loran-C outages are due to momentaries. For the ten Loran chains considered in this study, 90.2% of the outages in the collected database were due to momentaries (See Table 5).

Table 7 Loran Availability for 90 Kt. Approach Speed

Loran Chain	Approach 1	Approach 2	Approach 3	Approach 4	Approach 5
GRI 9960 Northeast U.S.	.9937941	.9998355	.9999157	.9999335	.9999443
GRI 5930 Canadian East Coast	.9953700	.9998762	.9999369	.9999547	.9999645
GRI 7930 Labrador Sea	.9935011	.9998141	.9999003	.9999205	.9999334
GRI 7980 Southeast U.S.	.9921334	.9997643	.9998924	.9999216	.9999376
GRI 8970 Great Lakes	.9931921	.9998273	.9999132	.9999308	.9999415
GRI 8290 North Central U.S.	.9929901	.9996391	.9997860	.9998339	.9998627
GRI 9610 Southwest U.S.	.9923087	.9998323	.9999303	.9999463	.9999561
GRI 9940 U.S. West Coast	.9889881	.9995353	.9997811	.9998624	.9999120
GRI 9990 North Pacific	.9926630	.9995610	.9997671	.9998606	.9999164
GRI 7960 Gulf of Alaska	.9906501	.9987312	.9991608	.9993700	.9994998
All Loran Chains Combined	.9923909	.9997178	.9998389	.9998710	.9998915

Table 8 Loran Availability for 120 Kt. Approach Speed

Loran Chain	Approach 1	Approach 2	Approach 3	Approach 4	Approach 5
GRI 9960 Northeast U.S.	.9951098	.9998651	.9999254	.9999412	.9999502
GRI 5930 Canadian East Coast	.9963520	.9998958	.9999414	.9999573	.9999662
GRI 7930 Labrador Sea	.9948776	.9998496	.9999128	.9999301	.9999405
GRI 7980 Southeast U.S.	.9938005	.9998065	.9999010	.9999271	.9999415
GRI 8970 Great Lakes	.9946350	.9998604	.9999241	.9999392	.9999481
GRI 8290 North Central U.S.	.9944855	.9996983	.9998104	.9998513	.9998757
GRI 9610 Southwest U.S.	.9939373	.9998652	.9999380	.9999520	.9999599
GRI 9940 U.S. West Coast	.9913200	.9996324	.9997954	.9998568	.9998990
GRI 9990 North Pacific	.9942294	.9996313	.9997758	.9998485	.9998974
GRI 7960 Gulf of Alaska	.9926724	.9989486	.9992561	.9994214	.9995304
All Loran Chains Combined	.9940070	.9997711	.9998607	.9998869	.9999034

A comparison of Loran and VOR availability is provided in Figure 5. This figure demonstrates that after the first approach attempt, Loran and VOR essentially provide the same signal availability.

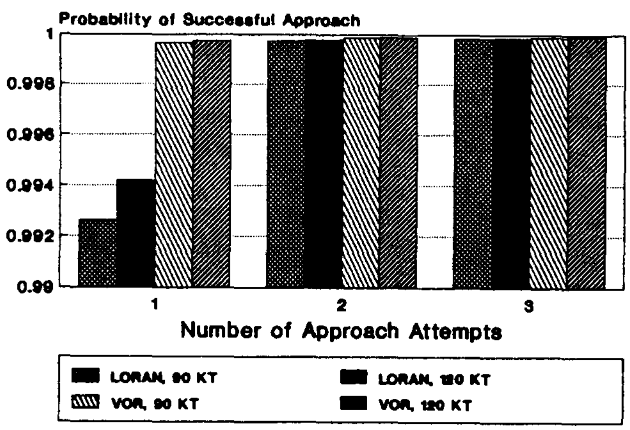

Figure 5 Loran and VOR Availability

Impact of Reducing of the Number of Loran-C Momentaries

As discussed earlier, the majority of Loran outages were due to momentaries. In fact, momentaries accounted for more than 90% of all Loran outages.

Therefore, if the number of momentaries could be reduced, Loran availability would significantly improve. In order to investigate the impact of momentary reduction, additional Markov analyses were performed. The failure rates for momentaries were reduced by 50% and 70% of their original value. These results are shown in Tables 9 and 10, as well as in Figure 6.

When momentaries were reduced by 50%, Loran availability increased from 99.24% to 99.58% for a 90 Kt. approach speed. When the approach speed was 120 Kt., signal availability increased from 99.4% to 99.67%.

Table 9 Loran Availability with Number of Momentaries Reduced by 50%

Approach Speed	Approach 1	Approach 2	Approach 3	Approach 4	Approach 5
90 Kt.	.9957809	.9997836	.9998659	.9998914	.9999065
120 Kt.	.9966840	.9998125	.9998817	.9999056	.9999184

Table 10 Loran Availability with Number of Momentaries Reduced by 70%

Approach Speed	Approach 1	Approach 2	Approach 3	Approach 4	Approach 5
90 Kt.	.9971362	.9997813	.9998631	.9998913	.9999078
120 Kt.	.9977545	.9998063	.9998769	.9998042	.9999184

As shown in Table 10, Loran availability exceeded 99.7% when momentaries were reduced by 70%. A previous study on Loran momentary reduction [1], indicated that a 70% reduction is most likely the best that could be achieved at a reasonable cost. One interesting note is that for the second and subsequent approaches (with the exception of Approach #5), the signal availability is not as high as for the case when only 50% of the momentaries are removed. This effect results from the database containing a greater percentage of medium and long term outages after the momentaries were removed. Therefore, the probability of the signal returning if more than one approach was attempted is lower.

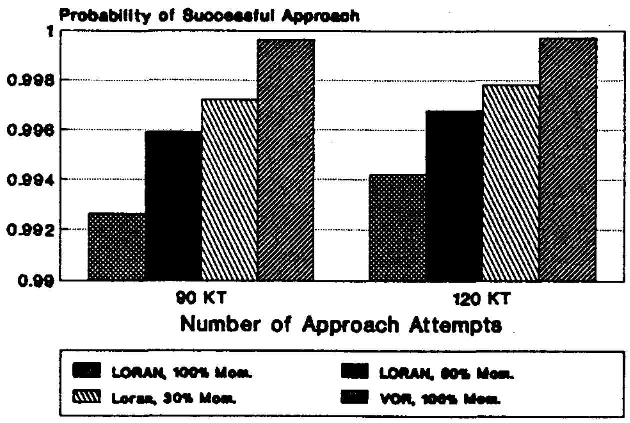

Figure 6 Comparison of NPA Availability for Loran Momentary Reduction

<u>Summary and Conclusions</u>

This study compared the availability performance of two nonprecision approach aids, VOR and Loran-C. This analysis is an important step toward the overall goal of developing a signal availability requirement for the National Airspace System.

Extensive databases of VOR and Loran-C outages were compiled at the Volpe Center. These data were used to determine outage and recovery characteristics of both systems. These results were then applied to a Markov model in order to evaluate and compare the availability of the two systems during nonprecision approaches.

The results of this analysis demonstrated that both Loran-C and VOR have a high signal availability for nonprecision approach navigation. On the initial approach attempt, VOR has an availability of 99.97%, while Loran-C has an availability of 99.42% (for 120 Kt approach speed). However, on the second attempt, Loran was available for an approach 99.98% of the time and VOR has an availability of 99.99%. For subsequent approach attempts VOR and Loran-C provided essentially the same availability. Both VOR and Loran were found to have a lower availability than in the Phase I study.

Momentaries accounted for more than 90% of all Loran-C outages. Reduction of these outages substantially improved the availability of Loran for NPA navigation. Methods for momentary reduction will be pursued with the USCG. A study of the Fox Harbour, Newfoundland station, which has averaged only 16 momentaries per year is near completion.

Setting an availability requirement for nonprecision approach navigation is related to the safety of the flight. The results of this study demonstrate that, when using Loran, the probability of a missed approach on the initial attempt, caused by lack of signal in space, is approximately 1 in 175. If a second attempt is allowed, the probability of a missed approach is 1 in 5,000.

This level of signal availability appears to be acceptable, especially when it is estimated that it would take a rated general aviation (GA) pilot approximately 15 years to make 1,000 IFR approaches [3]. For example, if the availability requirement for radionavigation aids was set so that there would be no more than one missed approach per year for a typical IFR rated GA pilot, then an acceptable availability level would be 98.5%. Both Loran and VOR would far exceed this requirement.

Pilot acceptability needs to be taken into consideration in the development of a signal availability requirement. Pilot acceptability refers to willingness of the pilot to use a particular navigational aid in attempting a nonprecision approach. The Volpe Center is currently preparing to conduct a pilot survey in order to investigate this issue. Tolerance of signal outages also needs to be considered from an Air Traffic standpoint as well.

When fully defined, the signal availability requirement will apply to all current and future nonprecision approach navigational aids.

Acknowledgments

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[3] Conversation with Donald Johnson of AOPA.

Biography

Karen L. Van Dyke received her BS and MS degrees in Electrical Engineering from the University of Massachusetts/Lowell. Since 1988 she has been at the DOT/Volpe Center working on GPS for the FAA and USCG. She is currently conducting GPS availability and integrity studies for the FAA in support of RTCA SC-159, and has been evaluating the availability of Loran for nonprecision approach. She also is involved in the development of a GPS NOTAM system for DoD. Ms. Van Dyke currently serves as an Air Navigation representative to the Institute of Navigation and is a member of the Wild Goose Association.

THE ECONOMIC IMPACT ON GENERAL AVIATION PILOTS OF THE EARLY SHUTDOWN OF THE LORAN-C NAVIGATION SYSTEM

by

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ABSTRACT

This paper discusses the adverse economic impact of the premature shut-down of the Loran-C system in the continental United States to the general aviation community. It specifically addresses the impact on the eight (8) states making up the Great Lakes Region, and projects the impact nationally. The concern generating the study was caused by the recent consideration being given to a shutdown of the Loran system by as early as 1996. The paper concludes a significant adverse financial burden would be placed on a vast number/percentage of general aviation aircraft owners and pilots.

OVERVIEW

Since the development of the transistor and solid state transceivers, the affordability of small, lightweight devices for use in aircraft opened a new means of navigation for general aviation aircraft. In actuality, we are now well into the second decade of use of Loran-C navigation systems. The first general aviation aircraft certified receivers began appearing in the early 1980s. The simplicity, accuracy, and reasonable cost were all catalysts to make Loran extremely popular in the general aviation community.

An early problem in the aviation community's use of the system was the lack of uniform signal availability over the continental United States. Since Loran was developed as a marine navigation system, the Loran chains were set up to give coverage around the coastal areas, to include the Great Lakes. This resulted in about 70-75% coverage of the continental United States. There was early resistance within some of the offices of the Federal Aviation Administration (FAA) with respect to the use of this marine system in aircraft. The momentum of users helped persuade the federal government to install additional transmitters in the far mid-west which ultimately resulted in filling "the mid-continent gap". Interestingly, during the same time, the United States Coast Guard deactivated the Hawaii chain.

In Wisconsin, we purchased Loran-C units for our aircraft for both IFR en route, and VFR navigation. We've used our Lorans for local flying around the state, as well as flying back east to Washington and Florida, and south to Louisiana and Texas. We have seen the number of Loran units increasing at a fairly significant rate during the EAA's annual convention, and fly-ins. In the late 80s, we began asking aircraft owners in Wisconsin whether or not they had a Loran unit in their aircraft. We were not concerned as to whether it was IFR or VFR, but rather, to determine how many pilots were using Loran as an aid to navigate through the skies.

Our last year of taking data on Loran units in Wisconsin aircraft was in 1992. At that time, we received over 50% affirmative comments from those who responded (1553 - yes, 1551 - no). This number corresponded somewhat with the information we were able to obtain from adjoining states in the Great Lakes Region. The AOPA did a similar study in order to determine the use of Loran-C by its members. They concluded it was between 40 and 50% nationally, which supports our data.

More specifically, the Aircraft Owners and Pilots Association conducted their own Loran-C survey in 1992 as a portion of their General Aviation survey. They received 1,355 total responses, of which 697 either owned individually or in partnership, their own aircraft. In response to their question: "Is the general aviation aircraft you own equipped with Loran-C navigation equipment?", 409 (58%) said yes. This is a significant number, and is slightly greater than the 50% figure from the Great Lakes Region.

Based on these figures and other supporting information from adjacent states regarding installation of Loran units in general aviation aircraft, we can reasonably project the most conservative national estimate would be as low as 40%, and the most liberal, 60%. In support of the more liberal figure, I personally noted 5 of 6 Wittman Tailwinds as having Loran units installed during a special fly-in at Wittman Field. The occasion was a celebration for Steve Wittman's 90th birthday, and these Tailwinds had flown in for the ceremony. Three of the units were King and two were STS.

COST ESTIMATES

The Lorans installed in general aviation aircraft range from the simplest, marine-type to sophisticated IFR en route boxes complete with data bases. Purchase prices of basic units have ranged from $350 to $5,000+ for early units, some IFR units approached $8,000.

Cost estimates for replacing an existing panel mounted Loran with a GPS receiver vary from a current minimum of $2,000, to a maximum of $7,000+. Actual costs will depend on the unit purchase price, and the installation required, to include the antenna. Other factors, such as complexity of existing cockpit equipment (tying into the autopilot system) would also mean additional time and associated costs. In addition, the IFR approach certified GPS unit also requires three hours of flight testing before it receives final certification.

The bottom end of $2,000 would be for a panel mounted VFR GPS unit. The top end of $7,000+ would be for IFR GPS units approved for flying non-precision approaches. Some may include moving map displays and other special features, such as dual GPS/Loran capability. As of now, there are no current units certified for Cat I public GPS or DGPS approaches.

One option would be for current Loran users to just discontinue use of area-type navigation if Loran shut down. This would result in some reduction in safety, as well as greater consumption of fuel because of not being able to fly direct. The actual amount would be difficult to project.

As a conservative target number, 5% of the existing Loran-C users may choose not to replace their units; that 5% would represent about 9,220 of the 184,434 active aircraft, as listed by FAA*. If these aircraft, averaging 100 hours per year and burning 10 gallons per hour, on average, are required to fly 5% further per flight, that would result in an estimated 461,000 gallons of fuel burned annually in excess of what would have been burned if they had been able to fly direct.

OVERALL ECONOMIC IMPACT

With the projected 40-60% of the active general aviation fleet having a Loran unit installed, that represents 13,924 to 20,880 aircraft in the Great Lakes Region, made up of Wisconsin, Michigan, Ohio, Indiana, Illinois, Minnesota, North and South Dakota. Taking the minimum investment of $2,000 per aircraft*, the replacement costs for aircraft in the Great Lakes Region would be $27,840,000 for 40% (13,924) of the fleet, and $41,760,000 for 60% (20,880). At the top end of $6,000 per aircraft, this would come to $83,520,000 for 40% (13,920) of the fleet, and $1,252,800,000 for 60% (20,880).

STATE AIRCRAFT GRID FOR GREAT LAKES STATES			
State	# of U.S. Registered Aircraft*	Projected Loran-C Units	
		40%	60%
Illinois	9,073	3,630	5,440
Indiana	4,699	1,880	2,820
Michigan	8,498	3,400	5,100
Minnesota	6,281	2,510	3,770
N. Dakota	1,963	790	1,180
Ohio	9,033	3,610	5,420
S. Dakota	1,687	670	1,010
Wisconsin	5,367	2,150	3,220
8 States	46,601	18,640	27,960
Active Aircraft	34,792	13,920	20,880
Active National Aircraft	184,433	73,770	110,660

Anticipating that the majority of the installations would be in the lower end, resulting in an estimated mean range of $2,500, and using a figure of 50% or half of the aircraft, less the 5% that would not replace their unit, the direct economic cost projected at $2,500 per aircraft for 45% of the fleet in the Great Lakes States would come to $39,141,000 (15,656 aircraft). Projected nationally, that conservatively lists 73,770 Loran units installed, and on the higher end, 110,660.

Great Lakes:
34,792 x 45% = 15,656 x $2,500 per installation = $39,141,000

National:
184,433 x 45% = 82,990 x $2,500 per installation = $2,074,870,000

I believe this is a conservative estimate, as actual figures are not available. The development of Loran-C usage by general aviation has opened the door to inexpensive, reliable area navigation. Now that the majority of aircraft owners have been exposed to the added convenience and safety provided, it is something that probably won't be given up easily. Technology will continue to improve area navigation systems, and the anticipated use in general aviation aircraft will expand proportionally.

DEGRADATION TO FLYING SAFETY

If the Loran system were to be shut off prematurely, tens of thousands of general aviation aircraft equipped with Loran units that were used daily for area navigation would be left with returning to basics. It would mean flying via the airways. This would result in increased congestion, forcing aircraft to fly over en route navigational aids (primarily VORs and VORTACs). It would also eliminate the capability many existing Loran receivers provide to warn pilots approaching controlled airspace. To include prohibited and restricted areas, Category B, C and D airspace, military operating areas, and warning areas.

Allowing general aviation pilots to fly direct reduces total flight time, which saves fuel. It also gives a pilot in VFR conditions more time to clear outside the aircraft. In IFR conditions, going direct allows air traffic control to spread traffic out and, therefore, increase capacity. There are over 600 airports/facilities in the Great Lakes Region alone that have instrument approaches. Ninety (90) of these are served by scheduled airlines, as well as general aviation aircraft. By allowing general aviation aircraft to go IFR direct to the other 510 airports/facilities (85%) not being used by the airlines, clears the skies, so to speak, for the airlines' use. Projected nationally, these figures increase proportionally.

STATE GRID FOR INSTRUMENT APPROACH FACILITIES AND AIR SERVICE FOR GREAT LAKES STATES

STATE	# OF INSTRUMENT APPROACH FACILITIES	# OF AIR SERVICE AIRPORTS
Illinois	87	14
Indiana	74	7
Michigan	101	21
Minnesota	84	12
N. Dakota	27	8
Ohio	110	10
S. Dakota	28	9
Wisconsin	89	9
Total	600	90

Note: O'Hare represents only one of Illinois' 87 facilities. That number includes public, private, and military facilities.

CONCLUSION:

It is clear that the general aviation use of the Loran navigation system is significant. It has been demonstrated that even the most conservative estimated economic impact is also very significant. In the Great Lakes Region alone, shutting down the Loran-C system in 1996 would impose an economic impact estimated conservatively at over $39 million on the general aviation community alone. Using the FAA's 1992 Statistical Handbook of Aviation, these figures projected nationally would total over $2 billion. These conservative figures, taken by themselves, show a devastating significant, adverse economic impact on general aviation if the Loran-C system known today in the United States is shut down prematurely. In view of the $2 billion projected cost to general aviation aircraft owners, it categorically supports the continued operation of the Loran system to its projected life of 2015.

A cost figure has been given as $17 million annually to operate the United States continental Loran system. At that rate, it would take over 100 years (117) to reach the $2 billion cost to general aviation if it is discontinued prematurely.

FAA Statistical Handbook of Aviation, Calendar Year 1992

ACKNOWLEDGEMENTS:

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TJT:srr:85311

GPS International Association

Abstract of Remarks Before the Annual Meeting of the Wild Goose Association by Dr. Francis X. Kane, GIA President

IS IT TOO LATE TO ADDRESS THE DECISION TO DELETE FUNDING FOR *LORAN C* FROM THE DEFENSE BUDGET FOR FY 1996?

That decision had its origins in the effort to find funding to start what is now the Navstar Global Positioning System (GPS) over 25 years ago. GPS is the first and only defense system which before it was underway had to prove that it could reduce defense costs. Two concepts were analyzed: make the civil users pay, and eliminate "duplicate" capabilities.

Efforts to find ways of charging fees for the service ensued, including adding a chip and "pay for use" like cable television. A satisfactory solution has yet to be found. However, new efforts will be made to charge users for differential and augmented services. The second approach was to identify the systems to be eliminated and when. The list included OMEGA, VOR/DME, and later MLS.

LORAN C also made the list; but the real question was not asked. Does it provide an efficient service which meets requirements at a reasonable cost? Over the past quarter century LORAN C has done so. It meets the demands for safe harbor entry, for example, thus earning ardent support in Northern Europe and elsewhere. LORAN has been in use by pilots and navigators for years and can provide an effective partner for GPS.

The situation is far different from what it was 25 years ago. Differential (DGPS) navigation is an important feature with many uses, and several companies now provide or are contemplating providing DGPS services. Some states, such as Texas and Florida, have blanketed the state with a network of reference towers. The DoD/DoT Joint Task Force on GPS recommended that a study be made on providing augmentation services. The final report is to be made public by end of October and may suggest a series of fees for civil users. In addition, the FAA has embarked on a new program for air navigation — the Wide Area Augmentation System (WAAS).

And *if* LORAN C is cut from the Defense Budget, are there other ways to provide the service, perhaps through private or commercial ventures, paid for by the users, just as other utilities are? Obviously, there are some serious factors to consider in finding solutions to the challenges facing LORAN C and the WGA. Integration with GPS could help with the answer.

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Symposium Papers

Session III

Technology

THE MYTH OF LORAN SIGNAL UNAVAILABILITY

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ABSTRACT

This paper discusses the results of a Loran-C system performance analysis that was part of a study of Signal Availability Requirements for Radionavigation Aids in the National Airspace System conducted by the Volpe National Transportation Systems Center. Specifically, the history of on-air performance at U.S. and Canadian Loran-C stations and the causes of momentary signal interruptions of less than one minute in duration, which are most detrimental to Loran-C instrument approaches, were investigated. Both U.S. and Canadian Loran-C stations report signal availabilities above 99%, but these statistics do not reflect "momentaries". The causes of planned and unplanned momentaries and the reasons why Canadian stations have far fewer momentaries are discussed. Recommendations are made for improving Loran-C signal availability in the U.S. thereby enhancing the use of Loran-C as a nonprecision approach navigational aid in the National Airspace System.

BACKGROUND

The Loran-C radionavigation system has been in operation for over 30 years. On May 16, 1974, it was declared the approved radionavigation system for the U.S. coastal confluence in a joint announcement by the Secretary of Transportation and the Commandant of the U.S. Coast Guard.

Other modes of transportation, in need of reliable radionavigation, began using Loran-C for operations such as aerial spraying of national forests, emergency vehicle location and tracking, and en route and nonprecision approach navigation in the National Airspace System (NAS). In all these applications, Loran-C has proven to be a truly cost effective navigational aid and, by serving safety and economic needs, has returned the public investment many times over.

It is interesting to note that the very first operational Loran-C stations (LORSTAs) were installed overseas in response to U.S. and NATO defense needs. The establishment of the North American Continent Loran-C systems came somewhat later and only after U.S. shores were threatened with possible oil spills from transiting tankers. From that start came a wide spread utilization of Loran-C in North America. Today, we observe Loran-C expanding overseas, while in the U.S. enthusiasm for change to the Global Positioning System (GPS) threatens the untimely demise of the Loran-C system.

As long as Loran-C was serving the relatively slow moving maritime user, little concern was directed toward momentary interruptions of radiated power at transmitting stations. Momentaries were prevalent particularly with early vacuum tube transmitters. These transmitters were shifted on schedule to balance out tube life, perform critical maintenance, and for training purposes. Because of these practices, mariners, and eventually other land and aviation users of Loran-C, became accustomed to infrequent outages and would simply wait for transmitted signals to return before taking their fixes.

Short interruptions in Loran-C transmissions, lasting up to one minute in duration, became so commonplace that even the U.S. Coast Guard's Aids to Navigation Manual - Radionavigation[1] permits, and under some conditions **directs,** the acceptance of momentary interruptions of transmitter output power of up to one minute. Called "momentaries", these outages are not counted as bad or unusable time UUT) when calculating the on-air and synchronous availability of the Loran-C system.

LORAN-C IN AVIATION

The most important effort to qualify Loran-C as a navigational aid in the NAS took place in the late 1970's. W. L. Polhemus, under the sponsorship of the DOT Research and Special Programs Administration, and the Volpe National Transportation Systems Center, conducted an extensive Loran-C flight test program in Vermont. The results of the program proved that Loran-C easily could meet all FAA accuracy requirements for en route, terminal, and nonprecision approach phases of flight. Unfortunately, the FAA chose to grant certification to use Loran-C, under instrument flight rules, only for en route and terminal area purposes. It was the first time that the FAA awarded a segmented certification for a navigational aid.

In 1985, the use of Loran-C in aviation took a dramatic surge upward with the advent of small, light weight, user friendly Loran-C receivers and navigators. In response to requests from their general aviation constituents, the National Association of State Aviation Officials petitioned the FAA to commence a program to bring Loran-C into the NAS as a nonprecision approach navigational aid.

Several manufacturers began concerted programs to obtain FAA certification of their receivers for nonprecision approaches. Perhaps no company expended more energy and funds to get receiver certification than the Bendix-King Corporation. It was during the certification process that a Bendix-King receiver was used in twelve flight tests, conducted from July 9 to July 12, 1991. The certification procedure included a requirement that the receiver indicate, or display, a "flag" within 10 seconds after detecting a Loran-C signal anomaly while the receiver was operating in the "approach" mode. During two of the approaches into the Orlando, Florida airport, the receiver displayed a flag indicating that the Loran-C signals had been lost. A subsequent check with the Coast Guard revealed that, indeed, the Loran-C station at Jupiter, Florida had experienced momentaries at the times the receiver flag was displayed. As a result of these tests, the FAA flight test engineer expressed some doubt that Loran-C system performance could meet the signal availability requirement for navigational aids in the NAS.

AVAILABILITY STUDY

As a consequence of the 1991 flight tests, the FAA commissioned the Volpe Center to conduct a study[2,3] of the signal availability performance of the Loran-C system.

During the initial stage of the study it was discovered that the FAA did not have documented navigational aid signal availability requirements. At that point, it was decided to expand the study to include an examination of Very High Frequency Omni-Directional Ranging (VOR) system performance so that it could be compared with Loran-C. VOR was selected because it is the most commonly used navigational aid in the NAS. In conjunction with the study of the signal availability requirements, another effort was initiated to investigate the causes of momentary interruptions of radiated power from LORSTAs. Analysis of the performance of the U.S. Southeast (SEUS) chain transmitting stations in the July 1991 period showed that the signal outages that occurred while the Bendix-King flight tests were being flown, resulted from the effects of natural phenomena (lightning). An assessment of other momentaries, that were recorded during that month, suggested that some percentage might have been the result of maintenance and operating procedures. The momentary investigation was expanded to include performance data from other U.S. chains and from Canadian stations. In addition, visits were made to selected U.S. LORSTAs.

STUDY RESULTS

The investigation revealed many reasons for momentaries. While some momentaries are caused by unexpected casualties or problems, there are others which are procedurally imposed. Generally, momentaries last longer than 10 seconds, and in most cases are longer than 20 seconds in duration. At U.S. stations, momentaries average one per day per station or about 2-3 per day per chain (triad). As discussed earlier, momentaries are permitted and do not affect the reported on-air availability of a Loran-C station. Hence, incurring frequent momentaries, up to one minute in duration, generally is viewed as acceptable performance.

Vacuum tube-type transmitting (TTX) stations continue to shift from operational to standby transmitters on a routine schedule. The process of properly retuning a TTX to the antenna after maintenance accounts for many intentional momentaries.

Another source of intentional momentaries is the training of the rotating force of technicians to handle casualties and to repair equipment. Training is done both at TTX and solid-state transmitting (SSX) stations. Finally, technical and performance inspections account for a certain number of momentaries at all LORSTAs.

Lightning strikes during thunderstorms, particularly at southern U.S. LORSTAs, are the leading reason for unintentional momentaries. Lightning strikes cause transmitter overloads and interruptions in commercial primary power.

At most U.S. LORSTAs that were visited, operating personnel were aware, only peripherally, that there were certain aviation uses of Loran-C that are sensitive to momentary interruptions of output power. The LORSTAs had no official documentation, either from USCG Headquarters or their Regional Managers, outlining the need to reduce momentaries in order to provide better service for aviation. Therefore, station personnel continued to regard momentaries as acceptable procedures pursuant to the provisions of the USCG Aids to Navigation Manual. While there was general interest in trying to reduce the number of momentaries incurred, most of the USCG personnel, who were interviewed during the study, stated that major reductions could not be realized until: 1) primary power sources were made more reliable and impervious to lightning strikes, and 2) the technical force became more stable thereby reducing the amount of on-the-job training at operating LORSTAs.

Based on performance records, it is evident that replacement of TTX transmitters with SSX equipment would improve on-air signal availability. It was noted, however, that the coupler network (CN) switches, in SSX transmitters, should be replaced with units that switch in less than 10 seconds in order to reduce interruptions of output signal. The overall view expressed at U.S. LORSTAs was that there definitely are ways to improve signal availability, but improvements will be difficult to attain with equipment in its present configuration, and with the policy of rotating technicians.

The study produced evidence that the frequency rate of momentaries at U.S. LORSTAs, operating either TTX or SSX, is markedly higher than at Canadian LORSTAs operating as part of the same chains. Although the newer mid-continent chains (NOCUS and SOCUS) appear to be operating with fewer momentaries than other U.S. stations, their performance does not equal that reported by the Canadian Stations at Port Hardy, British Columbia and Fox Harbour, Newfoundland.

Conclusions from this study[4] included:

1) Improving the primary power system at both TTX and SSX LORSTAs could reduce the occurrence of unplanned momentaries by as much as 50%.

2) Providing proper lightning protection would reduce momentaries by another 10-15%.

3) Improving maintenance management at TTX stations, including the use of a dummy load to emulate the antenna, and routinely replacing vacuum tubes, could reduce TTX momentaries by an estimated 50%,

4) Replacing the CN switch at SSX stations, and coordinating planned momentaries, could bring the total reduction in momentaries to about 70%.

FOLLOW ON STUDY

As previously noted, the Canadian LORSTAs at Port Hardy and Fox Harbour, experienced far fewer momentaries than their U.S. counterparts in the same Loran-C chains. During 1990 and 1991, Port Hardy reported an average of 53 momentaries per year. For the period between 1989 and 1993, Fox Harbour had an average of 16 momentaries per year. During the same periods of time, each U.S. LORSTA reported up to several hundred momentaries per year.

To explore the reasons for these differences, additional investigations were conducted. It first was verified that the procedures utilized by the Canadian Coast Guard to record and report momentaries were consistent with the those used at U.S. LORSTAs. Canadian Coast Guard personnel, including the Regional Managers, the Coordinators for Chain Operations , the Station Leaders and technical personnel for Port Hardy and Fox Harbour were interviewed. LORSTA Port Hardy was visited to confirm equipment configurations and to review documentation and procedures utilized to operate and maintain the Loran-C equipment.

Port Hardy and Fox Harbour have SSX that are identical to those used at U.S. LORSTAs. Great care is taken by the USCG to insure that Canadian LORSTAs operate with the latest equipment modifications and are in every respect the same as equivalent U.S. LORSTAs.

Both Port Hardy and Fox Harbour are located in northern latitudes. Consequently, they do not experience as many casualties and momentaries due to thunderstorms and lightning activity as southern U.S. LORSTAs. In addition, significant steps have been taken to condition and protect the commercial source of primary power for Port Hardy in order to reduce interruptions that cause momentaries. The Fox Harbour LORSTA operates from its own generator power source which is highly reliable, but not without some infrequent interruptions due to overheating and other generator anomalies.

The technical work forces at Port Hardy and Fox Harbour are very stable. The technicians must be highly qualified and experienced before they assume entry level positions. There is very little turnover of technicians once they are in place at a LORSTA -- they consider their jobs as career positions. The technicians are civilian employees of the Canadian Coast Guard and many have more than 20 years experience at one LORSTA. This has a tremendous impact on the maintenance and operation of these LORSTAs. First, there is not a continuous training cycle on the equipment for new technicians. Second, the Canadian Coast Guard technicians are not intimidated by the transmitters and they quickly and confidently handle casualties. It is the common consensus that during their tenure they have experienced every conceivable fault mode. The technicians anticipate and avoid pending casualties by observing small details in equipment performance and by making appropriate corrections or adjustments.
The Canadian technicians follow very conservative maintenance procedures. They do not follow the USCG Maintenance Manual to the letter and they avoid scheduling routine shifts to alternate equipment. Furthermore, they have found that normal casualties will cause eventual shifts of equipment and that switching, for the sake of switching, applies more to TTX than to SSX equipment. In other words, if isn't broken, don't try to fix it! Care is taken, to limit excessive insertion and removal of printed circuit cards in order to avoid undue wear on contacts and back plane connectors. This conservative philosophy, coupled with the experience of the technicians, produces an optimum relationship between man and machine and is reflected in the performance of the equipment.

Finally, the goal of the organization, including the administration, technical management and operators of both Port Hardy and Fox Harbour, is to incur as little down time as possible. The Canadian LORSTAs, like their U. S. counterparts, operate under the principle of serving the mariner. Although the Canadian Coast Guard is aware of aviation users of the system, and they participate in the Notice to Airmen (NOTAM) process, the basic needs of the mariner are paramount. The point is, however, that they make every effort to keep UUT and momentaries to a minimum. This policy starts at the top with the Regional Manager and goes all the way down to the individual technician. Canadian technicians understand that momentaries are allowed pursuant to the USCG Aids to Navigation Manual. Nevertheless, they have devised ways to perform several maintenance procedures with one momentary and they combine inspection momentaries whenever possible. Their suggestions for making more improvements in their momentary record include: 1) the replacement of the SSX CN switch with one that switches faster, and 2) providing fiberglass ladders for people who must climb the Loran-C antenna towers thereby eliminating the need to turn off the transmitters. Antenna towers are climbed at least once a year to inspect the condition of the tower structure and the insulators and when there is a failure of tower lighting.

ANALYSIS OF MOMENTARY DATA

Table 1 is a compilation of LORSTA performance data extracted from the Phase II Volpe Center report on Signal Availability Requirements[5], The total momentaries reported by station types (TTX and SSX) for each chain listed and the average number of momentaries per year for each transmitter type are shown. The SEUS chain has only SSX equipment, and three of the chains, Gulf of Alaska, U.S. West Coast, and North Pacific, have only TTX equipment. The remaining six chains have both TTX and SSX. The SSX data for the Canadian East Coast and Labrador Sea Chains were not used in the final average for SSX stations because the exceptionally low number of momentaries reported by Fox Harbour, as a member of these two chains, skewed the data.

Figure 1 is a graphical representation of the data in Table 1. It can be seen that there are increased incidences of momentaries in the southern latitudes (SOCUS and SEUS) where there are more thunderstorms and, conversely, there are fewer momentaries in the northern stations such as in the North Pacific chain.

The average number of momentaries for all the TTX stations exceeded the SSX stations by 114 or by about 35%. This does not consider the geographical location of these stations, so Table 2 was compiled to show the differences between TTX and SSX in the same chains. The momentary average for SSX is 142 less than that for TTX or about a 43% difference. Again, the chains which include Fox Harbour were not included in the compilation.

Table 1. Momentaries Per Year For Each Station Transmitter Type (TTX or SSX)

Loran-C Chain	No. TTX	Total # Moms.	No. SSX	Total # Moms.	Month Data	# Moms/yr TTX	# Moms/yr. SSX	REMARKS
Gulf of Alaska	4	2196	0	--	26	253	--	Fewer T-storms
North Central U.S. (NOCUS)	1	589	3	1177	25	283	188	
U.S. West Coast	4	3104	0	--	26	358	--	
North Pacific	4	1959	0	--	27	218	--	
Northeast U.S. (NEUS)	1	1432	4	2995	54	318	167	
Canadian East Coast	1	1482	3	1229	51	348	97*	Incl. Fox Harbour
Labrador Sea	2	2842	1	74	52	328	17*	Incl. Fox Harbour
Southeast U.S. (SEUS)	0	--	5	5534	54	--	246	More T-storms
Great Lakes	1	1485	4	3474	54	330	193	
South Central U.S. (SOCUS)	1	947	5	2517	29	392	208	
Avg. # Moms per Xmtr. Type						314	200	*Not incl. in Avg.

NOTE: Data for this table extracted from Appendix A to the report: "Signal Availability Requirement for Radionavigation Aids in the National Airspace System, Phase II Study", Volpe National Transportation Systems Center, June 1994

Figure 1. Average Momentaries By Tranmsitter Type

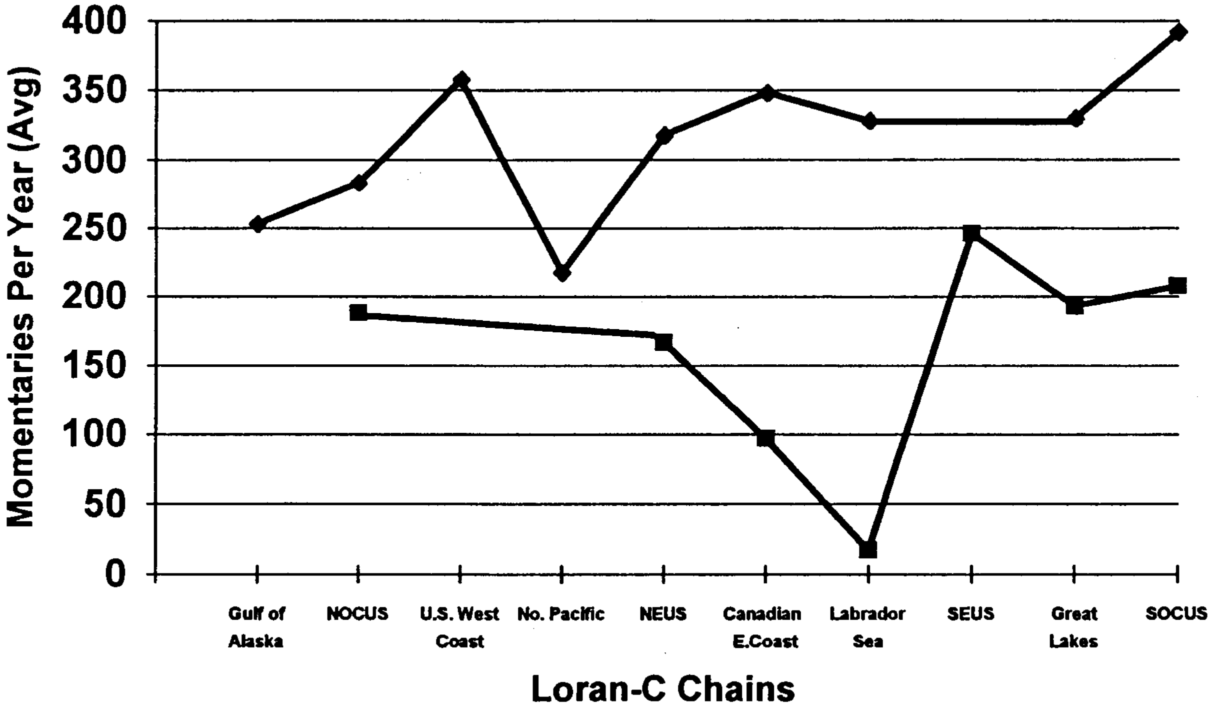


Table 2. Difference in Momentaries Per Year Between U.S. TTX and SSX LORSTAs

U.S. Loran-C Chains (non Canadian LORSTA)	No. Momentaries TTX	No. Momentaries SSX	Difference between TTX &SSX
SOCUS	392	208	184
Great Lakes	330	193	137
NEUS	318	167	151
NOCUS	283	188	95
AVERAGE	**331**	**189**	**142**

Coupled with the conclusions from the earlier studies, it is estimated that improvements at U.S. LORSTAs could result in the following reductions in momentaries:

1. Replacing TTX with SSX could reduce planned and unplanned momentaries by at least 40%. From the Table 2 averages, for example, this would reduce momentaries from 331 per year to about 200 per year.

2. Improving the primary power systems could reduce the momentaries by another 50%. This would apply to both TTX and SSX stations. This means that momentaries at the average SSX station could be reduced further from 200 to about 100 per year.

3. The earlier studies concluded that the overall result of replacing the CN switch and coordinating planned momentaries could result in a further reduction of 20%. Average SSX station momentaries would go from 100 to about 80 per year.

4. From observing the maintenance practices and personnel at LORSTAs Port Hardy and Fox Harbour, it is estimated that stabilization of the technical workforce at U.S. LORSTAs could reduce the number of both planned and unplanned momentaries by another 30%. This would bring the average SSX station momentaries down to approximately 50 per year.

These reductions are shown graphically in Figure 2.

Looking at the Canadian East Coast chain average for SSX of 97 momentaries per year and LORSTA Fox Harbour (the only SSX in the Labrador Sea Chain) average of 17 momentaries per year, reductions in the neighborhood of 50 per year would be very close to 35 momentaries per year per station which would greatly enhance Loran-C use for nonprecision approaches.

SO WHAT'S THE MYTH?

This study was undertaken because of events that occurred during flight tests for certification of a Loran-C receiver. When it appeared that the receiver had reacted as required to a loss of transmitted signals, then the signal availability of the Loran-C system was questioned. The study, however, confirmed that Loran-C availability already is very good, and identified measures that could be taken to achieve even better performance. The Canadians have demonstrated how some of these improvements can be made, and the U.S. can profit from Canadian operating and maintenance procedures.

There appear to be at least four major steps that would bring U.S. LORSTA operations in line with the same excellent on-air record of Canadian Stations:

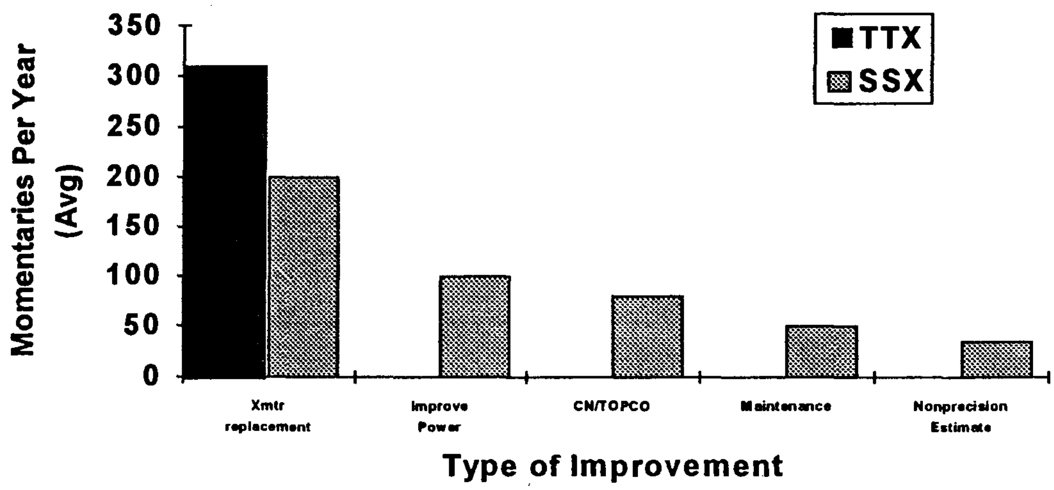
1. Replace TTX with SSX.

2. Condition primary power systems to make them less susceptible to the effects of natural phenomena.

3. Replace the CN switch at all SSX stations.

4. Stabilize the technical work force at LORSTAs.

Figure 2. Momentary Reductions per Transmitters



[1]. USCG Commandant Instruction (COMDTINST) M16500.13 of 3 January 1988

[2]. Signal Availability Requirement for Radionavigation Aids in the National Airspace System, Volpe National Transportation Systems Center, DOT-VNTSC-FA329-PM-93-2, March 1993

[3]. Signal Availability Requirement for Radionavigation Aids in the National Airspace System, Phase II study, Volpe National Transportation Systems Center, DOT-VNTSC-FA429-PM-94-7, June 1994

[4]. Signal Availability Requirement for Radionavigation Aids in the National Airspace System, Volpe National Transportation Systems Center, DOT-VNTSC-FA329-PM-93-2, March 1993

[5]. Signal Availability Requirement for Radionavigation Aids in the National Airspace System, Phase II Study, Volpe National Transportation Systems Center, DOT-VNTSC-FA429-PM-94-7, June 1994

The Final Design of the LORAN-C Automatic Blink System (ABS)

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Abstract

The FAA requested the Volpe Center to determine how Loran-C radionavigation could be enhanced to act as a supplemental approach aid for non-precision approaches in the NAS. This request led to a project to determine the feasibility of a Loran-C Automatic Blink System (ABS). During 1991, an ABS prototype unit was developed and tested at United States Coast Guard (USCG) Electronics Engineering Center (EECEN) to determine if the automatic blink theory could be realized. The results of that project successfully indicated that an ABS was feasible. This paper will present the final design of the ABS. The paper focuses on the differences between the feasibility model and the production unit. The mission of automatic blink has not changed; however, major changes were required to implement a product that met the needs of both the FAA and the USCG.

Introduction

During 1990, the FAA requested the Volpe Center to conduct a program to investigate the potential for using the Loran-C radionavigation system to supplement navigational aids in the National Airspace System (NAS). The program objectives were to: a) survey current Loran-C transmitters ground equipment to determine the detailed requirements for ABS; b) design and build an ABS prototype unit; c) test the prototype system using Loran-C equipment available at EECEN; and d) prepare an engineering specification for manufacturing operational units.

The ABS feasibility project successfully met its defined objectives. After completing the transmitter survey, an ABS prototype unit was designed, built, and tested. The design was based on using two IDMs (Intelligent Decision Modules) and three PTMs (Pulse Time Monitors) to detect any transmitter timing jumps. The prototype unit was integrated into the USCG test suite at EECEN for validation and verification of the design. Based on the test results, an engineering specification was developed. This specification detailed the design approach for an operational ABS unit.

The purpose of this paper is to describe the final design of the production ABS. One should review the ABS design paper written in 1991 by Poppe and Goddard (Reference 1) to understand the original Automatic Aviation Blink system. The term aviation was dropped from the project title because the production units will all process blink events the same way. The paper will highlight process differences between the original concept for the prototype unit and the unit currently in production.

What is Aviation Blink?

Aviation blink is the same "old" blink that current Loran-C users are familiar with, with the addition of the following features

(a) The Loran-C transmitter will start blinking the signal faster when an out-of-tolerance condition is found.

(b) If a master station is required to blink, it will create an off-air condition.

(c) Owners of Loran-C receivers will notice that a blink condition will last for a minimum of 30 seconds. However, current Loran-C receivers will process a blink event without hardware or software modification.

Specification

The design approach developed in the original specification was used as a starting point for creating documentation to support ABS production. It was quickly realized that many critical requirements for integrating an ABS into the Loran-C equipment suite were not documented. NavCom was requested to develop the Prime Item Development Specification for ABS. This document would detail all requirements for the ABS hardware and software, and interfaces for the Loran-C station (LORSTA). During the development of the prime item specification, the difference in ABS performance requirements for the FAA and the USCG were detailed.

The primary FAA requirements were:

(a) blink the Loran-C signal within two seconds of detecting an out-of-tolerance, transmitter timing jump (the FAA requirement is a timing jump of 500 nanoseconds or greater); insure the blink condition is maintained for a minimum of 30 seconds;

(b) blink or take the signal off-air if an out-of-tolerance condition exists except when a NOTAM has been issued;

The primary USCG requirements were:

(a) ABS design could not require redesign of the current transmitter system;

(b) no reduction of on-air time for aviation/maritime users: i.e., the current availability of the Loran-C signal will not be degraded;

(c) the watchstander will be used to operate and maintain the ABS;

(d) ABS must be designed to fit within a seven-inch high, nineteen-inch wide rack space.

Blink Event

Blink event is defined as the criteria established for the ABS unit to blink the Loran-C signal. The following blink-event criteria were adopted:

- Loss of two or more 5 MHZ frequency inputs;
- Loss of OPRF ("operate RF") or MPTs (multipulse triggers) for more than 240 seconds (selectable);
- Loss of two or more PTM processor cards;
- A MPT offset of 500 nanoseconds or greater;
- A standard zero crossing (SZC) offset of 500 nanoseconds or greater;
- Cycle slip (10 microsec MPT offset);
- Loss of the 5 MHZ frequency input or RF Gate of the operational PTM when the ABS is operating in the degraded mode.

With the basic blink criteria defined and agreed upon by the FAA and the USCG, a Prime Item Development Specification was generated. The birth was slow and at times painful. Many technical information meetings were held to ensure that all sides understood the requirements. Reference 2 provides the details and particulars of the ABS system specification.

Major Specification Changes

The process of creating the prime item development specification changed some thinking about how an ABS should operate in a Loran-C transmitter station.

Some of the major changes are:

(a) The redundancy requirement is to have a complete system available for backup in case of failure of the on-line system. Normally, only major components were required to be available for automatic failover. The switchover between the on-line and hot stand-by is to occur without loss of data. If failure occurs during blink then the LORSTA must remain in blink.

(b) RF Gate input was added to allow operation with one cesium input and one PTM, now defined as degraded mode.

(c) All commands from switches and buttons on the front panel had to be executable via software.

(d) ABS was to receive commands via the TTY/RCI (remote control interface) loop, and process only the messages addressed to it. All other messages were to be shipped as received.

(e) The Status Alarm Unit (SAU) and LEDs on the front panel were to be used to alert the watchstander of ABS activities and failures.

(f) A covered BY-PASS switch was added to provide the watchstander the ability to deactivate the ABS blink initiating capability.

Design Approach

The design of the prototype ABS was built around hardware available from previous Loran-C and Omega projects. The production ABS specifications require a design based on current technology, simple maintanence and high availability.

Using the above requirements as a goal, the ABS unit was designed using EURO standard size cards and hardware. The ABS was divided into three major subassemblies: (1) Automatic Blink Controller (ABC); (2) Automatic Blink Unit (ABU)(2 per ABS to meet redundancy requirements); and (3) Automatic Blink Chassis. Figures 1, 2 and 3 illustrate the layout of each of these subassemblies.

The ABC is used to switch between the ABUs to ensure that one ABU is available to monitor the Loran-C signal for blink events. Therefore, it is designed as the status input and output interface between the ABS and the LORSTA. This subassembly is the only common point between the two independent ABUs. This subassembly is designed using robust relay logic to address single point failure concerns.

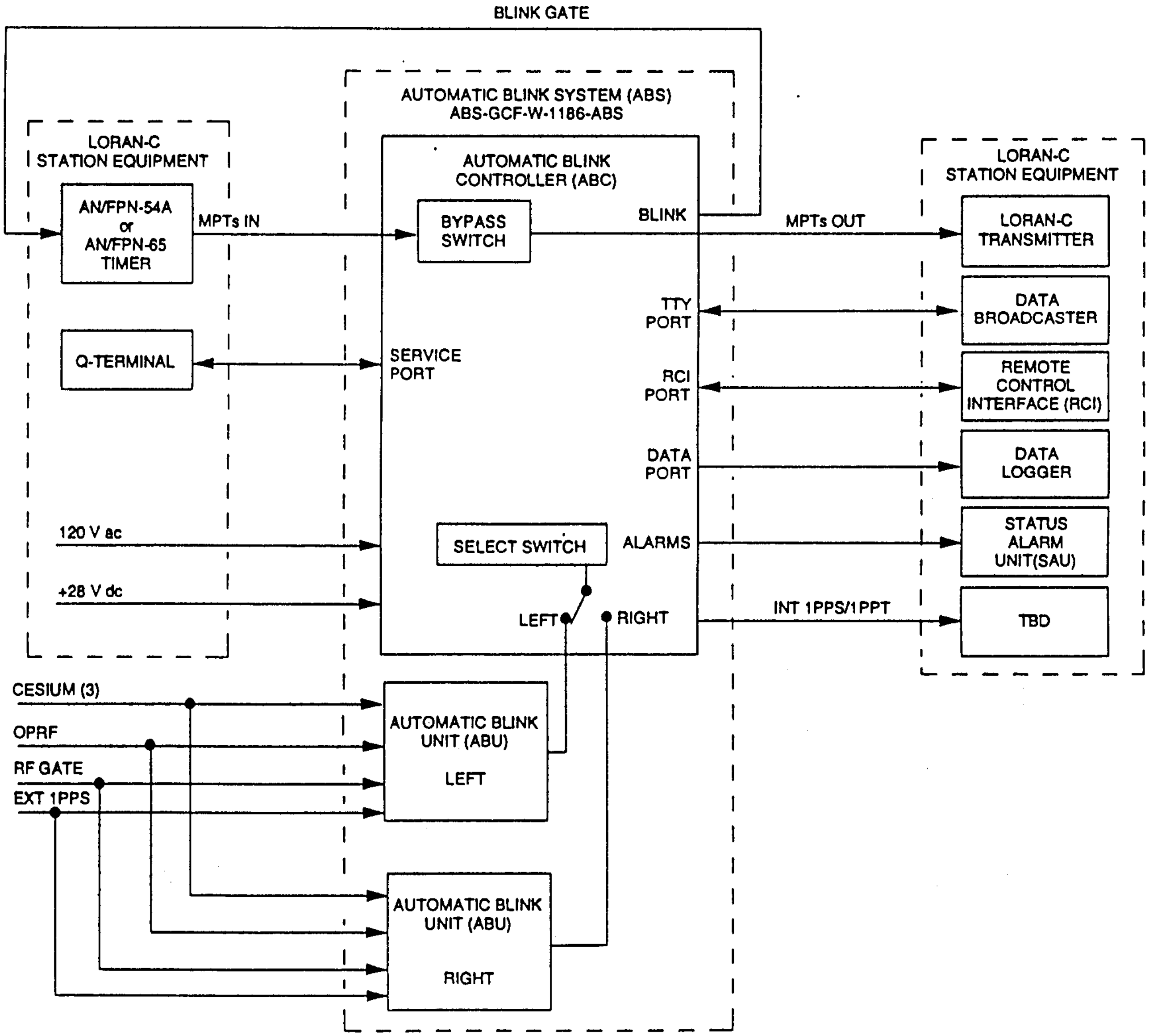

Figure 1
ABS Functional Configuration

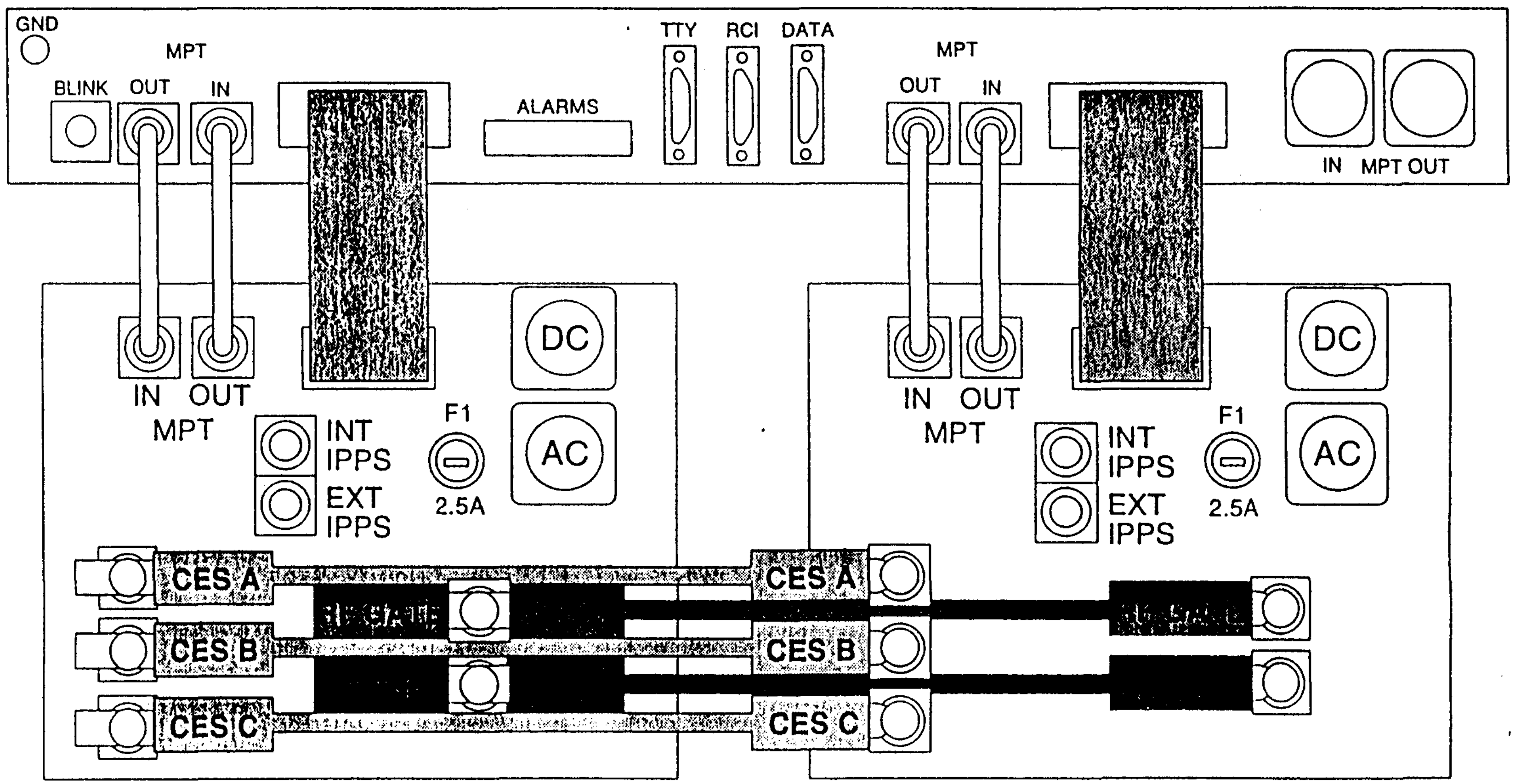

Figure 2
ABS Rear Panel

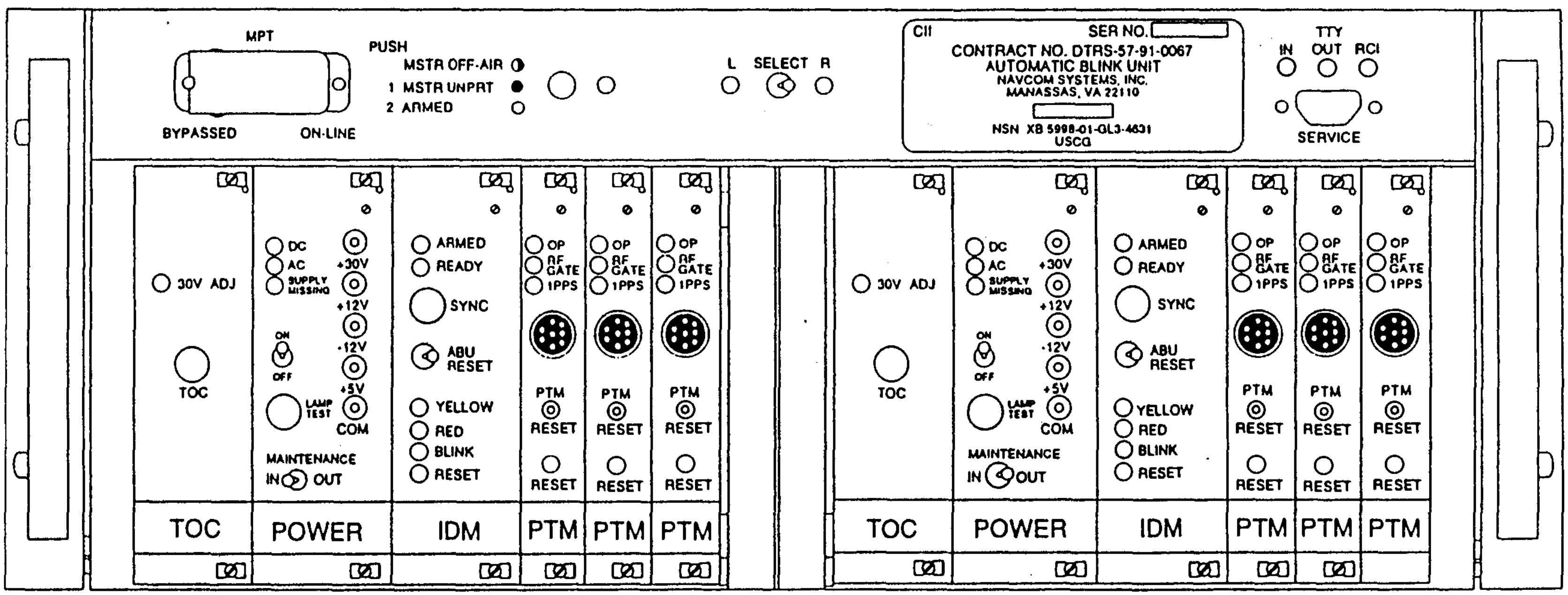

Figure 3
ABS Front Panel

The ABU (two per ABS) is the heart of the ABS Loran-C signal monitoring function. Each ABU has three PTM modules (one per cesium) and one IDM. The PTM measures timing jumps using the standard zero crossing as a reference point. Information concerning offsets is sent to the IDM by each PTM. The IDM checks this information for blink event conditions and issues a blink event alarm as required.

The ABS has a maintenance mode which allows the watchstander to set parameters, change system configuration, or check system operations. The ABU is programmed to recognize when major system configuration parameters change and will (if necessary) "reboot" the ABU when coming out of maintenance.

The ABS maintenance concept is to pull and replace any module (ABU, IDM, Power, or PTM). To ensure identical operation between replacement modules and the original system, manufacturing process tolerances are kept minimal.

Hardware Implementation

The hardware has changed significantly from the original design. The prototype unit was designed to contain two IDMs, three PTMs and a power module in a single chassis. The operational unit now has two ABUs, each with an IDM, three PTM and a power module. An ABC was developed to allow control between the ABUs. The signal inputs from the LORSTA (Cesium, RF Gate, OPRF) are distributed between the ABUs.

ABU

An ABU consists of an IDM, three PTMs, a power module, and a motherboard. The PTM is used to compute and provide pulse OFFSET information to the IDM. The IDM uses this information to determine when to pass the MPTs being received or to "blink" them. The motherboard is used as a data path among the IDM, PTM, and power module.

ABC

The ABC is the "traffic cop" for the ABS. This unit allows the on-line ABU system output data to be shipped to the LORSTA for processing. This unit also carries out the commands of the IDM to send information to the SAU, TTY communication system or RCI. There are two data ports on the ABC; the on-line unit uses one to pass operational data and the off-line uses one to pass its data. The ABC will allow operational data output based on whether an ABU is selected as on-line or off-line. Interfaces to the LORSTA are illustrated in Figures 2 and 3.

Printed Circuit Boards

The ABS is designed for ease of production and maintenance. Printed circuit board modules are designed to handle most ABS functions. There are eight unique PCB modules. All use thru-hole technology because it allows the USCG to repair boards using current repair workstations and staff. Two of the PCBs, IDM and PTM, are multi-layered. Each multi-layer board is bed-of-nails tested and certified prior to installing component parts.

Front Panel

The ABS front panel is an integral part of the PCB module. This approach was used to minimize the number of internal signal cables required to pass data within the ABS. All internal data is transmitted over SPI bus via a motherboard.

Software Design

The ABS software is programmed in "C" language using the Introl, Corp. HC11 compiler. Both the IDM and PTM software operate in a multi-tasking environment. The IDM tasks and their functions are illustrated in Figure 5, while the PTM software structure is depicted in Figure 6.

The functional software operational modes are detailed in Figure 4. The ABS will always be in one of these modes. Briefly, each mode is defined as follows:

NOT READY: The ABS is unable to detect timing jumps or determine a blink event. In this mode, the ABS will blink the signal output. This mode is entered upon start-up of the ABS.

READY: The ABS has passed all conditions required to be placed on-line to activate or process a blink event. In this mode, the ABS is blinking the Loran-C signals outputs. The ABS is ready to perform on-line blink monitoring duties (ARMED).

ARMED: The ABS has the authority to blink the Loran-C signal if a timing error occurs. This is the normal mode for an operational system.

BLINK-EVENT: A timing error has occured and ABS has alerted the watchstander that "ABS is causing blink." This is normal when a timing error has caused blink.

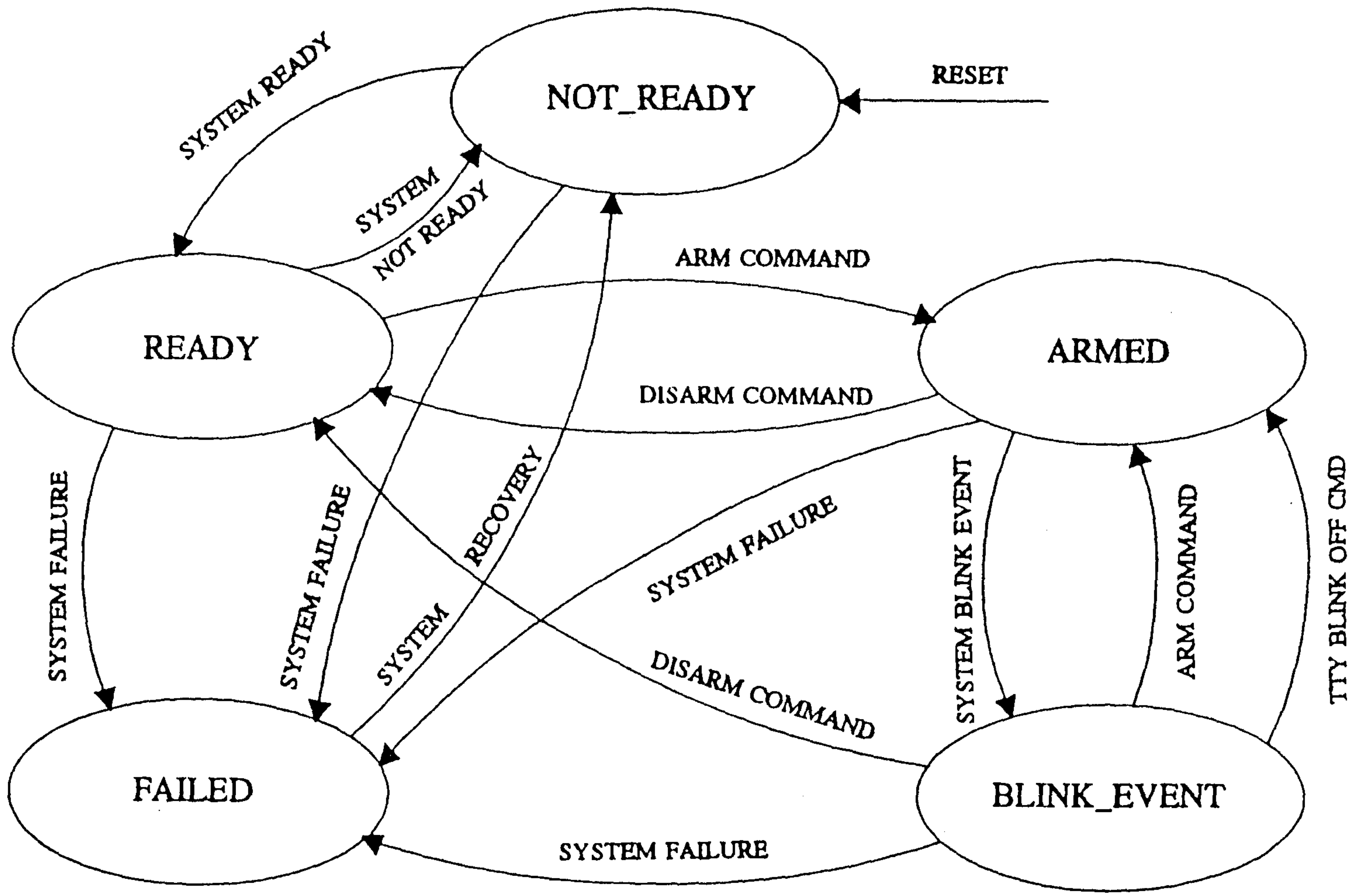

Figure 4
Mode Transition Diagram

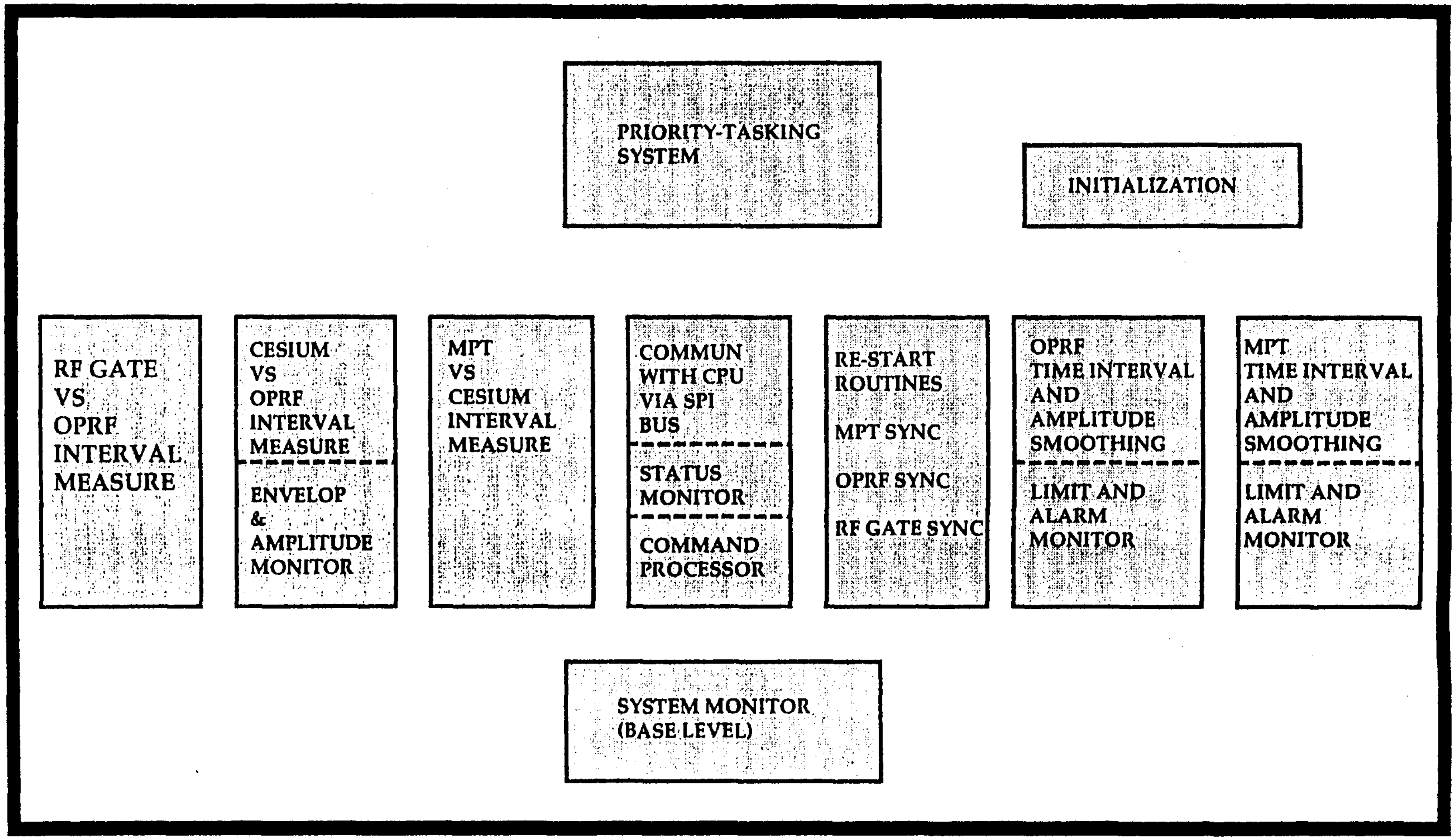

Figure 5
PTM Software Structure

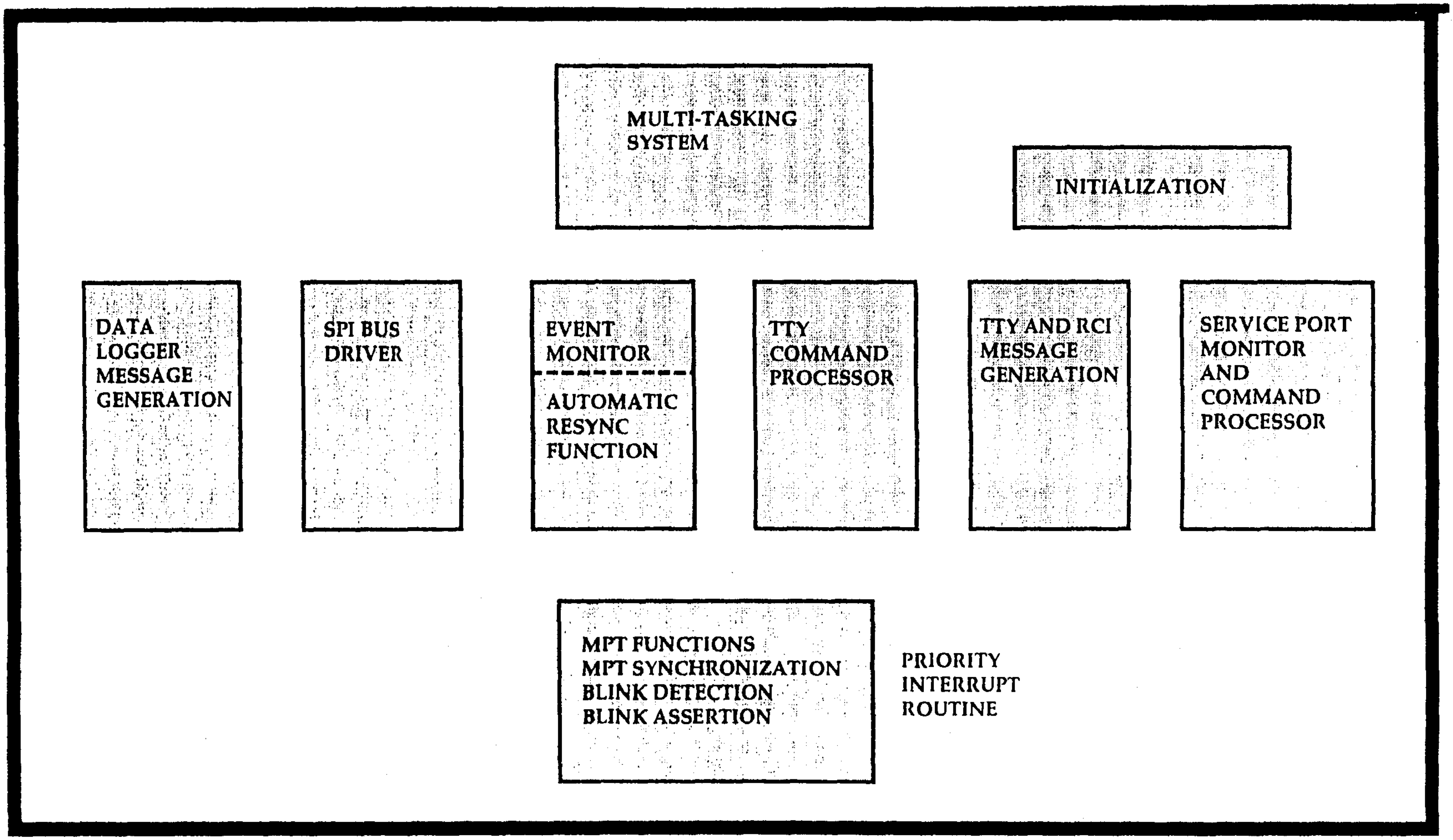

Figure 6
IDM Software Structure

FAILED: This mode is used to indicate an ABS failure that will not allow the unit to perform blink determination.

The current software was developed on a UNIX operating system. The software has been ported over to a Windows/DOS envornment so that changes can be performed using existing USCG software resources.

Testing

The ABS has undergone extensive testing at EECEN to ensure compliance with the system specification and to confirm the interoperability of the ABS with both solid state and tube type transmitters. Reference 3 details all testing performed. Listed below, in summary, are some test results that impacted the overall project:

(a) Signal acquisition and "blink" test were executed with high reliability.

(b) Automatic recovery from a blink event was impacted by jitter on the transmitter signal.

(c) The "blink gate" TTL logic circuit could not be successfully engaged every time by the ABS. This problem was solved by changing hardware drivers within the ABS and changing the TTL logic gate in the LORSTA.

(d) The 75 baud rate required to operate over the teletype loop caused messages to be lost. This is still a system problem; however, shortening messages, reducing the frequency of output and eliminating message timing delays has eliminated the loss of data for ABS. A message priority algorithm was developed to ensure that blink activation messages are always sent.

Summary

The current ABS design proved that the original concept was valid. The final design built upon the original concept and produced a system that is easy to install, operate and maintain. The timing accuracy that can be achieved using current technology makes it feasibility to use ABS to set the timing for the entire Loran-C network. The USCG has initiated such a program called one-pulse-per-second (IPPS), which is discussed in another conference paper (Reference 5).

The ABS is currently in production at NavCom Systems, Inc. Six prototype units have been delivered to EECEN for installation and evaluation.

References

All references prepared for Volpe National Transportation Center under contract DTRS57-91-C-00067 TTD#4.

1. Design, Development and Testing of a Loran-C Automatic Blink System (ABS)

2. Prime Item Development Specification

3. Automatic Blink Test Plans and Procedures

4. Automatic Blink Software Design Review

5. Poppe, M. (The Addition of a Standard Zero Crossing (SZC) Tracking 1PPS Capability to the Automatic Blink System (ABS)); paper prepared for presentation at the 23rd Annual Wild Goose Association Technical Symposium, November 1-4, 1994, in Newport, Rhode Island.

Biographpy

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Mr. Boykin is an electrical engineer who has spent over 20 years developing, designing, operating, and manufacturing hardware and software for major military systems. He has been responsible for designing special hardware for use in spacecraft, mobile system and airplane platforms.

Mr. Boykin joined *NavCom Systems, Inc.* in 1990 and served as Program Manager for the development and manufacturing of telecommunications hardware for use in the National Airspace System. He was a major contributor to the Vessel Traffic Service study performed by Volpe Center following the Valdez oil spill.

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Mr. Poppe is an electronics engineer and President of *Cambridge Engineering, Inc.* He has a Bachelor's Degree in Electrical Engineering from the Massachusetts Institute of Technology, Cambridge, Massachusetts, and a Master's Degree from Stanford University, Stanford, California. Since forming *Cambridge Engineering, Inc.*

21 years ago, Mr. Poppe has worked on various navigation systems including Loran-C, Omega, Transit and Differential GPS.

In addition to Mr. Poppe's work on the Automatic Blink System (ABS), recent projects have included: the design of a DSP based timer for the USCG Omega Navigation System transmitters; the design of radiobeacon receivers to demodulate MSK modulated differential GPS data; and the design of loop antennas for the reception of radiobeacon signals.

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Evaluation of Radionavigation Systems in an Urban Environment

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and
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Abstract

Growing interest in vehicle location and management systems requires more precise and reliable position information of vehicles in urban areas. Constraints of urban environments are well known. Dead reckoning systems suffer from error accumulation. Multipath and signal shadowing affect satellite system users. Loran-C signal reception is hindered by a high noise environment.

Extensive radionavigation data were collected in New York City and vicinity from 26 July to 7 August 1994. These data include the accuracy and availability of the Global Positioning System (GPS) and LORAN, a comparison of electric (E) field (whip) and magnetic (H) field (loop) antennas at both LORAN and Differential GPS frequencies. The data includes that collected among the narrow streets and tall buildings in the Wall Street area, in the more open streets and smaller buildings of the Bronx, among tall buildings but the wider space of Third Avenue, in the vicinity of the large metallic structure of the George Washington Bridge, and under a cover of foliage along the Hudson River.

Initial analysis of the data shows: a. In the deep urban canyons of Wall St. and under the elevated train tracks in the Bronx, the LORAN electric field signal is frequently highly attenuated and undetectable. The magnetic field signal is slightly attenuated but virtually always easily detectable and has repeatable phase characteristics. It may however, have very large phase shifts due to large structures making the generation of a calibrated LORAN grid and the algorithm to convert navigation data to position difficult. b. The availability of radionavigation fixes can be substantially enhanced in these areas by the integration of LORAN and GPS and by the use of a precise time standard making fixes from as few as two Times of Arrival (TOA's). c. In heavy foliage, the availability of LORAN (either E or H field) is much higher than that of GPS.

Introduction

Attempts to use LORAN for vehicle tracking in urban environments have met with mixed success over the past two decades. In locations with wide streets and no tall buildings signals can be tracked easily. In deep urban canyons, receivers had cycle selection problems or could not detect signals at all. With GPS now available, it is expected that it will dominate in non-covert vehicle tracking applications in locations where the satellites are not obstructed and where an exposed, visible GPS antenna is acceptable. It was felt that LORAN may still have certain advantages in some applications because its lower frequency signals may penetrate into locations where GPS signals can't and because LORAN antennas do not have to be on exposed locations on vehicles. Also, for non-covert applications, it may be advantageous to integrate LORAN and GPS for greater availability. In [1], LaChapelle and Townsend measured LORAN, GPS and integrated LORAN/GPS availability in the mountains of British Columbia and found availabilities of 75%, 60%, and 95% respectively. By integrated LORAN/GPS in their study they mean combining Lines Of Position (LOP's) of the two systems, not by integrating LORAN TOA's with GPS pseudoranges as is meant in this study.

Loop Antenna Design Considerations

Numerous tests carried out by Megapulse, Inc. in urban environments showed that Loran-C receivers, regardless of signal processing type (hard-limited or linear), present reliable and accurate performance in areas free of man-made interference, such as major highways and roads. Along local roads with power lines along them and in large cities, Loran-C receivers with whip antennas presented degraded accuracy or were incapable of tracking Loran-C signals. One reason for this degradation is the broad band E-field interference radiated by the power lines and harmonics of man-made noise, as well as signal attenuation by tall buildings in large cities. These reasons led to the design a loop antenna and investigation of its performance in urban environments. It is well known that loop antennas significantly reduce E-field noise pick-up and reduce electrostatic precipitation noise in airborne use.

There are certain peculiarities in loop antenna design and processing of its signals. The loop antenna pattern is bi-directional and looks like a figure eight. In order to obtain an omni-directional amplitude pattern, it is necessary to operate pairs of crossed loops oriented 90° with respect to each other. Additionally, signals coming to the opposite lobes of the pattern have a 180° phase shift. Figure 1 shows signals arriving from different directions. Since the signal from M (master) and S1 (secondary) arrive through different lobes of the antenna pattern there will be a 5-μsec shift in the signal from S1, resulting in a 5-μsec TD error. This problem is aggravated when crossed loops are used. A special signal processing algorithm in Loran-C receivers should be able to eliminate these predictable phase errors. If the envelope can be resolved to within 5-μsec it may be possible just to select the loop with the strongest signal. This would also require averaging times shorter than the time constants of vehicle turns. If not, a heading sensor is required, thus increasing complexity and cost.

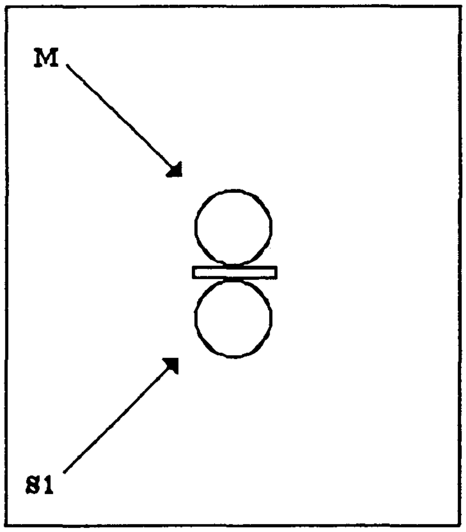

Figure 1 Loop Antenna Basics

A second problem with the loop antenna is low sensitivity or effective height. The effective height of a loop antenna is given as:

$$h_e = \frac{2\pi}{\lambda} n A \mu_{rod} F_A$$

Where:

h_e	Effective height in meters
$\frac{2\pi}{\lambda} = \beta$	Propagation constant in free space
λ	Wave length (3000 m for Loran-C signals)
n	Number of turns
A	Cross sectional area of one turn
μ_{rod}	Relative permeability of a ferrite rod
F_A	Emf averaging factor for the coil and rod (typically 0.5 to 0.7)

For example, a 15 cm long ferrite rod with $\mu_{rod} = 125$ and n = 100 will have an effective height of about 1 mm. This requires a high gain low-noise preamplifier circuit.

Looking at this formula for effective height, one can see that the three main variables affecting the loop sensitivity are number of turns n; cross sectional area of one turn A; and effective permeability μ_{rod}. In the present case, the main goal was to design a small-sized loop. For this reason cross sectional area was limited. Also, we could not increase μ_{rod} since it is dependent on the length to diameter ratio of the rod [2].

Consider the influence of the number of turns on the operation of the loop antenna itself and its combination with a preamplifier circuit. As the number of turns in the loop increases, the sensitivity increases. However, the loop becomes self-resonant due to the capacitance between turns. To reduce the winding capacitance, sectional windings were spread out over the ferrite core. For wideband systems, the maximum number of turns on a low μ ferrite material spread out over the entire core appears to offer more sensitivity than a high μ material core.

As mentioned earlier, ferrite loop antennas have low effective height which requires a high gain, low noise pre-amplifier. Excellent results were obtained with coupling symmetrical windings of the loop antenna to a differential J-FET amplifier, providing about 15db of gain in the first stage. The total gain of preamplifier was in the 40 - 55 decibel range, depending on a type of a loop used.

Description of the Experiment

With the sponsorship of the Advanced Research Projects Agency (ARPA) and in cooperation with several corporations, the Coast Guard Academy conducted a comprehensive study of radionavigation signals in the New York City area in the summer of 1994. These corporations include; Megapulse, Inc. of Bedford MA, LOCUS, Inc. of Madison WI, Integrated Systems Research Corporation (ISRC) of Englewood Cliffs, NJ and Science Applications International Corporation (SAIC) of Arlington, VA. For a number of reasons there was hope for success even though previous efforts had failed in particular areas. The LOCUS receiver had demonstrated the ability to track LORAN signals earlier receivers could not track. It was also felt that the magnetic field component of the LORAN signal would penetrate into the urban canyons better than the electric field that had been used in previous efforts. The LOCUS receiver was modified to use a Cesium based frequency reference and to generate fixes from two TOA's when three or more signals were not available.

The combination of signal availability and excellent geometry make the New York City area a good candidate for vehicle tracking using LORAN. The MXY triad of the

GRI9960 chain is specifically optimized for accuracy at the entrance to New York harbor. The signals from Seneca (Master) and Nantucket in particular, are quite strong. These two baselines are monitored and the time differences controlled using a monitor at Sandy Hook, NJ. The 2DRMS (95%) repeatable accuracy was seen to be 7.25m. at an exposed location on Governors Island. This is consistent with data observed a decade ago in the Coast Guard R & D Center's Harbor Monitor Survey [3]. Because the three stations in the MXY triad (Seneca, NY, Nantucket, MA., and Carolina Beach, NC) are almost equally spaced around the horizon, the Position Dilution Precision (PDOP) is at the minimum possible value. In addition, a two TOA fix is possible with any two of these three stations. Since the Carolina Beach signal is 10 dB weaker than those of Nantucket and Seneca, the ability to get a fix with only two signals can considerably enhance availability.

This paper is a condensed version of the quick look report of this project [4] and discusses the methodology, presents examples, and summarizes the data collected. The Appendices of [4] contain much more extensive plots of the data.

Hardware

An electronics van was obtained from the FAA Technical Center in Atlantic City, NJ. A block diagram of the hardware installed is shown in Figure 2. Ground truth and LOCUS LORAN receiver data were recorded using the Personal Command System (PCS) developed by and operated by ISRC. Ground truth was obtained by the PCS operator periodically, manually indicating the vehicle location on a computerized map and indicating which street and which direction the vehicle was travelling. Distance along that street was measured by a Terrafix® dead reckoning system that measured distance by counting odometer pulses. The Terrafix system also included a flux gate magnetic heading sensor, but this sensor was not used because it was felt the earth's magnetic field would be distorted in the urban environment. The ground truth and LOCUS LORAN data were tagged with both time and distance into scenario to facilitate the linking of data collected in subsequent scenarios and on other systems. The LOCUS receiver could be switched between a whip and a single loop antenna. Because of the directional properties of the single loop, the whip antenna was used in all scenarios except the straight path along Third Avenue. While the PCS also included its own GPS receiver, all GPS data recorded and analyzed were from the six and twelve channel Magnavox® receivers described below.

LORAN signal strength and noise of electric field and magnetic field antennas were measured and recorded using a Hewlett Packard® HP89410A Vector Signal Analyzer. After analysis of the first few days of data showed the LOCUS receiver could not track the E-field signal, particularly in the Wall St. scenario, but the HP89410A data indicated the availability of the H-field signal, the HP89410A program was modified to measure LORAN phase as well. An 18" JET® whip antenna with active coupler was used for the electric field. Original plans were to use a prototype crossed loop antenna being developed by Megapulse, Inc. but the prototype was not operational due to technical problems. Instead, Megapulse provided an aviation crossed loop antenna developed in the former Soviet Union for both civilian and military aircraft. Using an externally provided GRI trigger, a magnetic heading sensor, and a ROM look-up table, a logic circuit switches in the appropriate loop with the appropriate phase to produce the correct composite signal.

GPS data were collected using both a 12 channel Magnavox MX9212 receiver and a 6 channel Magnavox MX4200 receiver. The 12-channel MX9212 used a Starlink® combination GPS/magnetic loop DGPS antenna and the 6-channel MX4200 used the standard Magnavox antenna. DGPS signals were not routinely available and were not used..

Data comparing the performance of Starlink® loop and Magnovox whip antennas at DGPS beacon frequencies (286 kHz) were recorded using a second HP89410A but due to space it is not included here. The interested reader is referred to Appendix G of [4].

Scenarios

A total of 51 runs on five different scenarios were completed. The three main scenarios included the narrow streets and tall buildings in the Wall Street area, the relatively more open streets and smaller buildings of the Bronx, and in the vicinity of the large metallic structure of the George Washington Bridge. These scenarios were repeated fifteen times each. Because of the lack an E-field signal in the Wall St. scenario and because the LOCUS H-field antenna was a single (directional) loop, four runs were completed among tall buildings but the wider space of Third Avenue, two with the LOCUS using a whip antenna and two with the single loop antenna. Additionally, in order to evaluate GPS coverage under foliage, two runs were completed on a tree lined parkway along the New Jersey side of the Hudson River. Plots of the path of each scenario including street names are shown in [4].

Data Analysis

The data analysis can be divided into two general categories. These include the analysis of the availability of each of a number of types of fixes and the repeatable accuracy of the LORAN fixes. The approach used in the first case is to use either the binary information provided by the GPS and LOCUS LORAN receivers on whether they are tracking a

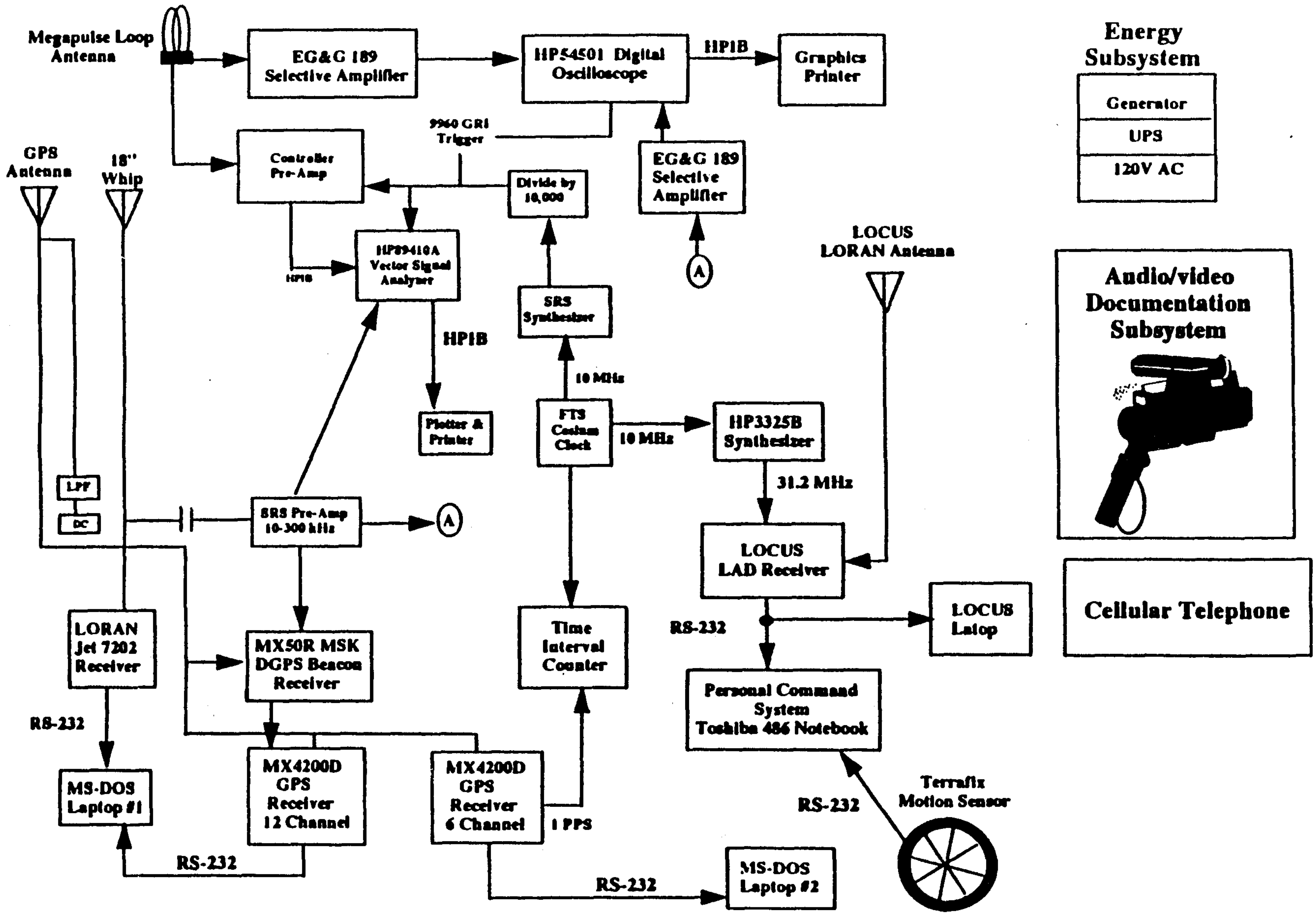

Figure 2. Block Diagram of ARPA-USCGA Radionavigation Experiment Hardware

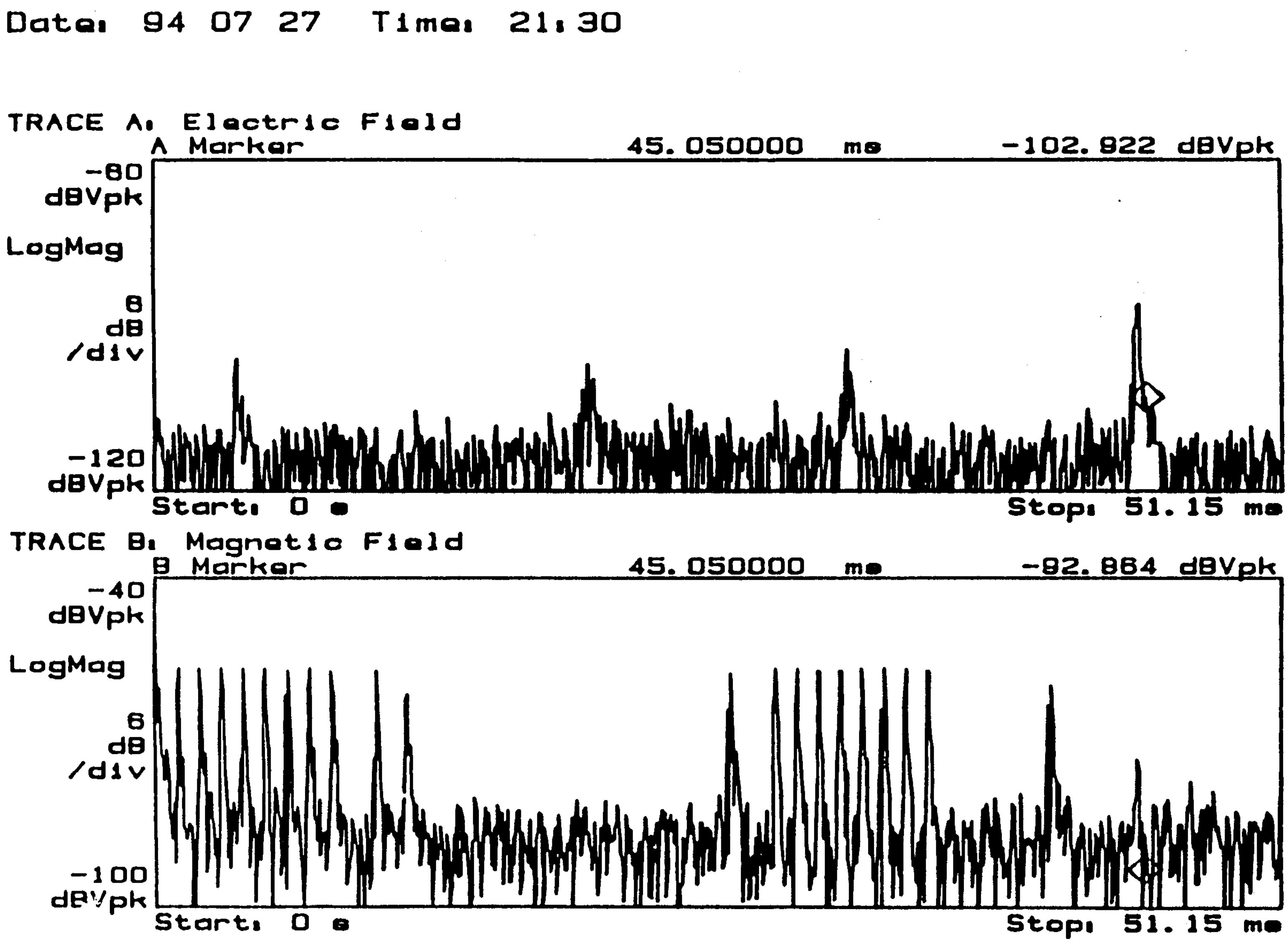

Figure 3. LORAN electric and magnetic signal strength under elevated railroad in the Bronx as measured on HP89410A Vector Signal Analyzer. Electric field antenna is 18" JET whip while magnetic field antenna is loop provided by Megapulse.

particular satellite or LORAN station or to make a binary decision of LORAN availability based on measured SNR from the HP89410A Vector Signal Analyzer. Then using the known azimuths and elevations of the satellites or the azimuths of the LORAN stations, the PDOP's are calculated for a number of fix categories and compared to a threshold of 6. Table 1 summarizes these fix categories. Integrated GPS/LORAN fixes assume a fully integrated receiver (not implemented in this experiment) where the offset between LORAN and GPS time plus any bias due to front end, etc. has been determined and stored when redundant information was available and a LORAN TOA can be considered equivalent to a GPS pseudorange. The categories, assuming a precise clock is used, make a similar assumption; namely, any clock bias has been determined in an open area with redundant signals and stored.

Figure 3 shows a typical HP89410A display under the elevated train in the Bronx. This is also typical of much of the data in the Wall St. scenario. The LORAN electric field signal is below the limits of the instrumentation, while the magnetic field is attenuated 11 dB relative to nominal but still very much detectable. The instrument vector averages with an exponential time constant of 60 PCI's or 12 seconds. The LORAN and noise are measured in a 15.6 kHz bandwidth. The instrument program reads the peak LORAN amplitude for Seneca, Nantucket, and Carolina Beach and reads and adds the noise power in 40 bins in a quiet part of the PCI. After noting the LOCUS receiver was unable to successfully track the E-field signal in the Wall St. scenario, the HP89410A program was modified to record the phase at the time of the peak amplitude of the pulse.

w/o precise clock		w/ precise clock	
3D GPS	(4G)	3D GPS	(3G)#
2D GPS	(3G)	2D GPS	(2G)#
LORAN	(3L)	LORAN	(2L)
3D LORAN/GPS	(4C)#	3D LORAN/GPS	(3C)#
2D LORAN GPS	(3C)#	2D LORAN/GPS	(2C)#

G = Number of GPS signals, L = LORAN,
C = Combined (With acceptable geometry)
#Post Processing only

Table 1. Categories of Fix availability

Figure 4 compares the attenuation of the E and H field signals relative to open area values for Seneca in the Wall St. scenario. Noted from Figure 3, that after about 40 dB of attenuation, the signal is undetectable and the actual attenuation of the E-field may be more than shown in Figure 4. To determine if a typical receiver could track the signal, the measured SNR is compared to a threshold and a binary decision made. After correcting for the cumulative affects of vector averaging, adding 40 noise bins, measuring peak vice amplitude at the standard sampling point, and measuring signal and noise in 15.6 vice 30 kHz NEBW, a threshold of -4 dB SNR was chosen. This corresponds to --12 dB defined in the conventional way [5].

It should be emphasized that the number of satellites tracked may not say much about fix availability. Explicit calculations of fix geometry are essential because the nature of the urban environment is to frequently allow only high altitude satellites and/or those from a single direction to be used. Figures 5 shows an example of this in the Bronx. Even though the receiver is tracking five GPS satellites, because the satellites tracked are clustered either overhead

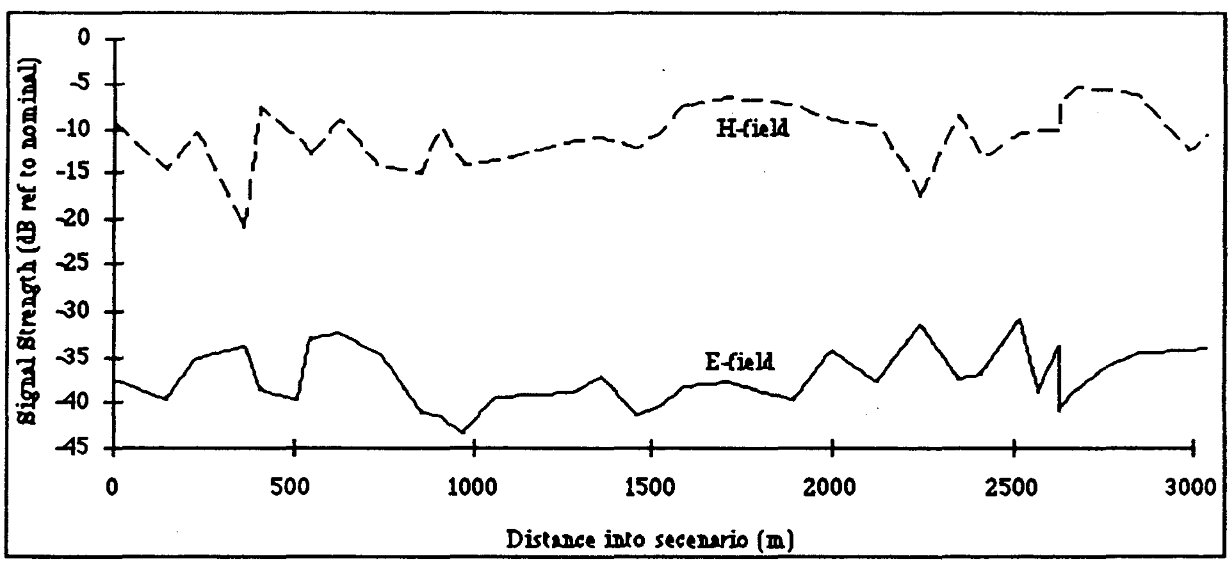

Figure 4. Signal Strength of Seneca for Wall St. Scenario referenced to nominal signal strength in the clear.

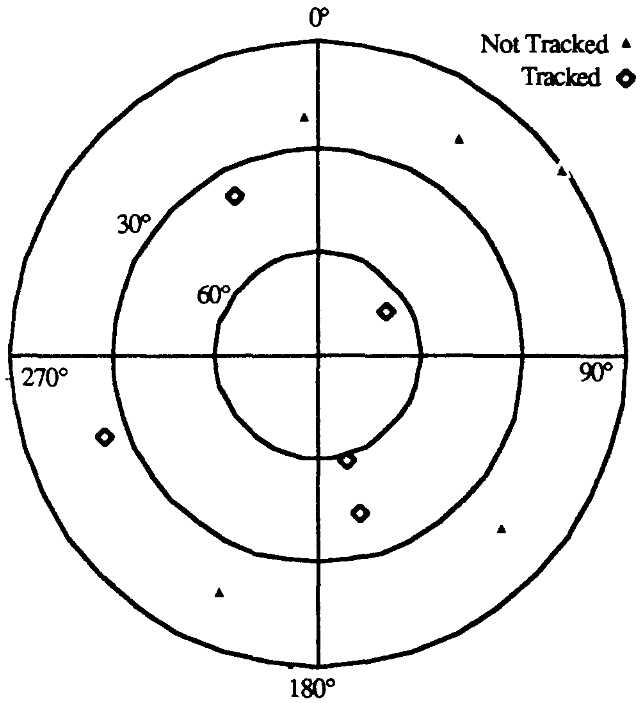

Figure 5. Example of poor GPS fix geometry in Bronx.

or to the west, the PDOP is poor (i.e. 8.1).

To determine the percentage fix availability of the various categories in Table 1, the information on the azimuth and elevation of each tracked satellite and LORAN signal is used to calculate the PDOP for each category. Figure 6 shows these availabilities as a function of time for a Wall St. scenario. The integrated receiver availabilities are based on LOCUS data and the E- and H-field are based on the SNR threshold of HP89410A data. Figure 7 illustrates comparable data obtained in the foliage scenario with availabilities based on percentage of distance into scenario opposed to time as in Figure 6. In the foliage case, there was not the same significant advantage of an H-field antenna over an E-field antenna. For many more plots such as Figures 6 and 7 and for all scenarios, the reader is referred to [4].

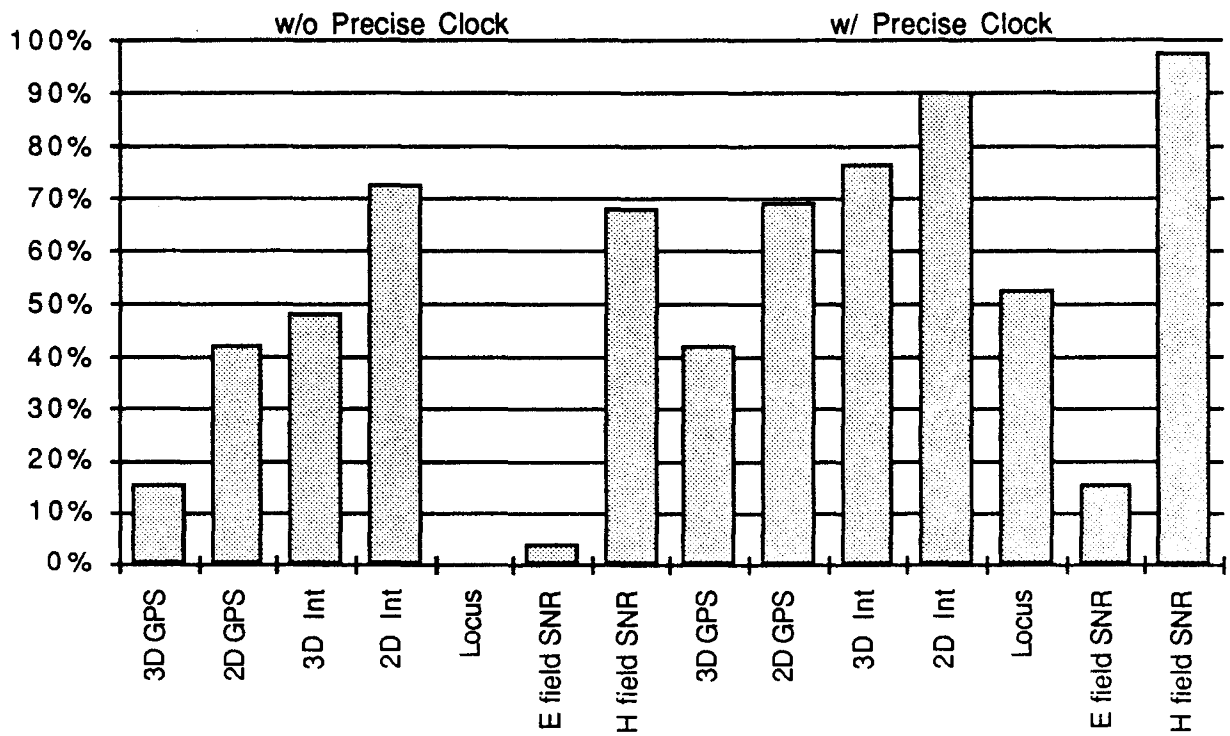

Figure 6. Comparison of Fix Availability, Wall Street Scenario, July 28, 1994

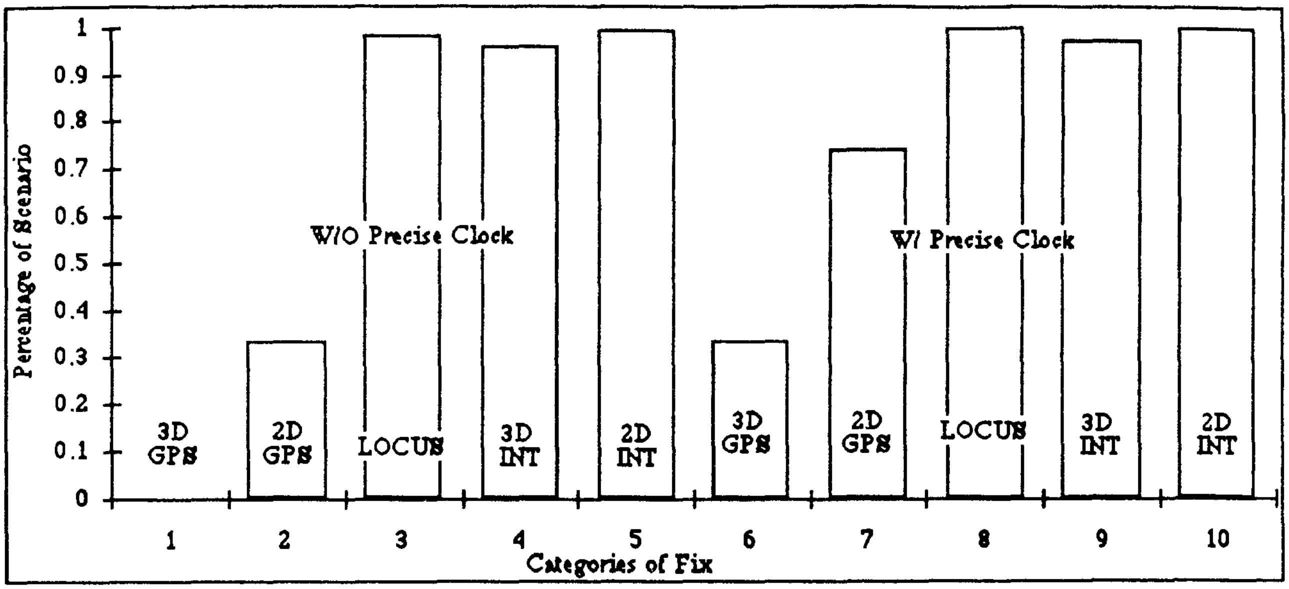

Figure 7. Fix Availability as Percentage of Distance into Scenario, Foliage Run 1. GPS receiver is 12-Channel in all cases.

The second part of the analysis attempts to determine the potential accuracy of LORAN in the New York City environment. The LOCUS receiver was modified to use a Cesium frequency reference and to calculate a fix based on two TOA's when only two signals were available. Even though, as shown in Figure 6, the LOCUS receiver indicated it was tracking two stations (Seneca and Nantucket) 53% of the time for the 28 July, Wall St. scenario, based on our HP89410A measurements of the LORAN E-field signal, and on the large fix error in even those not flagged, it is not clear what it was tracking. Figure 8 shows the results of measuring phase of the H-field using the HP89410A. We consider this data the most significant obtained. The measurement is sub-optimum as only one of sixteen pulses per PCI is used, a loss of 12 dB in SNR, yet the phase is quite repeatable from scenario to scenario.

This indicates that the H-field LORAN signal is usable in the deepest urban canyons. No attempt was made to select the appropriate zero crossing (i.e. resolve 10 µsec. ambiguity in TOA). Future efforts will focus on that issue and on the solution of position when such large phase shifts are present. It is unclear whether the large, repeatable phase shifts are actually in the RF, or due to (repeatable) shifts in the magnetic heading sensor/analog switches in the Megapulse loop antenna system.

Summary

Based on our preliminary analysis of the extensive radionavigation data collected in New York City during the period 26 July-7 August 1994, we make the following conclusions: 1. The LORAN E-field signal in the deep urban canyons is virtually unusable, the H-field signal is relatively much stronger and has repeatable phase. 2. The availability of LORAN H-field in the urban canyons and either LORAN E- or H-field under foliage is better than GPS. 3. In many areas and particularly Wall St., only Seneca and Nantucket, but not Carolina Beach can be received, so fix availability is considerably enhanced by the addition of a precise frequency reference enabling fixes from two TOA's. 4. The addition of this frequency reference to GPS and the integration of LORAN and GPS also enhance fix availability. 5. A twelve channel all-in-view GPS receiver performs significantly better than a six channel receiver.

Acknowledgements

This project was sponsored by the Advanced Research Projects Agency under project CO74. The cooperation of the companies mention in this report is greatly appreciated. The hard work and long hours of Mr. Lance Miller of SAIC, and LT Steve Bartlett, presently in graduate school at North Carolina State University were sincerely appreciated. In addition, without the generous support of the Ferryboat Maintenance Facility at the Coast Guard Base on Governors Island, completion of this effort would have been impossible.

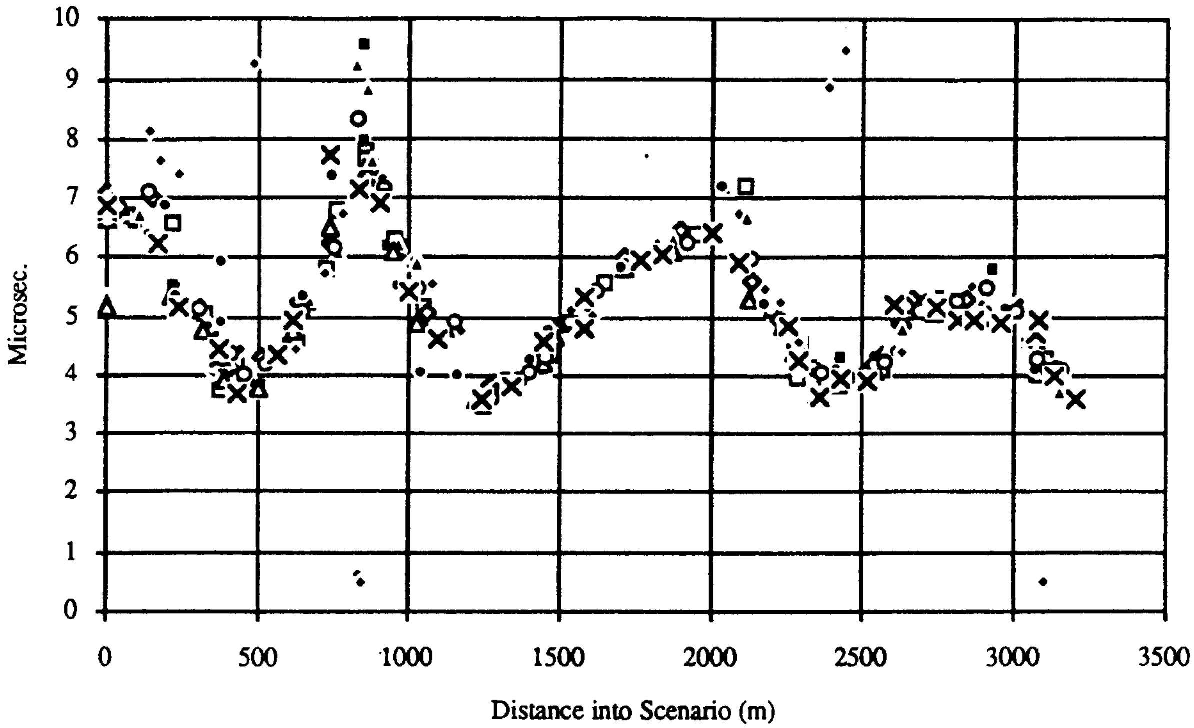

Figure 8. Phase Shift Relative to Ground Truth for Seneca.HP89410A, H-Field Antenna over nine Wall Street Scenarios

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Dynamics of Loran-C Skywaves

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Abstract:

In the course of testing LOCUS' Linear Averaging Digital (LAD)-LORAN receiver and other receivers, we have observed that a number of receivers use extremely long ECD averaging times. At 0dB S/N, these times are often several hours, compared with the 60 seconds or so used by the LAD-LORAN receiver. To find out why times vary so much, we collected waveform and ECD data at LOCUS' facility in Madison, Wisconsin. Resulting data show Loran skywaves vary in amplitude and phase on many time scales. This instability is most troublesome during the hours around sunrise, but nearly instantaneous dropouts of the skywave can happen any time at night. Skywave instability also adds to the interference which receivers suffer from crossrate signals, specifically receivers capable of processing from only one or a few chains simultaneously. Data demonstrate correct cycle tracking requires compensation for the ECD anomalies which are caused by these skywaves, and the LAD-LORAN receiver provides the necessary compensation. It is likely receivers based on other technologies must average the ECD for hours so the anomalies will not cause cycle slips.

We begin with data for received signal strength and waveform peak for the 8970 secondaries taken over the course of a typical night. The data are taken in a standardized way using a LOCUS LAD-LORAN receiver. Points are taken at 60 second intervals. TD averaging is set for 60 seconds with a simple first order filter. ECD averaging is approximately 60 seconds at 0dB indicated S/N, and doubles with each 3dB loss of S/N. For S/N better than 0dB, a soft floor of approximately 20 seconds is ultimately reached. Nominal field strength (ground wave) and peak field strength are plotted in dBuV/M, but they include an indefinite antenna factor resulting from roof mounting of the E-field antenna. They are plotted as an indication of the skywave size; when there is no skywave, the peak value is approximately 6dB larger than the nominal value.

The data in Figure 1 make it clear that Madison is well situated near a service area. Provided that M, X, and Y are on the air and the receiving antenna is well located, there are no tracking problems during a typical night. The geometrical triad is not too large; Y is 732KM away, and X is 1022KM away.

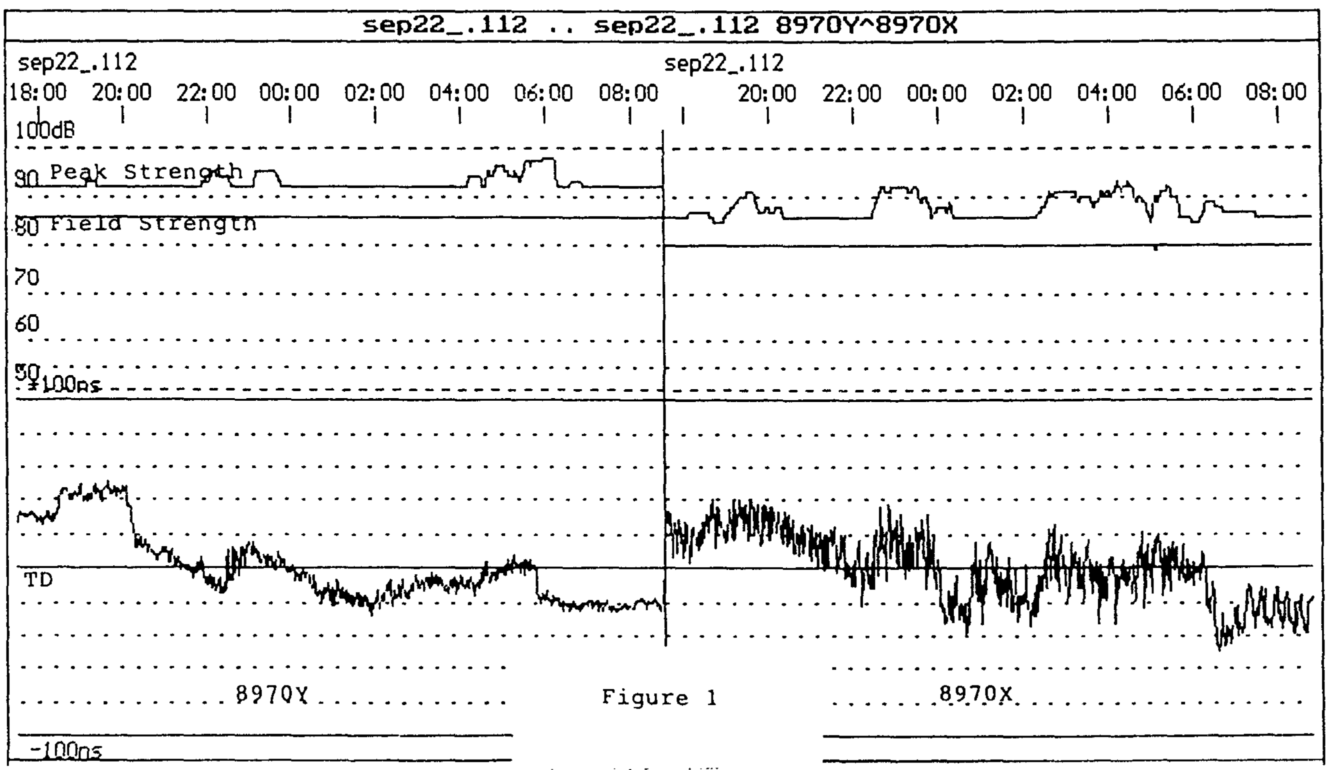

Figure 1

The X track is showing a considerable amount of 20nS oscillation arising at the transmitter[1], so its apparent noise level is misleadingly high.

To produce a high quality receiver, we must model and account for real world operation at a distance over the oceans, in fringe areas, and at high latitudes. In these circumstances, ground conductivity is poor and skywave reflections come earlier than they do under the favorable conditions of the American midwest. Accordingly, we must also look at data from more distant stations and see to it that the LOCUS LAD-LORAN receiver will track it correctly. Figure 2 shows the slightly more distant stations 8970 W and Z:

The data from Figure 2 show a sunrise disturbance for W which is about three times the size of that for Z. This is interesting, considering that the distances to the stations are virtually identical, at 1396KM and 1372KM respectively, and the power ratings are identical at 800KW. Clearly, we can't predict the degree of disturbance and instability by looking at distance and power alone.

They also show that although the skywave amplitudes are roughly comparable, the W skywave shows a very sharp, sudden dropout shortly after midnight (circled in Figure 2, 8970W). No similar event occurred on Z at the same time. Clearly, skywaves from stations at similar distance are not always correlated. It will not suffice to apply a skywave correction which is a simple function of distance.

[1] *"Loran Transmitter TD Instability"*, P.Schick and T. Blandino, The Goose Gazette, Winter 1994.

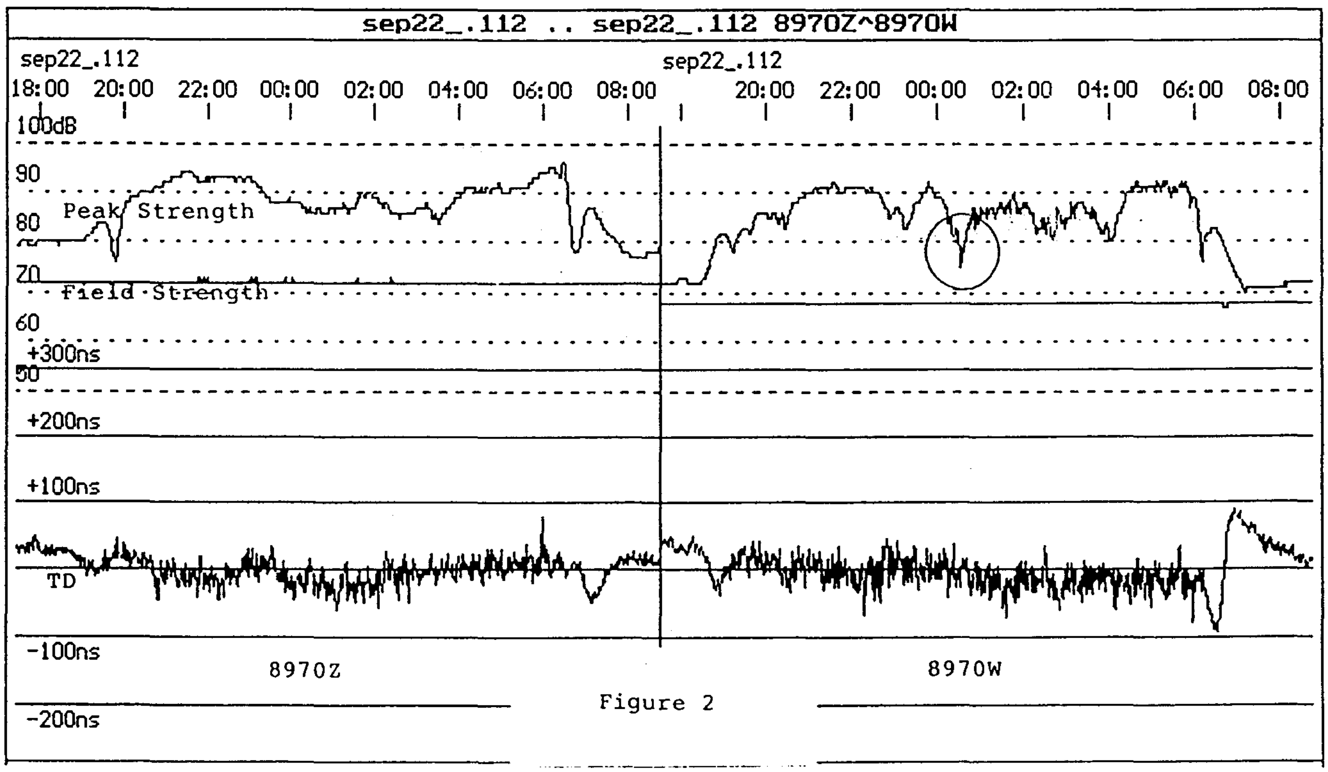

Figure 2

Finally, to complete the picture, we look at two very distant stations. Figure 3 shows 9960W, a 350KW station at a distance of 1732KM, and 7980X, a 400KW station 1995KM away.

In Figure 3, we observe something very peculiar. Because 9960W is significantly closer, we expect it to show a signal level about 4dB larger than that for 7980X. Instead, its ground wave is virtually missing, 8dB smaller than 7980X and 12dB smaller than what we expected, so that the TD trace is quite noisy. In addition, the ratio of sky wave to this weak ground wave resembles ratios reported anecdotally for high latitudes.

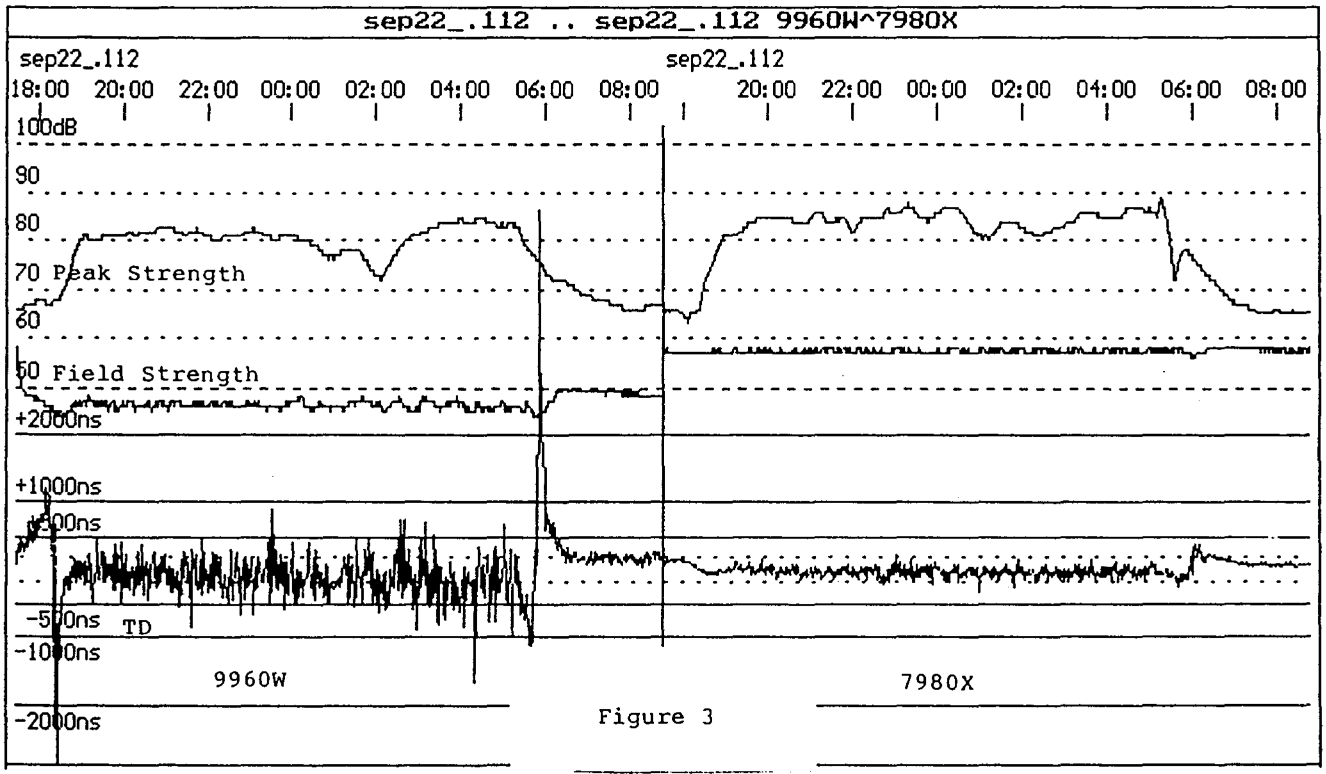

Figure 3

We turn now to ECD measurements. Figure 4 shows an ECD track for 8970W, as measured by two LAD-LORAN receivers:

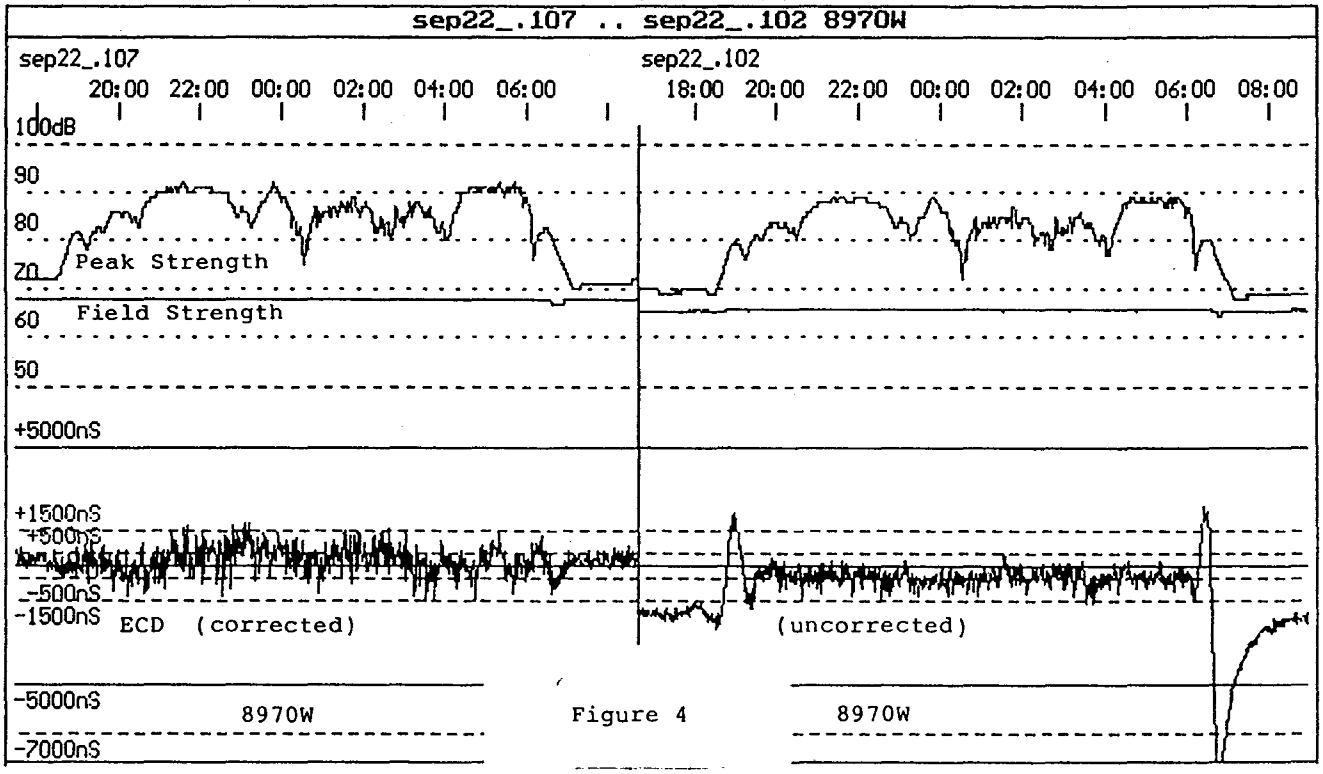

Figure 4

The left-hand version shows a track corrected for skywave effects. The right-hand version shows an uncorrected track designed to approximate the effect of using the industry standard add-and-delay circuit. Note that most receivers which actually use that circuit will show between 50% and 100% more ECD variation than is on LAD-LORAN's trace. This extra variation occurs because their bandpass filters are usually much narrower than the one in the LOCUS receiver.

There is a cost of correcting for skywave effects; one must either determine what the skywaves are and subtract them out, or else do something which has much the same mathematical effect. In this case, short term noise increases by about 6dB, and at night, there is somewhat more of the slow wobble. On the other hand, the value in the quiet right-hand trace isn't suitable for tracking, because it goes out of bounds for 40 minutes around sunrise. Nor is it suitable for ECD measurement, because the nighttime mean is two microseconds more negative than the daytime mean, due to the daytime skywave. In short, the uncorrected value is like more than a few numbers encountered in financial reports: reproducible, consistent, precise in some sense, and useless.

We now need to ask what it is that can render an uncorrected receiver useless for a period of time in this way. Previous efforts[2] have been made to collect waveform data and fit skywave models to it. LOCUS' LAD-LORAN receiver can be set to periodically dump waveform information from a station. Such a data run for 8970W is illustrated by the sequence in Figure 5, which begins just before sunset, 17:15 (local time).

[2] *"Loran and the Effects of Terrestrial Propagation"*, Capt B. Peterson and Cadet K. Dewalt, U.S. Coast Guard Academy, May 1992.

Around sunrise, the rapidity of the variation of the waveform can't be overstated; the 0447 and 0449 (local time) waveforms deserve special attention. In addition, the pulse shows very severe distortion at 0544, and this distortion begins so early that the ground wave is visibly affected at the 30uS point (also see Expanded Detail). The ECD of this pulse is essentially unmeasurable by the traditional approaches. The amplitudes of the peaks of half cycles immediately surrounding the waveform reference point are corrupted. One remedy is to measure ECD earlier in the waveform; however, the noise goes up approximately with the cube of the degree of earliness, and the loose published tolerances for transmission of the first cycle come progressively into play. The traditional value of 30uS or so (in the USA) is really about as short as one can go.

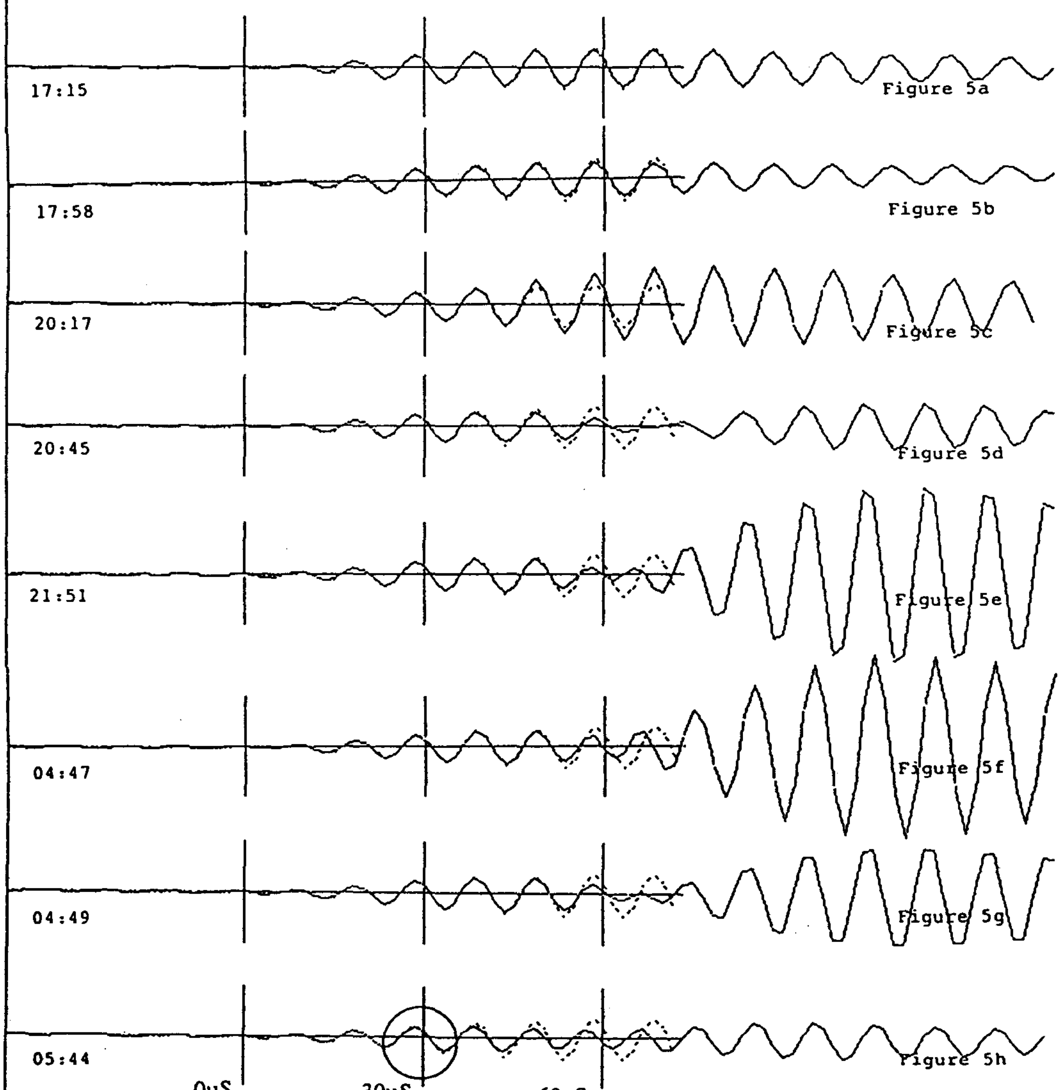

Figure 5
Waveforms During the Course of a Run

Figure 5h - Expanded detail at 30 uS.
Reference time 05:44.

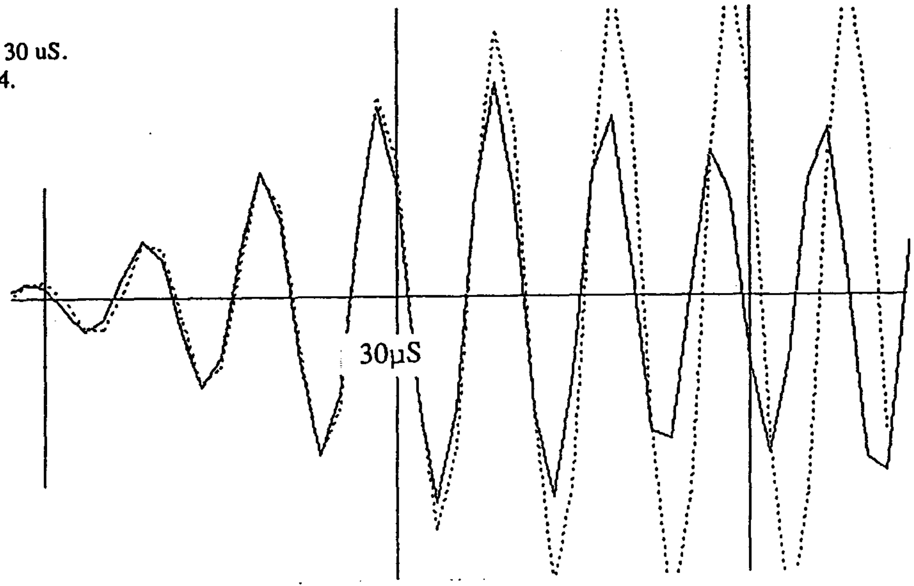

Figure 6 shows the events beginning at 0448 in more detail. Successive waveforms in the figure are approximately 35 seconds apart.

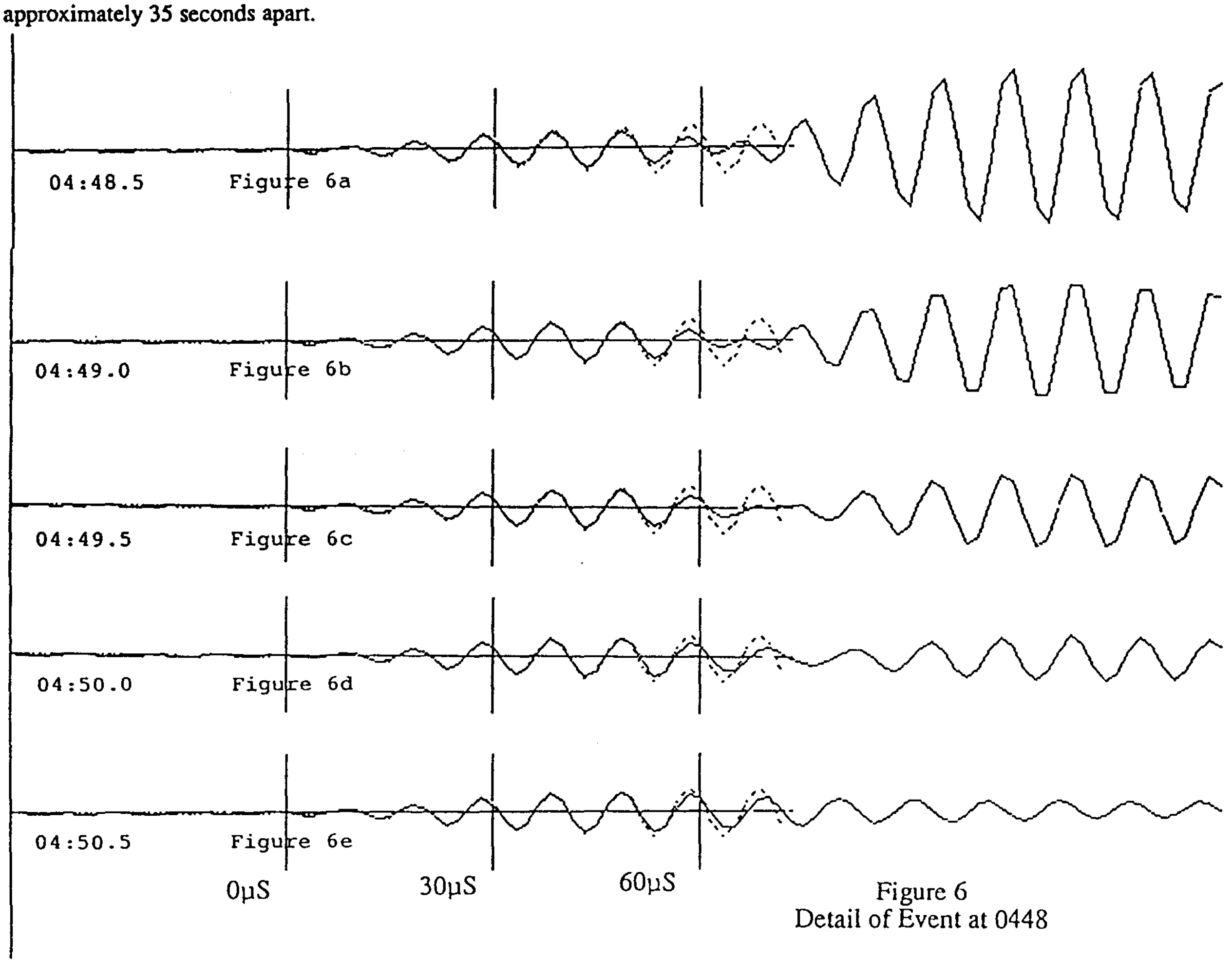

Figure 6
Detail of Event at 0448

At the greater distance of 7980X, the results are more interesting. Figure 7 shows similar data for that station, 1995KM away:

The successive figures show the skywave sliding away, a process which begins more slowly and then speeds up. The state which is reached before solar absorption sets in shows a severely distorted waveform (7f).

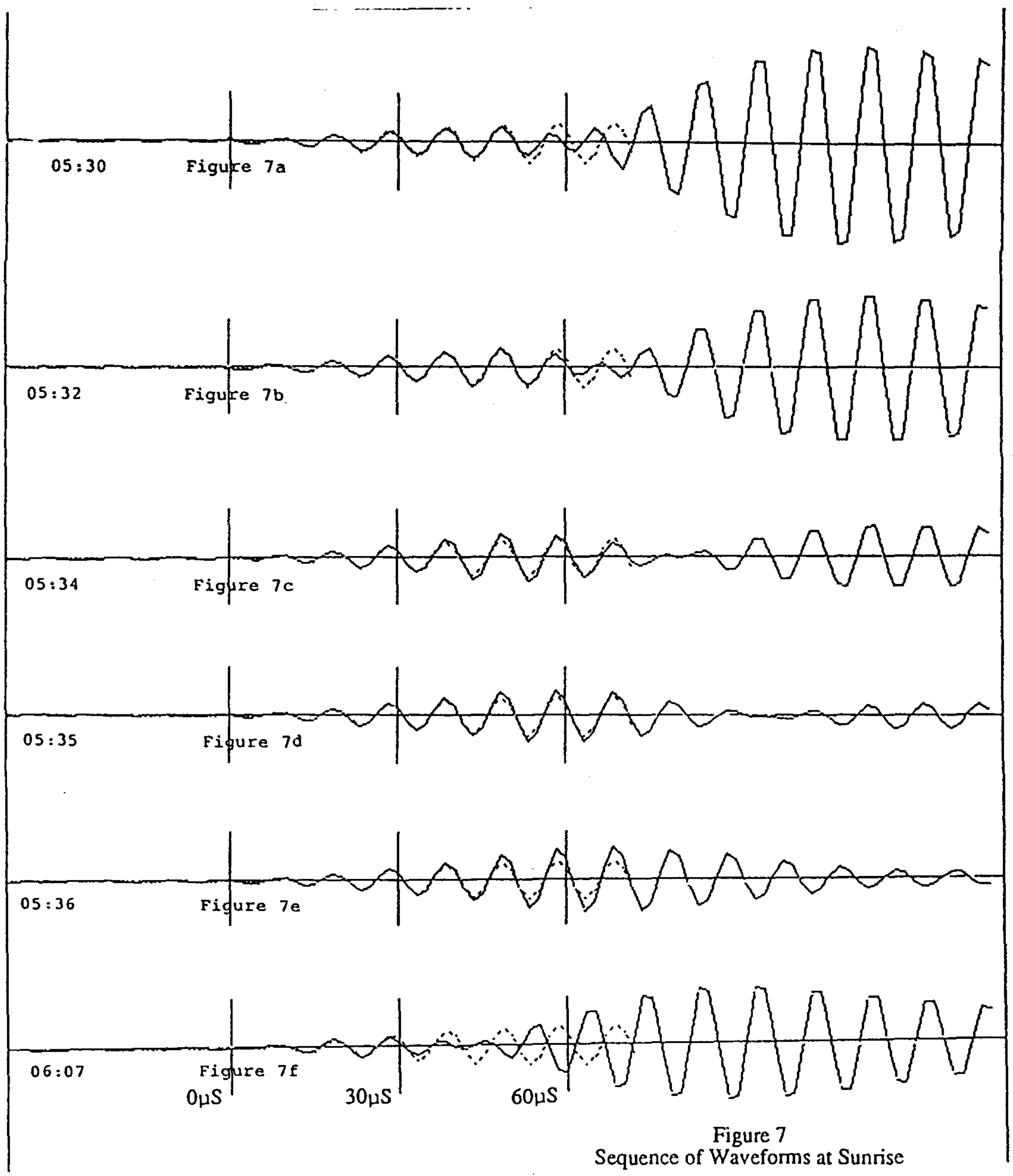

Figure 7
Sequence of Waveforms at Sunrise

For nearby stations at Madison's latitude, and during "typical" times at a good site, the skywaves are less severe and they originate further away from the groundwaves. The waveshape tends to change more slowly and less severely. Nonetheless, the data in Figure 8 show that high-speed changes in skywave phase and shape are possible at such times:

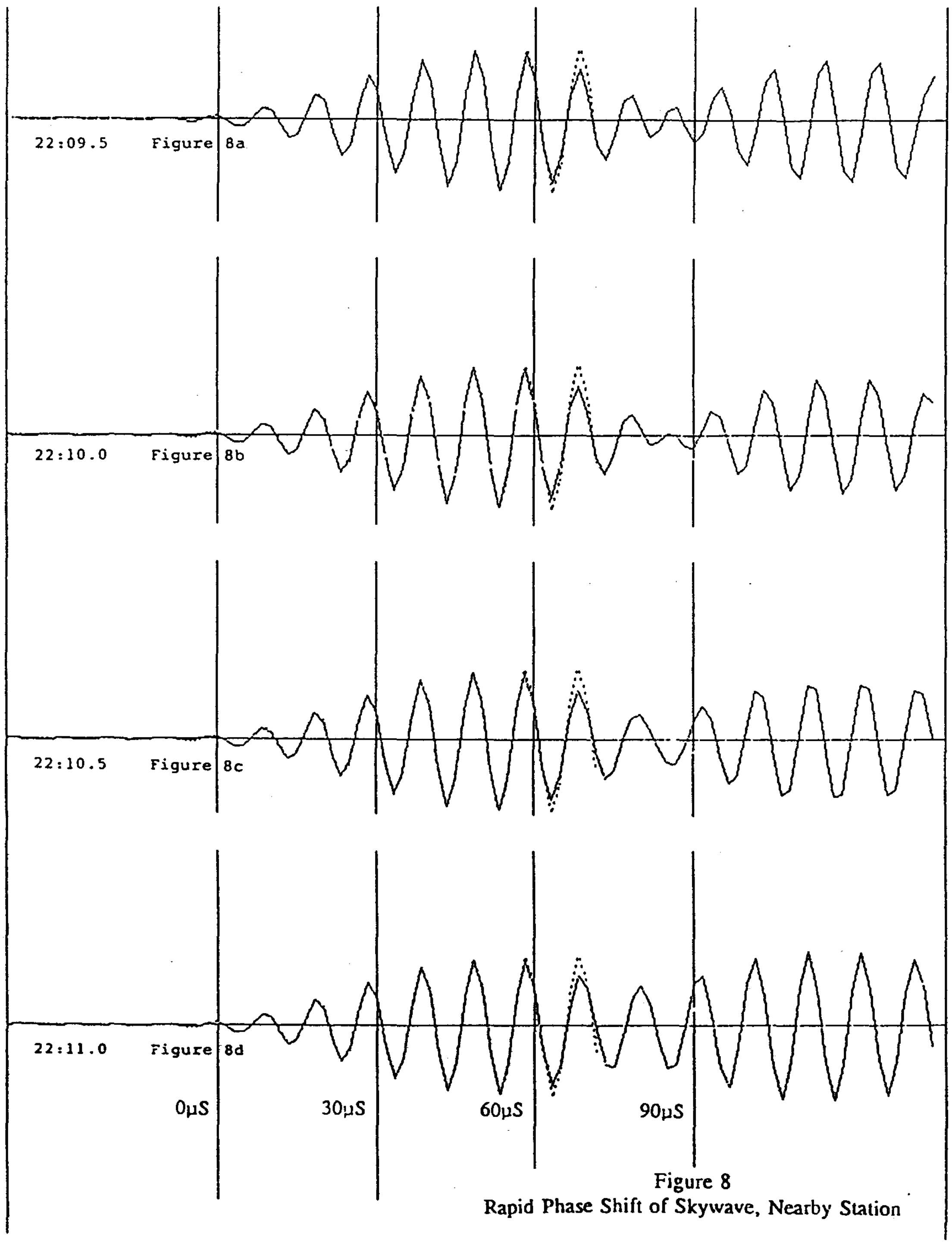

Figure 8
Rapid Phase Shift of Skywave, Nearby Station

However, during rainy weather when the cold front attached to a very large upper air storm was passing through, the skywave amplitude was quite noisy and unstable for a period of several hours. A set of four waveforms taken 48 hours later during the same run shows one of the larger changes, where the skywave amplitude nearly doubled in 100 seconds.

This sort of behavior seems to suggest that tropospheric weather has some effect on the skywave reflections. It is also possible that the data coincide with a geomagnetic disturbance.

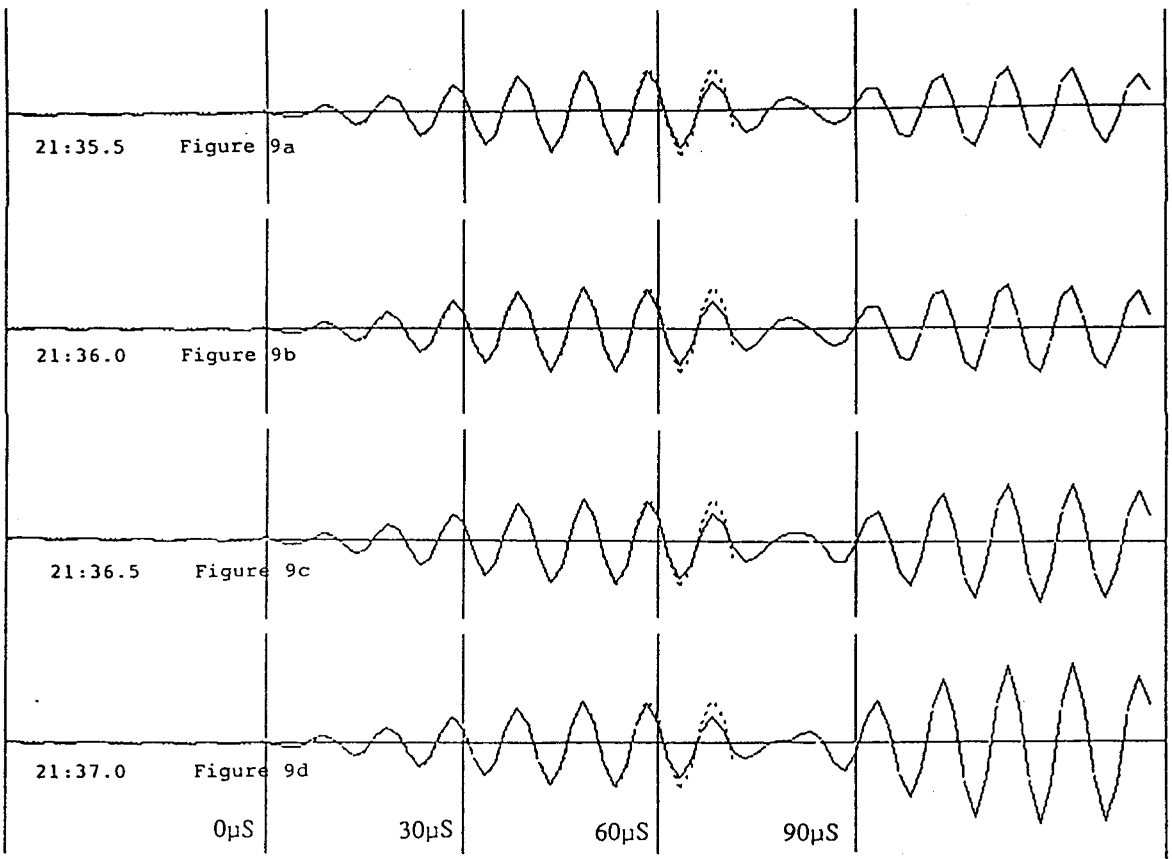

Figure 9
Rapid Change in Waveform from Nearby Station

Summary

In summary, skywaves are not always a slowly varying phenomenon. The ECD distortion caused by the skywaves will be unstable on a variety of time scales. While averaging helps at the short time scales, it becomes less helpful at the longer ones, and the practical result is that if no correction for skywave distortion is made, ECD averaging and cycle correction must be made so slow as to be nearly useless under conditions which are often encountered in practice.

While an uncorrected receiver can be made to work at some places and some times, it will usually be necessary to employ some skywave correction at twilight and during the night, and in fringe areas. LOCUS' LAD-LORAN receiver accomplishes the corrections by abandoning the traditional add-and-delay circuitry and performing the ECD computation with proprietary digital signal processing techniques, thus extending its tracking range 400KM or more beyond what is traditionally considered possible.

The N.E.L.S Network
(Northwest European LORAN C System)

Presented at the meeting OCEANS 94 (Brest - FRANCE)

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DÇN Brest (DGA)
Brest, FRANCE

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CAP GEMINI SOGETI
Brest, FRANCE

ABSTRACT

In order to put an end to the rumours of giving up of the LORAN C, this document, after a recall of the main characteristics of that radio-navigation system, shows the architecture of the new European NELS network, the policy of taking in charge of LORAN networks by the European states and the European Union, and also the extension and new utilization prospects, particularly in time/frequency scope.

The N.E.LS. Network (Northwest European Loran C System)

1. Introduction

At the present time, a large number of people know the radio-navigation system GPS (Global Positioning System). The Gulf War made it partly famous. Everywhere in the world, its user will be able to know easily his position, his vertical elevation and, in some cases, the time.
But, look out! The GPS is entirely under the authority of the american military. So, at any time, the non-aware user can be decoyed about his real position. This is the reason why it is advisable not to have a complete reliance in only GPS system.
So, a second system of navigation assistance is available in many areas of the northern hemisphere : the LORAN C. Many of you probably think that this system is going to disappear shortly because of the notice which came out in the Federal Radio-Navigation Plan (FRP) . As a matter of fact, all the LORAN chains located out of the american territory will not be operated any more by the United States Coast Guards after December 31st 1994.
In order to keep further means to GPS, absolutely necessary for the safety of the navigation, some countries decided to join in operating, modernizing end extending the networks given up by the USCG.
After the recall of LORAN characteristics, we will treat of:
- the future networks to be set up in europe.
- the utilization prospects of LORAN wave.
- the position of LORAN in the European Union policy.

2. General characteristics of LORAN

LORAN C is a low frequency radio navigation system (LOng RAnge Navigation). The carrier frequency is : 100 kHz.

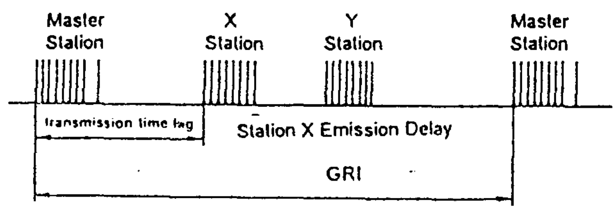
This is a land-based system organized into chains Each chain usually comprises a master transmission station and 2 to 4 secondary stations.

The user of this system can. with an appropriate receiver, obtain his position on the Earth. The operating modes can differ depending on whether the receiver uses the signals from 2 transmitters (circular mode still called "rho-rho-mode" or 3 transmitters in the same chain (normal hyperbolic mode) or 4 transmitters in 2 different chains (cross-rate hyperbolic mode) to calculate its position.

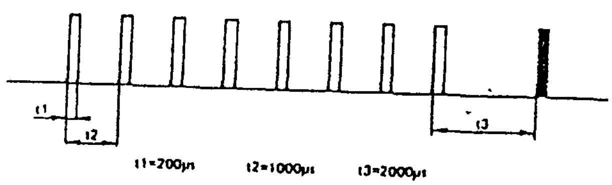
The rho-rho mode implies that the user must be in possession of a time reference linked with the time reference used by LORAN network.

2.1 LORAN C SIGNALS

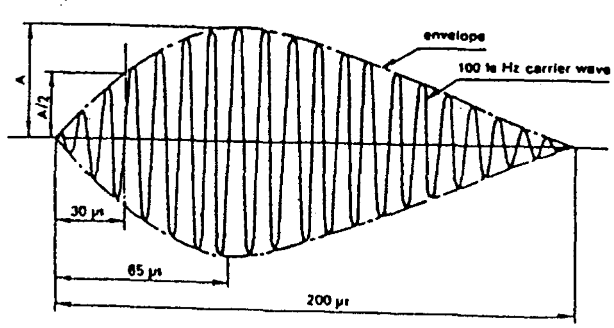
The LORAN C signals transmitted comply with a basic specification drafted by the USCG : M 16542- 4 July 1981



Sequencing



Pulse group



LORAN C pulse

. Carrier frequency : 100 kHz

. Pulsed signals
  . master station : 9 pulses
  . secondary stations : 8 pulses

. Pulse form such that 99 % of the energy is within the band : 90 to 100 kHz.

. Chain recognition : GRI (Group Repetition Interval).

. Phase Code : this is the sign of the first half-waye of the LORAN C signal. This code also allows recognition of a master station from a secondary station

The blink is a continuous warning system for users when the signal transmitted by a station is not absolutely safe for navigation. It consists in blinking either the 9th pulse of a master station, or the first two a secondary station.

. **Range** : this depends on the power of the transmitter and the sensitivity of the receiver. For a 250 kW transmitter, it is about 1000 NM for -10dB reception at sea.

2.2 SYNCHRONIZATION

Synchronization of a LORAN C chain follows two principles :

The **SAM** mode (System Area monitor). This mode allows synchronization of the secondary stations with the master stations. An SAM station located in a triad allows measurement and checking of the hyperbolae intersection point in relation to the reference point. As a general rule, this mode is manual. It is today used in most chains around the world.

The **TOE Control mode** (time of emission control) : this mode is used to control the time of emission from the stations in relation to the master station and in relation to a reference time. This control is therefore per station and per chain, in order to maintain the EDs (emission delays) constant for the given chain. The French chain is synchronized on this principle, as will be the case; from 1995, for the Northern Europe chain and for european Chain to come.

2.3 the LORAN in Europe

In 1987, six european countries, Denmark, France, Germany, Ireland, Netherlands and Norway decided to design and operate a radio-navigation system: the LORAN C.
By modernizing the four existing transmitters (Denmark, Germany, Norway), by creating three new ones (Ireland, Norway) and adding the two transmitters located in France, it became possible to ensure the sea coverage of a large part of northern Atlantic ocean, from the portuguese coasts to the Norway sea. (see figure).
On the 6th august 1992, at Oslo, the six governments above-mentionned created the " Europe of radio-navigation " with LORAN, even before the Maastricht treaty was ratified.

2.4 The NELS network (Northwest European Loran C System.)

a) Characteristics
- 9 transmission stations distributed in four chains . See figure 1.
- Availability: 99.9% for one station by periods of one month.
- Notice. The figure 1 gives NELS coverage in hyperbolic mode, with a location accuracy better than a quarter of mille.
- Synchronizing : time of emission control (TOE), UTC(B) time reference (Universal Time Reference coordonnated to Brest). Synchronizing of transmission times of the station in relation to UCT(B), better than 100 ns.
- Setting up : a control center located in Brest, ensure NELS control 24 hours a day. All operations are executed from the control center by way of public network using the X25 procedure.
- Maintenance: the maintenance of the net is ensured by DCN Brest.

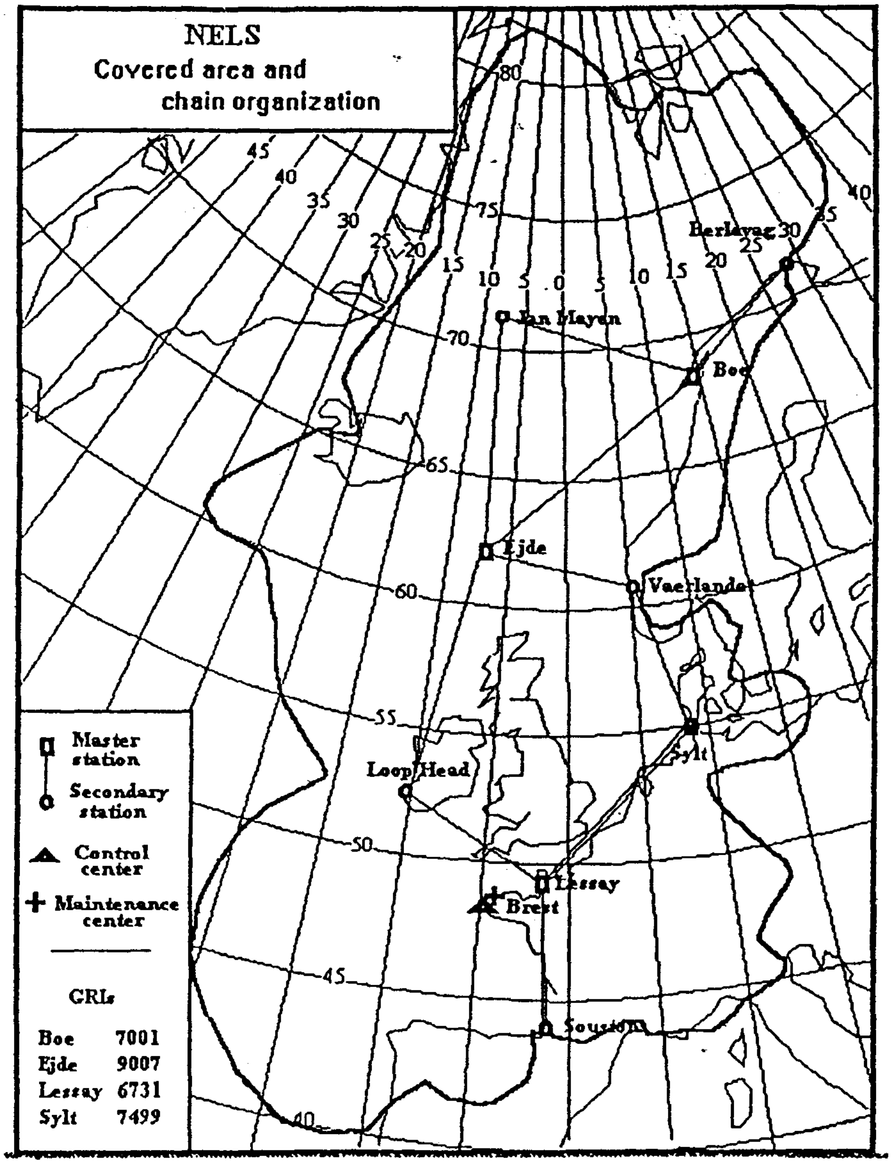


Figure 1 - Coverage of the NELS

b) Extension prospects.

Many extensions studies of LORAN are in progress.
* coverage of Baltic sea by connection of the european network with its russian equivalent, named CHAYKA. Germany is the leader country for that operation.
* Coverage of Mediterranean sea . In 1995, resumption of exploitation of the existing stations. An extension with CHAYKA stations is being designed in order to enable a better coverage of Adriatic and Black seas. Italy is the leader country for that operation with the assistance of the European Union.

* Coverage of the Iberian area to the Azores and Canary islands. France is the leader country for that operation.(See figure 2).

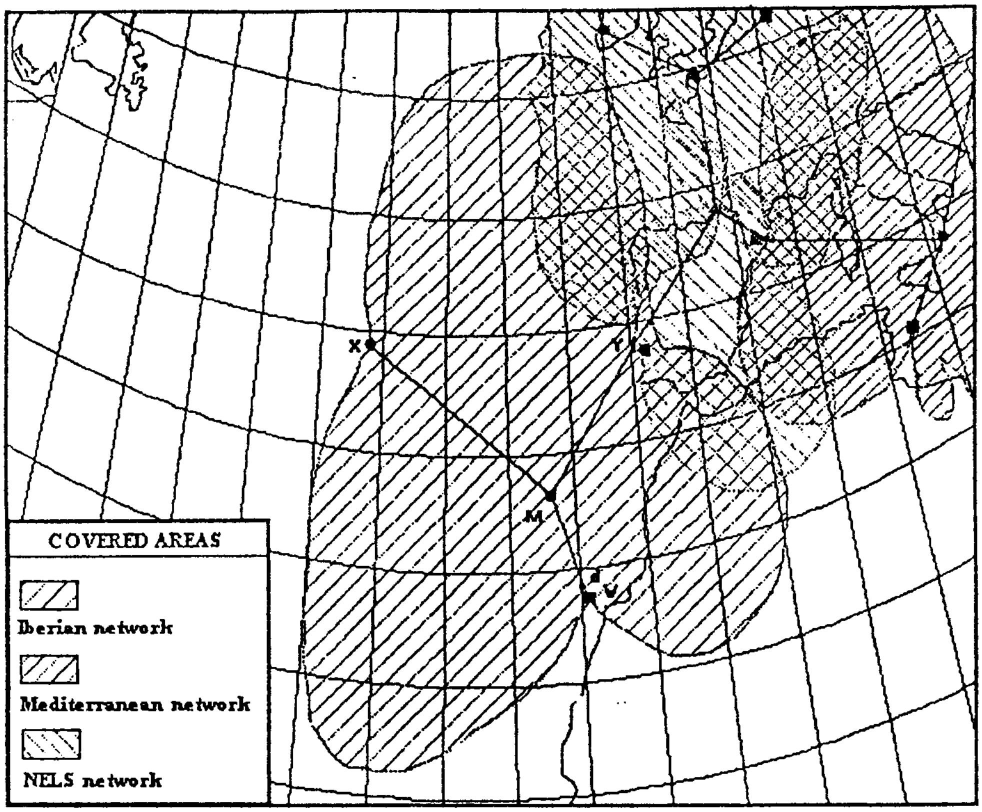


Figure 2 - Iberian Network

c) Using prospects.

In addition to its use as navigation assistance at sea, the LORAN C will be used for air navigation (as nowadays in USA), and for control of land and waterway traffic (some designs already exist).
The LORAN can also give to a still user some time information which, in spite of its restricted accuracy by the variations of the signal propagation speed, can be as accurate as those of the GPS.
Figure 3 shows the variations by observation during 2 years between Paris and the station of Lessay. For time/frequence users only having GPS in C/A code, the LORAN can improve the safety of the time/frequence information.
A new generation of time/frequence users using both GPS/LORAN should even use the respective advantages of both systems.

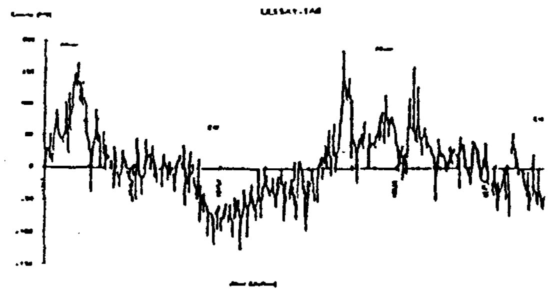


Figure 3 - Observation of seasonal ASF variations between LESSAY and PARIS (deviation less than 100 ns)

The land coverage rea of LORAN C is interesting. Western Europe is in effect fully covered and could be extended North-East by linking up with the CHAYKA network (the Russian equivalent of LORAN C). Thus LORAN C can offer any user the same information as and GPS. (location accuracy, time Frequency accuracy).

LORAN C should not be presented as an alternative to GPS; and the two means should complement each other. There is no doubt that dual capacity receivers will soon be marketed, offering the user improved or even total integrity.

While LORAN C is hard to deceive, the same is not true of GPS, as was intended by the United States. LORAN C is jammable (at atmospheric noise level), while GPS is less so. LORAN C is sensitive to reception conditions (mountains, forests, etc.) while GPS requires direct view between satellites and receivers. By stting up the European network, LORAN C will be under the control of the European countries.

In the Time/Frequency field, LORAN C can be used to good advantage by the scientific community, but also by all those (including the military) who need a precise time reference of a few hundred nanoseconds.

3. The place of LORAN in the European Union policy

In December 1993, the Brussels Committee approved new rules about Trans European Transport network. The Council and Parliament of the European Union should ratify those rules before the end of 1994. All the means of transport are concerned (air, sea, land and waterway). Particulary, every ship entering the territorial waters of the European Union, will have to give its position in real time.
Two location systems will be officially authorized:
- a satellite system (GPS+GLONASS)
- a land system (LORAN C+CHAYKA)

After ratification, the rules vill come into effect in 1998.

4. Conclusion

In spite of the giving up by the USCG of LORAN chains located outside the territory of the United States, the LORAN C is not disappearing. As a matter of fact:
- the whole territory of the United States is, at present, fit out with a LORAN C coverage, and the FAA (Federal Aviation Agency) has just approved the LORAN as an accurate approach system.
- some other nets in the world are now under modernizing, extending, and even in creation :

- Connection USA/Russia;
- Connection Russia/China/Japan/Korea;
- NELS network;
- Mediterranean network;
- Iberian network;

In Europe, the LORAN must be considered as a system in addition to GPS, in order to improve the safety for users. As, at the present time, for its maritime applications, the LORAN should know an enlargement of its applications in locating (air, land and waterways) and time/frequence applications with the impulse of the European Union and thanks to the political will of the concerned countries.

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MODIFICATION OF 350 FEET HIGH "DECCA" AERIAL MAST FOR USING IN LORAN-C TRANSMISSION SYSTEM

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ABSTRACT :

Indian West Cost Decca Chain (7 B) was established in 1959-60 and had aerial mast of 350 ft. with umbrella arms and guys with insulators. During the phasing out of Decca System to Loran-C in 1992, they were retained as transmitting antenna. The structures were offering 3000 pf capacitance which was less then the desired value of 5000 pf. While commissioning Loran-C transmitting system, these structures were tuned to transmission frequency of 100 KHz by adding additional inductance in series with antenna tuning coil. The peak aerial current was found to be 135 Amps. By implementing the modification, the current achieved was 165 Amps.

INTRODUCTION :

Indian LORAN-C West Coast Chain (GRI 6042) comprises the following transmitting stations.

1.	DHRANGADHRA MASTER STATION	LAT.23°00'14" N LONG.71°31'39"E
2.	VERAVAL - SECONDARY-X	LAT. 20°57'07" N LONG.70°20°13" E
3.	BILLIMORA SECONDARY-Y	LAT. 20°45'40" N LONG 73°02'17" E

These stations were commissioned during the first quarter of 1992 as replacement of "Decca Navigator Chain Stations". As these sites were having "Decca Aerial Mast" of 350 Ft.high (with Umbrella arms and aerial/ dressing wires) in good condition, utilisation of these aerial masts, without any modification, was attempted.

These masts were offering capacitance of about 3000 pf, which was less than the desired value of 5000 pF. While commissioning the LORAN-C Transmitting Stations, these aerials were tuned to the transmission frequency of 100 KHz by adding additional inductance in series with the antenna tuning coil. The required additional inductance was provided by use of an old Decca coil. With this arrangement, the peak aerial current was about 135 Amps

It was necessary to remove the old Decca Coil from the circuit. Also, it was necessary to improve the capacitance of the aerial mast thereby achieving :

i) improvement in aerial current and radiated power and
ii) omission of additional inductance from the circuit.

With these objectives, modification to the aerial masts was planned and executed.

MODIFICATIONS

The following modifications to the Aerial Masts were planned and executed.

i) Removal of Umbrella Arms, qty,6 Nos.from the top of the mast and aerial/dressing wires (cadmium copper wire) from the mast structure.

ii) Provision of 6 nos. of 'Top Loading Elements', subtending an angle of 45 degree with the axis of the mast and having 400 ft. of radiating element from the top of the mast. As the portion of the mast above the third level guy wires, was freely, mounted, without support of guy wires, it was decided to make the 'Top Loading Elements' as light in weight as possible. Orientation of the 'Top Loading Elements' was made as shown in Fig. 1 The planes containing the guy wires were avoided to eliminate the screening effect of guy wires.

EXECUTION OF MODIFICATIONS :

The aerial Mast at DHRANGADHRA was modified in the first phase. Results were encouraging. Subsequently, Aerial Masts at Veraval and Billimora were also modified. The various works carried out are as under.

a) REMOVAL OF AERIAL/DRESSING WIRES AND UMBRELLA ARMS :
Tools and gears needed for maintenance of aerial mast and for repairs to Umbrella Arms were utilised. Various works attempted are given in Appendix - A.

b) PROVISION OF TOP LOADING ELEMENTS
Six numbers of Top Loading Elements, as shown in Fig.1 were provided. Tinned Copper Braid and Twisted Polyester Rope were the core materials utilised for fabrication of these 'elements'. These materials were selected for reducting the weight of the 'top loading elements'. Different areas of work involved in fabricaqtion and commissioning of these 'Top Loading Elements' are given in Appendix-B.

c) RETUNING THE AERIAL SYSTEM
After the modification of the Aerial Mast, its capacitance had increased to the range of 5000 pF. Retuning of the aerial system was carried out for ensuring maximum power transfer to the radiating mast structure. Various steps under taken are given in Appendix-B.

On completion of the above works, the following were achieved.

i) Peak aerial current had increased to 165 Amps.
ii) The additional inductance incorporated with the aerial tuning coil was removed from the circuit.

OBSERVATIONS AND GENERAL REMARKS :

1. Prior to modification of the Aerial Mast, the peak aerial current was about 135 Amps. After the modifications, this has increased to 165 Amps.; thus resulting in increase in radiated power.
2. Variations in the method of fabrication of 'Top Loading Element' are possible. In place of the 'Copper Braid' the Cadmium Copper Wire removed from the Aerial Mast or Steel Wire Rope of 3 to 5 mm diameter (preferably with PVC sleeving) can be used.
3, The 'Twisted Polyster Rope' was utilised to serve the below purposes.

i) To provide a reinforcement base to the 'Copper Braid'.
ii) To provide insulation beyond the corona disc.
iii) To bear tension provided to the 'element'.

For trouble free service for a longer period, replacement of polyster rope by steel wire rope, will be desirable.
4. The number of pyrex/porcelain insulators provided in the 'Top Loading Element' can be increased to obtain higher 'break down voltage' of the insulator. This will be relevant when the piece of polyster rope after the insulator is replaced by steel wire rope.

APPENDIX - A

REMOVAL OF AERIAL/DRESSING WIRES AND UMBRELLA ARMS-VARIOUS WORKS INVOLVED

1. Remove the aerial/dressing wires from the lower portion of the aerial mast. The three rings which provides support to the aerial/dressing wires may be retained.
2. Remove the aerial / dressing wires from the middle level of guy wires. Clamps are also to be removed. Regrease the exposed portions of the guy wires. On completion of this work, one section of the removed aerial wire would be handing from the clamps of the top level guy wires.
3. Lower the umbrella arms. Dismantle all the components such as binding steel wire ropes, bottle neck screws, clamps, aerial wires, D-shackles, bulldog grips etc. from the arm. Let the arms freely hang from their hinges
4. Now it can be seen that two sections of the aerial wires are hanging from the clamps of the top level guy wires. Remove these wires and clamps and regrease the exposed portions of the guy wires.
5. Next step is to bring down the umbrella arms one by one. Manila rope or steel wire rope along with pulleys on top of the mast can be used. Hinge of the arms is to be removed carefully, after securing the arm with rope, 'Yale Pull' etc. When the arm had become free from its hinge, it can be lowered by using pulley and rope. (If the Top Loading Elements are kept ready, other end of the rope can be tied to the element so that when the umbrella arm comes down, the Top Loading Element will go up; thereby saving considerable amount of labour and time.
6. The pulleys on top of the mast are to be removed at the last stage, i.e. after lifting all the 'top loading' elements' on top of the mast. The holes wherein 'U' bolts for holding the pulleys are fitted, are to be used for fastening the 'top loading elements'. Clean these holes and surrounding area thoroughly.

7. Check verticality of the mast. If necessary, carry out replumbing work after commissioning the 'top loading elements'.

APPENDIX - B

PROVISION OF TOP LOADING ELEMENTS AREAS OF WORKS INVOLVED

MATERIALS NEEDED :

Materials needed for fabricating 'top loading element', quanity. 1 no., are given below.

1. 9/16" Tinned Copper Braid - 405 Ft.
2. 1/2" Twisted Polyster Rope -600 Ft.
3. 1" Black Heat Shrink Tubing-410 Ft
4. Pyrex or Porcelain Insulator with corona disc. - 1 no.
5. S.S.Thimble for 1/2" rope - 4 Nos.
6. Tinned Copper Lug 125 Amps.-2 Nos.
7. S.S.Eye Bolt, threaded and should dered, 1/2" dia, 1½" long, eye 1" with nuts washers etc. - 1 set.
8. Steel wire Rope 1/4" dia., 20' long with thimbles - 1 no.
9. D-Shackles - 5 Nos.
10. Bull dog grip - 6 Nos.
11. Rigging Screw 12" to 18" long - 1 No.
12. W.I.P. Frayed Rope Repair Compound 1 can or less.
13. E.J.C. Electrical Compound - 1 tube or less.
14. Denso Tape - as required
15. Electrical Insulation Tape - as required.
16. PVC Binding Thread - as required.

FABRICATION OF TOP LOADING ELEMENT ASSEMBLY - PROCEDURE

1. Unroll the reel of tinned copper braid to maintain a straight path.
2. Take a smooth flexible rod having a through and through hole at one end. Tie one end of the polyester rope with the rod, similar to a needle and thread. Now thread the rod and rope smoothly through the copper braid. Expand the braid if any difficulties in threading the rod is experienced. In this manner, thread the rope through the entire length of the braid. When handling the braid try not to splinter it because this could tear the heat shrink tubing and also increase any corona effect.
3. Pull the rope through the braid until the rope extends approximately 8 to 10 feet beyond the end of the braid.
4. When threading the rope through, the braid will try to expand. Therefore the braid must be pulled

down to the smallest size possible. This can be accomplished in the following manner. Using black electrical tape or equivalent, tightly tape the braid to the rope from the end of the braid. Holding the braid and rope stationary, gently pull the braid away from the stationary end so that it constricts around the polyster rope. (It is necessary to pull the rope for allowing possible stretching before commencing this work) Tightly take the braid to the rope approximately every 4 to 5 feet so that the braid does not loosen. Do this for the entire length of the braid.

5. Next step is to place the heat shrink tubing over the braid. Using the flexible rod, thread the assembly through the heat shrink tubing. If available, use an air compressor to expand the tubing. If any splinters on the braid are encountered, place electrical tape over them.

6. We may need 4 reels of heat shrink tubing for ech 'toploading element'. Pull the first reel of tubing to the end of the braid, i.e. the end towards the anchor block. Place the end of the tubing away from the end of the braid by 5 feet. Now using a standard heat gun, shrink the tubing. If a hole is made, carefully repair the hole with electrical tape so that no braid is showing. Pieces of heat shrink tubing can also be used for this purpose. After shrinkking the first piece of tubing, bring the second reel over the copper braid and rope. Give an overlapping of 2 to 3 feet over the first piece of tubing. Shrink this tubing also. In this manner complete the entire length of copper braid bare at the mast end of the 'top loading element assembly'.

7. Cut the polyster rope from the anchor end of the 'top loading element' leaving 5 feet of rope excess from the end of copper braid. Fish out the rope from both ends, from just above the termination of heat shrink tubing. This can be done by gently spreading the strands of the braid sidewise, thereby making an opening, without breaking the strands, to fish out the rope. This act forms a 'Y' junction between bare copper braid and polyster rope at both the ends. It may be noticed that at both the ends copper braid of 5 feet and polyster rope of more than 5 feet are available. Fig.2 may be referred.

8. Tie the 'Y' junction at the mast end of the 'top loading element' porperly with PVC binding wire, after applying E.J.C. electrical compound generously. Application of this compoundwill reduce heavily any corona effect.

9. Insert heat shrink tubing over the copper braid at the two ends and shrink. Solder the copper lug properly onto the ends of the braid. At the mast end, tie the braid with rope securely, 6" away from the 'Y' junction, using PVC binding thread and W.I.P. frayed rope repair compound. Then, cover the junction with 'denso tape' for preventing water loging. Fig.2 may be referred.

10. Splice the rope at both ends on S.S. thimble. At the mast end, insert the thimble in the eye of the S.S.Eye bolt before carrying out splicing. After splicing, the length of the rope from the 'Y' junction is to be kept at 3'; leaving copper braid portion lengthier than the rope. This is essential to provide tension only on the rope while commissioning; thus avoiding tension on copper braid.

11. Using D-shackles connect the pyrex/porcelain insulator with the rope at the anchor end of the 'element'. Connect the copper braid with corona disc of the insulator. The other end of the insulator will receive spliced rope (onto the S.S. thimble) of required length needed for installation. See Fig.2.

12. Between the piece of polyester rope mentioned at 11 above and the anchor block, a piece of Steel Wire Rope of ¼" dia and 20' length is to be provided to avoid damage to the polyester rope due to vandelism etc. A rigging screw, as in Fig.2, is to be provided at the anchor block to adjust tension on the 'top loading element'.

COMMISSIONING OF 'TOP LOADING ELEMENT

1. Pull the mast end of the 'element' one by one, to the top of the mast.
2. Connect the 'eye bolt assembly' in the outer hole of the 'pulley arm' tightly using nuts, washers etc.
3. Connect the tinned copper lug at the end of the braid in the inner

hole of the 'pulley arm' tightly, using bolt nuts, washers etc. Apply E.J.C. electrical compound lightly.
4. After connecting all the six 'elements' on top of the mast, the other end of the 'elements' be brought to the bottom of the mast.
5. Check electrical continuity of each of the 'top loading element' between corona disc and bottom of the mast structure. Ensure minimum contact resistance between the 'element' and mast at the top.
6. Pull each of the 'top loading element' to the respective anchor blocks. Fasten them with the anchor blocks. Give proper tension by adjusting the length of the steel wire rope and by rigging screws. Carry out tensioning of all the six 'elements' equally and in pairs. Tension may be provided to take out approximately 90% of the droop Care must be taken to avoid over tensioning. Lock the rigging screws.
7. Check verticality of the mast. If necessary, carry out replumbing work.
8. Repaint the portions of the mast where painting had gone bad due to the various works on the structure.

ANCHOR BLOCK :

Anchor blocks are to be located as shown in Fig.1. As the 'top loading elements' are light in weight, the anchor blocks are not expected to take much load as compared to the anchor blocks for guy wires. Thus, a construction with less volume, similar to the anchor blocks for guy wires, will meet the requirement.

APPENDIX - C

i) TEST INSTRUMENTS NEEDED

1. Function Generator, qty, 1 No.
   Signal Output : Sinusoidal, 30 volt peak to peak.
   Frequency range : 50 KHz to 300 KHz to select frequency in the vicinity of 100 KHz
2. Frequency Counter, qty. 1 No., to check frequency of the above Function Generator.
3. C.R.O., qty 1 No., to examine the R.F. Waveform.
4. Ferrite Core Transformer, qty.1 No.
   Core : Outer diameter - 60 Cm
   Inner diameter - 36 Cm
   Cross section-12Cmx12Cm

Primary : 13 turns, loosely wound on the ferrite core using insulated multistrand copper wire. Ends are terminated in BNC connector to receive RF signal from the Function Generator.

Secondary : 3 turns, loosely wound on the ferrite core using insulated multistrand copper wire. Ends are connected with crocodile clamps to connect on the terminals/leads.

ii) PROCEDURE :

1. Remove the additional inductance provided by the 'Dence Coil' from circuit.
2. Remove the additional turns, if any provided on the 'Variable Inductance Coil Assembly'. Keep the inner coil of this unit in the mid-position by operating the knob.
3. Remove the lead of the 'Variable Inductance Coil assembly' from the terminal of secondary of 'Output Transformer'.
4. Connect the Test Instruments as shown in Fig.3. Feed RF signal and note the frequency at which peaking takes place. At this frequency, Variable Inductance Coil Assembly, Vertically mounted Helical Coil Assembly and Aerial Mast will be in resonant state.
5. Set the Function Generator output signal to 102 KHz. Select the turns of the 'Vertically mounted Helical Coil Assembly' to get peaking (or nearly to peaking) in the CRO. Adjust the 'Variable' Inductance Coil Assembly' to get exact peaking condition.
6. Except the CRO and its connections, remove all other test instruments and their connections from circuit. Restore the lead of the 'Variable Inductance Coil Assembly' to the terminal of the secondary of 'Output Transformer'. Check all the terminals and connections thoroughly.
7. Energise the HCGs one by one. Monitor the RF waveform in the CRO. With all the HCGs in operation,

measure the peak current and the time period at which peaking takes place. Variable Inductance Coil Assembly can be adjusted slowly and carefully to achieve improvement in peak current. Obtain peak current by this way and mark the position of the knob.

8. Measure the period at which peaking takes place. This should be between 60 and 70 micro-seconds. If this period is not within this time slot, proceed as under.

a) De-energise the transmitter. Changes the tapping of the secondary of Output Transformer. Switch on the Transmitter and follow the steps in 7 above. Different tapping are to be tried till satisfactory results are obtained.

b) If steps at (a) above fail to yield desired results, addition or reduction of turns of the winding on the outer coil of the Variable Inductance Coil Assembly is to be tried. It may be, at times, necessary to strike a compromise between the value of 'Peak Current' and 'Time Period of Peak Current'. Slight reduction in the peak current obtained by adjustment of Variable Inductance Coil Assembly can bring the 'time period of peak current' in the desired time slot.

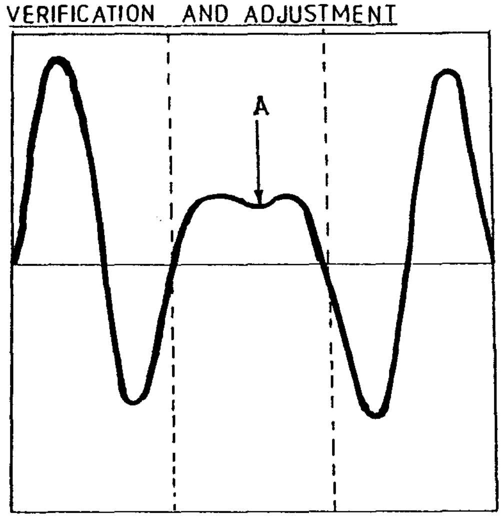
9. After obtaining the desired results, waveform is to be checked to verify occurrance of 'phase reversal' This can be done as under.

(a) Switch off transmissions and then power supply to transmitter. Remove leads from terminals E3 and E4 of 'Tailbiter Board' in 'Coupling and Output Network Assembly' in the Transmitter.

b) Switch on the transmission. Now there will be no tailbiting action.

c) Check the 'Phase Reversal' point in C.R.O. Desired pattern to be obtained is as under. If any abnormality is observed, adjust the 'Variable Inductable' coil assembly to get the more shape similar to that shown in the figure.

PHASE REVERSAL POINT VERIFICATION AND ADJUSTMENT



A: Phase Reversal Point
Desired wave shape

ACKNOWLEDGEMENT :

The Department of lighthouses and lightships gratefully acknowledge the receipt of hardware items supplied by M/s. Megapulse, USA, for modification of Aerial Masts.

BIOGRAPHY OF AUTHOR

Mr. S.G. Malpathak is presently working as Director (Regional) in the Department of Lighthouses, Ministry of Surface Transport, Government of India. After graduating as B.E.(Tele-communications) from University of Poona, in 1968, has joined the Department in 1975, after a tenure of 7 years in Defence Laboratory. He was trained at Decca College, UK, and has looked after Salaya Decca Chain in Gulf of Kachchh before joining of present post.

Mr.G.Somarajan, is presently working as Dy.Director (Electronics) in the same Department. After graduating as B.Sc. (Electronics & Communications) he has joined the Lighthouse service in 1977. During the period of modification of Masts, he was in-charge of West Coast Loran-C Chain.

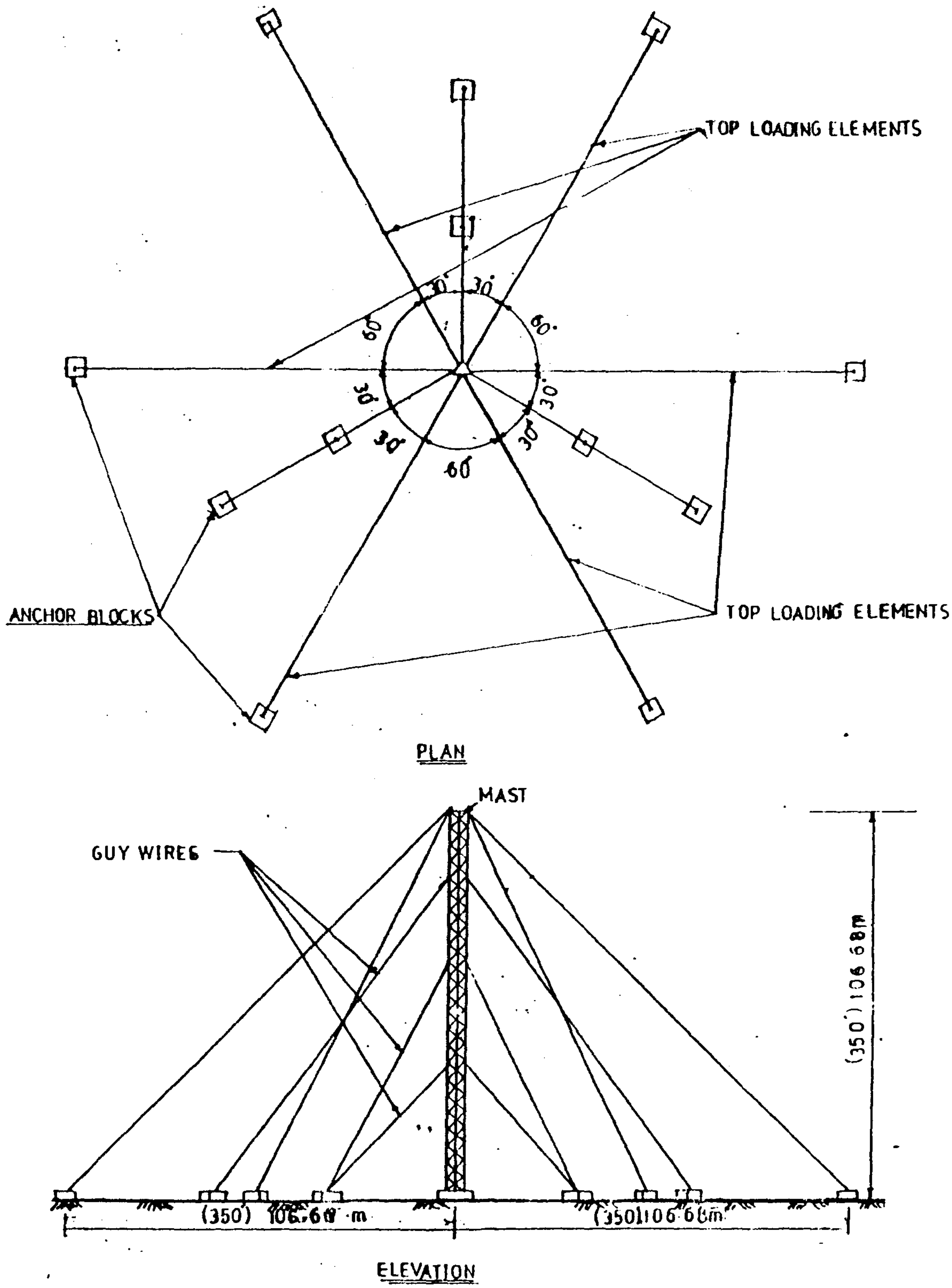

TOP LOADING ELEMENTS
30°
30°
60°
60°
30°
30°
30°
30°
60°
ANCHOR BLOCKS
TOP LOADING ELEMENTS
PLAN
MAST
GUY WIRES
(350') 106.68m
(350) 106.68 m
(350) 106.68m
ELEVATION

Figure 1

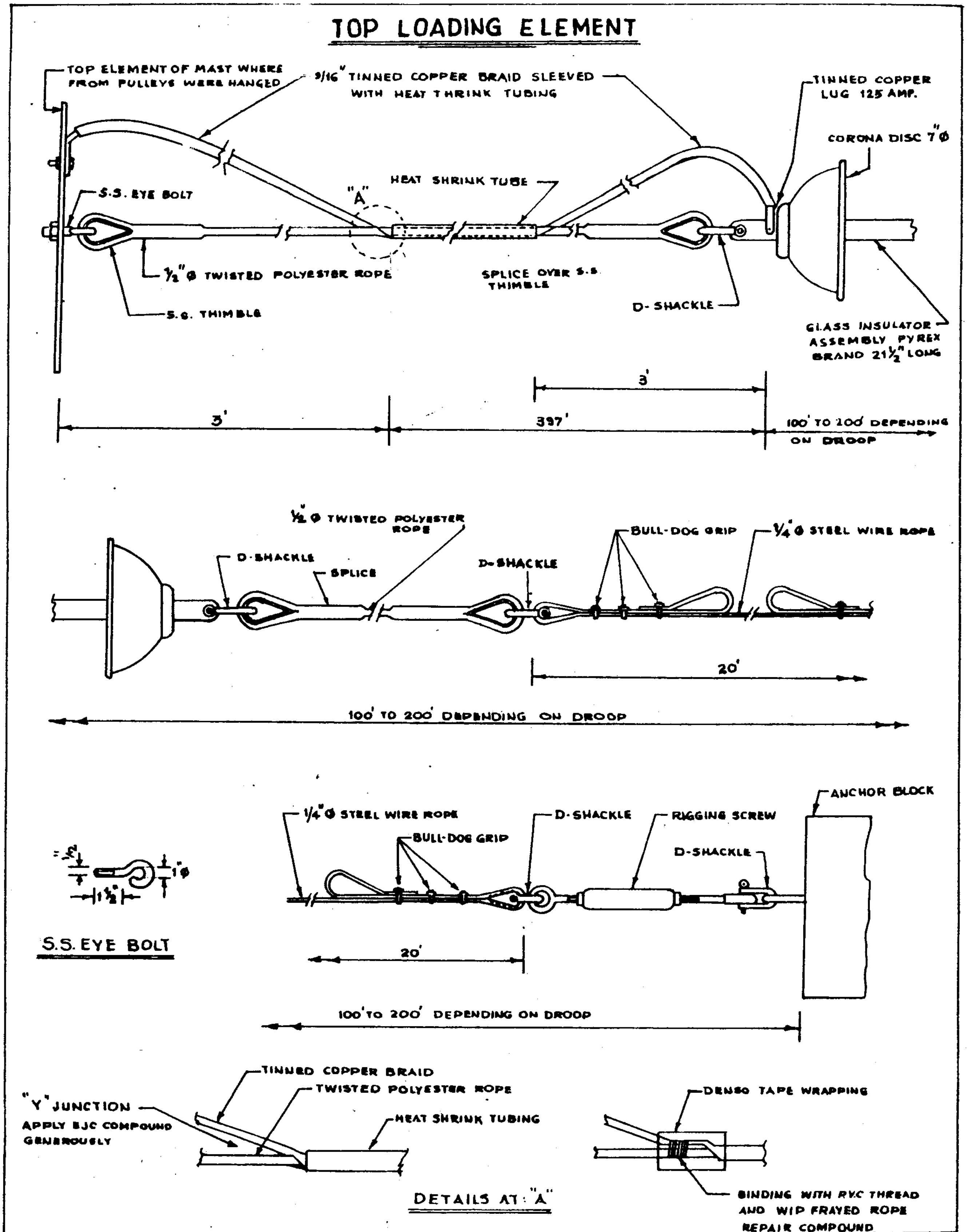

TOP LOADING ELEMENT
TOP ELEMENT OF MAST WHERE FROM PULLEYS WERE HANGED
9/16" TINNED COPPER BRAID SLEEVED WITH HEAT THRINK TUBING
TINNED COPPER LUG 125 AMP.
CORONA DISC 7" Ø
HEAT SHRINK TUBE
"A"
S.S. EYE BOLT
1/2" Ø TWISTED POLYESTER ROPE
SPLICE OVER S.S. THIMBLE
D-SHACKLE
S.S. THIMBLE
GLASS INSULATOR ASSEMBLY PYREX BRAND 21 1/2" LONG
3'
3'
397'
100' TO 200' DEPENDING ON DROOP
1/2" Ø TWISTED POLYESTER ROPE
D-SHACKLE
SPLICE
D-SHACKLE
BULL-DOG GRIP
1/4" Ø STEEL WIRE ROPE
20'
100' TO 200' DEPENDING ON DROOP
ANCHOR BLOCK
1/4" Ø STEEL WIRE ROPE
BULL-DOG GRIP
D-SHACKLE
RIGGING SCREW
D-SHACKLE
20'
100' TO 200' DEPENDING ON DROOP
1 1/2"
1"Ø
S.S. EYE BOLT
TINNED COPPER BRAID
TWISTED POLYESTER ROPE
HEAT SHRINK TUBING
"Y" JUNCTION
APPLY BJC COMPOUND GENEROUSLY
DENSO TAPE WRAPPING
BINDING WITH P.V.C THREAD AND WIP FRAYED ROPE REPAIR COMPOUND
DETAILS AT: "A"

Figure: 2

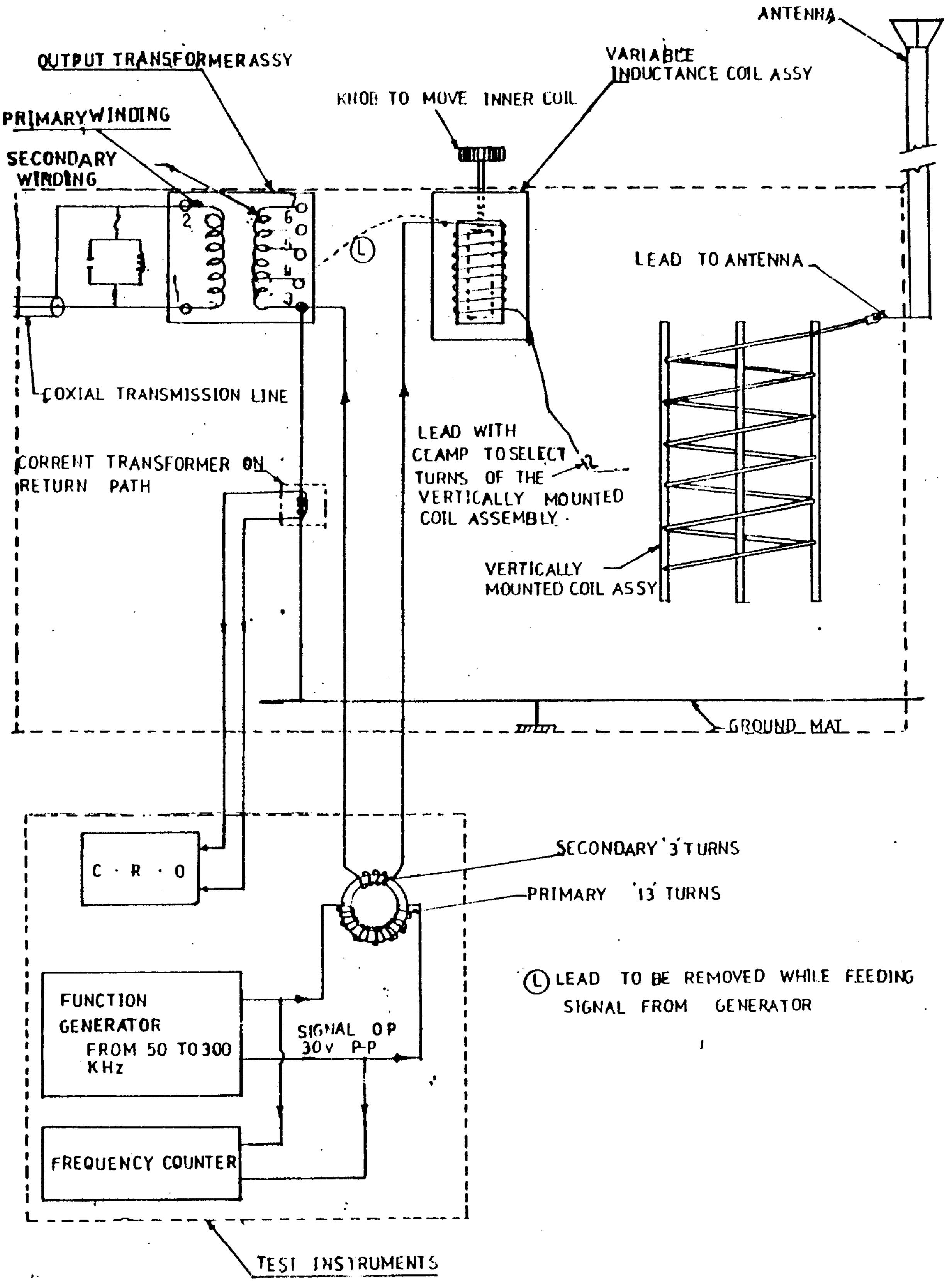

ANTENNA
OUTPUT TRANSFORMER ASSY
VARIABLE INDUCTANCE COIL ASSY
KNOB TO MOVE INNER COIL
PRIMARY WINDING
SECONDARY WINDING
LEAD TO ANTENNA
COXIAL TRANSMISSION LINE
LEAD WITH CLAMP TO SELECT TURNS OF THE VERTICALLY MOUNTED COIL ASSEMBLY
CORRENT TRANSFORMER ON RETURN PATH
VERTICALLY MOUNTED COIL ASSY
GROUND MAT
C · R · O
SECONDARY '3' TURNS
PRIMARY '13' TURNS
FUNCTION GENERATOR FROM 50 TO 300 KHz
SIGNAL OP 30V P-P
FREQUENCY COUNTER
TEST INSTRUMENTS
(L) LEAD TO BE REMOVED WHILE FEEDING SIGNAL FROM GENERATOR

Figure: 3

WILD GOOSE ASSOCIATION
23rd Annual Convention and Technical Symposium

THE ADDITION OF A STANDARD ZERO CROSSING (SZC) TRACKING 1 PPS CAPABILITY TO THE AUTOMATIC BLINK SYSTEM (ABS)

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INTRODUCTION

The VOLPE Department of Transportation System Center (VOLPE Center) under FA-329 is designing, developing and building an Automatic Blink System (ABS) to be installed by the U.S. Coast Guard at all LORAN transmitting stations in the NAS. The ABS equipment will provide an integrity monitor for LORAN precision approaches by rapidly and automatically applying BLINK to a LORAN signal upon detection of a timing anomaly of 500 ns or greater.

Public Law 100-223 requires the U.S. Coast Guard to synchronize all LORAN-C master stations to within 100 ns of coordinated universal time (UTC). As one way of satisfying this requirement, a LORAN-timed one pulse per second output has been added to the ABS equipment. The addition of this capability to the ABS equipment enables the ABS to serve two DOT missions: the FAA mission of providing integrity for LORAN non-precision approaches and the USCG mission of synchronized transmitted LORAN master signals to UTC.

WHY ONE PPS AND ABS

For a variety of reasons, the ABS system is a natural host for the one pulse per second hardware. First, the ABS system already interfaces with all of the existing LORSTA elements necessary to implement one pps except external one pps signal. These include the three Cesium standards, the sampled operate RF signal (antenna current), and the station TTY communication loop, as well as primary AC power and DC backup power. In terms of signal processing the ABS system was already accomplishing about half of the signal processing necessary for locking a one pps signal to the transmitted pulses standard zero crossing (SZC). These functions include acquiring and locking to the SZC of the transmitted pulse, and measuring the phase of the SZC with respect to the Cesium standards with a resolution of 20 ns and an accuracy of ± 40 ns. The ABS system had the expansion capability (real estate and processor power) to host the required one pps functions. And finally, the ABS system fills the last available rack opening at the existing LORAN-C NAS transmitting sites. If a separate one pps system were to be built, there would be no ready location in which to install the equipment.

BACKGROUND

Prior to discussing the implementation of one pps in the ABS system, we present a brief review of the relationships between a one pulse per second signal (1 pps), the time of coincidence (TOC), and the timing of the LORAN-C pulse transmissions.

LORAN-C pulse transmissions are referenced to coordinated universal time (UTC), which started at zero hours, zero minutes and zero seconds on 1 January 1958. At this second, one could imagine all LORAN-C master stations simultaneously transmitting the first master pulse of Phase Group A in what has been a virtual continuing sequence of master and secondary transmissions, with each chain repeating the sequence at its own group repetition interval. In fact, non-existing LORAN-C chains and many dual-rated chains could not have transmitted that first pulse, but in a timing sense all LORAN-C transmissions are traced back to that instant.

A perfect 1 pulse per second signal is a timing pulse which occurs on the second starting or traceable to that first UT second.

A TOC, or time of coincidence, is a time at which the first pulse of a master station transmission in Phase Group A (referred to in this paper as P1GA) and a universal time UT second are coincident. As discussed above, the first TOC for all master stations occurred, or would have occurred, simultaneously on 1 January 1958. Subsequent TOCs are dependent upon the group repetition interval (GRI) of each chain. The GRI assigned to a chain expresses the time interval between successive master station transmissions in 10 μsecond increments. For example, the Northeast chain GRI is 9960 μs between master group repetitions. If we consider the numeric value of the GRI for a given station; e.g., 9960, it can be shown that a TOC will occur each "GRI" second or at sub-multiples of "GRI" seconds where the value

$$\frac{\text{GRI}}{2^n \times 5^m}$$

is an integer. Again assuming a GRI of 9960, a TOC will occur at each 9960 seconds, at any multiple of 9960 seconds, and, in fact, forty times between each 9960 seconds at multiples of 249 seconds.

The time of day in hours, minutes and seconds in which TOC times will occur at any given GRI are computable from a knowledge of the station GRI, the January 1958 starting time of UTC, and a knowledge of the number of leap seconds that have been inserted into UTC since January 1958. The computation of these times on a daily basis are available from the United States Naval Observatory (USNO) and are published as a part of *Time Service Announcements, Series 9.*

The above, of course, assumes that the timing at the LORAN-C station is perfect; that is, LORSTA 1 pps signal occurs at the exact instant as a UTC second. In fact, realignment is never perfect, although the difference between the two 1 pps signals is quite small. But the difference does lead us to define two different 1 pps signals, LORSTA 1 pps and UTC 1 pps, or in the nomenclature used in the implementation of the 1 pps system modification, "Internal" and "External" 1 pps, respectively. The difference between these two signals represents the LORSTA/UTC synchronization error.

The above definitions of 1 pps and TOC mention only the 'occurrence' of P1GA at a master station and do not specify where in the LORAN pulse TOC occurs, or how 1 pps is defined at a secondary station. At a UTC synchronized master station, TOC occurs at the starting point of P1GA and is defined as a point 30 μs before the SZC. At a secondary station TOC occurs at a point in time 30 μs plus one emission delay time before a secondary P1GA pulse.. This means that a TOC second is never aligned with the start of a secondary pulse group, but rather with the start of the group repetition interval during which the secondary will transmit.[1] Figure 1 shows the relationship between the SZC of a master P1GA, the Internal 1 pps signal and the External 1 pps signal.

To align a master station to UTC, we must assure that: 1) a P1GA master pulse is transmitted at a TOC time; 2) the LORSTA 1 pps clock is aligned to UT; and 3) the station's clock is set to universal time. To align a secondary station, we must assure all of the above and account for emission delay between the master and the secondary transmissions. To control a chain to universal time we must assure that the error between the station's 1 pps clock, as shifted in time by movement of the SZC, and a UT second is within a specified tolerance.

THE ABS 1 PPS MODIFICATION

System Requirements.

The following system requirements were specified for the 1 pps ABS modification:

1. Generate an internal 1 pps, or optionally a 1 pulse per TOC signal, which is time-locked to the SZC of the transmitted LORAN-C signal.

2. Provide procedures to
   (a) align the Internal 1 pps signal to a TOC P1GA pulse;
   (b) align the internal 1 pps signal to the External pulse;
   (c) set the ABS clock to UTC.

3. Compute the time error between the internal and external 1 pps signals.

4. Provide an alarm capability to warn the system operator that the measured time error between the internal and external 1 pps signals has exceeded a preset limit.

5. Provide a visual indication of the occurrence of seconds and TOC pulses.

6. Provide for monitoring and controlling of the 1 pps subsystem via the TTY communications network.

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[1] None TOC seconds may align with the "start" of a P1GA secondary pulse. However, this alignment is not relevant to the 1 pps synchronization problem.

1 PPS System Approach.

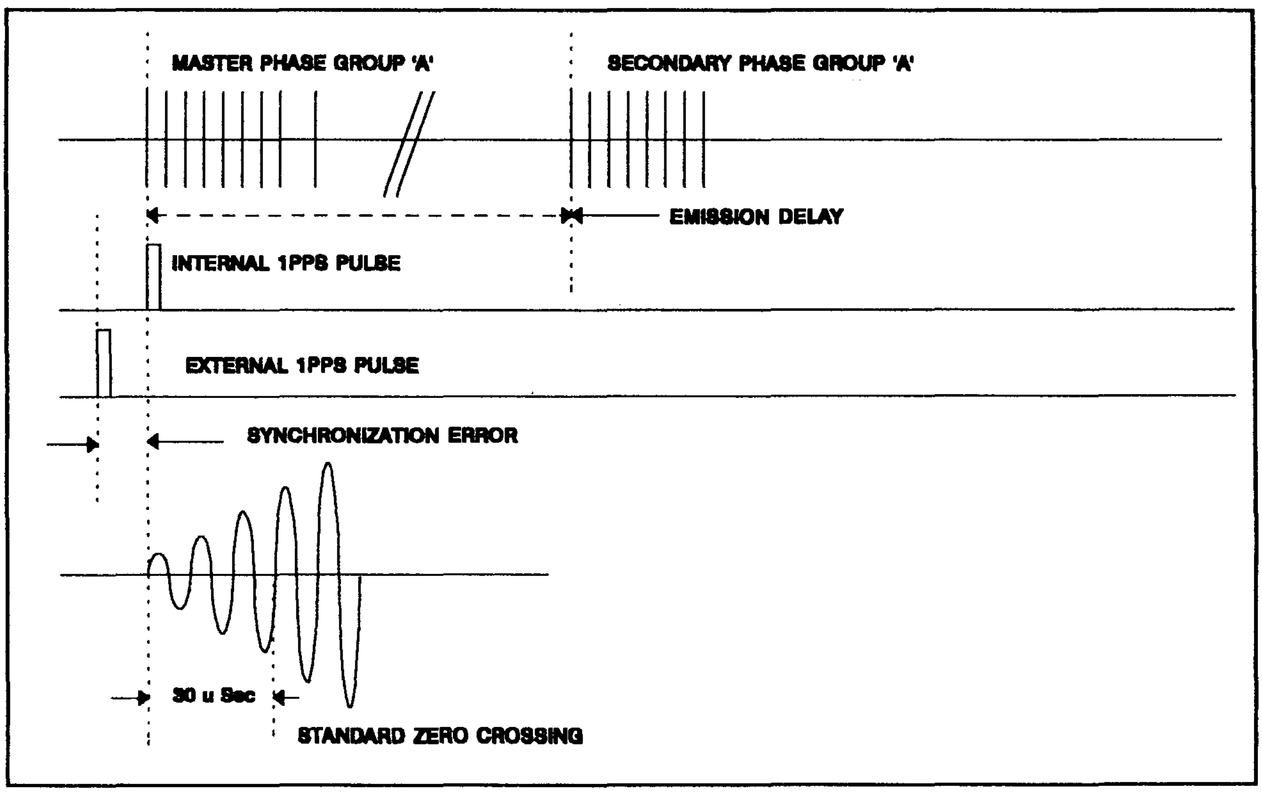
As a part of its primary mission, the ABS system establishes a LORAN timing which is referenced to the P1GA pulse. This reference is established by averaging the relative time position of all transmitted LORAN-C pulses over several seconds. To generate an internal 1 pps signal which is locked to the average SZC-based GRI reference, we first align the internal 1 pps signal to the external UT 1 pps signal. This is accomplished by measuring the time difference between the internal and external signals and, after removing known system calibration delays, moving the internal signal to reduce this error to zero. Next, by identifying a TOC second and noting the position of the SZC at this time, we move the internal 1 pps second to either 30 μs or 30 μs plus one emission delay in front of the P1GA at TOC. This process yields internal 1 pps signal which is aligned to the LORSTA second. Once the internal 1 pps signal is thus locked to the SZC of the TOC P1GA pulse, we adjust the position of internal 1 pps to follow the motion of the SZC relative to its position when we first establish TOC. This tracking technique will work as long as the standard zero crossing stays within ± 5 μs of the initial lock point. Should the LORAN-C timing jump, we have no means to follow the signal. However, when such a large jump occurs we have had a BLINK event and the ABS system will proceed with its normal function of placing the transmitted signal into BLINK (or in the case of a master station, taking the station off air) and placing the ABS system into the BLINK state. In the BLINK state, the internal 1 pps signal is no longer controlled by the SZC, but free runs off the Cesium Standard until the ABS is once again armed.

When the ABS returns to the armed state, one of three conditions will prevail:

1) The LORAN-C transmitter timing will have been returned to its pre-BLINK timing. In this case, the internal 1 pps signal is once again adjusted to maintain its position with respect to the SZC.

2) The timing of the LORAN-C transmitter will have been adjusted by less than ± 5 μs, and as part of that process, the operator establishes a new reference time for the ABS system by issuing an ABS synchronization command. As resynchronization involves a loss of the SZC reference time, the 1 pps system jumps the internal 1 pps to the specified point in front of the SZC, and then establishes a new SZC reference position.

FIGURE 1. The Time Relationship Between SZC, Internal and External One PPS.



3) There will have been a complete loss of timing (e.g., the loss of a Cesium reference input). In this case, the 1 pps output is put into a non-operational state and must be returned to an operational state by re-establishing TOC.

Setting Time and Marking TOC.

There are two times which must be set in the 1 pps system. We must establish the TOC second and set the ABS clock to UTC time. Either of these functions may be carried out independently; however, a complete synchronization of the 1 pps system will establish both TOC and UTC synchronization.

The 1 pps modification provides three initialization procedures: The first manually marks the TOC second, the second manually sets the ABS clock to UTC time, and the third automatically establishes both TOC and UTC synchronization. All three procedures assume that we have available to us an external source of UT derived 1 pps.

Manually establishing TOC requires the operator to depress, hold, and then release the TOC switch at a known TOC time. For this procedure to work, it is not necessary for the ABS to know UTC time, but only to know that a given second is, in fact, a TOC second. A flow diagram for this procedure is shown in Figure 2. First, the internal 1 pps pulse is aligned to the external pulse. Next, a TOC time is selected. At least five seconds prior to this TOC time, the operator pushes the TOC button. This delay, as in the case of manual UTC time setting, assures that an accidental bump of the switch will not disrupt system time. At each of the following seconds the system tags the time of the closest P1GA pulse in anticipation of the operator releasing the TOC switch. When the TOC switch is released, the internal 1 pps pulse is locked to the tagged P1GA pulse, and the internal 1 pps is adjusted to the proper point in front of the selected SZC. At this time, if the TOC second has been entered, the ABS clock will be set to the TOC time. Finally the system calculates and causes the front panel LED to illuminate for a full second at the next TOC time, permitting the operator to verify TOC.

Manual UTC time synchronization employs the TOC switch to start the internal UTC clock at a proper predesignated second. A flow diagram for this procedure is shown in Figure 3. First, using the UTC_TIME_HHMMSS command, the operator places the system into the UTC time-set mode. This command signals to the system that a manual UTC time synchronization is to be performed and also conveys the time at which the clock will be started. The system then waits for the TOC switch to be pushed for at least five seconds. After the TOC switch has been pressed for five seconds, the internal 1 pps signal is aligned to the external signal and waits for release of the TOC switch. Following release, the UTC clock is started from the entered time. At this time the UTC clock time is also transferred to the lower quality, battery backed-up, IDM clock. Once again, visual verification is provided by an extended flash of the LED for a full second ten seconds later.

The automatic TOC/UTC timeset mode eliminates the need for the operator to manually push and release the TOC switch at a specific second. This technique again requires that we have an external source of 1 pps to initially synchronize the internal signal, and further, that the IDM's battery backed-up clock is currently set within ± one-half TOC interval of UTC time (e.g.,

FIGURE 2. Manual TOC Procedure

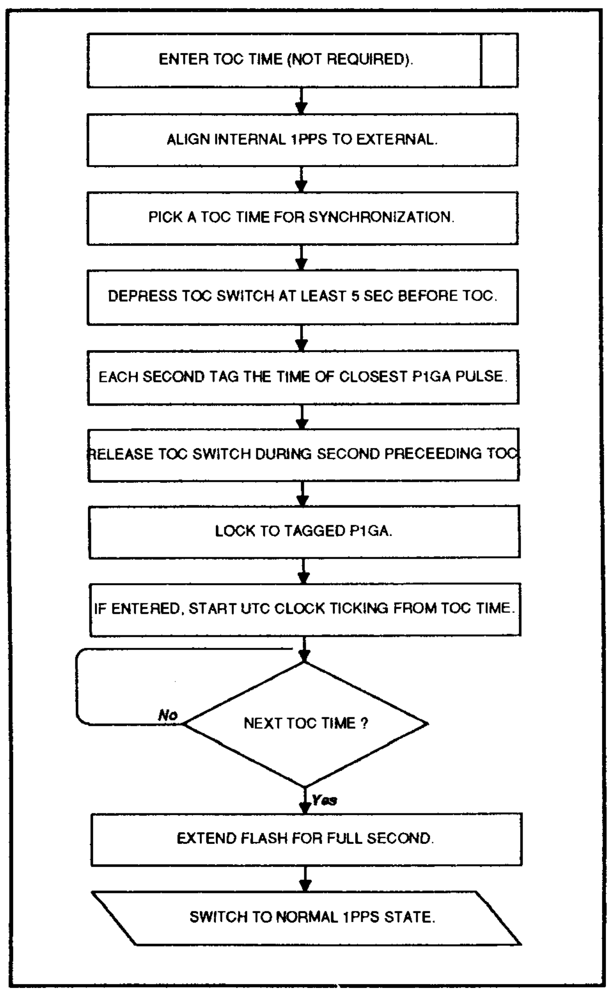
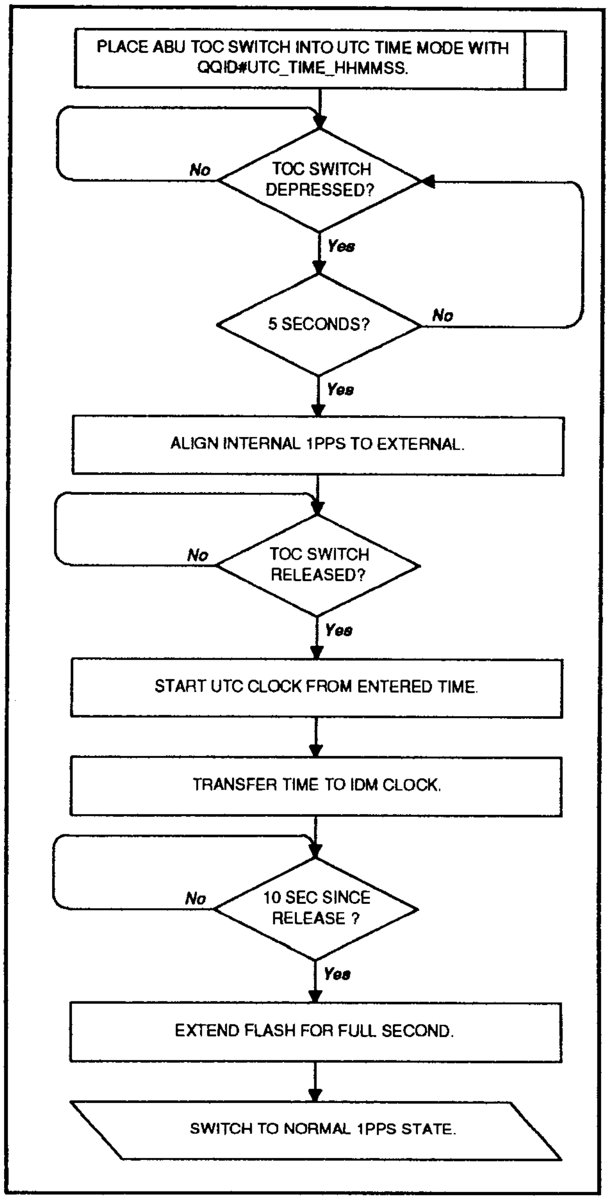


FIGURE 3. Manual UTC Time Synchronization.



within about two minutes of UTC for a GRI of 9960), and finally that the LORAN chain is initially synchronized to within ± 50 μs of UTC.[2]

The automatic synchronization procedure is based on the observation that only the TOC second pulse will be within ± 50 μs of the start of the master P1GA pulse position and that all other pulses will be displaced from a P1GA by 100 μs. (If adding one GRI to the previous P1GA time does not cause it to occur at an integral second, then it must miss by a multiple of 100 μs.) This is shown diagrammatically in Figure 4. Here we see the external 1 pps pulse in relation to the start of P1GA, including a synchronization error of about 10 μs. Superimposed on the external 1 pps pulse line are the positions of none TOC seconds with respect to the leading edge of the pulse. As shown, these will miss the front edge of the pulse by multiples of 100 μs.

The automatic procedure works as follows: The operator enters a TOC time and commands automatic TOC synchronization. At a time of one-half TOC interval prior to the specified TOC time as determined by the inaccurate IDM clock, or a time of minus one TOC interval to exactly the TOC time as determined by an external UTC clock, the system examines the relative position of P1GA at one second intervals. The TOC second is the second where the start of the GRI is closest to one second pulse. A flow diagram for this procedure is shown in Figure 5. As noted on the flow diagram, the actual implementation assumes that the true TOC pulse will be within ± 25 μs, since this tolerance provides a margin of error for the implementation of the technique and does not place a severe constraint on the initial synchronization of the LORSTA. As with the manual techniques, the process starts with an initial alignment of the internal 1 pps signal to the external signal. Next, the time of the IDM clock is either set or verified to be within ± one-half TOC interval of UTC, and the first or any other past TOC for the day is obtained from the USNO tables and entered using the UTC FTOC command. Using this information, the system computes the UTC time of the next usable TOC, avoiding TOCs which are so close to the present time that there is insufficient time to initialize the system. Following the receipt of the UTC_STOC synchronization command, the system waits until a P1GA occurs within ± 25 μs of a UTC second. When this occurs, the UTC second is used to start the UTC clock ticking from the entered TOC time. This time is also transferred to the IDM clock to set it to the now known UTC time. Finally, at the next TOC time, the TOC LED flash is extended for a full second.

ADDING 1 PPS TO ABS

As noted earlier, many of the functions required by 1 pps already existed in the ABS system with about half

[2] This assumes that GRIs are specified in 100 μs increments as in the case with the NAS. In general we require an initial accuracy of one-half the resolution to which the GRI is stated. For example, for a GRI of 7001 which grows in 10 us increments, we would require an initial synchronization of ± 5 μs.

of the 1 pps functions requiring use or expansion of existing facilities. These included expansion of the existing ABS command message and alarm structure, the use of the existing Cesium standard and Operate RF (OPRF) interface, and the use of the existing standard zero crossing time measurement system. The additional circuitry required by the 1 pps modification included 1) the generation of an internal 1 pps signal with a 20 ns resolution, 2) the capturing of the time of the external 1 pps signal with a resolution of 20 ns, 3) 50 Ohm line drivers and receivers to interface the internal and external 1 pps signals. In addition, a manual TOC button and an LED to visually indicate seconds and TOC seconds were required. Finally, software was required to drive the above hardware and to execute the required system commands and functions.

The majority of the hardware additions were added to the PTM cards. The time measurement functions were implemented using two programmable logic arrays and with spare input capture and output compare timers contained in Motorola 68HC11 CPU.

In addition to the PTM modifications, we had to provide for rear panel connectors, internal cabling and mother board modifications to bring the internal and external 1 pps signals to the rear panel of the ABS. Finally, the 1 pps LED was added to the front panel of the PTM and a TOC switch was added to the power supply cover panel.

The 1 pps software changes affected both the IDM and the PTM cards. Addition of the 1 pps functions to the IDM required additions to the existing IDM alarm command and message structure. As the programming space in the IDM was fairly limited, a part of this modification included the fruitful task of more efficiently grouping common routines into subroutines in order to gain code space, and the conversion of several alarm messages into simple status messages in order to gain additional alarm flags. In the end, IDM memory space proved sufficient to carry the necessary additions; however, the final system has less than 1 Kb of code space left out of 48 Kb of programming memory.

The PTM code additions were more extensive for two reasons. First, the addition of 1 pps required that the PTM real time system work in absolute rather than relative time. Before the addition of 1 pps, the ABS was only concerned with jumps with respect to a previously established time. For example, the resynchronization of the ABS merely required us to reestablish a new reference from which errors were computed, whereas 1 pps required us to constantly keep track of the absolute time position of the signal. The second reason the PTM code additions were more extensive is that the generation of a time pulse at a specific time is a more demanding task than capturing the relative time of a pulse. Capturing the time of a pulse requires that latches and counters be armed and that the computer examine these latched values after the occurrence of the pulse. The generation of a timing pulse requires that all timers and enabling signal levels be set and that output circuitry be armed

FIGURE 4. Possible Positions of P1GA with Respect to External (UT) Second Pulse.

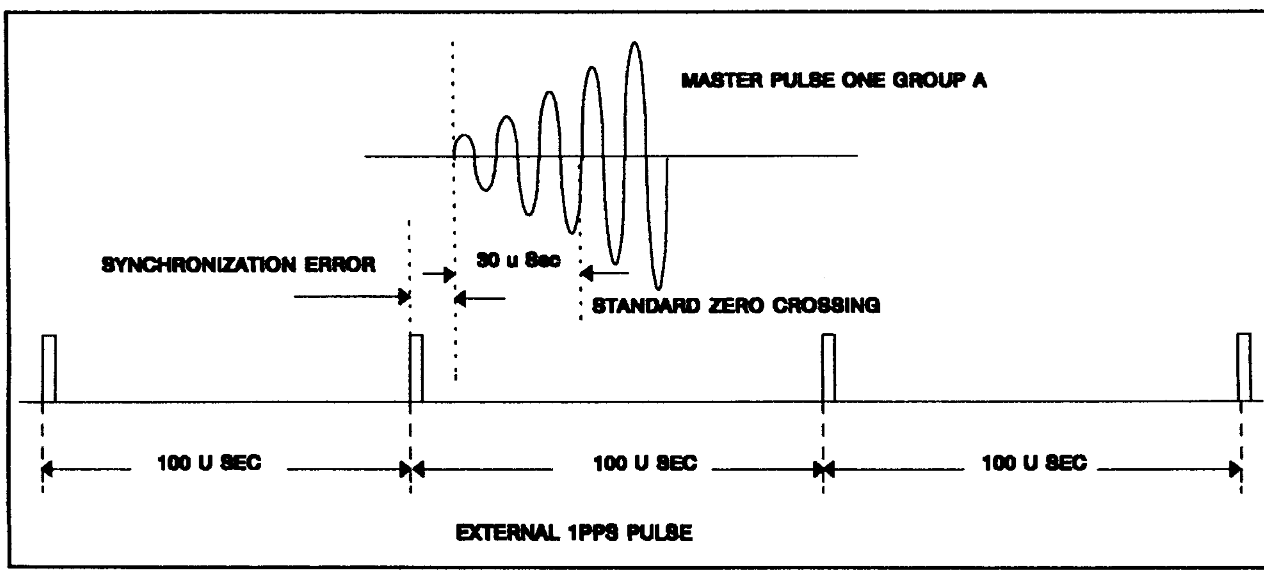
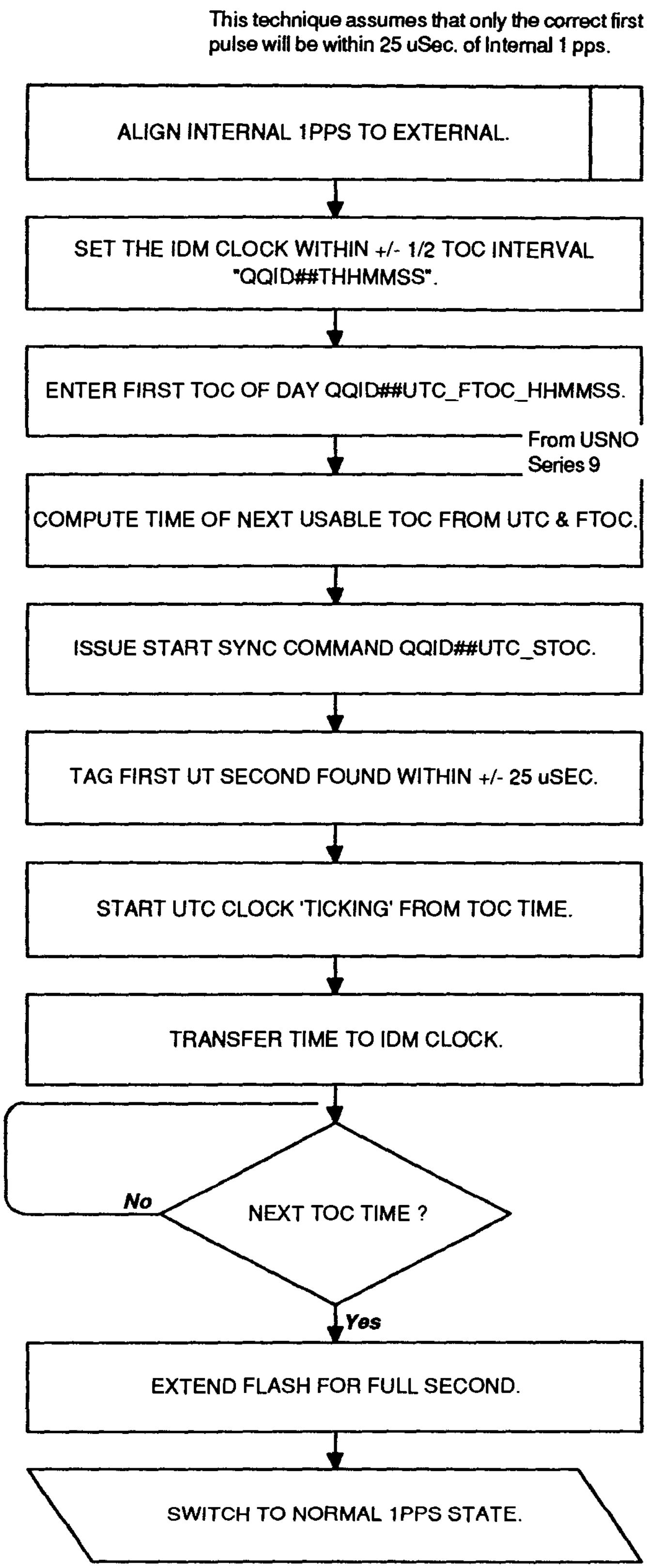


FIGURE 5. Automatic TOC and UTC Synchronization.



close to, but before, the specified pulse time.

CONCLUSIONS

The addition of the 1 pps capability to the ABS system makes available to the USCG a 1 pps TOC timing pulse which moves in time to reflect changes in the synchronization of the transmitted SZC. The system also provides a measure of the error between this SZC disciplined internal 1 pps pulse and an external 1 pps pulse, providing a continuous readout of the error between the LORSTA's 1 pps and a UT 1 pps signal. Including 1 pps into the ABS provided a relatively low cost, space and power efficient way of including 1 pps into the electronic suite of a standard LORSTA. This addition is currently undergoing testing by the U.S. Coast Guard Electronics Engineering Center at Wildwood, New Jersey.

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Mr. Poppe is an electronics engineer and President of *Cambridge Engineering, Inc.* He has a Bachelor's Degree in Electrical Engineering from the Massachusetts Institute of Technology, Cambridge, Massachusetts, and a Master's Degree from Stanford University, Stanford, California. Since forming *Cambridge Engineering, Inc.* 21 years ago, Mr. Poppe has worked on various navigation systems including Loran-C, Omega, Transit and Differential GPS.

In addition to Mr. Poppe's work on the Automatic Blink System (ABS), recent projects have included: the design of a DSP based timer for the USCG Omega Navigation System transmitters; the design of radiobeacon receivers to demodulate MSK modulated differential GPS data; and the design of loop antennas for the reception of radiobeacon signals.

Symposium Papers

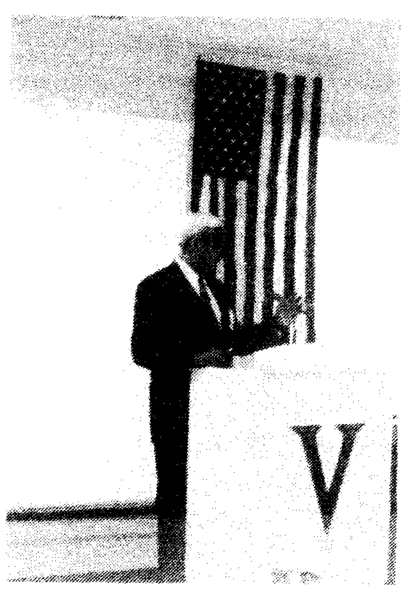
Session IV

Panel Discussion

Panel Discussion: "Is There Loran in the GNSS Future?"

A lively panel discussion can always be expected from this distinguished group of Geese!

Tom Thomas, David Last, Marty Shuey, Henry Marx, John Beukers and Will Johnson ...



...moderated by Mike Moroney!

Symposium Papers

Session V

Operations

Loran Performance:
A Report of Recent Operational Performance

by

CDR Louis R. Skorupa & LTJG Eugene V. L. Vogt

USCG Pacific Area (Ptl)

Abstract:

This paper provides an overview of Loran station operational performance in North America during a recent period of eighteen months. We analyzed types and amounts of unusable time and momentary signal outages by frequency, duration, and common causes.

Data was taken from operational reports to develop a database. The database was correlated with the types of stations so overall performance may be characterized. The impact of unusable events due to control, equipment failures, maintenance, propagation, and monitoring are included and examined. Groups of stations are compared by chain, crew type, remotely operated or manned, type of transmitter, and other relevant criteria. The database is examined using these criteria and graphics generated to simplify analysis and comparison.

This historical operational record is expected to reveal important information about reliability and recent performance history. This information should be of value to all persons responsible for planning, operating, or managing operational Loran systems.

Disclaimer:

Views expressed herein are those of the authors and are not to be construed as official or reflecting the views of the Commandant or U. S. Coast Guard. This paper describes USCG and Canadian Coast Guard Loran operations as an example, but does not recommend or describe official operational or maintenance policy or procedures. No endorsement of companies or products, either positive or negative, is intended.

Introduction:

A major challenge facing those individuals responsible for the operation of radionavigation systems is fulfilling extremely challenging requirements for operational availability. These requirements protect the safety of life and property of the public and system users. Loran systems operational management has used complex historical record keeping to track and characterize performance. Based on these performance measurements, and the in-depth analyses required whenever baseline criteria were not met, continuous improvements in system operations have been achieved. It is upon these existing historical records that this report is built and from which the data included here was extracted.

Gathering the Data

To accomplish this objective analysis, first the different monthly reports for all the North American Loran-C chains were gathered. While unusable time codes are standardized, some problems were found to occur. For example, lightning strikes at or near an unattended station, causes a commercial power flux, which results in a transmitter switch. What happened? Should the transmitter, power, lightning, or miscellaneous code be used? Each could be appropriate. So, the first challenge was determining the major classes of events of interest for the purposes of this report.

To facilitate across the board comparisons and analysis, we chose to use six momentary outage event classifications. Momentary reports originally given as described in the Atlantic or Pacific Area Regional Managers' Supplemental Instructions were converted to these classifications for graphing and analysis.

Momentaries

All data was gathered from chain operational reports, and is based on the station designator and Group Repetition Interval. There were 45 rate/designators entered, covering all the chains and stations primarily serving North America. For example, data on Lorsta Gillette Wyoming was entered twice - first all the data reported for 8290X, and then all the data reported for 9610V. Information on Labrador Sea and Russian American Chain stations in North America was not included, although the other rates' data from Attu, Fox Harbor, and Cape Race were. The data covered eighteen months, November 1992 to April 1994. We documented 14,775 momentaries. This is an average of just 18.53 momentaries per station rate/designator (i.e., Gillette, WY, 8290X) per month.

The momentary data was examined by classification in figure 1, "Total Momentaries - Percent by Classification." Following this, the momentaries were regrouped into a "Sum" of individual events. This sum was investigated to characterize system performance and to allow objective comparison and analysis between stations whether dual or single rated. In addition, monthly and station graphs of events are given, analyzed, and discussed.

In the graph of "Total Momentaries - Percent by Classification" (figure 1), please note that the leading cause of momentaries was Transmitters (XMTR) at 53.55%. This category is mainly composed of transmitter switches and overloads. In the Solid State Transmitter (SSX), these would be Output Coupler Network switches, while in the tube type transmitters it would include various types of overloads such as those due to overcurrent protection.

As noted earlier, transmitter momentaries often have a root cause related to power fluctuations, and in fact Power is the second most frequently reported cause of momentaries (17.81%). Also, both Transmitter and Power class momentary events frequently require a second momentary to switch back to or test the original configuration. An example is switching back to commercial power from generators, or to the original operate transmitter or SSX Output Coupling Network. This results in a higher impact of each individual initial event of these types to the total, as two momentaries often result.

Maintenance (MAINT), at 15.03% is the third most prevalent momentary cause. While significant, this area does not seem to offer major opportunities for reducing momentaries while ensuring all equipment is functional.

Of all the momentaries reported only 1.31% were the result of either Timing & Control Equipment (TCE) or Personnel (PERS). In fact, the Personnel total for the entire period was only 31 - an average station *might* have <u>a</u> personnel momentary in a *year!* Timing & Control Equipment is also performing exceptionally well, especially considering the age and complexity of this equipment.

The final category, Other, at 12.30%, is a catch all category. The comparatively high number of Other reports, especially when compared to Personnel and TCE, suggests that perhaps our reporting system should further categorize other areas. Future operational analyses might also be improved by breaking down the Transmitter and Power categories to allow more in depth analysis of these major areas.

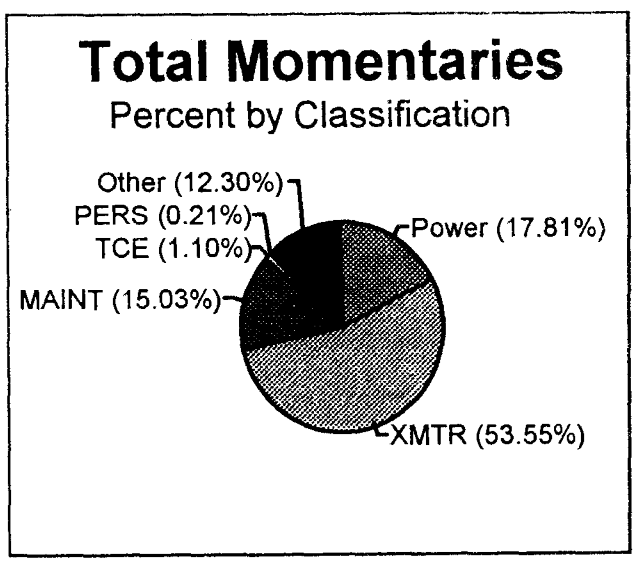


Figure 1.

Tube stations show a moderate distribution of total numbers of events. However, the distribution by class of events was fairly consistent. Combined average distribution by class is figure 5. The reported low was 128 events at Port Clarence - a manned AN/FPN-42 station with little lightning and their own generators. The reported high was 569 at Searchlight, which is an AN/FPN-44 station with frequent lightning and historically poor power. Last year, close work with the power company resulted in Searchlight's electrical feed being upgraded and lightning protection improved.

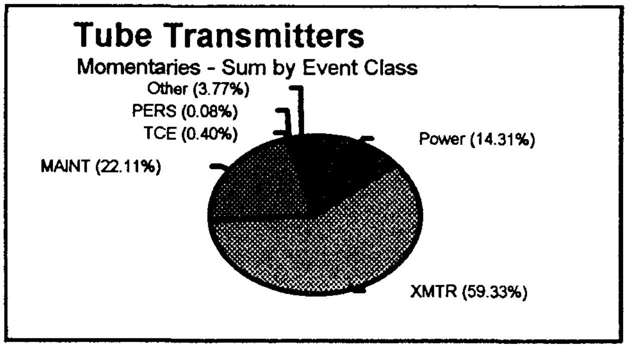


Figure 5.

SSX transmitters were consistently lower in average momentaries than other transmitters. Station local lightning and power conditions seemed to account for the variances in reported events. The SSXs averaged six fewer events per month than the TTXs. This is despite the fact that many of the SSX transmitters are located in severe weather areas.

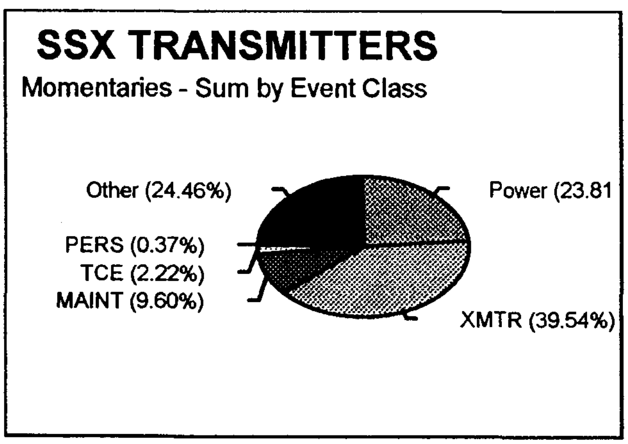


Figure 6.

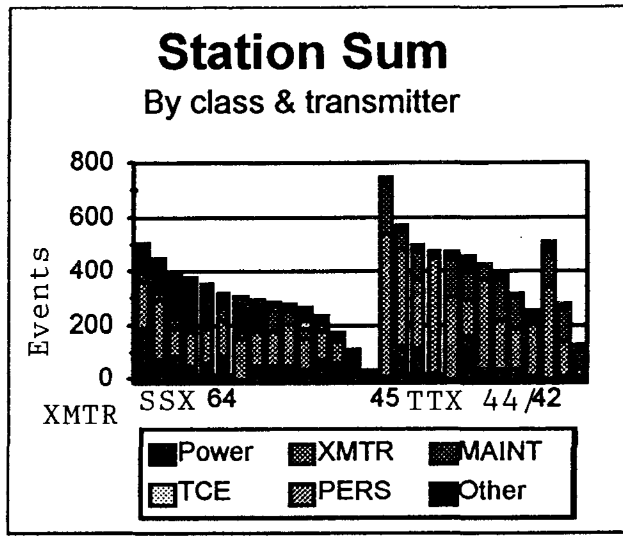


Figure 7.

"Station sum by class and transmitter," figure 7, shows the range and distribution of momentaries. The grouping of station totals shows quite clearly in this graph. The complete central tendency, range, and dispersion of events are shown. It is interesting to note that generally those stations with the best power - either very stable and reliable commercial power or generators, and few instances of lightning in the area, again had fewer power, transmitter, and overall momentaries, despite other factors.

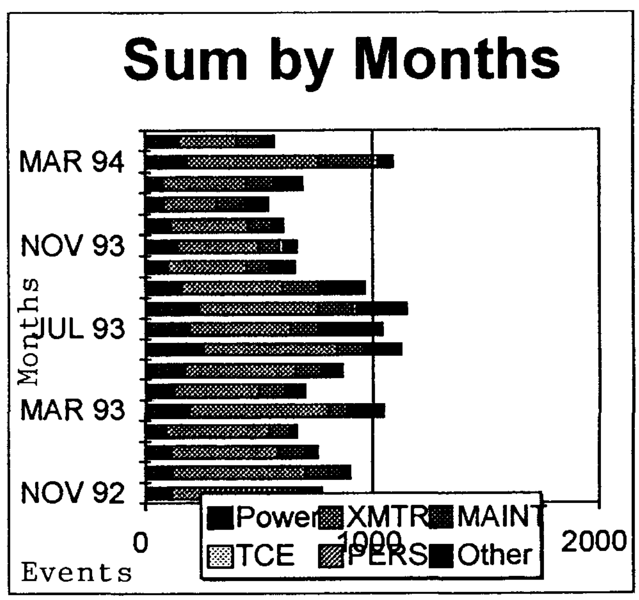


Figure 8.

Monthly momentary event sums in figure 8 show a very definite trend as well. There were over one thousand momentaries reported in North America during March, June, July, and August. These drastic changes in month to month totals are almost certainly due to weather. More exactly, increased numbers of events are likely due to lightning strikes and power fluctuations which accompany storms.

Long term performance being the key, the operational focus on reducing momentary outages is bearing fruit. Comparing this data with the data given in the "Signal Availability Requirement for Radionavigation Aids in the National Airspace System" dated March 1993, the U.S. West Coast Chain has reduced total annual momentaries over 22% since tracking began in 1987.

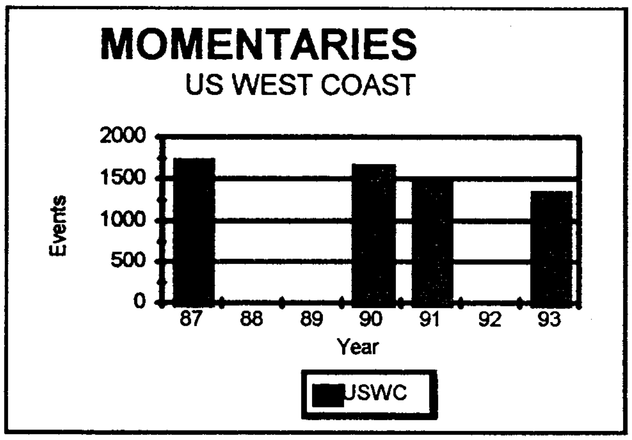


Figure 9.

Charts of stations manned or Remote Operating System (ROS) when compared showed no significant difference in momentary totals or distribution. Rather the opposite in fact - the stations totals and distribution of momentary classes followed quite closely other station characteristics below. Based on these charts it becomes apparent that the crucial issues in overall station momentary performance are the: 1) type of transmitters, 2) quality & control of power, and 3) severity of lightning & weather.

The fact that these items are major factors is not a revelation to operational chain management. However, it is interesting to note that those areas with the largest impact on operations are those over which we have the least control.

Conclusions on Momentaries

The margin of difference in performance between tube and SSX transmitters, though significant, was not as great as was anticipated, with the notable exception of the AN/FPN-45 transmitter. In all, power and weather appear to be the most heavily weighted variable factors. Of course, Loran chains are designed to provide coverage in a service area, which means that suitable sites' can not easily be chosen by weather patterns to reduce momentaries.

A recent initiative by the USCG Electronics Engineering Center has field tested a change to the SSX transmitters to decrease sensitivity to power and lightning caused faults. This is expected to reduce momentaries as well. Perhaps in the future new options in power configuration and back up will allow further improvements in operational performance.

Maintenance momentaries average just 2.74 per station per month. Still, some improvement in this area may be achieved by maintenance procedure changes, particularly with the Solid State Transmitter (SSX). One idea is increasing the period between required switches. Stations testing reduced SSX switches for maintenance have had very good success. U.S. Coast Guard Planned Maintenance System feedback reports were submitted to recommend these changes.

The West Coast and North Central U.S. Chain stations get a descriptive rating monthly on momentary performance. "Outstanding" to "Unsatisfactory" is the range. This provides timely performance feedback to the stations. To objectively compare stations the data suggests using a base level of 20 momentaries per station/rate. Modify this base by transmitter as follows: SSX x 1, AN/FPN-42 or 44 x 1.25, and x 1.5 for the AN/FPN-45. Power and lightning should also be assigned factors, probably .75 to 1.25 each. Since this relates back to overall system performance, any factors used for power or lightning should be relative. In other words, the product of all the factors should equal one. Applying this quick rule yields a performance comparison figure of average or "Satisfactory" performance. System managers can use these figures to give quick feedback, to identify trends, and to recognize problems and opportunities.

Unusable Time and Events

We evaluated all causes of unusable time (UT) during these eighteen months. A database was established and over seventeen hundred entries made from operational reports. This database described over 40,000 minutes of total unusable time using the categories established in Coast Guard Commandant's Instruction M16500.13, the Aids to Navigation Manual, Radionavigation, pagers 2-93 through 2-102. These categories are Transmitter, TCE, Communications, Monitor, Power, Personnel, Miscellaneous, and ROS.

Unusable Time & Events Analysis

The chart "Unusable Time - Percent by Category," figure 10, characterizes all unusable time for the period. This analysis revealed many interesting facts about long term operational performance.

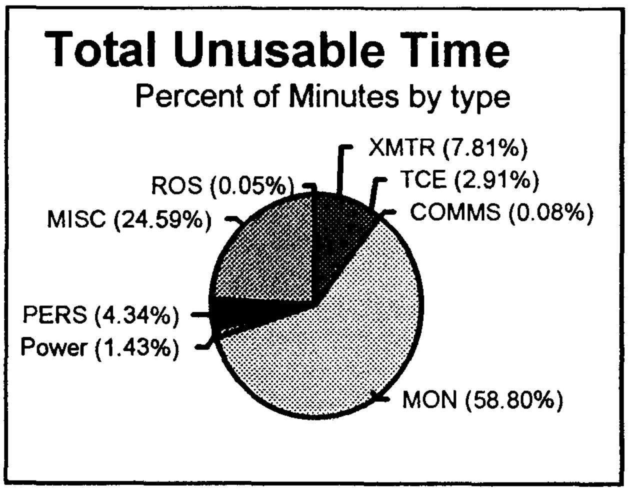


Figure 10.

By far the leading cause of unusable time is category four - Monitor Equipment. This category comprises almost 59% of *all* unusable time. On further review this becomes even more striking - the majority of category four time is caused by Sudden Ionospheric Disturbances (SIDs), which affect remote signal monitoring and reception. *This means the transmitted signal and equipment are not at fault.*

Furthermore, since SIDs and other Monitor category events are caused by solar and geomagnetic activity, the frequency, duration, and most particularly area of impact varies. Virtually all of the SIDs reported during this period occurred in Alaska. These northern stations are located under the polar auroral cap and are more frequently and severely impacted by solar, ionospheric, and geomagnetic activity. For the stations in the U.S. West Coast and North Central U.S. chains, little or no impact has been observed from most solar flares of class M5 or below. SID impact should vary with the number and intensity of solar events and the solar cycle.

Miscellaneous is the second most significant cause of unusable time at 24%. Again, a closer review of the individual items reveals a distinct pattern. Most AUTM periods were reported in the Miscellaneous group. These AUTM periods are needed to protect long term chain operations. Properly managed, although the impact is significant, it is necessary.

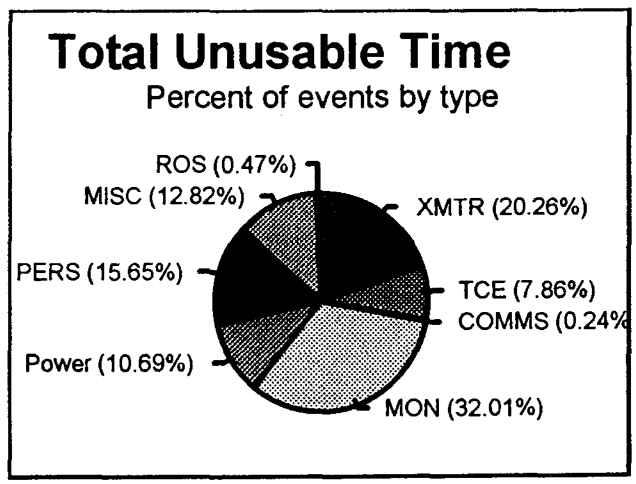


Figure 11.

Figure 11 shows the distribution of unusable events. Figure 12 gives the average number of minutes per event by type. Together, figures 10, 11, and 12 tell how each type of event impacts operations. The severe impact of SIDs and AUTMs on system availability is apparent. For performance tracking and operations optimization it is obvious that SIDs and AUTM are special cases. SIDs and AUTMs do not indicate how station equipment and personnel are actually performing.

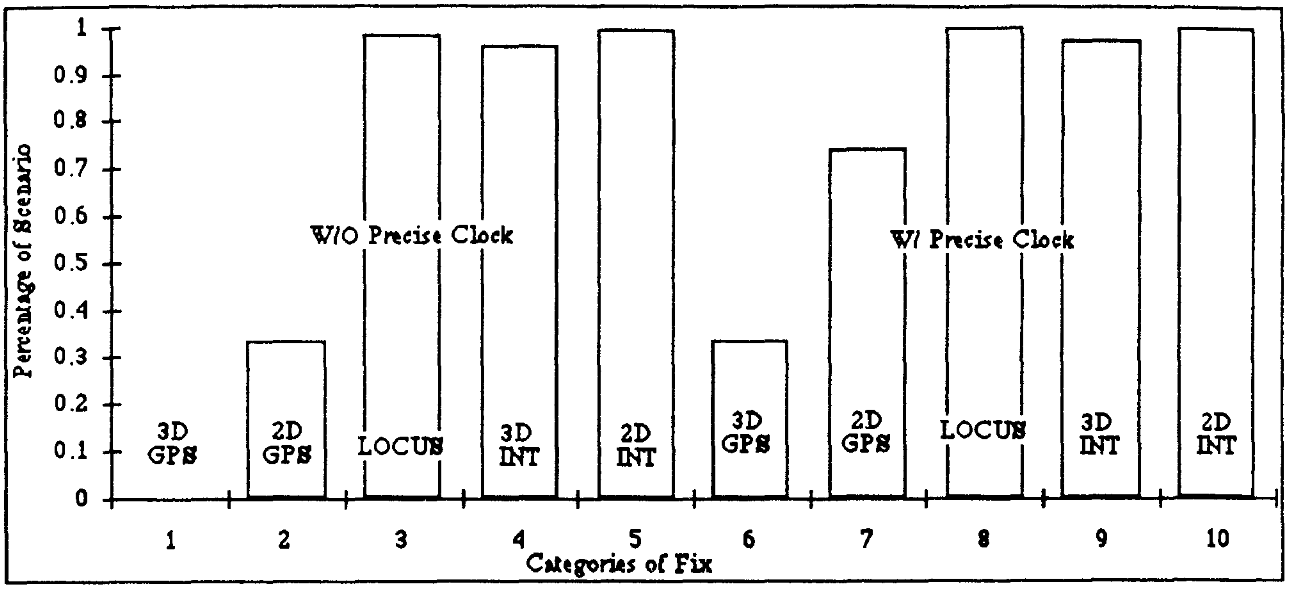


Figure 7. Fix Availability as Percentage of Distance into Scenario, Foliage Run 1.
GPS receiver is 12-Channel in all cases.

The second part of the analysis attempts to determine the potential accuracy of LORAN in the New York City environment. The LOCUS receiver was modified to use a Cesium frequency reference and to calculate a fix based on two TOA's when only two signals were available. Even though, as shown in Figure 6, the LOCUS receiver indicated it was tracking two stations (Seneca and Nantucket) 53% of the time for the 28 July, Wall St. scenario, based on our HP89410A measurements of the LORAN E-field signal, and on the large fix error in even those not flagged, it is not clear what it was tracking. Figure 8 shows the results of measuring phase of the H-field using the HP89410A. We consider this data the most significant obtained. The measurement is sub-optimum as only one of sixteen pulses per PCI is used, a loss of 12 dB in SNR, yet the phase is quite repeatable from scenario to scenario.

This indicates that the H-field LORAN signal is usable in the deepest urban canyons. No attempt was made to select the appropriate zero crossing (i.e. resolve 10 μsec. ambiguity in TOA). Future efforts will focus on that issue and on the solution of position when such large phase shifts are present. It is unclear whether the large, repeatable phase shifts are actually in the RF, or due to (repeatable) shifts in the magnetic heading sensor/analog switches in the Megapulse loop antenna system.

Summary

Based on our preliminary analysis of the extensive radionavigation data collected in New York City during the period 26 July-7 August 1994, we make the following conclusions: 1. The LORAN E-field signal in the deep urban canyons is virtually unusable, the H-field signal is relatively much stronger and has repeatable phase. 2. The availability of LORAN H-field in the urban canyons and either LORAN E- or H-field under foliage is better than GPS. 3. In many areas and particularly Wall St., only Seneca and Nantucket, but not Carolina Beach can be received, so fix availability is considerably enhanced by the addition of a precise frequency reference enabling fixes from two TOA's. 4. The addition of this frequency reference to GPS and the integration of LORAN and GPS also enhance fix availability. 5. A twelve channel all-in-view GPS receiver performs significantly better than a six channel receiver.

Acknowledgements

This project was sponsored by the Advanced Research Projects Agency under project CO74. The cooperation of the companies mention in this report is greatly appreciated. The hard work and long hours of Mr. Lance Miller of SAIC, and LT Steve Bartlett, presently in graduate school at North Carolina State University were sincerely appreciated. In addition, without the generous support of the Ferryboat Maintenance Facility at the Coast Guard Base on Governors Island, completion of this effort would have been impossible.

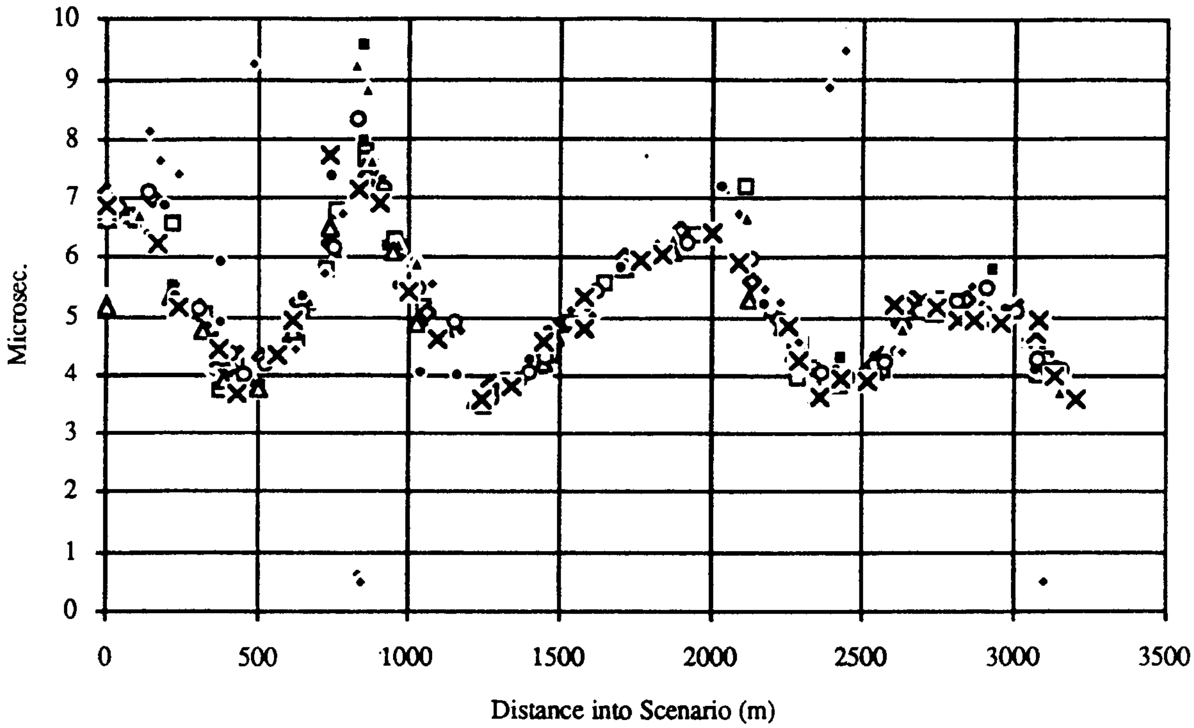


Figure 8. Phase Shift Relative to Ground Truth for Seneca.HP89410A, H-Field Antenna over nine Wall Street Scenarios

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Dynamics of Loran-C Skywaves

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Abstract:

In the course of testing LOCUS' Linear Averaging Digital (LAD)-LORAN receiver and other receivers, we have observed that a number of receivers use extremely long ECD averaging times. At 0dB S/N, these times are often several hours, compared with the 60 seconds or so used by the LAD-LORAN receiver. To find out why times vary so much, we collected waveform and ECD data at LOCUS' facility in Madison, Wisconsin. Resulting data show Loran skywaves vary in amplitude and phase on many time scales. This instability is most troublesome during the hours around sunrise, but nearly instantaneous dropouts of the skywave can happen any time at night. Skywave instability also adds to the interference which receivers suffer from crossrate signals, specifically receivers capable of processing from only one or a few chains simultaneously. Data demonstrate correct cycle tracking requires compensation for the ECD anomalies which are caused by these skywaves, and the LAD-LORAN receiver provides the necessary compensation. It is likely receivers based on other technologies must average the ECD for hours so the anomalies will not cause cycle slips.

We begin with data for received signal strength and waveform peak for the 8970 secondaries taken over the course of a typical night. The data are taken in a standardized way using a LOCUS LAD-LORAN receiver. Points are taken at 60 second intervals. TD averaging is set for 60 seconds with a simple first order filter. ECD averaging is approximately 60 seconds at 0dB indicated S/N, and doubles with each 3dB loss of S/N. For S/N better than 0dB, a soft floor of approximately 20 seconds is ultimately reached. Nominal field strength (ground wave) and peak field strength are plotted in dBuV/M, but they include an indefinite antenna factor resulting from roof mounting of the E-field antenna. They are plotted as an indication of the skywave size; when there is no skywave, the peak value is approximately 6dB larger than the nominal value.

The data in Figure 1 make it clear that Madison is well situated near a service area. Provided that M, X, and Y are on the air and the receiving antenna is well located, there are no tracking problems during a typical night. The geometrical triad is not too large; Y is 732KM away, and X is 1022KM away.

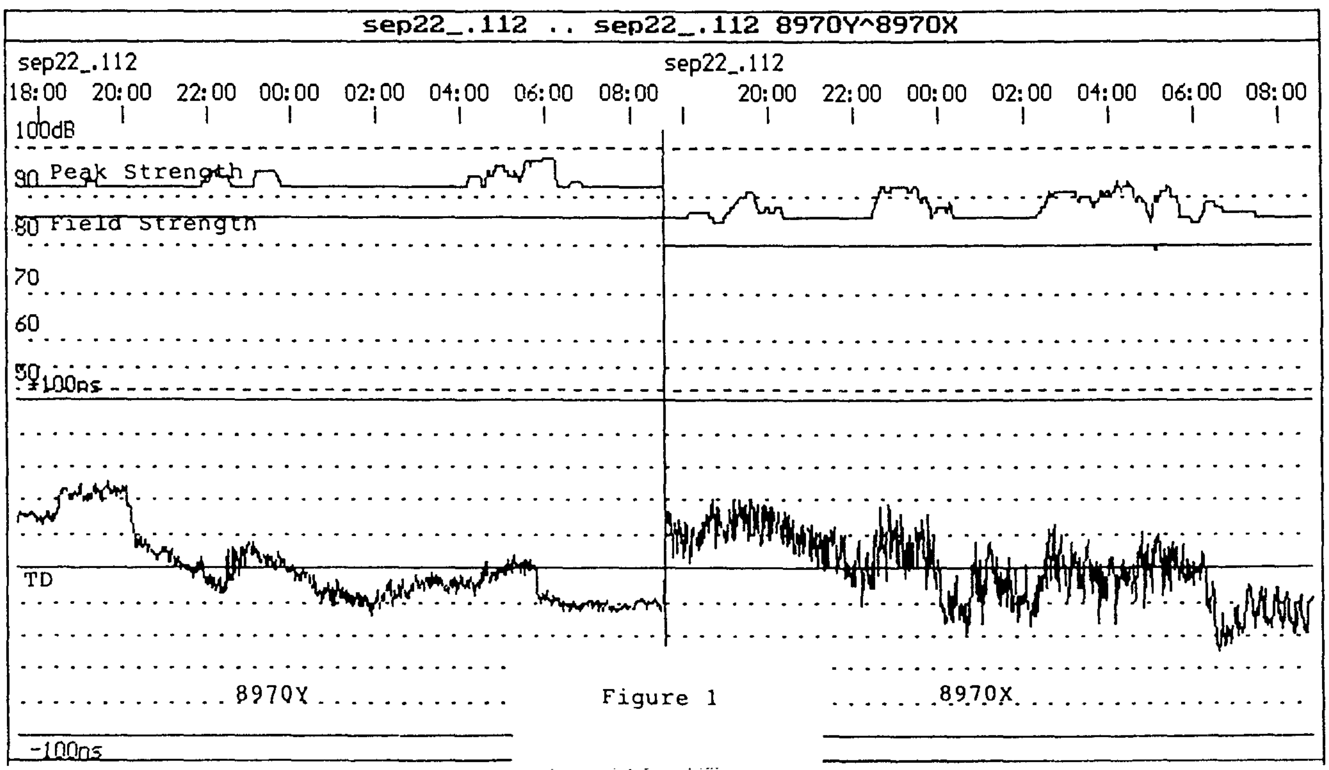

Figure 1

The X track is showing a considerable amount of 20nS oscillation arising at the transmitter[1], so its apparent noise level is misleadingly high.

To produce a high quality receiver, we must model and account for real world operation at a distance over the oceans, in fringe areas, and at high latitudes. In these circumstances, ground conductivity is poor and skywave reflections come earlier than they do under the favorable conditions of the American midwest. Accordingly, we must also look at data from more distant stations and see to it that the LOCUS LAD-LORAN receiver will track it correctly. Figure 2 shows the slightly more distant stations 8970 W and Z:

The data from Figure 2 show a sunrise disturbance for W which is about three times the size of that for Z. This is interesting, considering that the distances to the stations are virtually identical, at 1396KM and 1372KM respectively, and the power ratings are identical at 800KW. Clearly, we can't predict the degree of disturbance and instability by looking at distance and power alone.

They also show that although the skywave amplitudes are roughly comparable, the W skywave shows a very sharp, sudden dropout shortly after midnight (circled in Figure 2, 8970W). No similar event occurred on Z at the same time. Clearly, skywaves from stations at similar distance are not always correlated. It will not suffice to apply a skywave correction which is a simple function of distance.

[1] *"Loran Transmitter TD Instability"*, P.Schick and T. Blandino, The Goose Gazette, Winter 1994.

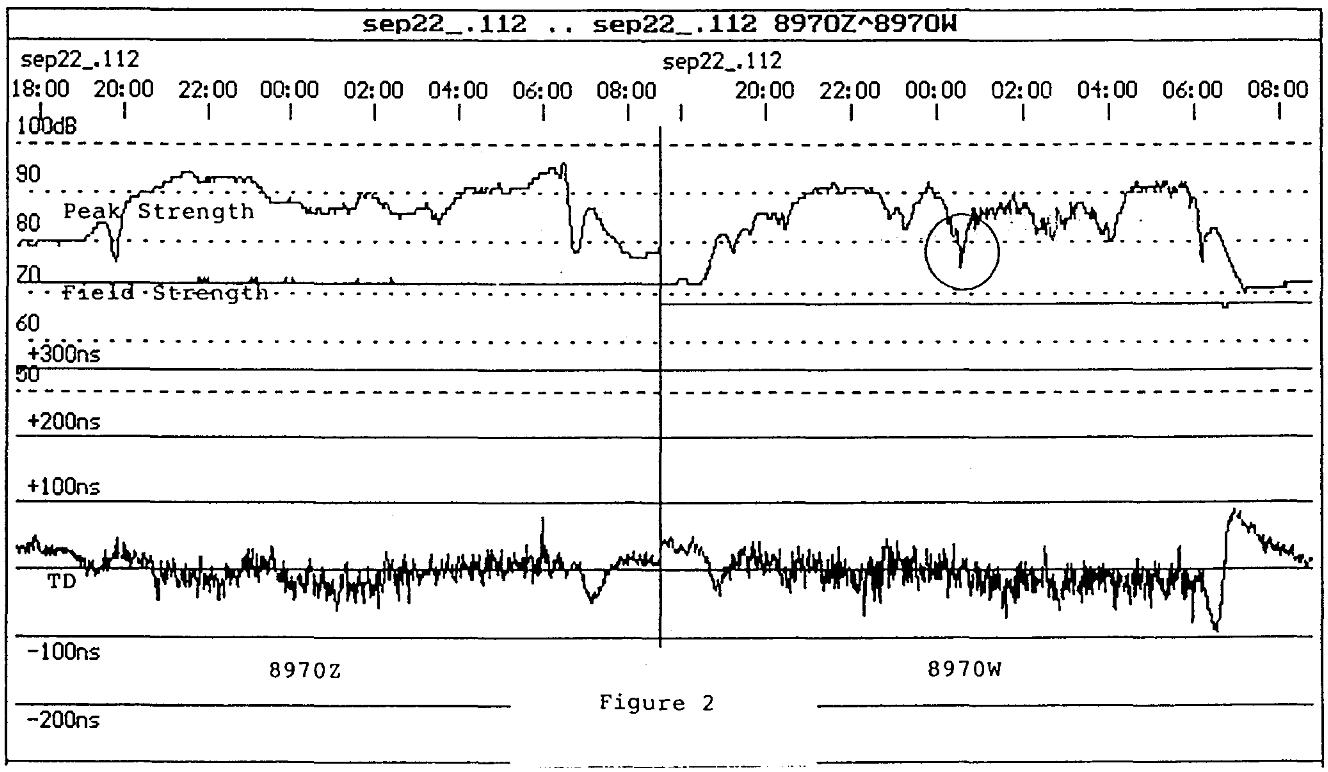

Figure 2

Finally, to complete the picture, we look at two very distant stations. Figure 3 shows 9960W, a 350KW station at a distance of 1732KM, and 7980X, a 400KW station 1995KM away.

In Figure 3, we observe something very peculiar. Because 9960W is significantly closer, we expect it to show a signal level about 4dB larger than that for 7980X. Instead, its ground wave is virtually missing, 8dB smaller than 7980X and 12dB smaller than what we expected, so that the TD trace is quite noisy. In addition, the ratio of sky wave to this weak ground wave resembles ratios reported anecdotally for high latitudes.

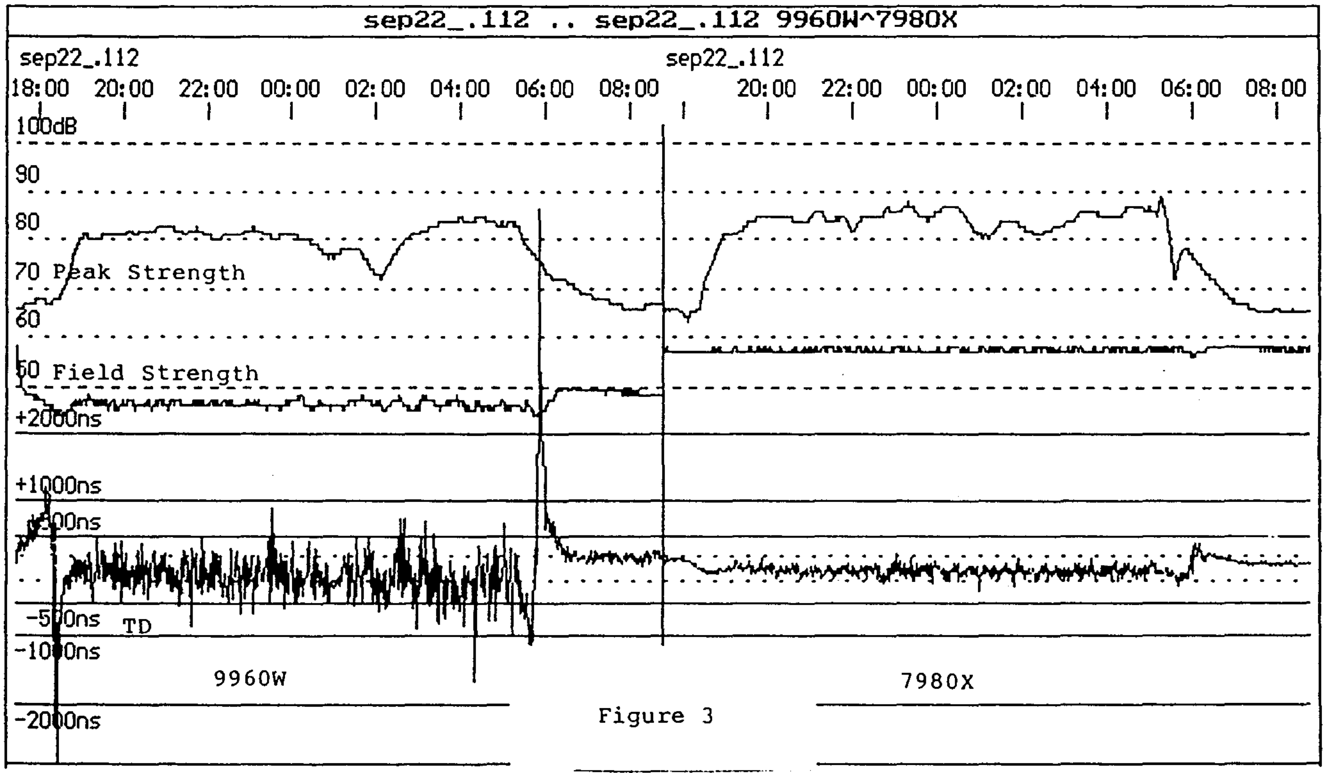

Figure 3

We turn now to ECD measurements. Figure 4 shows an ECD track for 8970W, as measured by two LAD-LORAN receivers:

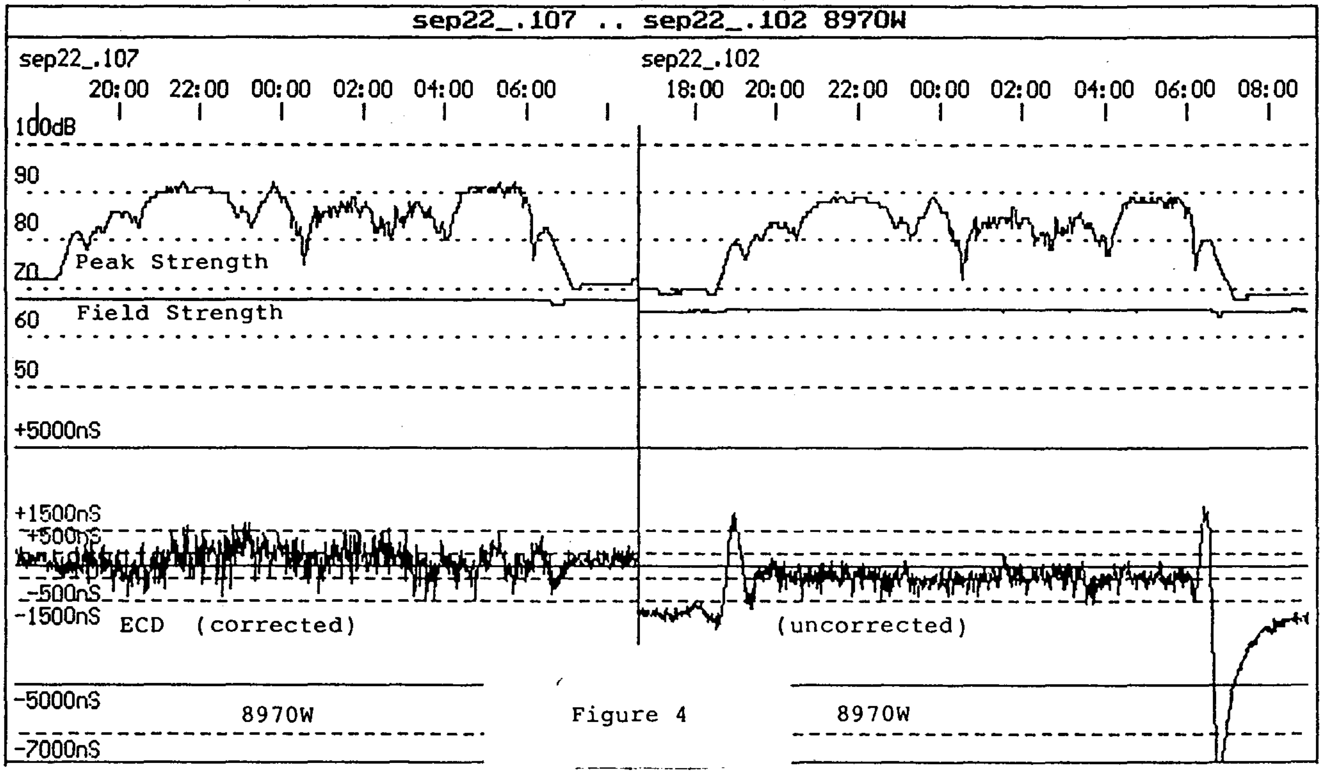

Figure 4

The left-hand version shows a track corrected for skywave effects. The right-hand version shows an uncorrected track designed to approximate the effect of using the industry standard add-and-delay circuit. Note that most receivers which actually use that circuit will show between 50% and 100% more ECD variation than is on LAD-LORAN's trace. This extra variation occurs because their bandpass filters are usually much narrower than the one in the LOCUS receiver.

There is a cost of correcting for skywave effects; one must either determine what the skywaves are and subtract them out, or else do something which has much the same mathematical effect. In this case, short term noise increases by about 6dB, and at night, there is somewhat more of the slow wobble. On the other hand, the value in the quiet right-hand trace isn't suitable for tracking, because it goes out of bounds for 40 minutes around sunrise. Nor is it suitable for ECD measurement, because the nighttime mean is two microseconds more negative than the daytime mean, due to the daytime skywave. In short, the uncorrected value is like more than a few numbers encountered in financial reports: reproducible, consistent, precise in some sense, and useless.

We now need to ask what it is that can render an uncorrected receiver useless for a period of time in this way. Previous efforts[2] have been made to collect waveform data and fit skywave models to it. LOCUS' LAD-LORAN receiver can be set to periodically dump waveform information from a station. Such a data run for 8970W is illustrated by the sequence in Figure 5, which begins just before sunset, 17:15 (local time).

2 *"Loran and the Effects of Terrestrial Propagation"*, Capt B. Peterson and Cadet K. Dewalt, U.S. Coast Guard Academy, May 1992.

Around sunrise, the rapidity of the variation of the waveform can't be overstated; the 0447 and 0449 (local time) waveforms deserve special attention. In addition, the pulse shows very severe distortion at 0544, and this distortion begins so early that the ground wave is visibly affected at the 30uS point (also see Expanded Detail). The ECD of this pulse is essentially unmeasurable by the traditional approaches. The amplitudes of the peaks of half cycles immediately surrounding the waveform reference point are corrupted. One remedy is to measure ECD earlier in the waveform; however, the noise goes up approximately with the cube of the degree of earliness, and the loose published tolerances for transmission of the first cycle come progressively into play. The traditional value of 30uS or so (in the USA) is really about as short as one can go.

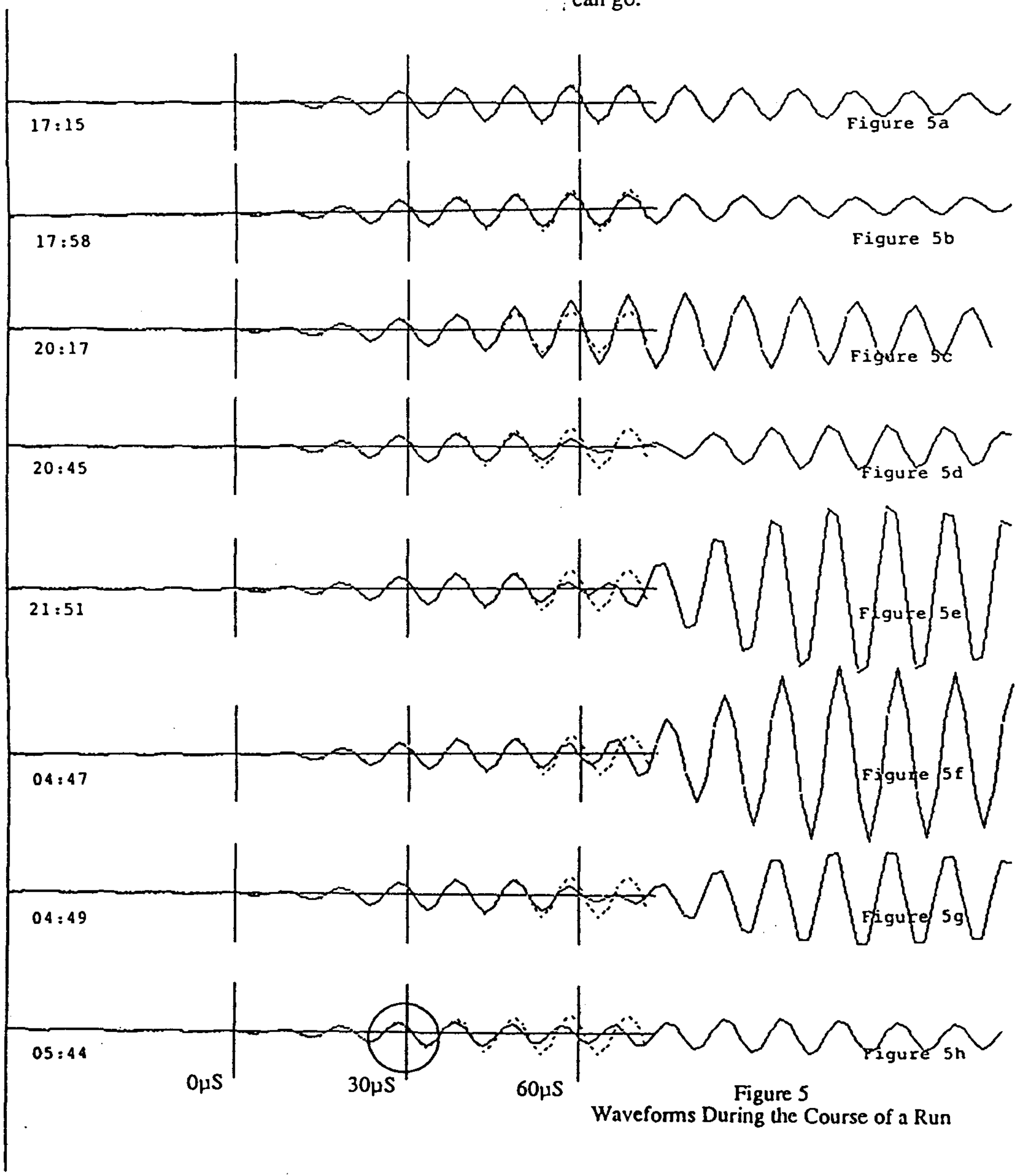

Figure 5
Waveforms During the Course of a Run

Figure 5h - Expanded detail at 30 uS.
Reference time 05:44.

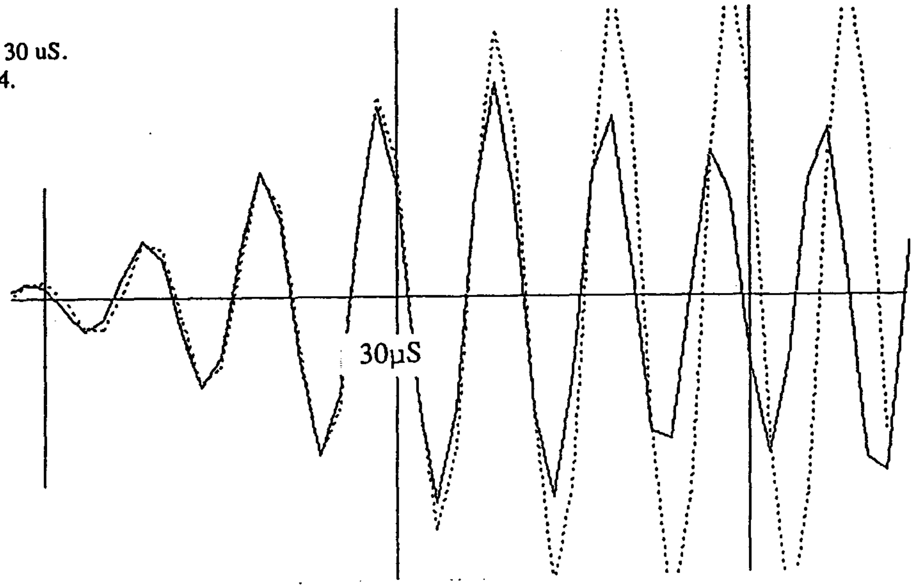

Figure 6 shows the events beginning at 0448 in more detail. Successive waveforms in the figure are approximately 35 seconds apart.

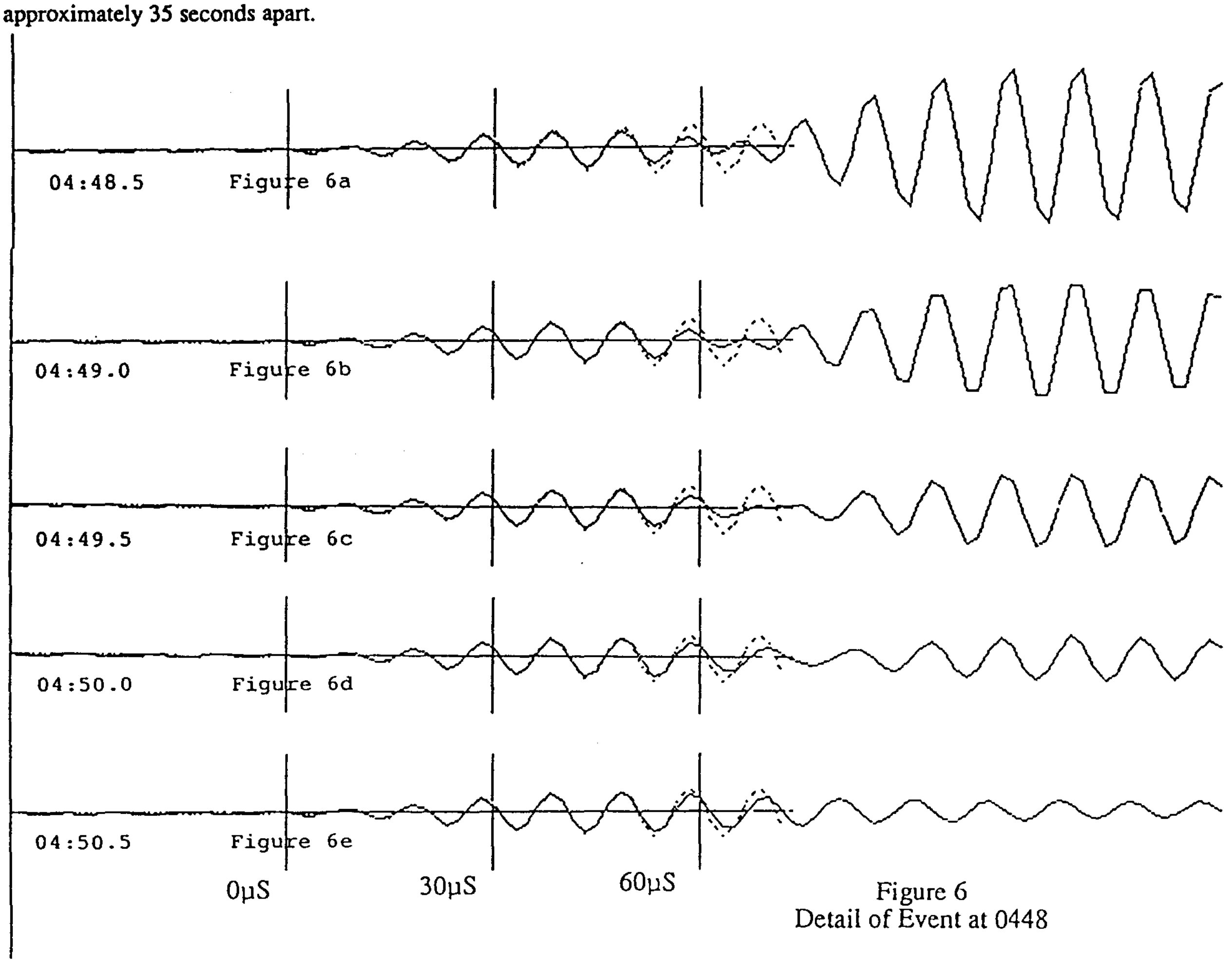

Figure 6
Detail of Event at 0448

At the greater distance of 7980X, the results are more interesting. Figure 7 shows similar data for that station, 1995KM away:

The successive figures show the skywave sliding away, a process which begins more slowly and then speeds up. The state which is reached before solar absorption sets in shows a severely distorted waveform (7f).

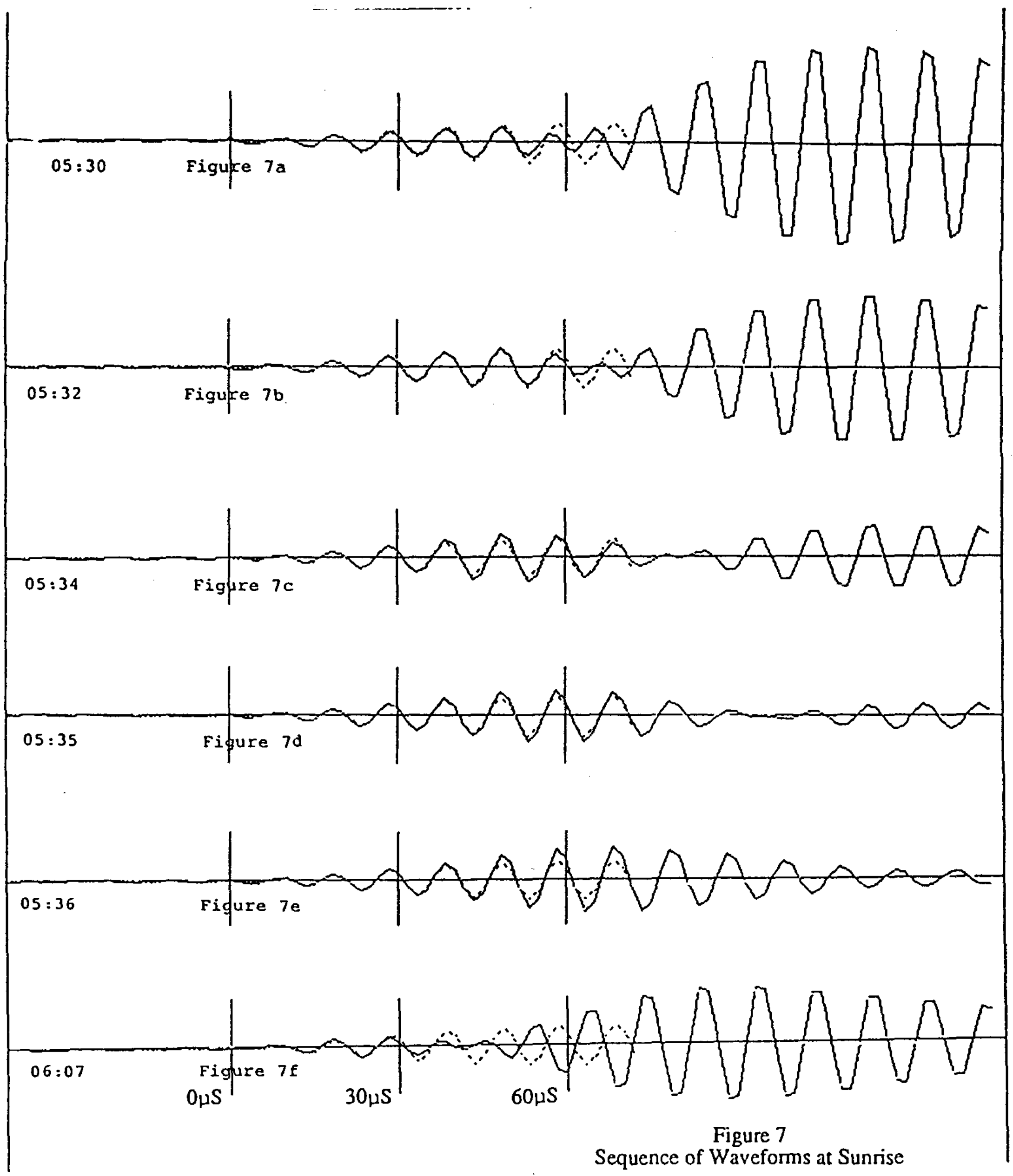

Figure 7
Sequence of Waveforms at Sunrise

For nearby stations at Madison's latitude, and during "typical" times at a good site, the skywaves are less severe and they originate further away from the groundwaves. The waveshape tends to change more slowly and less severely. Nonetheless, the data in Figure 8 show that high-speed changes in skywave phase and shape are possible at such times:

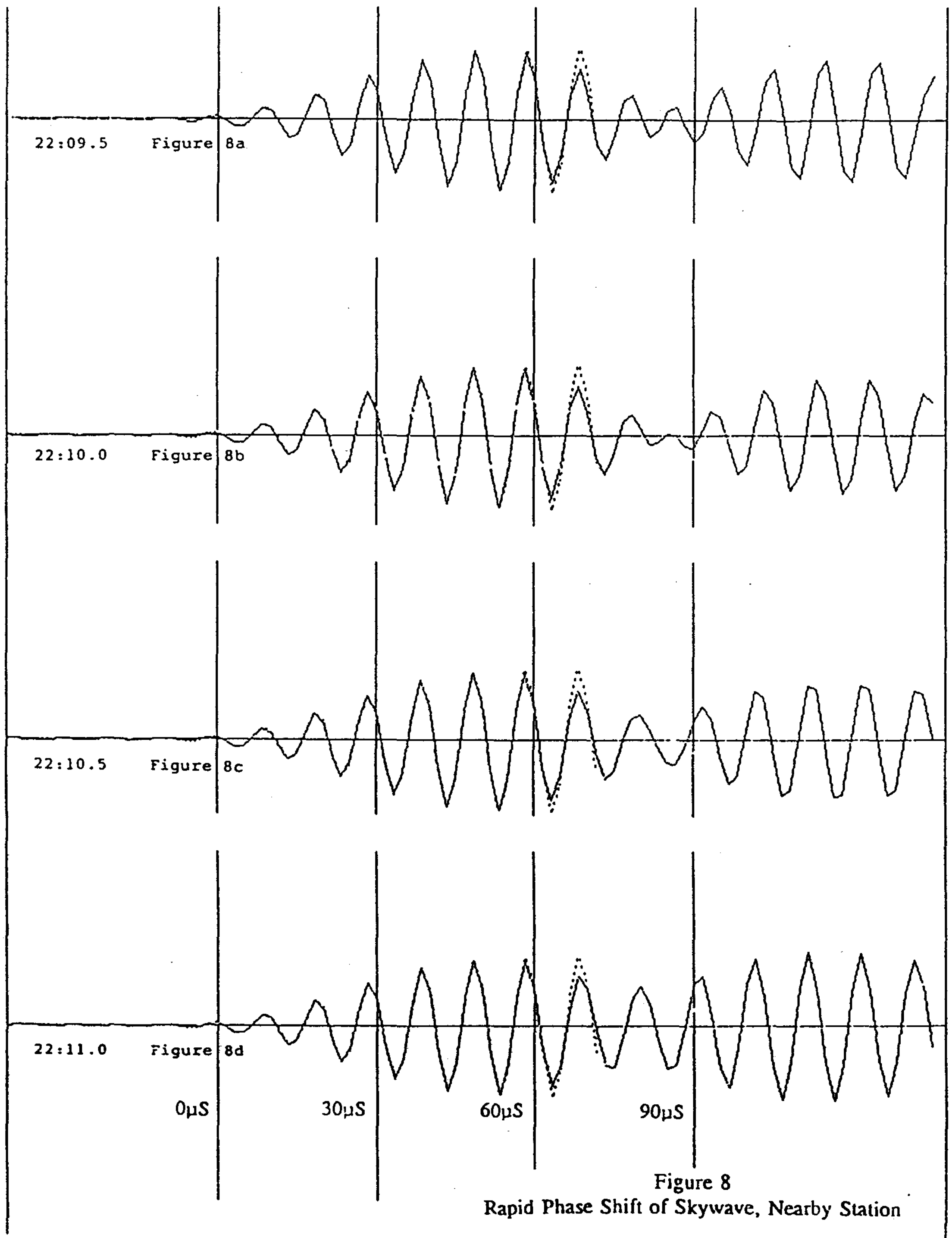

Figure 8
Rapid Phase Shift of Skywave, Nearby Station

However, during rainy weather when the cold front attached to a very large upper air storm was passing through, the skywave amplitude was quite noisy and unstable for a period of several hours. A set of four waveforms taken 48 hours later during the same run shows one of the larger changes, where the skywave amplitude nearly doubled in 100 seconds.

This sort of behavior seems to suggest that tropospheric weather has some effect on the skywave reflections. It is also possible that the data coincide with a geomagnetic disturbance.

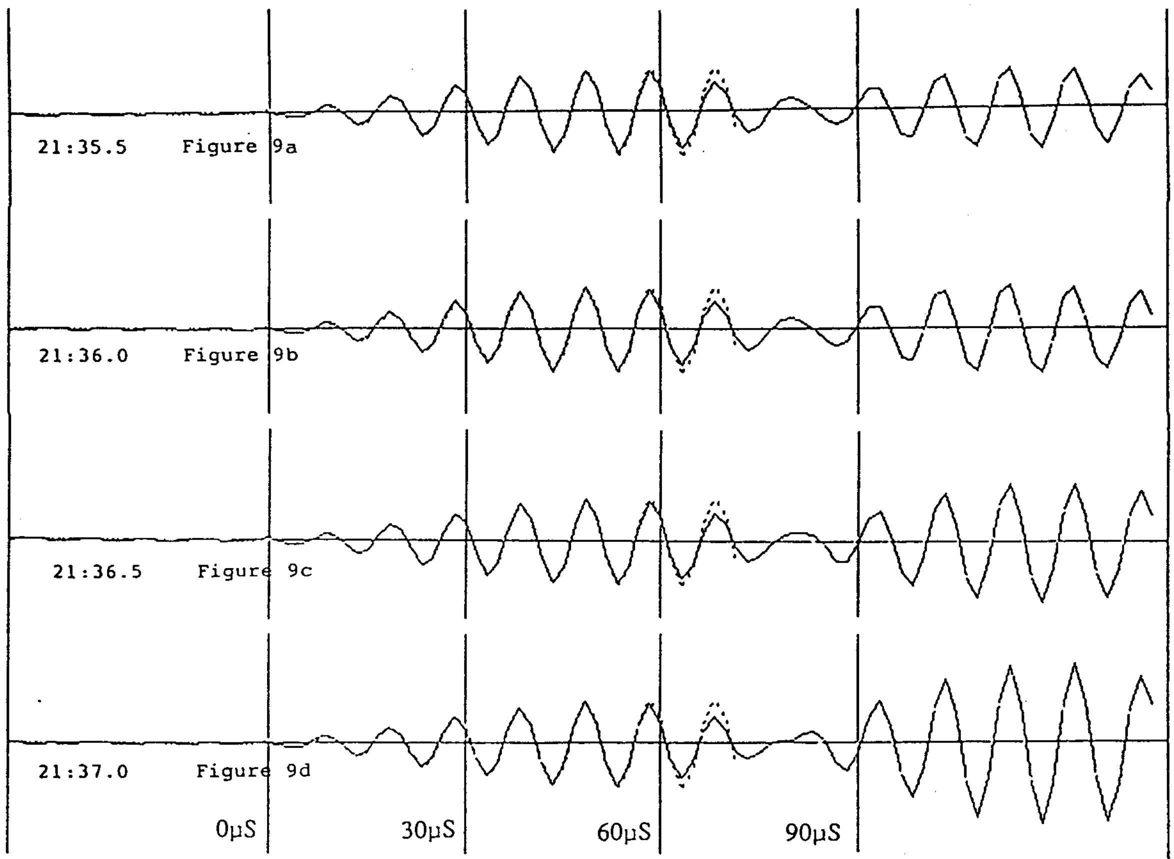

Figure 9
Rapid Change in Waveform from Nearby Station

Summary

In summary, skywaves are not always a slowly varying phenomenon. The ECD distortion caused by the skywaves will be unstable on a variety of time scales. While averaging helps at the short time scales, it becomes less helpful at the longer ones, and the practical result is that if no correction for skywave distortion is made, ECD averaging and cycle correction must be made so slow as to be nearly useless under conditions which are often encountered in practice.

While an uncorrected receiver can be made to work at some places and some times, it will usually be necessary to employ some skywave correction at twilight and during the night, and in fringe areas. LOCUS' LAD-LORAN receiver accomplishes the corrections by abandoning the traditional add-and-delay circuitry and performing the ECD computation with proprietary digital signal processing techniques, thus extending its tracking range 400KM or more beyond what is traditionally considered possible.

The N.E.L.S Network
(Northwest European LORAN C System)

Presented at the meeting OCEANS 94 (Brest - FRANCE)

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ABSTRACT

In order to put an end to the rumours of giving up of the LORAN C, this document, after a recall of the main characteristics of that radio-navigation system, shows the architecture of the new European NELS network, the policy of taking in charge of LORAN networks by the European states and the European Union, and also the extension and new utilization prospects, particularly in time/frequency scope.

The N.E.LS. Network (Northwest European Loran C System)

1. Introduction

At the present time, a large number of people know the radio-navigation system GPS (Global Positioning System). The Gulf War made it partly famous. Everywhere in the world, its user will be able to know easily his position, his vertical elevation and, in some cases, the time.
But, look out! The GPS is entirely under the authority of the american military. So, at any time, the non-aware user can be decoyed about his real position. This is the reason why it is advisable not to have a complete reliance in only GPS system.
So, a second system of navigation assistance is available in many areas of the northern hemisphere : the LORAN C. Many of you probably think that this system is going to disappear shortly because of the notice which came out in the Federal Radio-Navigation Plan (FRP) . As a matter of fact, all the LORAN chains located out of the american territory will not be operated any more by the United States Coast Guards after December 31st 1994.
In order to keep further means to GPS, absolutely necessary for the safety of the navigation, some countries decided to join in operating, modernizing end extending the networks given up by the USCG.
After the recall of LORAN characteristics, we will treat of:
- the future networks to be set up in europe.
- the utilization prospects of LORAN wave.
- the position of LORAN in the European Union policy.

2. General characteristics of LORAN

LORAN C is a low frequency radio navigation system (LOng RAnge Navigation). The carrier frequency is : 100 kHz.

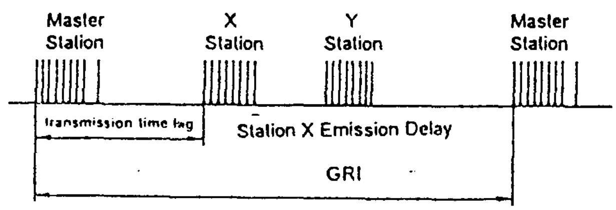
This is a land-based system organized into chains Each chain usually comprises a master transmission station and 2 to 4 secondary stations.

The user of this system can. with an appropriate receiver, obtain his position on the Earth. The operating modes can differ depending on whether the receiver uses the signals from 2 transmitters (circular mode still called "rho-rho-mode" or 3 transmitters in the same chain (normal hyperbolic mode) or 4 transmitters in 2 different chains (cross-rate hyperbolic mode) to calculate its position.

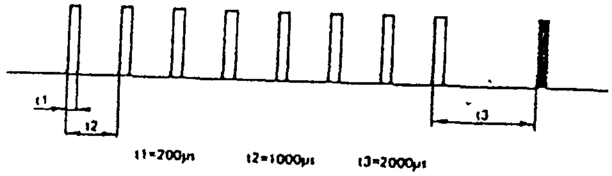
The rho-rho mode implies that the user must be in possession of a time reference linked with the time reference used by LORAN network.

2.1 LORAN C SIGNALS

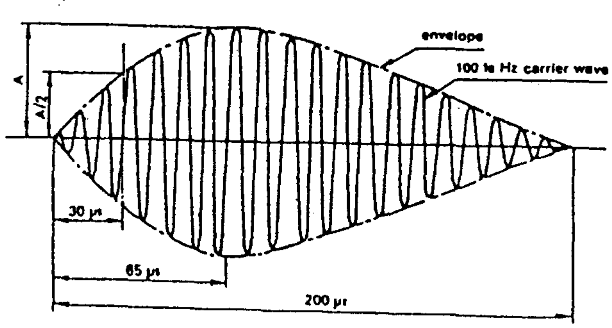
The LORAN C signals transmitted comply with a basic specification drafted by the USCG : M 16542- 4 July 1981



Sequencing



Pulse group



LORAN C pulse

. Carrier frequency : 100 kHz

. Pulsed signals
. master station : 9 pulses
. secondary stations : 8 pulses

. Pulse form such that 99 % of the energy is within the band : 90 to 100 kHz.

. Chain recognition : GRI (Group Repetition Interval).

. Phase Code : this is the sign of the first half-waye of the LORAN C signal. This code also allows recognition of a master station from a secondary station

The blink is a continuous warning system for users when the signal transmitted by a station is not absolutely safe for navigation. It consists in blinking either the 9th pulse of a master station, or the first two a secondary station.

. **Range** : this depends on the power of the transmitter and the sensitivity of the receiver. For a 250 kW transmitter, it is about 1000 NM for -10dB reception at sea.

2.2 SYNCHRONIZATION

Synchronization of a LORAN C chain follows two principles :

The **SAM** mode (System Area monitor). This mode allows synchronization of the secondary stations with the master stations. An SAM station located in a triad allows measurement and checking of the hyperbolae intersection point in relation to the reference point. As a general rule, this mode is manual. It is today used in most chains around the world.

The **TOE Control mode** (time of emission control) : this mode is used to control the time of emission from the stations in relation to the master station and in relation to a reference time. This control is therefore per station and per chain, in order to maintain the EDs (emission delays) constant for the given chain. The French chain is synchronized on this principle, as will be the case; from 1995, for the Northern Europe chain and for european Chain to come.

2.3 the LORAN in Europe

In 1987, six european countries, Denmark, France, Germany, Ireland, Netherlands and Norway decided to design and operate a radio-navigation system: the LORAN C.

By modernizing the four existing transmitters (Denmark, Germany, Norway), by creating three new ones (Ireland, Norway) and adding the two transmitters located in France, it became possible to ensure the sea coverage of a large part of northern Atlantic ocean, from the portuguese coasts to the Norway sea. (see figure).

On the 6th august 1992, at Oslo, the six governments above-mentionned created the " Europe of radio-navigation " with LORAN, even before the Maastricht treaty was ratified.

2.4 The NELS network (Northwest European Loran C System.)

a) Characteristics

- 9 transmission stations distributed in four chains . See figure 1.
- Availability: 99.9% for one station by periods of one month.
- Notice. The figure 1 gives NELS coverage in hyperbolic mode, with a location accuracy better than a quarter of mille.
- Synchronizing : time of emission control (TOE), UTC(B) time reference (Universal Time Reference coordonnated to Brest). Synchronizing of transmission times of the station in relation to UCT(B), better than 100 ns.
- Setting up : a control center located in Brest, ensure NELS control 24 hours a day. All operations are executed from the control center by way of public network using the X25 procedure.
- Maintenance: the maintenance of the net is ensured by DCN Brest.

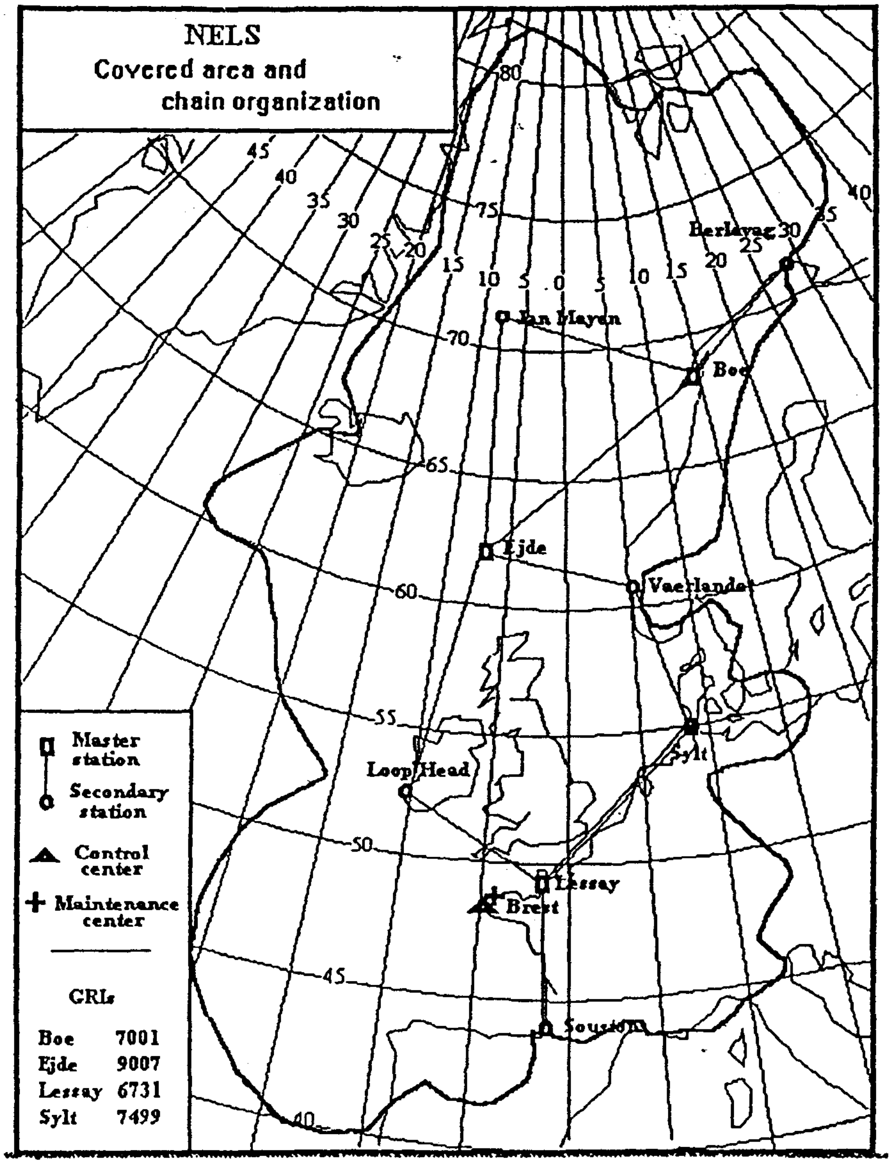


Figure 1 - Coverage of the NELS

b) Extension prospects.

Many extensions studies of LORAN are in progress.
* coverage of Baltic sea by connection of the european network with its russian equivalent, named CHAYKA. Germany is the leader country for that operation.
* Coverage of Mediterranean sea . In 1995, resumption of exploitation of the existing stations. An extension with CHAYKA stations is being designed in order to enable a better coverage of Adriatic and Black seas. Italy is the leader country for that operation with the assistance of the European Union.

* Coverage of the Iberian area to the Azores and Canary islands. France is the leader country for that operation.(See figure 2).

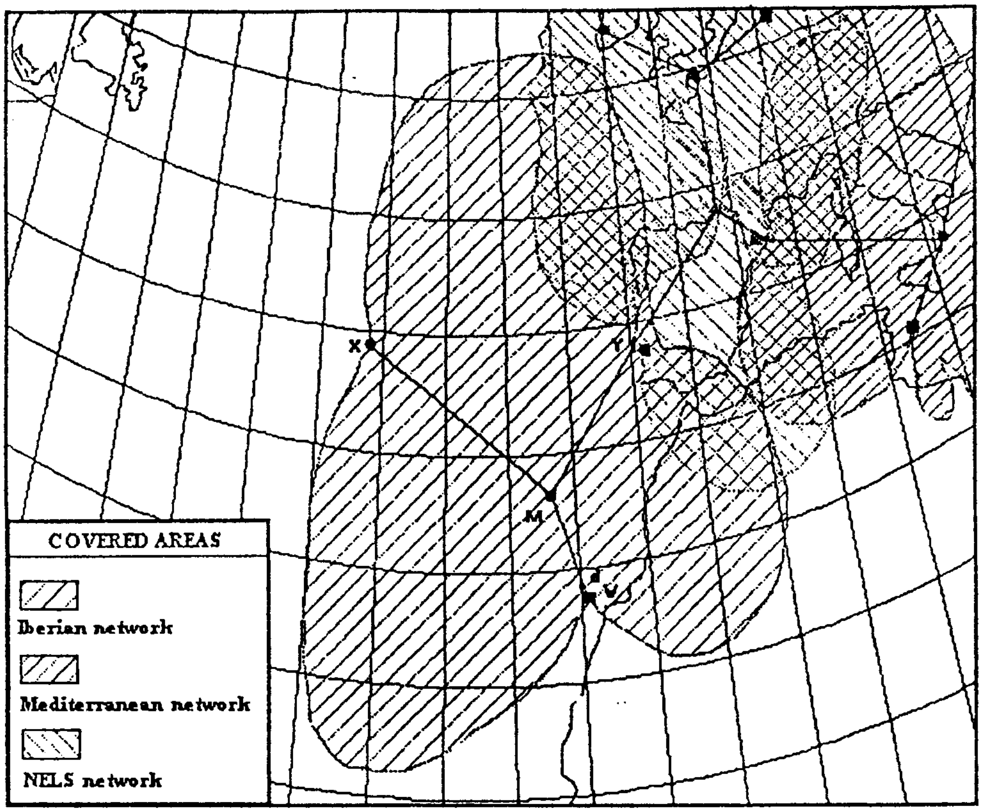


Figure 2 - Iberian Network

c) Using prospects.

In addition to its use as navigation assistance at sea, the LORAN C will be used for air navigation (as nowadays in USA), and for control of land and waterway traffic (some designs already exist).
The LORAN can also give to a still user some time information which, in spite of its restricted accuracy by the variations of the signal propagation speed, can be as accurate as those of the GPS.
Figure 3 shows the variations by observation during 2 years between Paris and the station of Lessay. For time/frequence users only having GPS in C/A code, the LORAN can improve the safety of the time/frequence information.
A new generation of time/frequence users using both GPS/LORAN should even use the respective advantages of both systems.

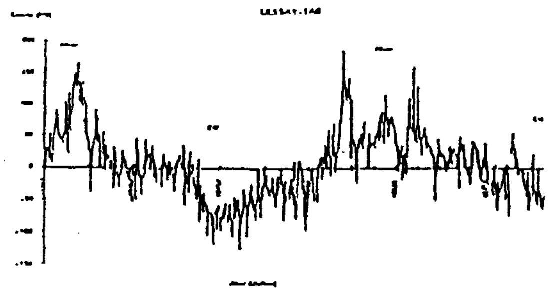


Figure 3 - Observation of seasonal ASF variations between LESSAY and PARIS (deviation less than 100 ns)

The land coverage rea of LORAN C is interesting. Western Europe is in effect fully covered and could be extended North-East by linking up with the CHAYKA network (the Russian equivalent of LORAN C). Thus LORAN C can offer any user the same information as and GPS. (location accuracy, time Frequency accuracy).

LORAN C should not be presented as an alternative to GPS; and the two means should complement each other. There is no doubt that dual capacity receivers will soon be marketed, offering the user improved or even total integrity.

While LORAN C is hard to deceive, the same is not true of GPS, as was intended by the United States. LORAN C is jammable (at atmospheric noise level), while GPS is less so. LORAN C is sensitive to reception conditions (mountains, forests, etc.) while GPS requires direct view between satellites and receivers. By stting up the European network, LORAN C will be under the control of the European countries.

In the Time/Frequency field, LORAN C can be used to good advantage by the scientific community, but also by all those (including the military) who need a precise time reference of a few hundred nanoseconds.

3. The place of LORAN in the European Union policy

In December 1993, the Brussels Committee approved new rules about Trans European Transport network. The Council and Parliament of the European Union should ratify those rules before the end of 1994. All the means of transport are concerned (air, sea, land and waterway). Particulary, every ship entering the territorial waters of the European Union, will have to give its position in real time.
Two location systems will be officially authorized:
- a satellite system (GPS+GLONASS)
- a land system (LORAN C+CHAYKA)

After ratification, the rules vill come into effect in 1998.

4. Conclusion

In spite of the giving up by the USCG of LORAN chains located outside the territory of the United States, the LORAN C is not disappearing. As a matter of fact:
- the whole territory of the United States is, at present, fit out with a LORAN C coverage, and the FAA (Federal Aviation Agency) has just approved the LORAN as an accurate approach system.
- some other nets in the world are now under modernizing, extending, and even in creation :

- Connection USA/Russia;
- Connection Russia/China/Japan/Korea;
- NELS network;
- Mediterranean network;
- Iberian network;

In Europe, the LORAN must be considered as a system in addition to GPS, in order to improve the safety for users. As, at the present time, for its maritime applications, the LORAN should know an enlargement of its applications in locating (air, land and waterways) and time/frequence applications with the impulse of the European Union and thanks to the political will of the concerned countries.

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MODIFICATION OF 350 FEET HIGH "DECCA" AERIAL MAST FOR USING IN LORAN-C TRANSMISSION SYSTEM

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ABSTRACT :

Indian West Cost Decca Chain (7 B) was established in 1959-60 and had aerial mast of 350 ft. with umbrella arms and guys with insulators. During the phasing out of Decca System to Loran-C in 1992, they were retained as transmitting antenna. The structures were offering 3000 pf capacitance which was less then the desired value of 5000 pf. While commissioning Loran-C transmitting system, these structures were tuned to transmission frequency of 100 KHz by adding additional inductance in series with antenna tuning coil. The peak aerial current was found to be 135 Amps. By implementing the modification, the current achieved was 165 Amps.

INTRODUCTION :

Indian LORAN-C West Coast Chain (GRI 6042) comprises the following transmitting stations.

1.	DHRANGADHRA MASTER STATION	LAT.23°00'14" N LONG.71°31'39"E
2.	VERAVAL - SECONDARY-X	LAT. 20°57'07" N LONG.70°20°13" E
3.	BILLIMORA SECONDARY-Y	LAT. 20°45'40" N LONG 73°02'17" E

These stations were commissioned during the first quarter of 1992 as replacement of "Decca Navigator Chain Stations". As these sites were having "Decca Aerial Mast" of 350 Ft.high (with Umbrella arms and aerial/ dressing wires) in good condition, utilisation of these aerial masts, without any modification, was attempted.

These masts were offering capacitance of about 3000 pf, which was less than the desired value of 5000 pF. While commissioning the LORAN-C Transmitting Stations, these aerials were tuned to the transmission frequency of 100 KHz by adding additional inductance in series with the antenna tuning coil. The required additional inductance was provided by use of an old Decca coil. With this arrangement, the peak aerial current was about 135 Amps

It was necessary to remove the old Decca Coil from the circuit. Also, it was necessary to improve the capacitance of the aerial mast thereby achieving :

i) improvement in aerial current and radiated power and
ii) omission of additional inductance from the circuit.

With these objectives, modification to the aerial masts was planned and executed.

MODIFICATIONS

The following modifications to the Aerial Masts were planned and executed.

i) Removal of Umbrella Arms, qty,6 Nos.from the top of the mast and aerial/dressing wires (cadmium copper wire) from the mast structure.

ii) Provision of 6 nos. of 'Top Loading Elements', subtending an angle of 45 degree with the axis of the mast and having 400 ft. of radiating element from the top of the mast. As the portion of the mast above the third level guy wires, was freely, mounted, without support of guy wires, it was decided to make the 'Top Loading Elements' as light in weight as possible. Orientation of the 'Top Loading Elements' was made as shown in Fig. 1 The planes containing the guy wires were avoided to eliminate the screening effect of guy wires.

EXECUTION OF MODIFICATIONS :

The aerial Mast at DHRANGADHRA was modified in the first phase. Results were encouraging. Subsequently, Aerial Masts at Veraval and Billimora were also modified. The various works carried out are as under.

a) REMOVAL OF AERIAL/DRESSING WIRES AND UMBRELLA ARMS :
Tools and gears needed for maintenance of aerial mast and for repairs to Umbrella Arms were utilised. Various works attempted are given in Appendix - A.

b) PROVISION OF TOP LOADING ELEMENTS
Six numbers of Top Loading Elements, as shown in Fig.1 were provided. Tinned Copper Braid and Twisted Polyester Rope were the core materials utilised for fabrication of these 'elements'. These materials were selected for reducting the weight of the 'top loading elements'. Different areas of work involved in fabricaqtion and commissioning of these 'Top Loading Elements' are given in Appendix-B.

c) RETUNING THE AERIAL SYSTEM
After the modification of the Aerial Mast, its capacitance had increased to the range of 5000 pF. Retuning of the aerial system was carried out for ensuring maximum power transfer to the radiating mast structure. Various steps under taken are given in Appendix-B.

On completion of the above works, the following were achieved.

i) Peak aerial current had increased to 165 Amps.
ii) The additional inductance incorporated with the aerial tuning coil was removed from the circuit.

OBSERVATIONS AND GENERAL REMARKS :

1. Prior to modification of the Aerial Mast, the peak aerial current was about 135 Amps. After the modifications, this has increased to 165 Amps.; thus resulting in increase in radiated power.

2. Variations in the method of fabrication of 'Top Loading Element' are possible. In place of the 'Copper Braid' the Cadmium Copper Wire removed from the Aerial Mast or Steel Wire Rope of 3 to 5 mm diameter (preferably with PVC sleeving) can be used.

3, The 'Twisted Polyster Rope' was utilised to serve the below purposes.

i) To provide a reinforcement base to the 'Copper Braid'.
ii) To provide insulation beyond the corona disc.
iii) To bear tension provided to the 'element'.

For trouble free service for a longer period, replacement of polyster rope by steel wire rope, will be desirable.

4. The number of pyrex/porcelain insulators provided in the 'Top Loading Element' can be increased to obtain higher 'break down voltage' of the insulator. This will be relevant when the piece of polyster rope after the insulator is replaced by steel wire rope.

APPENDIX - A

REMOVAL OF AERIAL/DRESSING WIRES AND UMBRELLA ARMS-VARIOUS WORKS INVOLVED

1. Remove the aerial/dressing wires from the lower portion of the aerial mast. The three rings which provides support to the aerial/dressing wires may be retained.
2. Remove the aerial / dressing wires from the middle level of guy wires. Clamps are also to be removed. Regrease the exposed portions of the guy wires. On completion of this work, one section of the removed aerial wire would be handing from the clamps of the top level guy wires.
3. Lower the umbrella arms. Dismantle all the components such as binding steel wire ropes, bottle neck screws, clamps, aerial wires, D-shackles, bulldog grips etc. from the arm. Let the arms freely hang from their hinges
4. Now it can be seen that two sections of the aerial wires are hanging from the clamps of the top level guy wires. Remove these wires and clamps and regrease the exposed portions of the guy wires.
5. Next step is to bring down the umbrella arms one by one. Manila rope or steel wire rope along with pulleys on top of the mast can be used. Hinge of the arms is to be removed carefully, after securing the arm with rope, 'Yale Pull' etc. When the arm had become free from its hinge, it can be lowered by using pulley and rope. (If the Top Loading Elements are kept ready, other end of the rope can be tied to the element so that when the umbrella arm comes down, the Top Loading Element will go up; thereby saving considerable amount of labour and time.
6. The pulleys on top of the mast are to be removed at the last stage, i.e. after lifting all the 'top loading' elements' on top of the mast. The holes wherein 'U' bolts for holding the pulleys are fitted, are to be used for fastening the 'top loading elements'. Clean these holes and surrounding area thoroughly.

7. Check verticality of the mast. If necessary, carry out replumbing work after commissioning the 'top loading elements'.

APPENDIX - B

PROVISION OF TOP LOADING ELEMENTS AREAS OF WORKS INVOLVED

MATERIALS NEEDED :

Materials needed for fabricating 'top loading element', quanity. 1 no., are given below.

1. 9/16" Tinned Copper Braid - 405 Ft.
2. 1/2" Twisted Polyster Rope -600 Ft.
3. 1" Black Heat Shrink Tubing-410 Ft
4. Pyrex or Porcelain Insulator with corona disc. - 1 no.
5. S.S.Thimble for 1/2" rope - 4 Nos.
6. Tinned Copper Lug 125 Amps.-2 Nos.
7. S.S.Eye Bolt, threaded and should dered, 1/2" dia, 1½" long, eye 1" with nuts washers etc. - 1 set.
8. Steel wire Rope 1/4" dia., 20' long with thimbles - 1 no.
9. D-Shackles - 5 Nos.
10. Bull dog grip - 6 Nos.
11. Rigging Screw 12" to 18" long - 1 No.
12. W.I.P. Frayed Rope Repair Compound 1 can or less.
13. E.J.C. Electrical Compound - 1 tube or less.
14. Denso Tape - as required
15. Electrical Insulation Tape - as required.
16. PVC Binding Thread - as required.

FABRICATION OF TOP LOADING ELEMENT ASSEMBLY - PROCEDURE

1. Unroll the reel of tinned copper braid to maintain a straight path.
2. Take a smooth flexible rod having a through and through hole at one end. Tie one end of the polyester rope with the rod, similar to a needle and thread. Now thread the rod and rope smoothly through the copper braid. Expand the braid if any difficulties in threading the rod is experienced. In this manner, thread the rope through the entire length of the braid. When handling the braid try not to splinter it because this could tear the heat shrink tubing and also increase any corona effect.
3. Pull the rope through the braid until the rope extends approximately 8 to 10 feet beyond the end of the braid.
4. When threading the rope through, the braid will try to expand. Therefore the braid must be pulled

down to the smallest size possible. This can be accomplished in the following manner. Using black electrical tape or equivalent, tightly tape the braid to the rope from the end of the braid. Holding the braid and rope stationary, gently pull the braid away from the stationary end so that it constricts around the polyster rope. (It is necessary to pull the rope for allowing possible stretching before commencing this work) Tightly take the braid to the rope approximately every 4 to 5 feet so that the braid does not loosen. Do this for the entire length of the braid.

5. Next step is to place the heat shrink tubing over the braid. Using the flexible rod, thread the assembly through the heat shrink tubing. If available, use an air compressor to expand the tubing. If any splinters on the braid are encountered, place electrical tape over them.

6. We may need 4 reels of heat shrink tubing for ech 'toploading element'. Pull the first reel of tubing to the end of the braid, i.e. the end towards the anchor block. Place the end of the tubing away from the end of the braid by 5 feet. Now using a standard heat gun, shrink the tubing. If a hole is made, carefully repair the hole with electrical tape so that no braid is showing. Pieces of heat shrink tubing can also be used for this purpose. After shrinkking the first piece of tubing, bring the second reel over the copper braid and rope. Give an overlapping of 2 to 3 feet over the first piece of tubing. Shrink this tubing also. In this manner complete the entire length of copper braid bare at the mast end of the 'top loading element assembly'.

7. Cut the polyster rope from the anchor end of the 'top loading element' leaving 5 feet of rope excess from the end of copper braid. Fish out the rope from both ends, from just above the termination of heat shrink tubing. This can be done by gently spreading the strands of the braid sidewise, thereby making an opening, without breaking the strands, to fish out the rope. This act forms a 'Y' junction between bare copper braid and polyster rope at both the ends. It may be noticed that at both the ends copper braid of 5 feet and polyster rope of more than 5 feet are available. Fig.2 may be referred.

8. Tie the 'Y' junction at the mast end of the 'top loading element' porperly with PVC binding wire, after applying E.J.C. electrical compound generously. Application of this compoundwill reduce heavily any corona effect.

9. Insert heat shrink tubing over the copper braid at the two ends and shrink. Solder the copper lug properly onto the ends of the braid. At the mast end, tie the braid with rope securely, 6" away from the 'Y' junction, using PVC binding thread and W.I.P. frayed rope repair compound. Then, cover the junction with 'denso tape' for preventing water loging. Fig.2 may be referred.

10. Splice the rope at both ends on S.S. thimble. At the mast end, insert the thimble in the eye of the S.S.Eye bolt before carrying out splicing. After splicing, the length of the rope from the 'Y' junction is to be kept at 3'; leaving copper braid portion lengthier than the rope. This is essential to provide tension only on the rope while commissioning; thus avoiding tension on copper braid.

11. Using D-shackles connect the pyrex/porcelain insulator with the rope at the anchor end of the 'element'. Connect the copper braid with corona disc of the insulator. The other end of the insulator will receive spliced rope (onto the S.S. thimble) of required length needed for installation. See Fig.2.

12. Between the piece of polyester rope mentioned at 11 above and the anchor block, a piece of Steel Wire Rope of ¼" dia and 20' length is to be provided to avoid damage to the polyester rope due to vandelism etc. A rigging screw, as in Fig.2, is to be provided at the anchor block to adjust tension on the 'top loading element'.

COMMISSIONING OF 'TOP LOADING ELEMENT

1. Pull the mast end of the 'element' one by one, to the top of the mast.
2. Connect the 'eye bolt assembly' in the outer hole of the 'pulley arm' tightly using nuts, washers etc.
3. Connect the tinned copper lug at the end of the braid in the inner

hole of the 'pulley arm' tightly, using bolt nuts, washers etc. Apply E.J.C. electrical compound lightly.
4. After connecting all the six 'elements' on top of the mast, the other end of the 'elements' be brought to the bottom of the mast.
5. Check electrical continuity of each of the 'top loading element' between corona disc and bottom of the mast structure. Ensure minimum contact resistance between the 'element' and mast at the top.
6. Pull each of the 'top loading element' to the respective anchor blocks. Fasten them with the anchor blocks. Give proper tension by adjusting the length of the steel wire rope and by rigging screws. Carry out tensioning of all the six 'elements' equally and in pairs. Tension may be provided to take out approximately 90% of the droop Care must be taken to avoid over tensioning. Lock the rigging screws.
7. Check verticality of the mast. If necessary, carry out replumbing work.
8. Repaint the portions of the mast where painting had gone bad due to the various works on the structure.

ANCHOR BLOCK :

Anchor blocks are to be located as shown in Fig.1. As the 'top loading elements' are light in weight, the anchor blocks are not expected to take much load as compared to the anchor blocks for guy wires. Thus, a construction with less volume, similar to the anchor blocks for guy wires, will meet the requirement.

APPENDIX - C

i) TEST INSTRUMENTS NEEDED

1. Function Generator, qty, 1 No.
   Signal Output : Sinusoidal, 30 volt peak to peak.
   Frequency range : 50 KHz to 300 KHz to select frequency in the vicinity of 100 KHz
2. Frequency Counter, qty. 1 No., to check frequency of the above Function Generator.
3. C.R.O., qty 1 No., to examine the R.F. Waveform.
4. Ferrite Core Transformer, qty.1 No.
   Core : Outer diameter - 60 Cm
   Inner diameter - 36 Cm
   Cross section-12Cmx12Cm

Primary : 13 turns, loosely wound on the ferrite core using insulated multistrand copper wire. Ends are terminated in BNC connector to receive RF signal from the Function Generator.

Secondary : 3 turns, loosely wound on the ferrite core using insulated multistrand copper wire. Ends are connected with crocodile clamps to connect on the terminals/leads.

ii) PROCEDURE :

1. Remove the additional inductance provided by the 'Dence Coil' from circuit.
2. Remove the additional turns, if any provided on the 'Variable Inductance Coil Assembly'. Keep the inner coil of this unit in the mid-position by operating the knob.
3. Remove the lead of the 'Variable Inductance Coil assembly' from the terminal of secondary of 'Output Transformer'.
4. Connect the Test Instruments as shown in Fig.3. Feed RF signal and note the frequency at which peaking takes place. At this frequency, Variable Inductance Coil Assembly, Vertically mounted Helical Coil Assembly and Aerial Mast will be in resonant state.
5. Set the Function Generator output signal to 102 KHz. Select the turns of the 'Vertically mounted Helical Coil Assembly' to get peaking (or nearly to peaking) in the CRO. Adjust the 'Variable' Inductance Coil Assembly' to get exact peaking condition.
6. Except the CRO and its connections, remove all other test instruments and their connections from circuit. Restore the lead of the 'Variable Inductance Coil Assembly' to the terminal of the secondary of 'Output Transformer'. Check all the terminals and connections thoroughly.
7. Energise the HCGs one by one. Monitor the RF waveform in the CRO. With all the HCGs in operation,

measure the peak current and the time period at which peaking takes place. Variable Inductance Coil Assembly can be adjusted slowly and carefully to achieve improvement in peak current. Obtain peak current by this way and mark the position of the knob.

8. Measure the period at which peaking takes place. This should be between 60 and 70 micro-seconds. If this period is not within this time slot, proceed as under.

a) De-energise the transmitter. Changes the tapping of the secondary of Output Transformer. Switch on the Transmitter and follow the steps in 7 above. Different tapping are to be tried till satisfactory results are obtained.

b) If steps at (a) above fail to yield desired results, addition or reduction of turns of the winding on the outer coil of the Variable Inductance Coil Assembly is to be tried. It may be, at times, necessary to strike a compromise between the value of 'Peak Current' and 'Time Period of Peak Current'. Slight reduction in the peak current obtained by adjustment of Variable Inductance Coil Assembly can bring the 'time period of peak current' in the desired time slot.

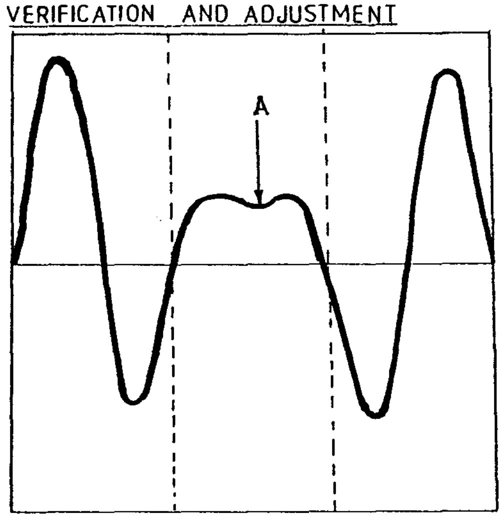
9. After obtaining the desired results, waveform is to be checked to verify occurrance of 'phase reversal' This can be done as under.

(a) Switch off transmissions and then power supply to transmitter. Remove leads from terminals E3 and E4 of 'Tailbiter Board' in 'Coupling and Output Network Assembly' in the Transmitter.

b) Switch on the transmission. Now there will be no tailbiting action.

c) Check the 'Phase Reversal' point in C.R.O. Desired pattern to be obtained is as under. If any abnormality is observed, adjust the 'Variable Inductable' coil assembly to get the more shape similar to that shown in the figure.

PHASE REVERSAL POINT VERIFICATION AND ADJUSTMENT



A: Phase Reversal Point
Desired wave shape

ACKNOWLEDGEMENT :

The Department of lighthouses and lightships gratefully acknowledge the receipt of hardware items supplied by M/s. Megapulse, USA, for modification of Aerial Masts.

BIOGRAPHY OF AUTHOR

Mr. S.G. Malpathak is presently working as Director (Regional) in the Department of Lighthouses, Ministry of Surface Transport, Government of India. After graduating as B.E.(Tele-communications) from University of Poona, in 1968, has joined the Department in 1975, after a tenure of 7 years in Defence Laboratory. He was trained at Decca College, UK, and has looked after Salaya Decca Chain in Gulf of Kachchh before joining of present post.

Mr.G.Somarajan, is presently working as Dy.Director (Electronics) in the same Department. After graduating as B.Sc. (Electronics & Communications) he has joined the Lighthouse service in 1977. During the period of modification of Masts, he was in-charge of West Coast Loran-C Chain.

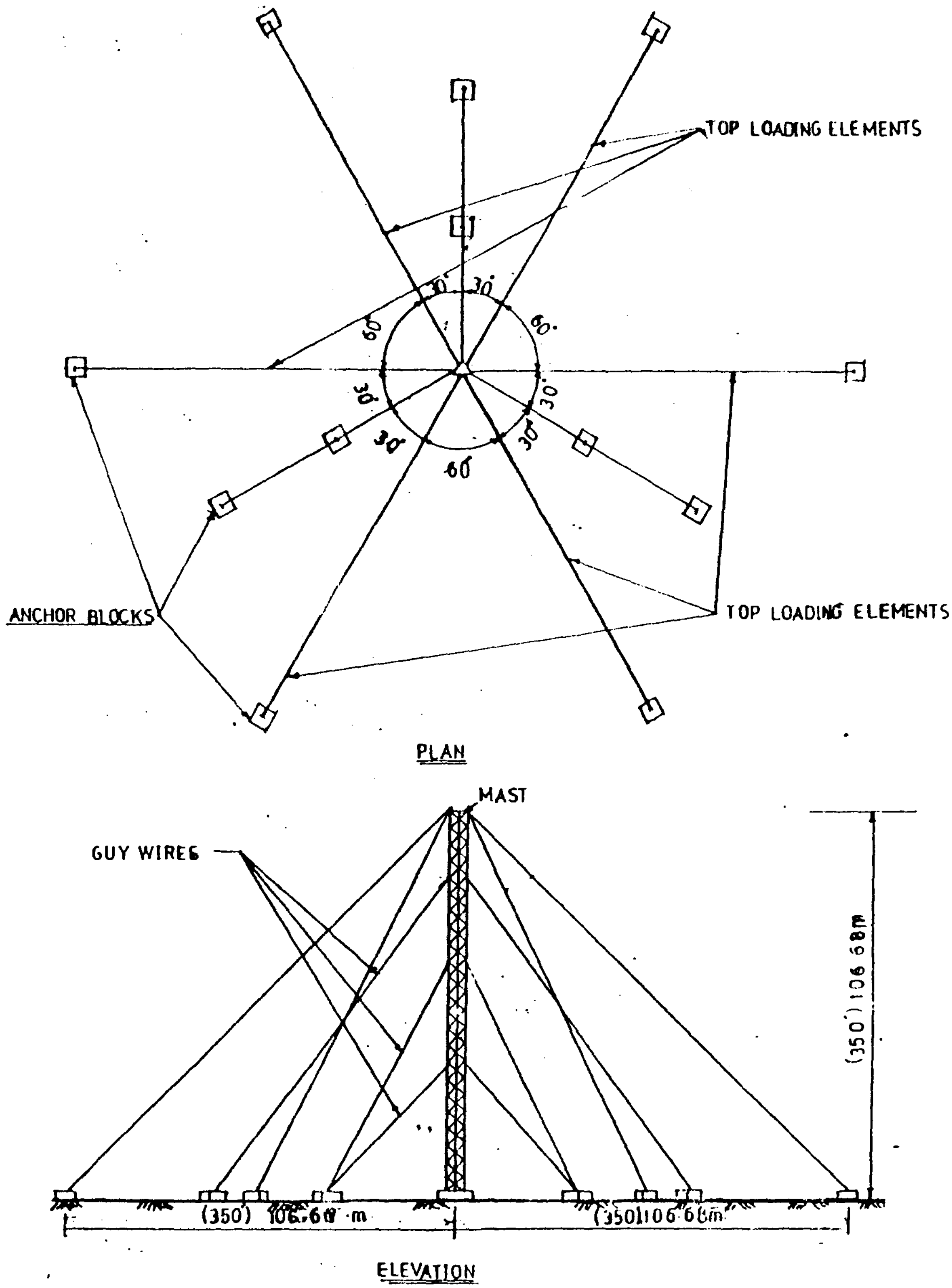

TOP LOADING ELEMENTS
30°
30°
60°
60°
30°
30°
30°
30°
60°
ANCHOR BLOCKS
TOP LOADING ELEMENTS
PLAN
MAST
GUY WIRES
(350') 106.68m
(350) 106.68 m
(350) 106.68m
ELEVATION

Figure 1

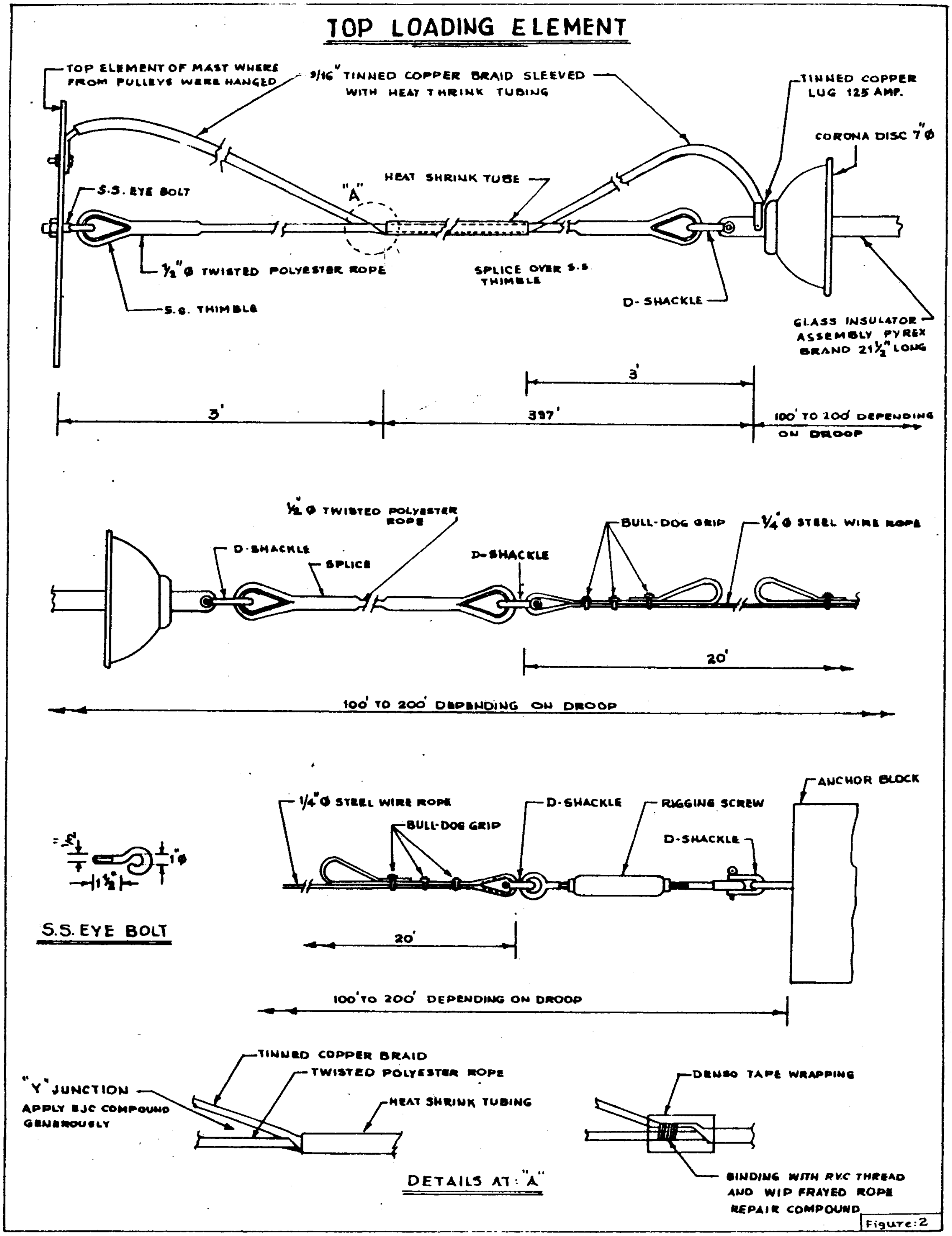

TOP LOADING ELEMENT
TOP ELEMENT OF MAST WHERE FROM PULLEYS WERE HANGED
9/16" TINNED COPPER BRAID SLEEVED WITH HEAT THRINK TUBING
TINNED COPPER LUG 125 AMP.
CORONA DISC 7"Ø
HEAT SHRINK TUBE
"A"
S.S. EYE BOLT
1/2"Ø TWISTED POLYESTER ROPE
S.S. THIMBLE
SPLICE OVER S.S. THIMBLE
D-SHACKLE
GLASS INSULATOR ASSEMBLY PYREX BRAND 21 1/2" LONG
3'
3'
397'
100' TO 200' DEPENDING ON DROOP
1/2"Ø TWISTED POLYESTER ROPE
D-SHACKLE
SPLICE
D-SHACKLE
BULL-DOG GRIP
1/4"Ø STEEL WIRE ROPE
20'
100' TO 200' DEPENDING ON DROOP
ANCHOR BLOCK
1/4"Ø STEEL WIRE ROPE
D-SHACKLE
RIGGING SCREW
BULL-DOG GRIP
D-SHACKLE
20'
100' TO 200' DEPENDING ON DROOP
1 1/2"
1"Ø
S.S. EYE BOLT
TINNED COPPER BRAID
TWISTED POLYESTER ROPE
"Y" JUNCTION APPLY BJC COMPOUND GENEROUSLY
HEAT SHRINK TUBING
DENSO TAPE WRAPPING
BINDING WITH P.V.C THREAD AND WIP FRAYED ROPE REPAIR COMPOUND
DETAILS AT: "A"

Figure:2

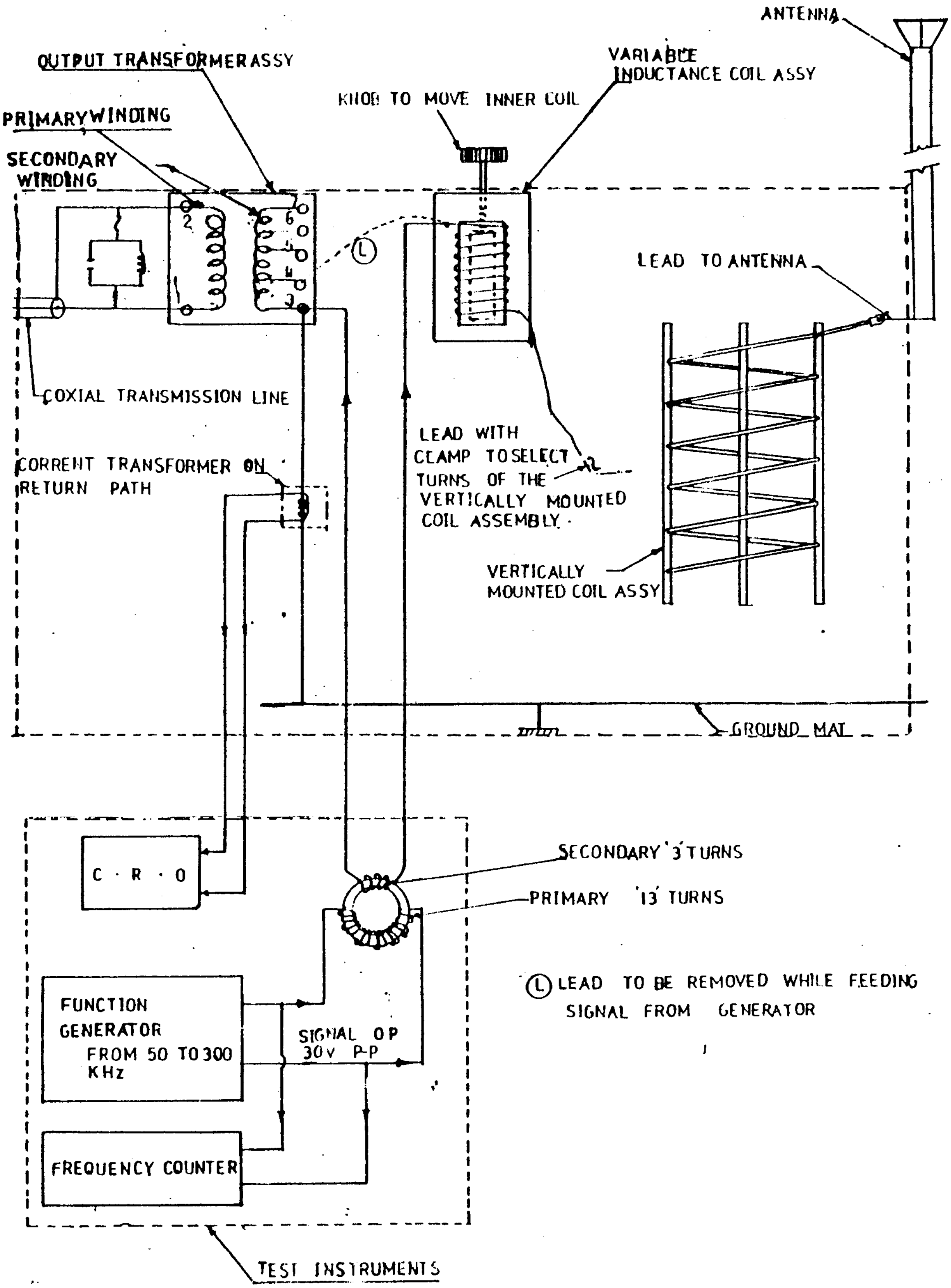

ANTENNA
OUTPUT TRANSFORMER ASSY
VARIABLE INDUCTANCE COIL ASSY
KNOB TO MOVE INNER COIL
PRIMARY WINDING
SECONDARY WINDING
LEAD TO ANTENNA
COXIAL TRANSMISSION LINE
LEAD WITH CLAMP TO SELECT TURNS OF THE VERTICALLY MOUNTED COIL ASSEMBLY
CORRENT TRANSFORMER ON RETURN PATH
VERTICALLY MOUNTED COIL ASSY
GROUND MAT
C · R · O
SECONDARY '3' TURNS
PRIMARY '13' TURNS
FUNCTION GENERATOR FROM 50 TO 300 KHz
SIGNAL OP 30V P-P
(L) LEAD TO BE REMOVED WHILE FEEDING SIGNAL FROM GENERATOR
FREQUENCY COUNTER
TEST INSTRUMENTS

Figure: 3

WILD GOOSE ASSOCIATION
23rd Annual Convention and Technical Symposium

THE ADDITION OF A STANDARD ZERO CROSSING (SZC) TRACKING 1 PPS CAPABILITY TO THE AUTOMATIC BLINK SYSTEM (ABS)

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INTRODUCTION

The VOLPE Department of Transportation System Center (VOLPE Center) under FA-329 is designing, developing and building an Automatic Blink System (ABS) to be installed by the U.S. Coast Guard at all LORAN transmitting stations in the NAS. The ABS equipment will provide an integrity monitor for LORAN precision approaches by rapidly and automatically applying BLINK to a LORAN signal upon detection of a timing anomaly of 500 ns or greater.

Public Law 100-223 requires the U.S. Coast Guard to synchronize all LORAN-C master stations to within 100 ns of coordinated universal time (UTC). As one way of satisfying this requirement, a LORAN-timed one pulse per second output has been added to the ABS equipment. The addition of this capability to the ABS equipment enables the ABS to serve two DOT missions: the FAA mission of providing integrity for LORAN non-precision approaches and the USCG mission of synchronized transmitted LORAN master signals to UTC.

WHY ONE PPS AND ABS

For a variety of reasons, the ABS system is a natural host for the one pulse per second hardware. First, the ABS system already interfaces with all of the existing LORSTA elements necessary to implement one pps except external one pps signal. These include the three Cesium standards, the sampled operate RF signal (antenna current), and the station TTY communication loop, as well as primary AC power and DC backup power. In terms of signal processing the ABS system was already accomplishing about half of the signal processing necessary for locking a one pps signal to the transmitted pulses standard zero crossing (SZC). These functions include acquiring and locking to the SZC of the transmitted pulse, and measuring the phase of the SZC with respect to the Cesium standards with a resolution of 20 ns and an accuracy of ± 40 ns. The ABS system had the expansion capability (real estate and processor power) to host the required one pps functions. And finally, the ABS system fills the last available rack opening at the existing LORAN-C NAS transmitting sites. If a separate one pps system were to be built, there would be no ready location in which to install the equipment.

BACKGROUND

Prior to discussing the implementation of one pps in the ABS system, we present a brief review of the relationships between a one pulse per second signal (1 pps), the time of coincidence (TOC), and the timing of the LORAN-C pulse transmissions.

LORAN-C pulse transmissions are referenced to coordinated universal time (UTC), which started at zero hours, zero minutes and zero seconds on 1 January 1958. At this second, one could imagine all LORAN-C master stations simultaneously transmitting the first master pulse of Phase Group A in what has been a virtual continuing sequence of master and secondary transmissions, with each chain repeating the sequence at its own group repetition interval. In fact, non-existing LORAN-C chains and many dual-rated chains could not have transmitted that first pulse, but in a timing sense all LORAN-C transmissions are traced back to that instant.

A perfect 1 pulse per second signal is a timing pulse which occurs on the second starting or traceable to that first UT second.

A TOC, or time of coincidence, is a time at which the first pulse of a master station transmission in Phase Group A (referred to in this paper as P1GA) and a universal time UT second are coincident. As discussed above, the first TOC for all master stations occurred, or would have occurred, simultaneously on 1 January 1958. Subsequent TOCs are dependent upon the group repetition interval (GRI) of each chain. The GRI assigned to a chain expresses the time interval between successive master station transmissions in 10 μsecond increments. For example, the Northeast chain GRI is 9960 μs between master group repetitions. If we consider the numeric value of the GRI for a given station; e.g., 9960, it can be shown that a TOC will occur each "GRI" second or at sub-multiples of "GRI" seconds where the value

$$\frac{\text{GRI}}{2^n \times 5^m}$$

is an integer. Again assuming a GRI of 9960, a TOC will occur at each 9960 seconds, at any multiple of 9960 seconds, and, in fact, forty times between each 9960 seconds at multiples of 249 seconds.

The time of day in hours, minutes and seconds in which TOC times will occur at any given GRI are computable from a knowledge of the station GRI, the January 1958 starting time of UTC, and a knowledge of the number of leap seconds that have been inserted into UTC since January 1958. The computation of these times on a daily basis are available from the United States Naval Observatory (USNO) and are published as a part of *Time Service Announcements, Series 9.*

The above, of course, assumes that the timing at the LORAN-C station is perfect; that is, LORSTA 1 pps signal occurs at the exact instant as a UTC second. In fact, realignment is never perfect, although the difference between the two 1 pps signals is quite small. But the difference does lead us to define two different 1 pps signals, LORSTA 1 pps and UTC 1 pps, or in the nomenclature used in the implementation of the 1 pps system modification, "Internal" and "External" 1 pps, respectively. The difference between these two signals represents the LORSTA/UTC synchronization error.

The above definitions of 1 pps and TOC mention only the 'occurrence' of P1GA at a master station and do not specify where in the LORAN pulse TOC occurs, or how 1 pps is defined at a secondary station. At a UTC synchronized master station, TOC occurs at the starting point of P1GA and is defined as a point 30 μs before the SZC. At a secondary station TOC occurs at a point in time 30 μs plus one emission delay time before a secondary P1GA pulse.. This means that a TOC second is never aligned with the start of a secondary pulse group, but rather with the start of the group repetition interval during which the secondary will transmit.[1] Figure 1 shows the relationship between the SZC of a master P1GA, the Internal 1 pps signal and the External 1 pps signal.

To align a master station to UTC, we must assure that: 1) a P1GA master pulse is transmitted at a TOC time; 2) the LORSTA 1 pps clock is aligned to UT; and 3) the station's clock is set to universal time. To align a secondary station, we must assure all of the above and account for emission delay between the master and the secondary transmissions. To control a chain to universal time we must assure that the error between the station's 1 pps clock, as shifted in time by movement of the SZC, and a UT second is within a specified tolerance.

THE ABS 1 PPS MODIFICATION

System Requirements.

The following system requirements were specified for the 1 pps ABS modification:

1. Generate an internal 1 pps, or optionally a 1 pulse per TOC signal, which is time-locked to the SZC of the transmitted LORAN-C signal.

2. Provide procedures to
   (a) align the Internal 1 pps signal to a TOC P1GA pulse;
   (b) align the internal 1 pps signal to the External pulse;
   (c) set the ABS clock to UTC.

3. Compute the time error between the internal and external 1 pps signals.

4. Provide an alarm capability to warn the system operator that the measured time error between the internal and external 1 pps signals has exceeded a preset limit.

5. Provide a visual indication of the occurrence of seconds and TOC pulses.

6. Provide for monitoring and controlling of the 1 pps subsystem via the TTY communications network.

[1] None TOC seconds may align with the "start" of a P1GA secondary pulse. However, this alignment is not relevant to the 1 pps synchronization problem.

1 PPS System Approach.

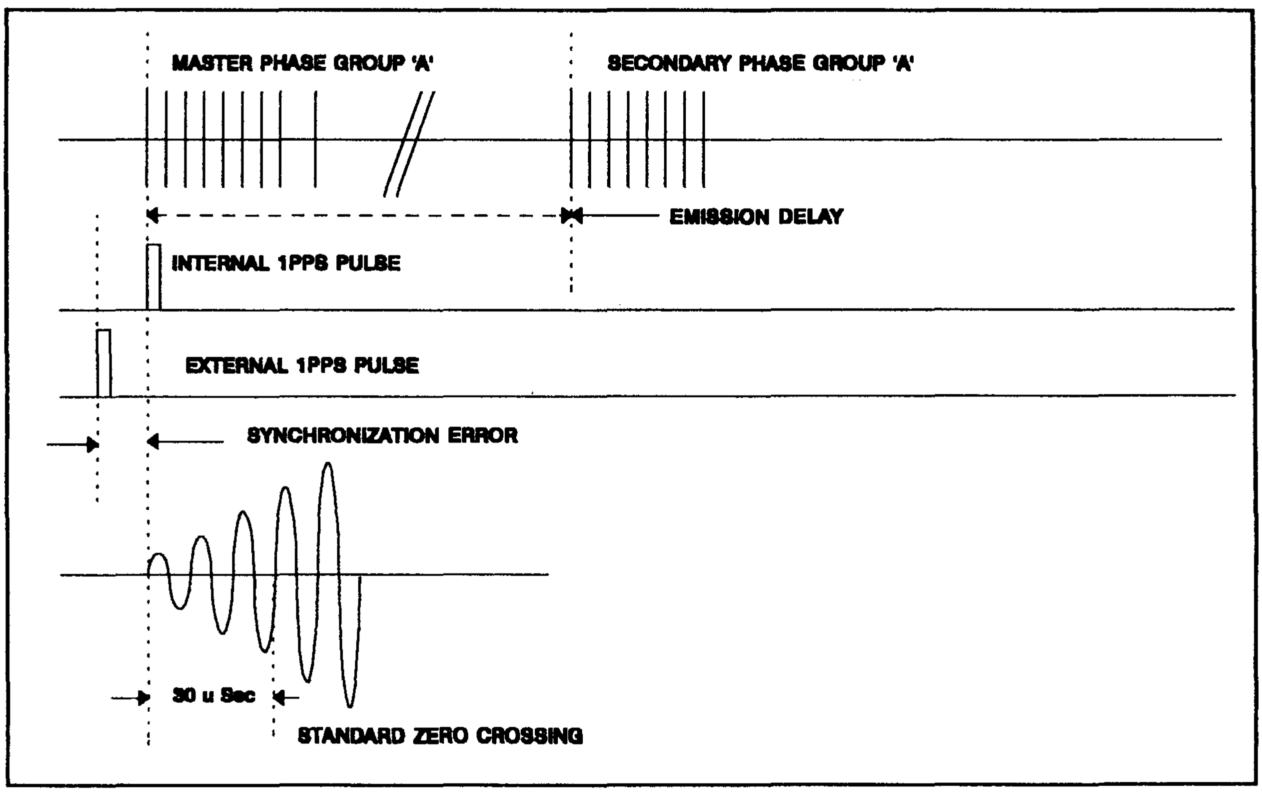
As a part of its primary mission, the ABS system establishes a LORAN timing which is referenced to the P1GA pulse. This reference is established by averaging the relative time position of all transmitted LORAN-C pulses over several seconds. To generate an internal 1 pps signal which is locked to the average SZC-based GRI reference, we first align the internal 1 pps signal to the external UT 1 pps signal. This is accomplished by measuring the time difference between the internal and external signals and, after removing known system calibration delays, moving the internal signal to reduce this error to zero. Next, by identifying a TOC second and noting the position of the SZC at this time, we move the internal 1 pps second to either 30 μs or 30 μs plus one emission delay in front of the P1GA at TOC. This process yields internal 1 pps signal which is aligned to the LORSTA second. Once the internal 1 pps signal is thus locked to the SZC of the TOC P1GA pulse, we adjust the position of internal 1 pps to follow the motion of the SZC relative to its position when we first establish TOC. This tracking technique will work as long as the standard zero crossing stays within ± 5 μs of the initial lock point. Should the LORAN-C timing jump, we have no means to follow the signal. However, when such a large jump occurs we have had a BLINK event and the ABS system will proceed with its normal function of placing the transmitted signal into BLINK (or in the case of a master station, taking the station off air) and placing the ABS system into the BLINK state. In the BLINK state, the internal 1 pps signal is no longer controlled by the SZC, but free runs off the Cesium Standard until the ABS is once again armed.

When the ABS returns to the armed state, one of three conditions will prevail:

1) The LORAN-C transmitter timing will have been returned to its pre-BLINK timing. In this case, the internal 1 pps signal is once again adjusted to maintain its position with respect to the SZC.

2) The timing of the LORAN-C transmitter will have been adjusted by less than ± 5 μs, and as part of that process, the operator establishes a new reference time for the ABS system by issuing an ABS synchronization command. As resynchronization involves a loss of the SZC reference time, the 1 pps system jumps the internal 1 pps to the specified point in front of the SZC, and then establishes a new SZC reference position.

FIGURE 1. The Time Relationship Between SZC, Internal and External One PPS.



3) There will have been a complete loss of timing (e.g., the loss of a Cesium reference input). In this case, the 1 pps output is put into a non-operational state and must be returned to an operational state by re-establishing TOC.

Setting Time and Marking TOC.

There are two times which must be set in the 1 pps system. We must establish the TOC second and set the ABS clock to UTC time. Either of these functions may be carried out independently; however, a complete synchronization of the 1 pps system will establish both TOC and UTC synchronization.

The 1 pps modification provides three initialization procedures: The first manually marks the TOC second, the second manually sets the ABS clock to UTC time, and the third automatically establishes both TOC and UTC synchronization. All three procedures assume that we have available to us an external source of UT derived 1 pps.

Manually establishing TOC requires the operator to depress, hold, and then release the TOC switch at a known TOC time. For this procedure to work, it is not necessary for the ABS to know UTC time, but only to know that a given second is, in fact, a TOC second. A flow diagram for this procedure is shown in Figure 2. First, the internal 1 pps pulse is aligned to the external pulse. Next, a TOC time is selected. At least five seconds prior to this TOC time, the operator pushes the TOC button. This delay, as in the case of manual UTC time setting, assures that an accidental bump of the switch will not disrupt system time. At each of the following seconds the system tags the time of the closest P1GA pulse in anticipation of the operator releasing the TOC switch. When the TOC switch is released, the internal 1 pps pulse is locked to the tagged P1GA pulse, and the internal 1 pps is adjusted to the proper point in front of the selected SZC. At this time, if the TOC second has been entered, the ABS clock will be set to the TOC time. Finally the system calculates and causes the front panel LED to illuminate for a full second at the next TOC time, permitting the operator to verify TOC.

Manual UTC time synchronization employs the TOC switch to start the internal UTC clock at a proper predesignated second. A flow diagram for this procedure is shown in Figure 3. First, using the UTC_TIME_HHMMSS command, the operator places the system into the UTC time-set mode. This command signals to the system that a manual UTC time synchronization is to be performed and also conveys the time at which the clock will be started. The system then waits for the TOC switch to be pushed for at least five seconds. After the TOC switch has been pressed for five seconds, the internal 1 pps signal is aligned to the external signal and waits for release of the TOC switch. Following release, the UTC clock is started from the entered time. At this time the UTC clock time is also transferred to the lower quality, battery backed-up, IDM clock. Once again, visual verification is provided by an extended flash of the LED for a full second ten seconds later.

The automatic TOC/UTC timeset mode eliminates the need for the operator to manually push and release the TOC switch at a specific second. This technique again requires that we have an external source of 1 pps to initially synchronize the internal signal, and further, that the IDM's battery backed-up clock is currently set within ± one-half TOC interval of UTC time (e.g.,

FIGURE 2. Manual TOC Procedure

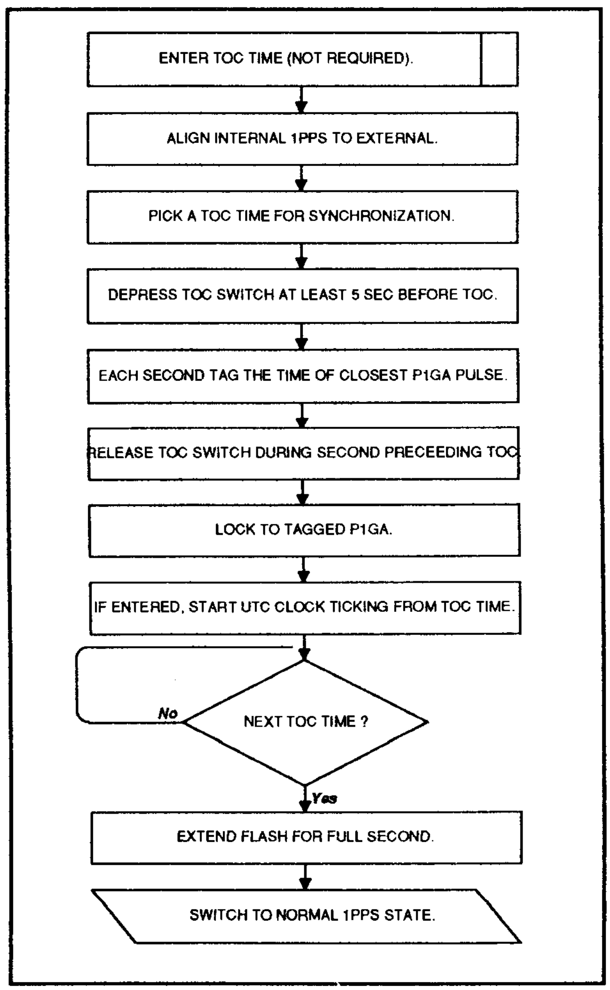
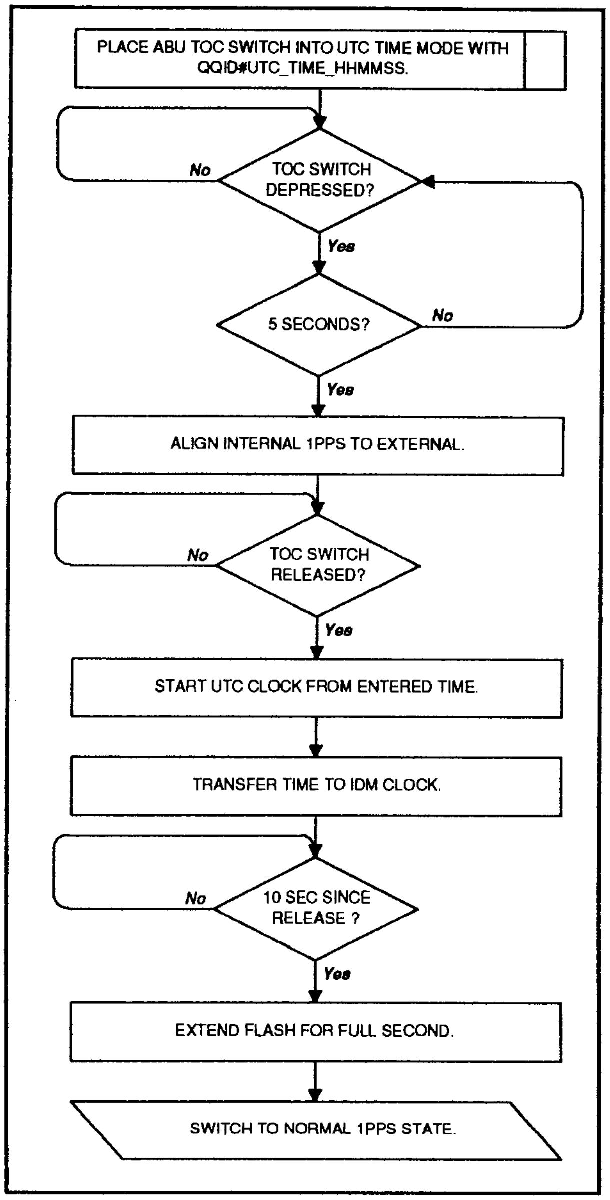


FIGURE 3. Manual UTC Time Synchronization.



within about two minutes of UTC for a GRI of 9960), and finally that the LORAN chain is initially synchronized to within ± 50 µs of UTC.[2]

The automatic synchronization procedure is based on the observation that only the TOC second pulse will be within ± 50 µs of the start of the master P1GA pulse position and that all other pulses will be displaced from a P1GA by 100 µs. (If adding one GRI to the previous P1GA time does not cause it to occur at an integral second, then it must miss by a multiple of 100 µs.) This is shown diagrammatically in Figure 4. Here we see the external 1 pps pulse in relation to the start of P1GA, including a synchronization error of about 10 µs. Superimposed on the external 1 pps pulse line are the positions of none TOC seconds with respect to the leading edge of the pulse. As shown, these will miss the front edge of the pulse by multiples of 100 µs.

The automatic procedure works as follows: The operator enters a TOC time and commands automatic TOC synchronization. At a time of one-half TOC interval prior to the specified TOC time as determined by the inaccurate IDM clock, or a time of minus one TOC interval to exactly the TOC time as determined by an external UTC clock, the system examines the relative position of P1GA at one second intervals. The TOC second is the second where the start of the GRI is closest to one second pulse. A flow diagram for this procedure is shown in Figure 5. As noted on the flow diagram, the actual implementation assumes that the true TOC pulse will be within ± 25 µs, since this tolerance provides a margin of error for the implementation of the technique and does not place a severe constraint on the initial synchronization of the LORSTA. As with the manual techniques, the process starts with an initial alignment of the internal 1 pps signal to the external signal. Next, the time of the IDM clock is either set or verified to be within ± one-half TOC interval of UTC, and the first or any other past TOC for the day is obtained from the USNO tables and entered using the UTC FTOC command. Using this information, the system computes the UTC time of the next usable TOC, avoiding TOCs which are so close to the present time that there is insufficient time to initialize the system. Following the receipt of the UTC_STOC synchronization command, the system waits until a P1GA occurs within ± 25 µs of a UTC second. When this occurs, the UTC second is used to start the UTC clock ticking from the entered TOC time. This time is also transferred to the IDM clock to set it to the now known UTC time. Finally, at the next TOC time, the TOC LED flash is extended for a full second.

ADDING 1 PPS TO ABS

As noted earlier, many of the functions required by 1 pps already existed in the ABS system with about half

[2] This assumes that GRIs are specified in 100 µs increments as in the case with the NAS. In general we require an initial accuracy of one-half the resolution to which the GRI is stated. For example, for a GRI of 7001 which grows in 10 us increments, we would require an initial synchronization of ± 5 µs.

of the 1 pps functions requiring use or expansion of existing facilities. These included expansion of the existing ABS command message and alarm structure, the use of the existing Cesium standard and Operate RF (OPRF) interface, and the use of the existing standard zero crossing time measurement system. The additional circuitry required by the 1 pps modification included 1) the generation of an internal 1 pps signal with a 20 ns resolution, 2) the capturing of the time of the external 1 pps signal with a resolution of 20 ns, 3) 50 Ohm line drivers and receivers to interface the internal and external 1 pps signals. In addition, a manual TOC button and an LED to visually indicate seconds and TOC seconds were required. Finally, software was required to drive the above hardware and to execute the required system commands and functions.

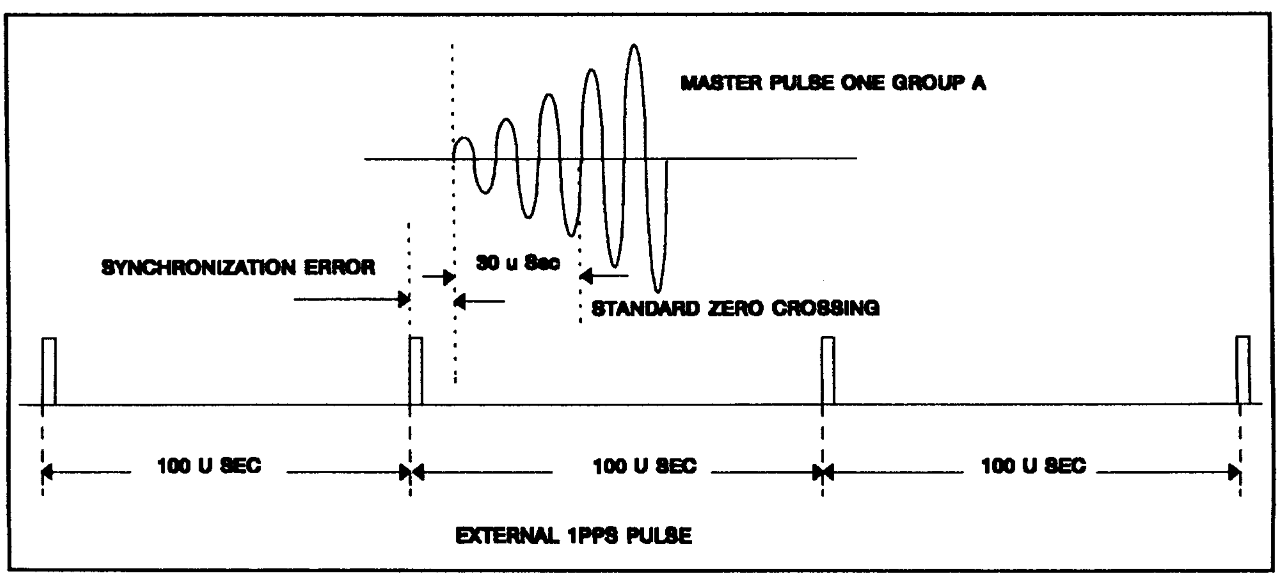
The majority of the hardware additions were added to the PTM cards. The time measurement functions were implemented using two programmable logic arrays and with spare input capture and output compare timers contained in Motorola 68HC11 CPU.

In addition to the PTM modifications, we had to provide for rear panel connectors, internal cabling and mother board modifications to bring the internal and external 1 pps signals to the rear panel of the ABS. Finally, the 1 pps LED was added to the front panel of the PTM and a TOC switch was added to the power supply cover panel.

The 1 pps software changes affected both the IDM and the PTM cards. Addition of the 1 pps functions to the IDM required additions to the existing IDM alarm command and message structure. As the programming space in the IDM was fairly limited, a part of this modification included the fruitful task of more efficiently grouping common routines into subroutines in order to gain code space, and the conversion of several alarm messages into simple status messages in order to gain additional alarm flags. In the end, IDM memory space proved sufficient to carry the necessary additions; however, the final system has less than 1 Kb of code space left out of 48 Kb of programming memory.

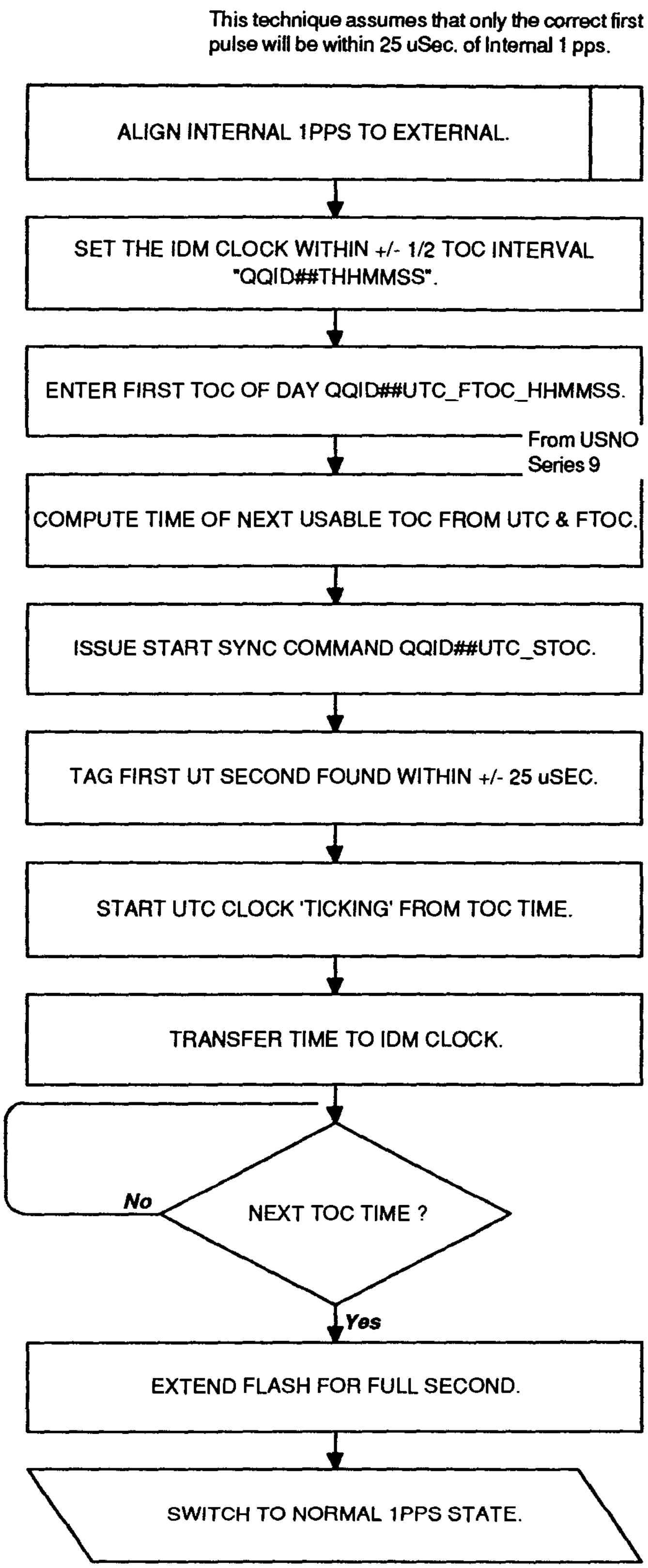
The PTM code additions were more extensive for two reasons. First, the addition of 1 pps required that the PTM real time system work in absolute rather than relative time. Before the addition of 1 pps, the ABS was only concerned with jumps with respect to a previously established time. For example, the resynchronization of the ABS merely required us to reestablish a new reference from which errors were computed, whereas 1 pps required us to constantly keep track of the absolute time position of the signal. The second reason the PTM code additions were more extensive is that the generation of a time pulse at a specific time is a more demanding task than capturing the relative time of a pulse. Capturing the time of a pulse requires that latches and counters be armed and that the computer examine these latched values after the occurrence of the pulse. The generation of a timing pulse requires that all timers and enabling signal levels be set and that output circuitry be armed

FIGURE 4. Possible Positions of P1GA with Respect to External (UT) Second Pulse.



close to, but before, the specified pulse time.

FIGURE 5. Automatic TOC and UTC Synchronization.



CONCLUSIONS

The addition of the 1 pps capability to the ABS system makes available to the USCG a 1 pps TOC timing pulse which moves in time to reflect changes in the synchronization of the transmitted SZC. The system also provides a measure of the error between this SZC disciplined internal 1 pps pulse and an external 1 pps pulse, providing a continuous readout of the error between the LORSTA's 1 pps and a UT 1 pps signal. Including 1 pps into the ABS provided a relatively low cost, space and power efficient way of including 1 pps into the electronic suite of a standard LORSTA. This addition is currently undergoing testing by the U.S. Coast Guard Electronics Engineering Center at Wildwood, New Jersey.

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BIBLIOGRAPHY

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Mr. Poppe is an electronics engineer and President of *Cambridge Engineering, Inc.* He has a Bachelor's Degree in Electrical Engineering from the Massachusetts Institute of Technology, Cambridge, Massachusetts, and a Master's Degree from Stanford University, Stanford, California. Since forming *Cambridge Engineering, Inc.* 21 years ago, Mr. Poppe has worked on various navigation systems including Loran-C, Omega, Transit and Differential GPS.

In addition to Mr. Poppe's work on the Automatic Blink System (ABS), recent projects have included: the design of a DSP based timer for the USCG Omega Navigation System transmitters; the design of radiobeacon receivers to demodulate MSK modulated differential GPS data; and the design of loop antennas for the reception of radiobeacon signals.

Symposium Papers

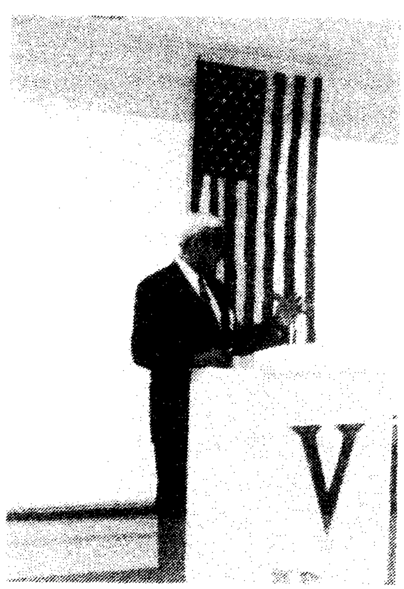
Session IV

Panel Discussion

Panel Discussion: "Is There Loran in the GNSS Future?"

A lively panel discussion can always be expected from this distinguished group of Geese!

Tom Thomas, David Last, Marty Shuey, Henry Marx, John Beukers and Will Johnson ...



...moderated by Mike Moroney!

Symposium Papers

Session V

Operations

Loran Performance:
A Report of Recent Operational Performance

by
CDR Louis R. Skorupa & LTJG Eugene V. L. Vogt
USCG Pacific Area (Ptl)

Abstract:

This paper provides an overview of Loran station operational performance in North America during a recent period of eighteen months. We analyzed types and amounts of unusable time and momentary signal outages by frequency, duration, and common causes.

Data was taken from operational reports to develop a database. The database was correlated with the types of stations so overall performance may be characterized. The impact of unusable events due to control, equipment failures, maintenance, propagation, and monitoring are included and examined. Groups of stations are compared by chain, crew type, remotely operated or manned, type of transmitter, and other relevant criteria. The database is examined using these criteria and graphics generated to simplify analysis and comparison.

This historical operational record is expected to reveal important information about reliability and recent performance history. This information should be of value to all persons responsible for planning, operating, or managing operational Loran systems.

Disclaimer:

Views expressed herein are those of the authors and are not to be construed as official or reflecting the views of the Commandant or U. S. Coast Guard. This paper describes USCG and Canadian Coast Guard Loran operations as an example, but does not recommend or describe official operational or maintenance policy or procedures. No endorsement of companies or products, either positive or negative, is intended.

Introduction:

A major challenge facing those individuals responsible for the operation of radionavigation systems is fulfilling extremely challenging requirements for operational availability. These requirements protect the safety of life and property of the public and system users. Loran systems operational management has used complex historical record keeping to track and characterize performance. Based on these performance measurements, and the in-depth analyses required whenever baseline criteria were not met, continuous improvements in system operations have been achieved. It is upon these existing historical records that this report is built and from which the data included here was extracted.

Gathering the Data

To accomplish this objective analysis, first the different monthly reports for all the North American Loran-C chains were gathered. While unusable time codes are standardized, some problems were found to occur. For example, lightning strikes at or near an unattended station, causes a commercial power flux, which results in a transmitter switch. What happened? Should the transmitter, power, lightning, or miscellaneous code be used? Each could be appropriate. So, the first challenge was determining the major classes of events of interest for the purposes of this report.

To facilitate across the board comparisons and analysis, we chose to use six momentary outage event classifications. Momentary reports originally given as described in the Atlantic or Pacific Area Regional Managers' Supplemental Instructions were converted to these classifications for graphing and analysis.

Momentaries

All data was gathered from chain operational reports, and is based on the station designator and Group Repetition Interval. There were 45 rate/designators entered, covering all the chains and stations primarily serving North America. For example, data on Lorsta Gillette Wyoming was entered twice - first all the data reported for 8290X, and then all the data reported for 9610V. Information on Labrador Sea and Russian American Chain stations in North America was not included, although the other rates' data from Attu, Fox Harbor, and Cape Race were. The data covered eighteen months, November 1992 to April 1994. We documented 14,775 momentaries. This is an average of just 18.53 momentaries per station rate/designator (i.e., Gillette, WY, 8290X) per month.

The momentary data was examined by classification in figure 1, "Total Momentaries - Percent by Classification." Following this, the momentaries were regrouped into a "Sum" of individual events. This sum was investigated to characterize system performance and to allow objective comparison and analysis between stations whether dual or single rated. In addition, monthly and station graphs of events are given, analyzed, and discussed.

In the graph of "Total Momentaries - Percent by Classification" (figure 1), please note that the leading cause of momentaries was Transmitters (XMTR) at 53.55%. This category is mainly composed of transmitter switches and overloads. In the Solid State Transmitter (SSX), these would be Output Coupler Network switches, while in the tube type transmitters it would include various types of overloads such as those due to overcurrent protection.

As noted earlier, transmitter momentaries often have a root cause related to power fluctuations, and in fact Power is the second most frequently reported cause of momentaries (17.81%). Also, both Transmitter and Power class momentary events frequently require a second momentary to switch back to or test the original configuration. An example is switching back to commercial power from generators, or to the original operate transmitter or SSX Output Coupling Network.

This results in a higher impact of each individual initial event of these types to the total, as two momentaries often result.

Maintenance (MAINT), at 15.03% is the third most prevalent momentary cause. While significant, this area does not seem to offer major opportunities for reducing momentaries while ensuring all equipment is functional.

Of all the momentaries reported only 1.31% were the result of either Timing & Control Equipment (TCE) or Personnel (PERS). In fact, the Personnel total for the entire period was only 31 - an average station *might* have a personnel momentary in a *year!* Timing & Control Equipment is also performing exceptionally well, especially considering the age and complexity of this equipment.

The final category, Other, at 12.30%, is a catch all category. The comparatively high number of Other reports, especially when compared to Personnel and TCE, suggests that perhaps our reporting system should further categorize other areas. Future operational analyses might also be improved by breaking down the Transmitter and Power categories to allow more in depth analysis of these major areas.

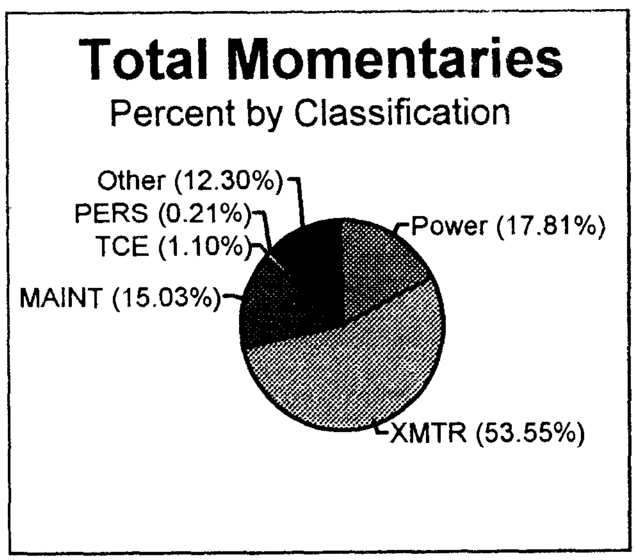


Figure 1.

Tube stations show a moderate distribution of total numbers of events. However, the distribution by class of events was fairly consistent. Combined average distribution by class is figure 5. The reported low was 128 events at Port Clarence - a manned AN/FPN-42 station with little lightning and their own generators. The reported high was 569 at Searchlight, which is an AN/FPN-44 station with frequent lightning and historically poor power. Last year, close work with the power company resulted in Searchlight's electrical feed being upgraded and lightning protection improved.

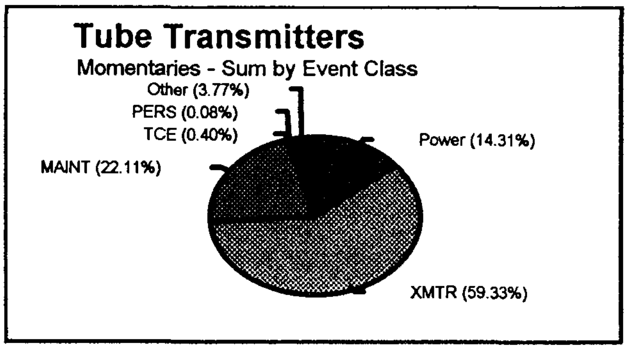


Figure 5.

SSX transmitters were consistently lower in average momentaries than other transmitters. Station local lightning and power conditions seemed to account for the variances in reported events. The SSXs averaged six fewer events per month than the TTXs. This is despite the fact that many of the SSX transmitters are located in severe weather areas.

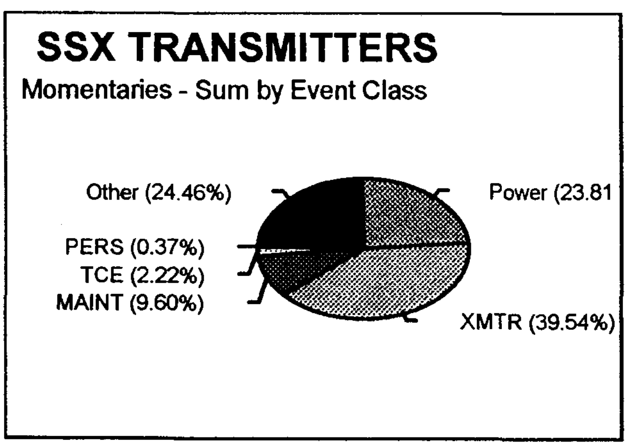


Figure 6.

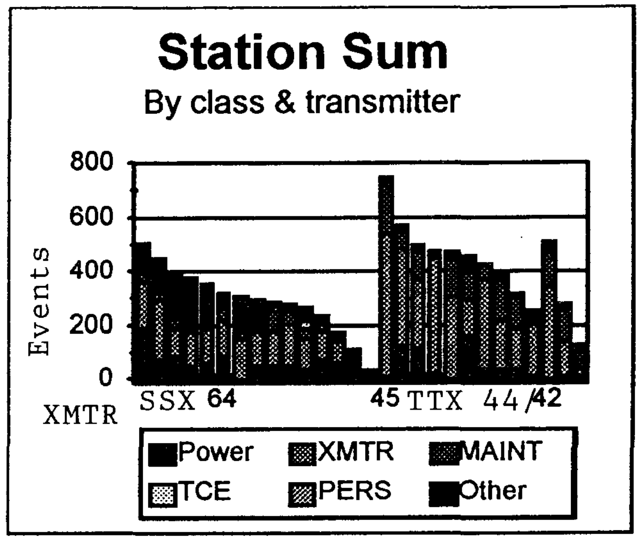


Figure 7.

"Station sum by class and transmitter," figure 7, shows the range and distribution of momentaries. The grouping of station totals shows quite clearly in this graph. The complete central tendency, range, and dispersion of events are shown. It is interesting to note that generally those stations with the best power - either very stable and reliable commercial power or generators, and few instances of lightning in the area, again had fewer power, transmitter, and overall momentaries, despite other factors.

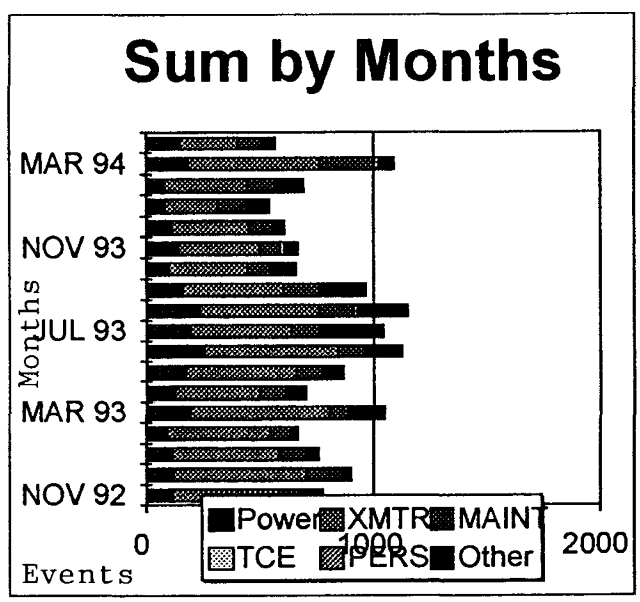


Figure 8.

Monthly momentary event sums in figure 8 show a very definite trend as well. There were over one thousand momentaries reported in North America during March, June, July, and August. These drastic changes in month to month totals are almost certainly due to weather. More exactly, increased numbers of events are likely due to lightning strikes and power fluctuations which accompany storms.

Long term performance being the key, the operational focus on reducing momentary outages is bearing fruit. Comparing this data with the data given in the "Signal Availability Requirement for Radionavigation Aids in the National Airspace System" dated March 1993, the U.S. West Coast Chain has reduced total annual momentaries over 22% since tracking began in 1987.

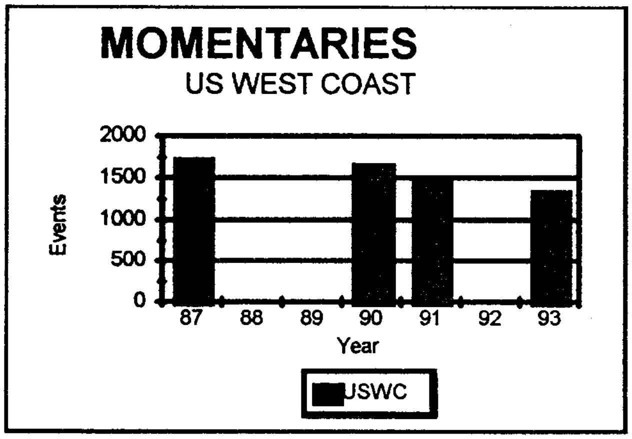


Figure 9.

Charts of stations manned or Remote Operating System (ROS) when compared showed no significant difference in momentary totals or distribution. Rather the opposite in fact - the stations totals and distribution of momentary classes followed quite closely other station characteristics below. Based on these charts it becomes apparent that the crucial issues in overall station momentary performance are the: 1) type of transmitters, 2) quality & control of power, and 3) severity of lightning & weather.

The fact that these items are major factors is not a revelation to operational chain management. However, it is interesting to note that those areas with the largest impact on operations are those over which we have the least control.

Conclusions on Momentaries

The margin of difference in performance between tube and SSX transmitters, though significant, was not as great as was anticipated, with the notable exception of the AN/FPN-45 transmitter. In all, power and weather appear to be the most heavily weighted variable factors. Of course, Loran chains are designed to provide coverage in a service area, which means that suitable sites' can not easily be chosen by weather patterns to reduce momentaries.

A recent initiative by the USCG Electronics Engineering Center has field tested a change to the SSX transmitters to decrease sensitivity to power and lightning caused faults. This is expected to reduce momentaries as well. Perhaps in the future new options in power configuration and back up will allow further improvements in operational performance.

Maintenance momentaries average just 2.74 per station per month. Still, some improvement in this area may be achieved by maintenance procedure changes, particularly with the Solid State Transmitter (SSX). One idea is increasing the period between required switches. Stations testing reduced SSX switches for maintenance have had very good success. U.S. Coast Guard Planned Maintenance System feedback reports were submitted to recommend these changes.

The West Coast and North Central U.S. Chain stations get a descriptive rating monthly on momentary performance. "Outstanding" to "Unsatisfactory" is the range. This provides timely performance feedback to the stations. To objectively compare stations the data suggests using a base level of 20 momentaries per station/rate. Modify this base by transmitter as follows: SSX x 1, AN/FPN-42 or 44 x 1.25, and x 1.5 for the AN/FPN-45. Power and lightning should also be assigned factors, probably .75 to 1.25 each. Since this relates back to overall system performance, any factors used for power or lightning should be relative. In other words, the product of all the factors should equal one. Applying this quick rule yields a performance comparison figure of average or "Satisfactory" performance. System managers can use these figures to give quick feedback, to identify trends, and to recognize problems and opportunities.

Unusable Time and Events

We evaluated all causes of unusable time (UT) during these eighteen months. A database was established and over seventeen hundred entries made from operational reports. This database described over 40,000 minutes of total unusable time using the categories established in Coast Guard Commandant's Instruction M16500.13, the Aids to Navigation Manual, Radionavigation, pagers 2-93 through 2-102. These categories are Transmitter, TCE, Communications, Monitor, Power, Personnel, Miscellaneous, and ROS.

Unusable Time & Events Analysis

The chart "Unusable Time - Percent by Category," figure 10, characterizes all unusable time for the period. This analysis revealed many interesting facts about long term operational performance.

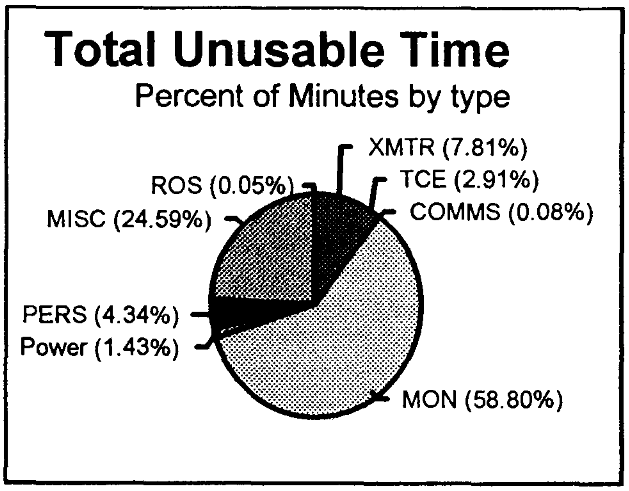


Figure 10.

By far the leading cause of unusable time is category four - Monitor Equipment. This category comprises almost 59% of *all* unusable time. On further review this becomes even more striking - the majority of category four time is caused by Sudden Ionospheric Disturbances (SIDs), which affect remote signal monitoring and reception. *This means the transmitted signal and equipment are not at fault.*

Furthermore, since SIDs and other Monitor category events are caused by solar and geomagnetic activity, the frequency, duration, and most particularly area of impact varies. Virtually all of the SIDs reported during this period occurred in Alaska. These northern stations are located under the polar auroral cap and are more frequently and severely impacted by solar, ionospheric, and geomagnetic activity. For the stations in the U.S. West Coast and North Central U.S. chains, little or no impact has been observed from most solar flares of class M5 or below. SID impact should vary with the number and intensity of solar events and the solar cycle.

Miscellaneous is the second most significant cause of unusable time at 24%. Again, a closer review of the individual items reveals a distinct pattern. Most AUTM periods were reported in the Miscellaneous group. These AUTM periods are needed to protect long term chain operations. Properly managed, although the impact is significant, it is necessary.

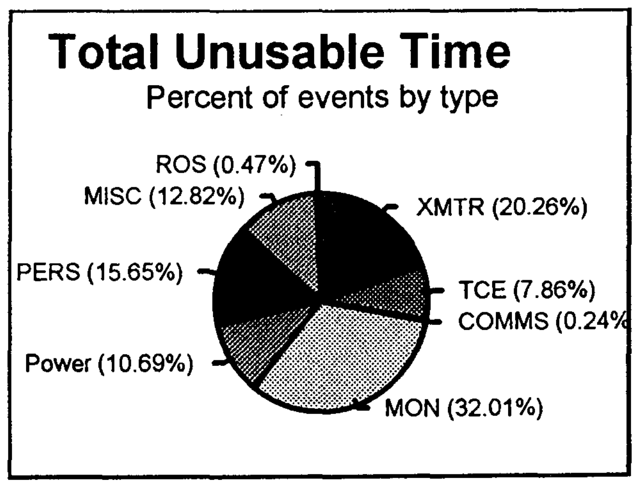


Figure 11.

Figure 11 shows the distribution of unusable events. Figure 12 gives the average number of minutes per event by type. Together, figures 10, 11, and 12 tell how each type of event impacts operations. The severe impact of SIDs and AUTMs on system availability is apparent. For performance tracking and operations optimization it is obvious that SIDs and AUTM are special cases. SIDs and AUTMs do not indicate how station equipment and personnel are actually performing.

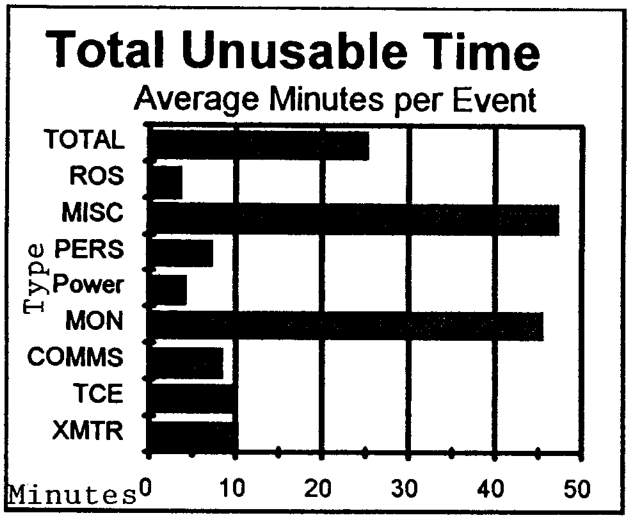


Figure 12.

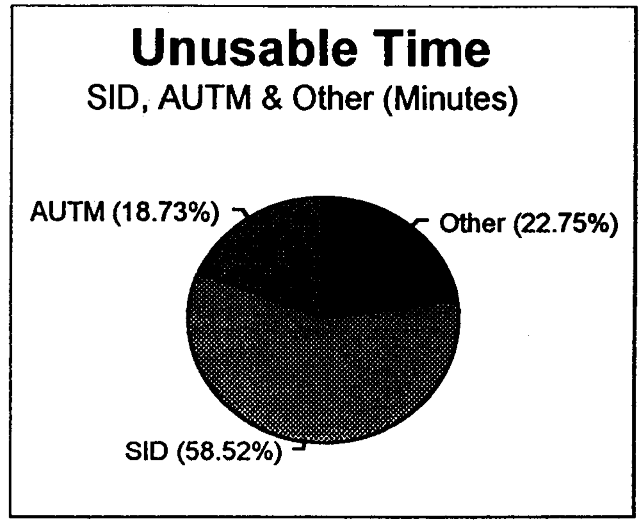


Figure 13.

For these reasons, SIDs are normally noted and discounted from operational performance reports, as is AUTM. This is done to achieve a more accurate comparison of station performance. SIDs and AUTM together account for more than three quarters of all unusable time, as shown in figure 13.

The significant amounts of AUTM during this period may be higher than normal. All towers were inspected during this period. Also, several significant field changes were field tested and introduced. The SSX transmitters were modified and changes installed in Signal Distribution Amplifiers (SDA), Transmitter Controller (TOPCO), and Output Coupling Network circuitry. Due to these circumstances there may have been more AUTM than normal during the period for which the data was gathered.

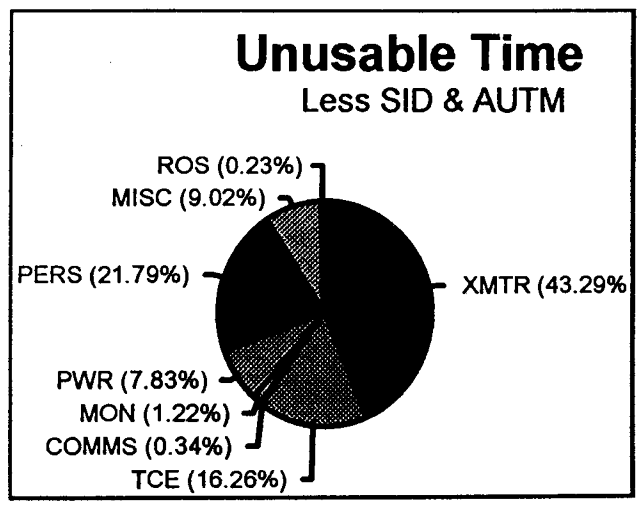


Figure 14.

Again, as with momentary events, we see that the areas with the largest impact on operations are those over which we have the least control. All other categories combined of unusable time represented just 22.75% of the total time. Other in figure 13 consists of the unplanned events that affect our users. These are the areas we must evaluate closer to achieve incremental operational improvements. These 9,379 minutes of the 41,229 minute total are called "Unusable Time less SID and AUTM." Figure 14 shows the distribution of this time by category.

Figure 15 is a graph of total unusable time (Blue/black plots) and unusable time less SID and AUTM (Gray/Green Plots) by station. This breakdown shows all stations to which the UT was attributed to, including Control stations. Wherever the plots of Total UT and UT less SID/AUTM overlap the gray/green (UT less SID/AUTM) only shows up in the graph. For example, the Control station totals are the same, hence gray/green, with the exceptions of 7960 (Kodiak) and 9940 (Middletown). These two are different because of SID UT attributed to Control.

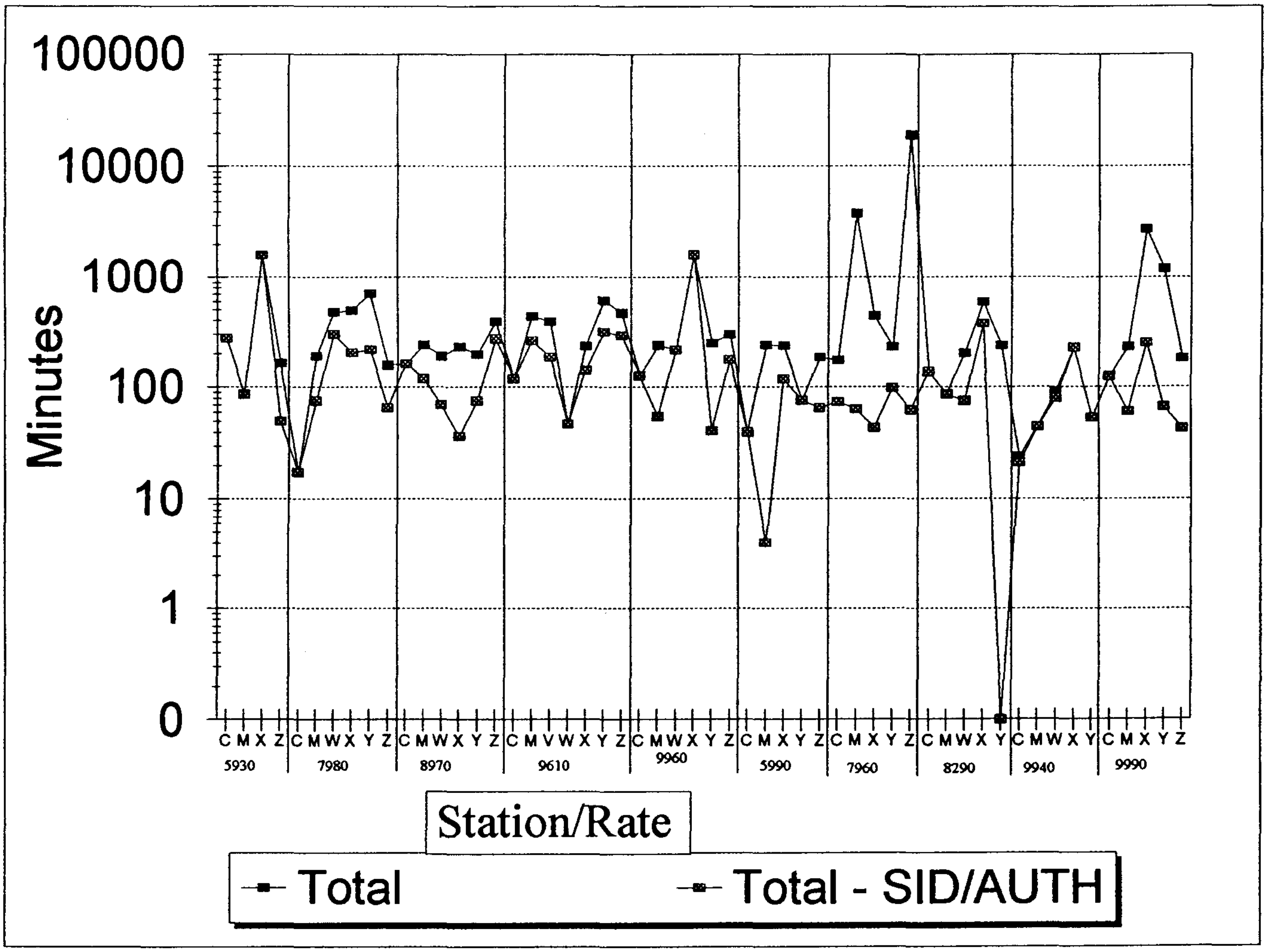


Figure 15.

There are several outliers in the figure 15 data which deserve further explanation. Chain 9990, the North Pacific chain stations X (Attu) and Y (Port Clarence) both had significant amounts of UT due to SIDs and AUTM. Chain 7960, Gulf of Alaska chain, stations M (Tok) and Z (Port Clarence) have high totals primarily due to SID activity. These events represent a significant amount of total UT.

Station X (Nantucket) of 5930 (Canadian East Coast) and 9960 (North East U.S.), had a prolonged outage of 1078 minutes. Multiple lightning strikes severely damaged the SSX SDA in this case. The damage was beyond the ability of the station to repair with available spares. In fact, Transmitters accounted for 43% of unusable time less SID and AUTM (see figure 14). The particular type of event which occurred at Nantucket is significant and will be covered further in conclusions.

This logarithmic graph in figure 15 shows the central tendency of UT time quite well. The mean total UT per station is 763 minutes, while the mean of UT less SID and AUTM is 174 minutes. These mean unusable minutes convert to effective station availability percentages of 99.903% total and 99.978% discounting SIDs and AUTM.

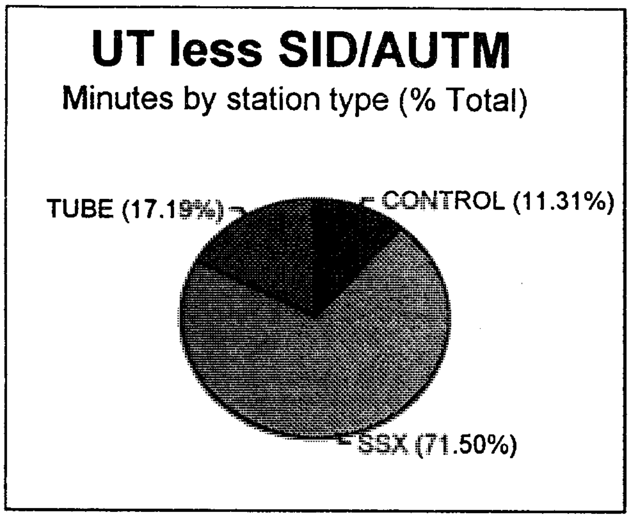


Figure 16.

Conclusions - Unusable Time

The total of all failures by station type is given in figure 16. This is using reported totals by station rate/designator. Dual rated station events are doubly weighted as was noted earlier. Events such as Nantucket's thousand plus minute off air count twice - once for each rate transmitted. That single event is almost 23% of *all* the UT time in this graph.

Several types of transmitter failures were identified as accounting for significant amounts of unusable time. Tube failures in the TTX and three types of critical failures in the SSX were identified. Most of these failures are typically related to lightning strikes and power. Also, especially in the SSX transmitter, UT is often extended by the time needed for crew recall.

Most TTX tube failures result in short periods of UT. Several overloads in a short time or low power may result in a transmitter switch. These events, although frequent, typically result in only one to three minutes unusable time.

In one SSX scenario, the transmitter suffers damage to the Output Coupling Network. Recent Remote TOPCO (Transmitter Operational Controller) Reset and Remote Operating System (ROS) field changes have significantly reduced the impact and severity of these event types.

The second SSX scenario is a failure of the SDA chassis and/or multiple cards. Extended time results when the damage is beyond the ability of the unit to repair from on board spares. This is typically due to multiple lightning strikes.

In the third SSX scenario, during an Output Coupling Network switch, a power loss occurs. This leaves the transmitter off-line, the switch incomplete. The switch must be manually commanded to restore operations. Of course, the atmospheric phenomena normally associated with automatic Output Coupler Network switches *and* power fluctuations is lightning. There have been at least four cases of the last class of SSX event in the past year, resulting in over two hours of unusable time. A suggestion to correct this is under evaluation.

The review of this data indicates the major causes of unusable time are SIDs, AUTM, and the transmitter events already covered. Personnel errors (21% of UT less SID/AUTM) can result in significant amounts of time, especially remote emergency stops of transmitters. Currently, additional training is used to reduce the potential for these events.

Another area worthy of comment is communications. Although the reported percentage and number of events attributed to communications is extremely low, many other events would either have not occurred or would have had negligible impact if not for a communications failure or shortfall. These communications events, though not the primary cause, are significant contributors to UT.

A case in point was the 24 September 1992 North Central U.S. event. Control Station Middletown suffered a total catastrophic communications loss due to a commercial microwave link failure. A few minutes later, the Havre, Montana 8290 Master station operate timing suddenly moved out of tolerance. This resulted in over sixty minutes of Master UT. With normal communications this event would have "cost" 2-5 minutes, as opposed to a total of over 180 minutes, with an entire chain involved. Several initiatives are being implemented to improve communications, increase redundancy, and eliminate critical nodes to prevent a reoccurrence of this type of event.

Overall Conclusions

As an analysis of performance this paper has focused on what went wrong and how it could have been avoided. That is generally the *raison de être* of operational post mortems. In this case we must conclude that the vast majority of events and time, both unusable and momentary, were either needed to maintain the equipment and operations (AUTM & Maintenance), protect the users (SID), or were unavoidable given current physical, financial and technical limitations (Power & Lightning related events).

Overall, operations of the North American Loran system appear outstanding. Only relatively minor incremental improvements are identified here. Again, mean station availability was 99.978%, discounting SIDs and AUTM. This is an enviable record for long term performance.

Momentary event levels are dropping. Field changes to reduce both momentaries and UT are being introduced. Initiatives in policies and procedures are cutting operational risks. New communications technology is being integrated into control systems. All these efforts should result in long term improvements to operations.

Remember, however, that only 22.75% of all the UT reported is controllable or avoidable. A single event accounted for 23% of this. Can operations improve? Yes. Will improvement continue? Yes. Can a single catastrophic event undo this prediction? Definitely. In this world disaster is not a rarity, it is a certainty! Given a large enough universe of complex systems, unlikely things happen. During this period a tower collapsed, lightning damaged stations, communications failed, fires burnt and earthquakes struck. Despite all these, the system still succeeded 99.978% of the time.

On a recent fishing trip off California the skipper said, "I've had this here boat three years. Yeah, my Loran didn't work once - we'd headed out, got over the fish, and it just died. Another boat told me they was working on the antenna. But it was working again before we had to come in through the fog. Caught some nice fish that day." Another satisfied customer.

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Biographies

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LTJG Gene Vogt is the Coordinator of Chain Operations for the West Coast and North Central U.S., and was previously an Atlantic Area Loran Chain Manager. Other assignments have included Coast Guard Training Centers, the cutters Dallas, Gallatin, and Point Swift, and Air Force assignments in Tactical Reconnaissance, Fighter Wing Operations, and training units. His degrees are in Photographic Systems (A.A.S. - Community College of the Air Force, 1980), Management (A.S.M.-Edison State College, 1993) & Business (B.S.-SUNY Regents College, 1993).

The Space Environment, Circa 1994

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Abstract

In 1994, solar cycle 22 is declining and approaching its minimum. Solar flare activity is less frequent and less impressive than that of a few years ago. Occasionally the Sun produces large events such as the episode in late February 1994, but on most days there is little in the way of solar pyrotechnics. It may be somewhat surprising, then, that the Sun continues to affect navigation systems even though the activity occurring now is of a less dramatic nature. For example, the long-term record of geomagnetic data has a secondary maximum of storm activity during the declining phase of the solar cycle. Ground-based navigation systems, experiencing fewer ionospheric disturbances from solar flare x-rays, still struggle with ionospheric irregularities associated with these geomagnetic storms. Space-borne systems must contend with the vagaries of the environment on two fronts: signal propagation and, perhaps more important, the integrity of the satellite itself. Ionospheric scintillations that accompany geomagnetic storms hamper the proper propagation of the radio wave from the spacecraft to the ground. Recent failures of spacecraft at geosynchronous orbit have dramatically demonstrated the ultimate effect energetic protons and electrons can have on the satellite electronics. A record of GPS anomaly reports shows a pronounced peak in October 1989, the time of one of the most severe energetic solar proton events yet seen. Even though that period of increased single event upsets (SEU), also known as "bit hits," was during solar maximum, it illustrates the fact that spacecraft are prey to radiation hazards posed in the near-Earth environs. Navigation system operators, therefore, should be careful not to equate *solar minimum* with *solar quiet*.

Introduction

The solar activity cycle is approximately 11 years long. The parameter traditionally used to measure the cycle is sunspots. The current cycle, number 22, reached its maximum in mid-1989 and is now well into its declining phase. This behavior is illustrated in the plot shown in Figure 1.

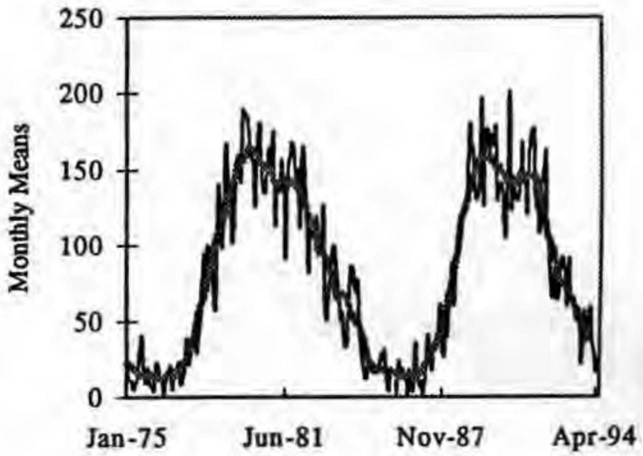

Figure 1. Monthly mean sunspot numbers since 1975. A smoothed 13-month running value is superposed. These data span all of Cycle 21 (1976-1986) and Cycle 22 to the present.

Cycle 22 is the third highest in the modern record, which extends back a few hundred years. The amplitude accelerated quickly in the early stage of the cycle, causing speculation that it may be the highest yet seen. This quick start then gave way to a more leisurely maximum phase. Near maximum, in the spring and fall of 1989, there were episodes of very high solar activity that lasted about 2 weeks each. Electric power companies, spacecraft operators, and NASA, with a Space Shuttle flight aloft in October 1989, all experienced the consequences of this elevated activity. These were but a few of the areas affected by the Sun's fury.

Navigation systems, Loran-C and GPS, also had problems during these times. A very perturbed geomagnetic field and ionosphere, due to increased ionization from an influx of solar flare x-rays, made operations very difficult for Loran-

C [1]. Blink periods were commonplace. GPS receivers could not track the carrier phase, which was doppler shifted by irregularities in the electron content of the ionosphere. A GPS campaign in California reported great difficulty while working during the high activity period in March 1989 [2].

Another impact on GPS operations during the solar maximum era was not immediately known to the public at large. As part of the proper maintenance and operation of the GPS constellation, the 2nd Space Operations Squadron, United States Air Force, maintains a record of single-event upsets (SEU) experienced by GPS spacecraft. These anomalies are thought to be due to the passage of a high-energy particle --usually a proton or heavy ion--through the micro-electronics of the onboard computer. When this passage occurs, the result is often a change of state of a bit, called a "bit hit." Data made available to the National Geophysical Data Center in Boulder by the 2nd Space Operations Squadron showed the occurrence of bit hits over a span of years in the 1980s and early in the 1990s. Figure 2 is a plot of the bit hit record, with the frequency of occurrence shown on the vertical axis.

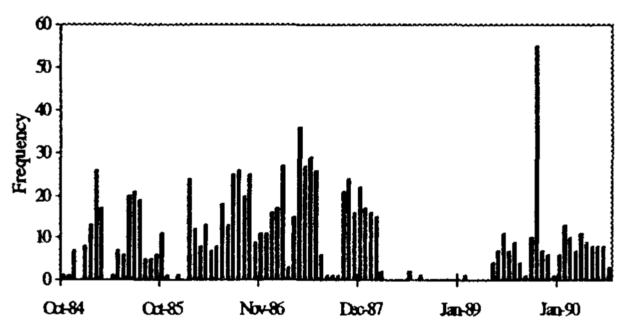

Figure 2. GPS satellite bit hits 1984-1990. The spike in late 1989 occurs during a period of extreme solar activity. These data are for the block I series of spacecraft.

There is a clear correspondence between high solar activity and the very high number of GPS bit hits during the fall of 1989. From late September-October 1989, a series of very energetic solar particle events occurred. These events were characterized by large fluxes and by very hard proton spectrum. It is not surprising that the GPS constellation felt the effects of this bombardment of solar energetic protons, but it should be made clear that bit hits are usually not severe enough to cause any long-term damage to the spacecraft. However, the data clearly show the vulnerability of GPS craft to large enhancements of solar energetic protons. These data pertain to the older, block I series of GPS spacecraft, of which all, or the vast majority, have since been replaced with newer, block II satellites. It appears that the bit hit problem has been largely alleviated by the new design.

One must be cautious when characterizing the potential for serious damage to a satellite by a bit hit. Although most SEUs are likely to be only temporary problems, NASA's Clementine lunar mission was ended prematurely--and unexpectedly--when an SEU caused a communication outage with the spacecraft. This outage resulted in three thrusters turning on and depleting the supply of hydrazine fuel, which was required to manuever the spacecraft; its loss meant that the second portion of the mission, filming the asteroid *Geographos*, had to be scrubbed [3]. This malfunction occurred in what was termed as "tried-and-true" technology by NASA officials. Department of Defense analysts speculate that the root of the problem was a SEU due to radiation that had a probability of occurrence of about 1 in 1,000.

These examples serve to illustrate the types of problems that can hamper systems during the height of the solar cycle. The problems tend to fall in two general areas: those related to the proper transmission of the electromagnetic wave and those related to the integrity of the system. Questions like "will the Loran-C skywave and groundwave arrive simultaneously?" or "will a GPS receiver fail to lock on to L2?" are of the former type, and usually relate to conditions of a transitory nature. When normal conditions return in the operating environment the problems generally go away. The more devastating issues, such as if a system will be put out of commission for a long period of time--or forever--can be categorized as of the latter type.

While a Loran-C antenna collapse such as the one at Cape Race in 1993 [4] is a very serious problem, at least it is possible to go to the site and repair the antenna. For GPS satellites the problem is more acute. When a spacecraft computer fails there is no way to go fix it, and if the communications system fails, there is no way to resurrect it. The engineering design must be such that the system can withstand whatever the environment has to offer. Failures of the Anik E-1 and E-2 satellites on January 20, 1994, dramatize the plight of satellites in Earth orbit [5]. Though the environment varies with both the altitude and inclination of a given satellite, each orbit will have its own unique set of difficulties.

Therefore, the question of "*what happens to navigation systems during solar minimum*?" must be addressed from both of these perspectives. Both wave propagation and system integrity are at risk and each is affected by different factors. System operators will find that they still must take into account the space environment; but the mechanisms that cause the problems, as well as the problems themselves, are now different.

The Good News

During the declining phase of the solar cycle, solar flares are relatively uncommon. Back during the maximum phase in 1989, it was not unusual to have a day on which as many as 40-50 flares occurred, some of them quite large. In 1994, there have been days during which no flares occurred, and a "busy" day may count 10 events in the flare log. The large flares are very rare, although one did occur on February 20 of this year.

Few solar flares means few periods of large increases of x-rays from the Sun. Few x-rays mean that the dayside ionosphere stays relatively stable for long periods of time. When the ionosphere-- the layer that causes the reflection of the Loran-C skywave--is stable, Loran-C receivers have little trouble distinguishing between the desired groundwave and the unwanted skywave. Solar flare x-rays can reach down to the D-region of the ionosphere, causing the wave reflection height to drop and the skywave to arrive at the receiver nearly concurrent with the groundwave. These conditions are problematic for Loran-C, but now, in the solar minimum epoch, they are rare.

GPS operations are largely unaffected by solar flare x-rays, no matter what the stage of the solar cycle. The signals transit the ionosphere, and being at L-band, are high enough in frequency to be immune to the x-ray effects. So the fact that the Sun is in the declining phase of its cycle and generating few flares is of little concern to GPS.

One particular group of GPS users who should experience much more benign conditions during this phase of the solar cycle are those working in the equatorial regions. This area, covering almost 50 percent of Earth's surface, is bounded by bands about 30° on either side of the magnetic equator. During the maximum phase of the solar cycle strong ionospheric irregularities, usually appearing in the evening hours, severely hamper high-precision GPS positioning [6]. However, during the current declining phase of the cycle those periods of disruption become increasingly rare.

Another bit of good news for GPS operations at all latitudes is that currently there are fewer solar energetic protons to cause SEUs. A quick look back at Figure 2 reveals the large increase in SEUs during late 1989, a time of elevated solar flare activity. But a closer look at Figure 2 begs the question of why are there so many SEUs during 1986-87. This was the time just after solar minimum, before flare activity became very severe. The probable answer is that SEUs can be caused by any large cross-section particle that passes through the circuitry onboard the satellite. While solar energetic protons can certainly do this, the Sun is not the only source of protons and heavy ions; another source is deep space.

Galactic cosmic rays (GCR) also cause SEUs. They consist primarily of energetic protons and of lesser amounts of helium and heavier elements through iron. They are thought to be remnants of supernovae that enter the heliosphere from afar. Although the fluxes of GCRs are low, their biological and electronic radiation effects are significant [7]. GCR flux varies by about 30% for particles at energies greater than 1 GeV over an eleven-year period [8]. In fact the GCR flux is anti-correlated with the sunspot cycle. This property has an impact on GPS operations and will be discussed later in this paper.

The Bad News, Part 1: Propagation Effects

Radio wave propagation, both through the ionosphere and reflected off it, is affected when the geomagnetic field is disturbed. Current systems that flow in the ionosphere become enhanced when the magnetic field is rapidly changing, causing increased ionization and inhomogeneity in the ionospheric region. This instability of the ionosphere may hamper both the proper passage of signals through the medium (GPS), and the reflection of radio waves off it (Loran-C). For GPS users, the term often applied to these circumstances is scintillation. As was previously mentioned, scintillation effects become less of a problem to GPS users operating in the equatorial region. However, for GPS users that inhabit the other 50 percent of the globe, scintillation effects accompany geomagnetic storm activity [9].

Unfortunately, geomagnetic activity does not track with the sunspot cycle. A time of few flares is not necessarily a time of few magnetic storms. Recent studies on the relationship between solar activity and geomagnetic activity have argued that the flare is but a minor player in the processes that govern geomagnetic activity [10]. The Coronal Mass Ejection (CME), a much larger but difficult-to-detect transient leaving the Sun, is thought to be the true driver in the scenario. These ejecta sometimes have a velocity very much faster than the normal solar wind and, as such, they push a shock wave in front of them. When the shock and then the CME pass Earth, a geomagnetic storm may ensue if the direction of the associated magnetic field is favorable [11]. This is one of the primary mechanisms thought to produce magnetic storms at Earth, and the frequency of

CMEs does have a positive solar-cycle dependence [12]. However, a different phenomenon, the structure and location of areas of the solar corona called coronal holes, is anti-correlated with the number of sunspots and seems to be predominant during the declining phase (i.e., though CMEs are fewer, coronal hole effects are much greater). Coronal holes allow the efflux of high-speed solar wind away from the Sun, buffeting Earth's magnetic field and causing storms.

Figure 3 is a time series of a geomagnetic indicator, the aa index, that illustrates the recent behavior of the geomagnetic field in 1994. The data are plotted back to 1975 so they can be compared with the sunspot data in Figure 1.

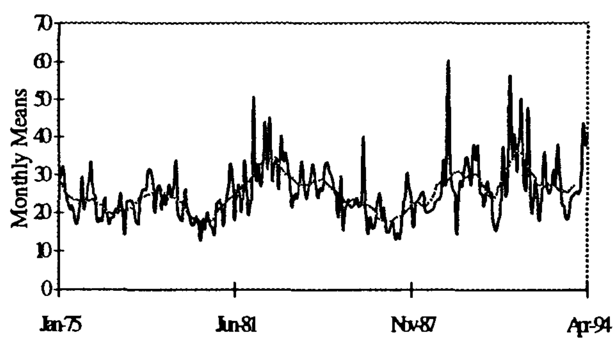

Figure 3. The geomagnetic aa index since 1975. A smoothed 13-month running mean is superposed. High values denote times of disturbance in Earth's magnetic field. Note the recent local maximum in early 1994.

It is difficult to succinctly characterize the geomagnetic data. They show maxima occurring in late 1982, during solar cycle 21, and in late 1991, during solar cycle 22. Both of these high water marks lagged the sunspot maxima by at least 2 years. The 11-year periodicity of the sunspot data is absent in the geomagnetic data. Figure 3 also shows a recent local maximum in the early months of 1994.

During times of elevated geomagnetic activity, navigation systems are affected. Loran-C operators will find it necessary to declare the signal out-of-tolerance more frequently, especially in geographic locations such as Kodiak, which is at a fairly high geomagnetic latitude. If the magnetic storm is more severe, the necessity to blink will also occur over the lower 48 states. During extremely disturbed times, the effects will be felt as far equatorward as the Carribean. The March 1989 storm brought visible aurora to Key West, Florida, and caused many problems for Loran-C. The very strongest storms seem to occur during the maximum phase of the solar cycle, as CME occurrence is greatest then. This is good news for Loran-C operations in 1994.

GPS is also hampered by geomagnetic activity. However, the ionospheric irregularities that are problematic occur at the very top of the ionosphere, much higher than the region where Loran-C signals are impacted. Large irregularities in the electron content in the F-region cause the amplitude of the GPS carrier to fade in and out. This variability has an impact on the ability of GPS receivers to lock onto the carrier, the technique used for the most precise type of positioning. In contrast, receivers that track GPS code are usually not affected by amplitude scintillation.

GPS users in the auroral and polar latitudes will see the adverse effects of elevated geomagnetic activity at this point in the solar cycle. This is the opposite of what their contemporaries in the equatorial region will experience for the next few years. Mid-latitude GPS operations will also suffer few effects, although the rare large storm will drive the disturbed ionosphere equatorward and cause intervals of amplitude scintillation.

The Bad News, Part 2: System Effects

The 1994 era brings with it circumstances that can result in long-lasting, serious damage to the electronic components that constitute a modern navigation system. It seems, though, that the distribution of problems that may befall Loran-C and GPS is skewed such that Loran-C system effects are minor, and fixable, while GPS system effects are severe and permanent. This is entirely due to the space-based nature of GPS--or any satellite, for that matter--and the harshness of the near-Earth environment during solar minimum. Yet another issue, associated with the use of GPS by the commercial airlines, is the implementation of the Wide Area Augmentation System (WAAS), which advertises greater system reliability for the commercial sector. This plan purports to use geosynchronous-orbit satellites to downlink corrected GPS signals to the airlines. These geosynchronous communication satellites must also contend with the whims of the radiation environment in which they fly.

Perhaps most threatening to the health of spacecraft in 1994 are lengthy episodes of large increases in the numbers of energetic electrons (>2 MeV). This situation, first observed during the declining phase of cycle 21 in the early 1980s, seems unique to this point in the solar cycle

[13]. The integrated effect of bombarding a satellite with fast electrons for many days is to charge the dielectrics embedded in the heart of the on-board computers and associated systems. These high-energy electrons bury themselves in dielectric materials such as co-axial cables or circuit boards, and then stop there. They give rise to very high, local electric fields until a breakdown eventually occurs [14]. The problems experienced by the Anik E-1 and Anik E-2 spacecraft in late January of this year are thought to be due to this phenomenon. Additionally, the Intelsat K satellite, also at geosynchronous orbit, had problems with its momentum wheel control circuitry just prior to the more publicized Anik woes.

The GPS spacecraft orbit (17,600 km) is different from that of the Anik or Intelsat satellites; it is just less than one-half the distance out to geosynchronous orbit. The GPS orbit goes through the heart of the outer zone, where large fluxes of energetic electrons are commonly observed in concert with high levels of geomagnetic activity [15]. These particle fluxes are on par with the values seen earlier this year at geosynchronous orbit when the satellite problems occurred.

Radiation hardening of the spacecraft will mitigate the damage from deep dielectric charging. Presumably the GPS block II series of spacecraft were designed to avoid the effects experienced by the aforementioned commercial satellites. When the WAAS concept comes to fruition, great care must be taken to design these new geosynchronous relay satellites to withstand periods of increased radiation.

Galactic Cosmic Rays, mentioned earlier in this paper, are another distinct source of potential problems for satellites at any altitude. These large particles may cause SEUs when they pass through any satellite.

At this point in the solar cycle, GCRs are more abundant in Earth orbit. This fact is illustrated in Figure 4. The plot of data from the Deep River Neutron monitor in Canada, shows the number of neutrons seen by that detector. Neutrons are produced in the chain reaction that follows when a GCR collides with neutrals in the upper atmosphere, causing a cascade of secondary particles. The greater the count of neutrons on the ground, the greater the flux of GCRs impinging at the top of the atmosphere.

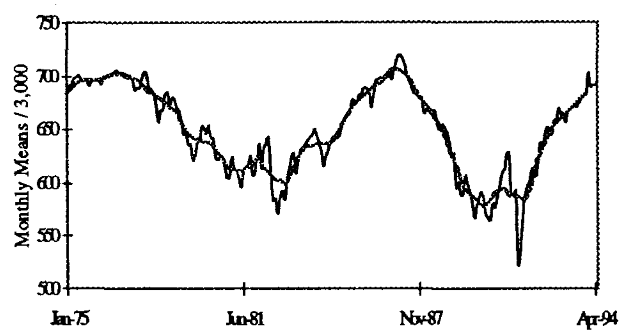

Figure 4. Deep River neutron counts since 1975. A 13-month smoothed value is superposed. These data are anti-correlated with sunspots (see Figure 1) and show the high values of GCRs seen during solar minimum.

The data in Figure 4 show a periodicity comparable to that of sunspots (but missing in the geomagnetic aa index). The data suggest that a turbulent inner heliosphere, occurring when the Sun is very active, inhibits the entry and propagation of GCRs. The converse of this situation, the easy access to Earth by GCRs, occurs when the Sun is in a quiet phase. In 1994, satellite operators are likely to see increased numbers of SEUs from the higher numbers of GCRs passing through their spacecraft.

Conclusion

Certainly, 1994 is in the declining phase of solar cycle 22. But, for navigation systems, is experiencing the declining phase of a solar cycle preferable to being in the ascending or maximum phase? The short answer is *maybe*.

Loran-C will see fewer upsets due to solar flare x-rays but must still contend with outages from a disturbed geomagnetic field. GPS, always immune to x-ray effects, will find conditions generally poorer. It is true that for a GPS user working in the equatorial region, the likelihood of strong evening-hour scintillations will decrease: but elsewhere on the globe, scintillations will come with geomagnetic activity.

And then there's the serious issue of damage to the components, electronic or otherwise, that are the heart and soul of the individual navigation system. Loran-C operations must always worry about transmitter towers icing up and falling over, but as yet no link has been established between those failures and the solar activity cycle.

Unfortunately, for GPS the same statement cannot be made. GPS satellites will be subjected to more radiation, from electrons and GCRs, which will be at least harmful and at worst fatal to the fragile miniaturized microelectronics onboard. These particles will also prey on communications satellites in geosynchronous orbit, a critical link in the newly proposed WAAS.

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Biography

Joseph M. Kunches is the lead forecaster at NOAA's Space Environment Laboratory, a world center for monitoring and predicting solar and geophysical activity. His involvement in solar-terrestrial physics dates to the SKYLAB era of the early 1970s, when he worked at NASA's Johnson Space Center in support of the Apollo Telescope Mount (ATM) program, dedicated to the study of Solar Physics. Professional interests include the effects of solar and geomagnetic activity on navigation systems, and the study of radiation issues pertaining to the acceleration and propagation of solar energetic particles. He is a member of the Wild Goose Association, the Institute of Navigation, and the American Geophysical Union. Academic work includes a Bachelor of Science in Aerospace Engineering from the University of Notre Dame (1970) and a Masters of Basic Science from the University of Colorado, Boulder (1985). He was formerly a lecturer at the University of Colorado, Boulder from 1983-1991.

Availability and RAIM Integrity Analysis of a Combined GPS/Loran-C System

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Abstract - Operational air navigation systems not only must provide accurate and reliable signals that can be used to determine aircraft position, but they also must be available to the user when needed, and must be able to warn the user in a timely manner when system signals are unsafe to use. Signal availability requirements are being developed for the en route, terminal area, and nonprecision approach (NPA) flight phases. The most stringent requirement applies to the approach phase, because of the critical need to provide timely notification of lack of ability to navigate.

The Global Positioning System is capable of providing navigation signals worldwide, and for this reason the FAA is moving to incorporate GPS into the National Airspace System as soon as possible. Although certified as a supplemental navigation system for nonprecision approaches,

GPS cannot provide the integrity or availability necessary to be certified as a sole means NPA navigation system.

The FAA has therefore initiated a project to determine the ability of integrated radio-navigation systems, such as GPS and Loran-C, to meet sole means nonprecision approach requirements.

The purpose of this paper is to present an analysis of how the availability of GPS is enhanced when GPS is combined with Loran-C ("augmented" GPS). The main result is that the unavailability of a GPS/Loran-C system is at least two orders of magnitude better than GPS alone. When GPS, with Receiver Autonomous Integrity Monitoring (RAIM), is aided by a barometric altimeter, it has an availability of about 99 %. When this GPS system is augmented by Loran-C, availability exceeds 99.997 %. Further validation by field tests should confirm that the GPS plus Loran-C augmented system, aided by a barometric altimeter, meets sole means approach requirements.

Introduction. The Federal Radionavigation Plan [1] 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 navigational signals transmitted from external sources are available for use. It (signal availability) is a function of both the physical characteristics of the environment and the technical capabilities of the transmitter facilities."

Integrity is the ability of a system to provide timely warnings to users when the system should not be used for navigation. Integrity means the capability to detect and isolate faults in the navigation system, and to alert the user in a timely manner. Recent analysis indicates that GPS by itself cannot meet the sole means integrity requirements for NPA [2], [3]. Supplemental navigation systems require only a fault detection capability to ensure integrity, whereas sole means systems require fault detection and isolation (FDI).

Loran-C integrity is provided by blinking the signals of the master transmitter. This process is on the verge of being automated to meet FAA approach integrity requirements. GPS integrity can be provided by requiring that satellites in addition to those required for a navigation solution be tracked. The need to track more satellites simultaneously reduces GPS availability.

The results presented in this paper show that the *unavailability* of a GPS/Loran-C system is at least two orders of magnitude *less* than stand alone GPS. That is, GPS RAIM without a barometric altimeter (unaugmented GPS), has an availability of 94.4 %; when the altimeter is added, system availability increases to about 99 %. When the GPS RAIM plus baro system is augmented by Loran-C, availability exceeds 99.997 %. Further validation by field tests should confirm that the GPS plus

Loran-C augmented system, aided by a barometric altimeter, meets sole means approach requirements.

In addition, Loran-C can use the same approach geometry and cockpit display instruments now allowed for GPS. The two systems thus are very compatible, yet also are complementary with respect to integrity and redundancy. Several Loran receiver models have been certified for the en route and terminal area flight phases, and about 150,000 receivers are now in active use among the general aviation community.

The Volpe Center has played a key role, for the last several years, in supporting the FAA effort to incorporate radionavigation systems into the NAS. This support has included work on GPS and Loran-C, and has involved all system aspects from the development of operational and performance requirements, to analysis of these systems in the laboratory, and to field performance assessment and prototype installation of several Loran and GPS-based systems.

The objective of the present effort is to determine the extent to which Loran-C improves the availability of GPS. It will be demonstrated that, unlike other augmentation schemes such as baro aiding, Loran-C itself can function in a stand alone mode, using the same approach plates as GPS, thereby providing protection against interference or jamming of the GPS system. The "reversion" capability of a GPS/Loran-C system makes it especially attractive for general aviation.

Availability Considerations. The availability measure used in this paper is signal availability as defined in the introduction. For NPA, it means that the navigation system is available at the initiation of the approach. The integrity process, which warns the pilot in a timely manner if there is no navigation ability, involves continual monitoring of system status and performance. The availability requirement of a system which must provide integrity is more stringent than the availability requirement needed only to provide a navigation solution.

For example, four GPS satellites must be "visible" for navigation, but until the Wide Area Augmentation System (WAAS) is established, at least five visible satellites are needed to provide RAIM for nonprecision approaches. Since four satellites are visible more often than five, implementing RAIM integrity reduces availability. *Precision* approach integrity requirements are more demanding than the nonprecision approach requirements.

Assumptions. The availability study described here considers GPS, Loran-C, and the barometric altimeter. GPS is the primary navigation aid (navaid) for NPA, and Loran-C and baro provide augmentation to GPS in all navigation modes except the Loran reversion mode, in which Loran-C operates as a stand alone system. The analysis assumes that the onboard navigation equipment is functional at all times, and that it has been installed properly, so that, for example, the effects of precipitation static interference on Loran-C performance are minimal. Based on the FRP definition, the navigation system is considered "available" if reliable navigation signals are present at the start of a nonprecision approach[1] [2].

GPS availability data are derived from coverage and geometry software, as well as DOD system availability guarantees. The operational constellation, Optimized 24, and mask angles of 7.5° and 5.0° are used in estimating GPS availability.

Analysis Methodology. There are no historical GPS availability data because full operational capability has not been achieved yet. Loran-C NPA availability was determined from Markov analysis of selected NPA scenarios, and by using historical transmitter signal availability data primarily from the Northeast U. S. chain (GRI 9960) [2]. The augmented GPS and Loran-C coverage and geometry (dilution of precision - DOP) analysis tool was derived from software developed at the Volpe Center under related projects [4,5].

The availability measure used in this report is determined from

$$\text{Availability} = 1 - \frac{\text{No. unavailable space-time points in 24 hours}}{\text{Total space-time points in 24 hours}} \qquad (1)$$

where a space-time point is a location in the three dimensional space consisting of the time line and two position dimensions (latitude, longitude). *Un*availability is computed first, and availability derived from it using Equation (1).

A simulation and analysis capability was established at the Volpe Center to quantify GPS/Loran-C NPA availability using Equation (1). The primary elements in this activity included:

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[1] Because of system integrity, loss of navigation, once an NPA has been initiated, will be announced to the pilot, who then must execute a missed approach according to published procedures.

- Assimilating Loran-C and GPS data
- Developing realistic assumptions and scenarios
- Adapting or upgrading existing software, and generating new software as needed
- Conducting simulations and analyses

The availability statistics were computed at the locations of 2310 public use airports. Evaluating availability every six-minutes generates 240 time points over a full day at each location. Consequently, there are 554,400 space-time points used in the CONUS for this analysis. Availability values are quantized by the inverse of this number, 1.8×10^{-6}, making 99.99982 % the highest possible computed availability value short of 100 %. Note that the availability value given by Equation (1) is measured over the entire CONUS, and is not a reliable number for determining the likelihood of executing an NPA at a given airport at a given time.

The availability values are displayed as percents, and were computed over a 24 hour day, using 6 minute intervals. GPS Fault Detection (FD) RAIM was calculated using the parity space algorithm with a protection radius of 555.6 meters [3]. Availability values were computed for the different navigation modes for the cases of 0, 1, and 2 "failed" GPS satellites (no navigation signal). Three levels of GPS augmentation ("navigation modes") were compared in the analysis. Each mode had the additional augmentation option of using the barometric altimeter.

<u>Mode 1 - GPS</u> - This is the reference mode. It essentially is GPS as a sole means navigation system.

<u>Mode 2 - GPS + Loran-C (Augmentation)</u> - In this mode, Loran-C measurements are used as GPS pseudolites to augment the GPS constellation. The baro altimeter also can assume the role of a pseudolite. In the analysis reported here, the Loran receiver is constrained to monitor the approach chain. Any combination of three or more Loran transmitters in the approach chain which are in view and which produce signals acceptable for navigation can be used. Conservative Loran NPA requirements on signal-to-noise ratio and chain selection are assumed, since no MOPS exists for a combination system. The approach chain is the chain which contains the approach triad as defined by the Airport Screening Model (ASM) [5].

<u>Mode 3 - GPS + Loran-C + Loran-C "Reversion" (Reversion)</u> - This mode provides the best overall availability since Loran is used as a stand alone, "reversion" system to provide navigation whenever the GPS or augmentation modes fail to meet NPA requirements. The availability of the augmentation mode is thus enhanced by stand alone Loran availability in a direct "add-on" sense. Navigating in Loran-C Reversion requires use of the designated approach triad. At a minimum, the designated approach triad requires for Loran navigation a (dimensionless) GDOP less than 3.0 and an SNR greater than -6 dB, in accordance with RTCA MOPS DO-194 [6]. Thus Loran-C receivers used in the reversion mode must be certified according to TSO-C60b.

The analysis procedure consisted of four steps:

<u>Analysis Procedure Step 1. Evaluate Availability of GPS or GPS Augmented with Barometric Altimeter.</u> For each airport at each time (space-time point), the protection radius for GPS or GPS augmented by barometric altimeter was determined. If the protection radius was satisfied, then the space time point was declared available. If the protection radius was not satisfied, then two phases of Loran-C augmentation were considered (Analysis Procedure Steps 2 and 3, respectively).

<u>Analysis Procedure Step 2. Loran-C Augmentation as Pseudolite.</u> The GPS or GPS plus barometric altimeter mode is unavailable under RAIM integrity if the geometry of the available satellites cannot satisfy the maximum protection radius. This occurred in the analysis either because there were fewer than five satellites available, or because the geometry could not support the required protection radius. The first level of augmentation (Step 2) was to use Loran-C to provide additional pseudolites for the parity space algorithm. All stations in the primary chain which had a calculated SNR exceeding -6 dB at the worst time of the year (summer) were used as pseudolites.

Using the parity space fault detection algorithm [3], the protection radius of the augmented system was computed. If it was less than the 555.6 meter NPA maximum radius at the space-time point, the augmented navigation system was considered to be available. In addition, a calculation of reversion capability (Loran-C GDOP less than 3.0 for the primary triad) at each space-time point was made.

<u>Analysis Procedure Step 3. Loran-C Augmentation in Stand Alone Reversion Mode.</u> If an airport failed the integrity protection radius requirement (Step 2), then a check was made to see if the Loran reversion criteria were satisfied (Step 3). In this analysis the conservative criteria currently in use for Loran-C NPAs were applied [6]. An airport was suitable for Loran-C nonprecision approach if:

(i) GDOP (HDOP) on the primary approach triad (as defined by the ASM) was 3.0 or less.

(ii) the SNR (See RTCA document DO-194a and TSO-C60b) was greater than -6 dB.

The Airport Screening Model was used for this determination. If these criteria were satisfied, then the space-time point was considered available at the third or reversion level. Loran stand alone capability exists at about 98.5 % of the 2310 airports used in the study.

Analysis Procedure Step 4: Compute Overall Statistics. Each of the 544,400 CONUS space-time points was evaluated by the analysis tool at least once for RAIM availability, starting with stand alone GPS. Extra evaluations were conducted only for space-time points which failed RAIM availability and thus required augmentation. Baro aiding was included with the three basic modes in a separate set of simulations, for comparison. This made a total of six navigation modes for which statistics of availability and unavailability were computed, at 7.5 and 5.0 degree mask angles.

Results. The complete results are found in Reference [7]. Availability results were generated for each of the three navigation modes (stand alone GPS, augmented GPS, and augmented GPS with Loran-C reversion), for the following scenarios: with and without baro aiding, and for 0, 1, and 2 failed GPS satellites. This produces 18 availability scenarios which were run at mask angles of 7.5 and 5.0 degrees (36 scenarios total). Table 1 shows how Loran-C augmentation and augmentation with reversion increases significantly the availability of GPS for nonprecision approach.

With two failed satellites, GPS alone can provide only 70 % availability with RAIM at an NPA protection radius of 555.6 meters. When supplemented with a barometric altimeter, availability increases to 84 %. GPS plus Loran has better than 97 % availability with two satellites out. Using the complete 24 satellite constellation along with Loran reversion and baro aiding, the availability is better than 99.99 %. For reference, VOR system availability also is 99.99 % [2].

Figure 1 summarizes the simulation results using a 7.5° mask angle. It plots in bar chart form the unavailability for the navigation modes analyzed in this report, each for the Optimized 24 GPS constellation with 0,1, and 2 Satellites unusable. Note that when all satellites are available, reversion adds little to the availability measure. This occurs in this case because points which fail the GPS plus baro aiding plus Loran-C mode do so because

Table 1. Summary of Availability (per cent) for Hybrid GPS/Loran-C System Using RAIM FD and 7.5° Mask Angle

Navigation Mode	Satellites Available 24	23	22
GPS	93.4890	80.4660	70.3788
GPS+baro	98.9363	96.5608	83.7086
GPS+Loran	99.9343	99.5148	97.9481
GPS+baro+Loran	99.9944	99.9450	99.5020
GPS+Loran+reversion	99.9654	99.8236	99.5615
GPS+baro+Loran+ reversion	99.9955	99.9836	99.7610

Loran-C coverage is poor (high GDOP), or not provided from US-only chains.

Results showing the percentage of the 2310 airports with full RAIM availability over 24 hours for the six GPS navigation modes are presented in Table 2. The percentage of airports with full availability increases from about 15 % to about 94 % when GPS is augmented with Loran-C, when all GPS satellites are operating. This is a significant improvement. As more satellites fail, the additional augmentation with a barometric altimeter becomes significant. Further, if Loran-C reversion is used (last two rows of Table 2), more than 96 % of all 2310 public CONUS airports become fully available even with up to two failed GPS satellites. This table confirms an unambiguous need for Loran-C augmentation if GPS is to be used as a sole means NPA navigation aid.

Table 2. Percentage of Airports with Full Availability, 7.5° Mask Angle

Navigation Mode	Satellites Available 24	23	22
GPS	0.0	0.0	0.0
GPS+baro	15.23	0.99	0.0
GPS+Loran	94.45	73.37	37.88
GPS+baro+Loran	99.09	95.32	84.80
GPS+Loran+reversion	97.53	96.88	96.88
GPS+baro+Loran+ reversion	99.22	98.53	97.01

For reference, if up to one hour per day of *un*availability were an accepted operational minimum, then all of the CONUS airports qualify for this relaxed criterion, without resorting to reversion, and with 0 or 1 failed GPS satellites. Augmentation results for the 7.5 degree mask angle case are so dramatic that, in most modes there is little added availability performance to be realized by making approaches at the less restrictive 5.0 degree mask angle.

Conclusions. The results show that there is a significant advantage gained by augmenting GPS with Loran-C. The NPA availability of the augmented GPS navigation system is greatly enhanced by at least two orders of magnitude (a hundred fold), from about 99 % to 99.997 %, relative to stand alone GPS. This means that only 3 out of every 100,000 NPA attempts cannot be initiated because the navigation system does not satisfy the required integrity and accuracy minimums. This maximum availability, 99.997 %, results from using "all-stations-in-view" Loran-C, and is twice as good as using the current Loran-C NPA requirement which restricts navigation to the approach triad.

With Loran-C and baro altimeter augmentation, and no failed GPS satellites, fewer than 20 airports in the CONUS experience any outages, when the 7.5° mask angle is used. When the less stringent 5.0° mask angle is used with this configuration, *only two airports in Florida and one in Washington state, out of the 2310 CONUS public airports, have even 18 minutes of unavailability a day.*

The augmented system is capable of providing sole means capability for NPA, based on integrity and availability criteria. Integrity requirements restrict stand alone GPS to use as a supplemental approach navigation aid. Hence, GPS must be combined with Loran-C in order to achieve sole means NPA capability. Relaxing the GPS mask angle requirement does not affect significantly stand alone GPS RAIM availability as a sole means approach system, but it can provide a noticeable operational enhancement to an augmented system.

If the Loran-C reversion mode is used, more than 96 % of all 2310 public CONUS airports become fully available even with up to two failed GPS satellites. None of these airports have full, 24 hour availability using stand alone GPS. Furthermore, Loran-C transmitters, used as pseudolites, can provide significant enhancement to the overall availability of the GPS system; and Loran-C, in a stand alone (reversion) mode, can provide a totally redundant navigation system. Because of increasing concern about the vulnerability of GPS to both intentional and unintentional jamming, it is prudent to add to the system a stand alone navigation aid which uses a totally different frequency band.

Other navigation aids also can supplement GPS, but Loran-C is available for use now, and can be integrated with GPS with relatively little cost, effort, or lost time. Further, Loran-C offers the additional benefits of mitigating interference and jamming effects on GPS, and providing full system redundancy. Clear beneficiaries of an augmented GPS/Loran-C system are general aviation pilots and small commercial air businesses which use thousands of airports currently without approach aids. There is therefore an unambiguous need for Loran-C augmentation in order for GPS to be used as a sole means NPA navigation aid.

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Biographies

Dr. James V. Carroll has been at the DOT Center for Navigation at the Volpe Center in Cambridge, Mass., for over four years. His work at the Volpe Center focuses on Loran-C and GPS applications. Prior to this, he has spent nearly twenty years working for engineering consulting firms, including the C. S. Draper Lab at M.I.T. Dr. Carroll's areas of specialty are guidance, navigation, control, and dynamics of flight vehicles. He has received degrees in aerospace engineering from M.I.T., and obtained his Ph.D. from Stanford in 1972. Dr. Carroll is a member of the ION, the IEEE, and the Wild Goose Association.

Prof. Jay A. Weitzen is Professor of Electrical Engineering at University of Massachusetts Lowell. He received the Ph. D. degree in Electrical Engineering from the Univer-sity of Wisconsin, Madison, in 1983. His interests are in communication theory, radio communi-cation and propagation, and navigation systems. Prior to joining the university in 1986, Dr. Weitzen worked at Signatron, Inc. in Lexington, MA, where he was involved in the design of several real time channel simulators for VHF, meteor burst, HF, and troposcatter. He is a Senior Member of IEEE and an editor of the IEEE *Transactions on Communication*. He is also a member of ION and the Wild Goose Association.

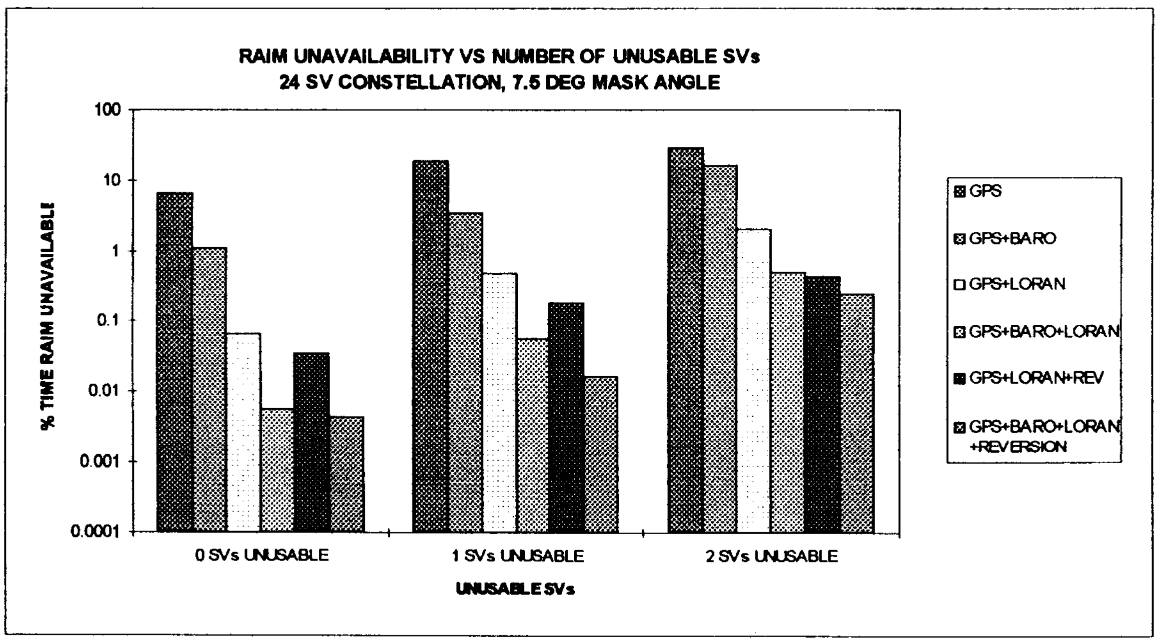

Figure 1. RAIM Unavailability (percent), 7.5° Mask Angle

ABSTRACT:

The LORAN C System is a good, simple and reliable Electronic Navigation System run by the U. S. Coast Guard that has been around for a long time. Small vessel and coastwise commercial mariners presently rely on its Accuracy and Repeatability. These mariners have already invested what to them is a lot of money on their receivers, they have learned to use this System regularly and safely - and they may not be able or inclined to buy the new higher cost GPS receivers with DGPS etc. The Loran C System is PAID FOR - both by the U. S. Coast Guard who operate it and the users, and does not cost much by present standards to operate. The civilian mariner also has a lot more confidence in the U. S. Coast Guard than in the Department of Defense and what they are both apt to do tomorrow. THIS SYSTEM IS NOT BROKEN - LETS NOT FIX IT.

LORAN C - THE NEED IS STILL THERE!

During the past few months, there have been a lot of rumors that the U. S. Coast Guard will be terminating the LORAN C System prior to the scheduled 2015 date historically in the Federal Radio Navigation Plan.

My background is primarily in the recreational vessel and very small commercial marine field and I can say without reservation that any termination of LORAN C availability in the near future (5 years) will result in an unnecessary financial hardship and increased danger to vessels, navigation, and persons in this area of marine activity.

There are numerous estimates of the number of LORAN C receivers presently in use: summarizing the BOATS US and U. S. Coast Guard Numbers, there appear to be approximately 1 Million units in operation - 7-900,000 Marine and 100-150,000 Aviation. If we take the average cost of these units at \$500 - this represents \$1/2 Billion in investment/expenditures. Many of the small boat owners and commercial fishermen would not be able or possibly willing to replace this equipment immediately. Also, to purchase GPS receivers which to date lack the accuracy, repeatability, and reliability of the proven LORAN C System, would probably cost twice as much.

At the present, we are receiving many complaints from our customers that the GPS does not give them the precision that LORAN C delivers. In Long Island Sound, where I operate, we consistently get 15 metre accuracy with LORAN C while GPS with Selective Availability is at least 100 Metres. Also, with Selective Availability, the repeatability of the location being used as a waypoint is unreliable. Picture the Maine lobsterman using a GPS Waypoints for his lobster traps. In the normal fog condition in Penobscot Bay - do you really think 100 Metres is close enough to actually find a lobster buoy? Similarly, what about the annual cost to the commercial fishing dragger for nets when the hangs that he used to avoid with LORAN C Waypoints now move about a 100 Metre Circle using GPS with Selective Availability.

Now I have been told that ASF - Secondary Phase Factors will change the geographic position of a LORAN C Fix. This is not true, if the position was "Saved" from a receiver position - or if the position was defined in T-D's. It is, however, true that ASF can change seasonally, but remember that the recreational boater normally operates in a given area at only certain times of the year - when the ASF should be similar. I have talked with local lobstermen, and they tell me the same thing - that they tend to fish the same areas at the same time of the year - also nullifying any seasonal ASF movement.

I have experienced the precision of DGPS on a U. S. Coast Guard Buoy Tender and have to admit that it is very impressive. However, we have now increased the cost of the receiver by at least $500.00 - very significant to the commercial fisherman and small recreational boater. Also, we have increased the number of antennas, "Black Boxes" and the overall complexity of the Electronic Navigation System for the busy fisherman or relatively inexperienced recreational boater. Also, DGPS is not available everywhere "yet".

A few years ago, I presented a Paper to this Symposium on the Use of LORAN C by the Recreational Boating Community. In that paper, I deplored the lack of Basic Navigation Training by these boaters, a tendency to "let the Loran do it", and the emphasis by the Electronic Navigation Manufacturers to "dazzle us" (read confuse) with supplemental features of marginal value to basic navigation and watch standing. Now, with appropriate "political correctness" we find ourselves rushing to support the space age military GPS System - it is new, the wave of the future, glamorous, and afterall we have to pay for it so we may as well use it.

Don't get me wrong, I think it is a great system and if you are going offshore, it is definitely the System to use - so long as you remember your Sextant and Tables as a backup. However, for the majority of recreational boaters who will probably never sail more than 25 Nautical Miles offshore - and we already have a reliable, proven and more important Familiar System that is pretty much Paid For, Inexpensive to Operate, and THERE.

Recently, I was hired by an elderly couple who had bought a 25 Ft. outboard cabin boat to do day trips. They had also purchased and had installed a combination Fish Finder/LORAN C Receiver which they could not operate. I spent 2 hours with them and once I had taken the unit out of the Simulation Mode, showed them how to find their position, how fast they were going and in what direction, the water depth and how to put in their Destination Waypoint. The lady found plotting T-Ds with a Plotting Card simple - on that boat opening up the chart to get to the Latitude/ Longitude Borders would have been unmanageable at best. These people will never go more than 25 Miles from home and this Set cost them under $500.00 including a Depth Sounder! While they understood the concept of a couple of radio towers broadcasting a signal - satellites would not have been comprehended.

It is my understanding from Elaine Dickenson of BOATS US that the Boating Safety Advisory Committee of the U. S. Coast Guard has passed a Motion recommending that LORAN C be operated until at least the year 2000. I also understand that the U. S. Coast Guard and Elisabeth Carpenter of the Volpe National Transportation Center have been flooded with letters opposing the Early Termination of the LORAN C System. Apparently it only costs $17-20 Million Dollars per year to operate - which is certainly a small price to pay for the added safety for the small vessel mariner and commercial fisherman.

Another very sound reason for the continued use of LORAN C is that it provides an independent confirmation - ie: redundancy - of your GPS Position. Unfortunately, the people in the Decision Making Seats are far removed from the Bridge/Cockpit and have forgotten what it is like to be in zero-zero visibility, hearing surf off to Port and knowing that there are a series of ledges awash off to Starboard.

I found myself in just that situation this past June when delivering a 40 Ft. Yawl down the Muscle Ridge Channel in Penobscot Bay, Maine. The Trimble Nav-Graphics was great - but the Sailboat Locator was moving around outside the parameters of the channel - while the Northstar LORAN C kept us going straight down the center of the channel! Radar was helpful - but the awash ledges and submerged rocks did not appear on the screen and by the time they would have registered on the Fathometer, they would have been in the main cabin.

To summarize: The LORAN C System is a good, simple, and reliable Electronic Navigation System that has been around for a long time. Small vessel and coastwise mariners presently rely on its accuracy and repeatability. They have already invested what is a lot of money to them on their Receivers and may not be able or inclined to buy GPS Receivers with DGPS etc. The System is PAID FOR and does not cost much by present standards to operate. The Civilian Mariner has a lot more confidence in the U. S. Coast Guard than in the Department of Defense and what they will do tomorrow. THE SYSTEM IS NOT BROKEN - LETS NOT FIX IT.

THE EFFECTS OF GEOMAGNETIC ACTIVITY ON SKYWAVE INTERFERENCE AND THE QUALITY OF THE PORT CLARENCE LORAN-C RADIO NAVIGATION SIGNAL

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1.0 ABSTRACT

Loran-C is extremely reliable in most regions of the world. An exception to this performance record has been observed at station Port Clarence on the Gulf of Alaska (7960) chain. While the signals as radiated are within all related specifications, the signals as observed at the system monitor site in Fairbanks are frequently judged to be unsuitable for navigation.

Using signal characteristic data from February to April 1994, a study has been made to identify, if possible, those factors which are responsible for the deterioration in signal quality.

Analysis of data collected using the Coast Guard Skywave Data Acquisition System has shown the presence of skywave signals of unusually large amplitude and relatively short delay at certain times of day at the location in question. The connection between periods of poor signal quality with concurrent upper atmosphere activity and the presence of skywaves has been explored in detail.

Geomagnetic data collected by the Space Environmental Services Center is used to explore the connection between geomagnetic activity, skywave amplitude and delay, and the Port Clarence signal. Periods of unusable signals were correlated with the location of the auroral oval, the periodicity of average daily geomagnetic activity, and elevated K-indices.

From this comparative analysis, those propagation conditions which have a high probability of creating poor signal quality have been identified and, based on this information, tentative predictions of ionospheric conditions which could cause Loran signal interference have been made.

2.0 INTRODUCTION

This paper is concerned with the signal "quality" of the Loran-C system, in particular, Loran-C Station Port Clarence on the 7960 Gulf of Alaska chain.

Presented here, are excerpts from a Master's Thesis completed at the University of New Hampshire under the supervision of Dr. Albert Frost. Research was completed in cooperation with the Director, Center for Advanced Studies, at the U.S. Coast Guard Academy and funded by the Radionavigation Division, Coast Guard Headquarters.

Past investigations have determined that skywaves of large amplitude and short delay as compared to the Port Clarence groundwave signals are present in this part of the world [1,2]. The presence of these skywaves can adversely affect the Loran-C waveform as it propagates to the primary monitor station in Fairbanks, Alaska. As shown in figure 2.1, the 1993 availability of the Port Clarence signal on the 7960 chain is well below other stations in this chain and the overall Coast Guard average.

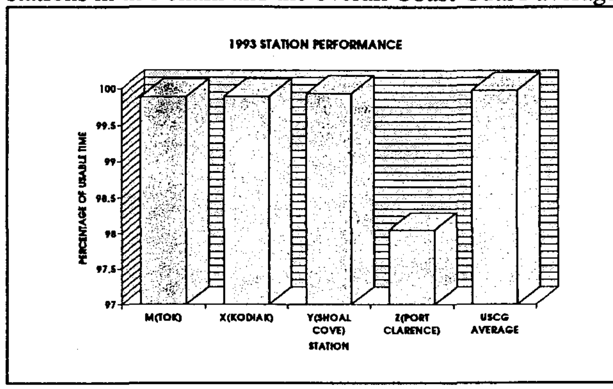

Figure (2.1) 1993 Station Performance

The goal of this paper is to determine if a connection exists between unusable navigation signals from station Port Clarence and activity in the upper atmosphere which could encourage the presence of skywaves. Due to the uncontrollable nature of the problem at hand, it is not intended to identify a specific solution as a product of this research, but to determine possible times when the Port Clarence navigation signal *could* be adversely affected by enhanced skywave signals.

This paper presents the methods used for the collection and processing of skywave, geomagnetic activity, and monitor site data. A great deal of data is used in order to determine diurnal and seasonal variations of these variables. In addition, changes in skywave characteristics and links with geomagnetic activity are investigated and compared with times when the navigation signal from station Port Clarence is unusable. From these results, conclusions, recommendations, and suggestions for future research are made. A table is provided in an attempt to predict when it is most probable that signals from station Port Clarence as seen at the monitor in Fairbanks may be unusable.

3.0 Data Collection

Data used for this research was collected using the Coast Guard Skywave Data Acquisition System [1,2] and from the Space Environmental Services Center (SESC) located in Boulder, CO.

The Coast Guard Skywave Data Acquisition System measures and records Port Clarence Time Difference (TD), Envelope-to-Cycle Difference (ECD), and Signal-to-Noise Ratio (SNR). In addition, the system measures and stores received signal data and enables the processing of data to determine skywave-to-groundwave amplitude ratio and skywave delay. The system was installed in early February 1994 at the Fairbanks, AK monitor site solely for this research. Port Clarence data was collected from February - May 1994. Figure 3.1 shows the geographic layout of the 7960 Gulf of Alaska chain.

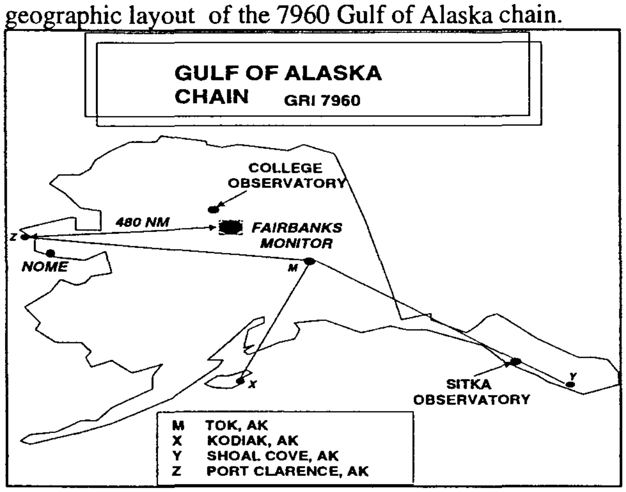

Figure (3.1) The 7960 Gulf of Alaska Chain

SESC data was collected in the form of solar forecasts, geomagnetic forecasts, and K-indices. Geomagnetic data was collected from February - April 1994 from observatories located in College and Sitka, Alaska. The location of these observatories is also shown in figure 3.1.

The K-index characterizes irregular geomagnetic activity caused by plasma from the sun [3]. This plasma produces electric currents around the earth, which in turn, "distort" the regular magnetic properties of the field. K-indices are calculated every three hours and represent the difference between magnetically "quiet" and magnetically "disturbed" days. At the College and Sitka observatories, magnetometer data is obtained for the H, D, and Z (SESC definition for H and D) magnetic components of the earth's field. The maximum deviation of these components (H or D only) during a three-hour time frame is used to formulate the K-index.

The geomagnetic disturbance represented by the K-index changes in magnitude depending upon the location of the observatory. From the K-index, linear a_K and A_K indices can be calculated. The A_K-index represents daily geomagnetic activity, giving an overall picture of diurnal activity levels.

4.0 Data Analysis/Results

Data analysis and results have been broken down into several different categories. Skywave, TD, ECD, SNR, geomagnetic activity, and Port Clarence unusable time data are discussed in sections 4.1 - 4.4.

4.1 Skywave Data

Figures 4.1 and 4.2 show average skywave-to-groundwave ratio and skywave delay as compared to time of day from February - April 1994 . Figure 4.1 shows that the average skywave-to-groundwave ratio is larger during the day (between sunrise and sunset) than at night.

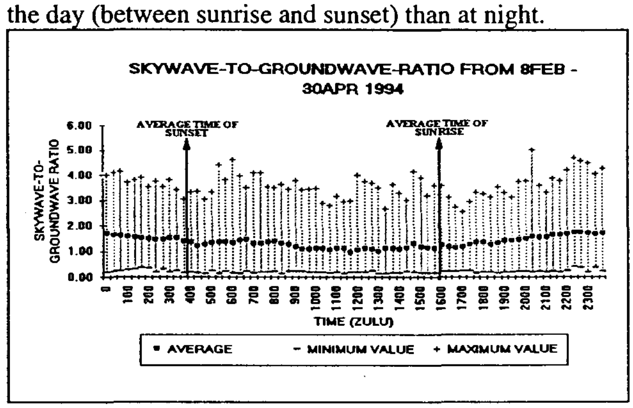

Figure (4.1) Average Skywave-to-Groundwave Ratio from February through April 1994

Skywave-to-groundwave ratio will increase as the distance from the transmitter to receiver is increased (between 100km and 2000km) [4]. This is because the groundwave is attenuated in direct proportion to distance traveled, whereas skywave amplitude remains relatively constant for distances between 100 and 2000km. Results as shown in figure 4.1 contradict results shown by Sheppard [1] for observations conducted from 24 February - 8 April 1993. In this report, the majority of skywave-to-groundwave ratios were larger at night than by day. In addition, these results contradict expected ionospheric behavior. Skywaves "should" be absorbed more during the day than at night due to the increased concentration of charged particles and higher collision frequency. Results show that "something" is causing the characteristics of the ionosphere to change.

Figure 4.2 shows that the average skywave delay is slightly smaller during the day than at night. Although there is only a slight diurnal variation of skywave delay, the maximum deviation from the mean is clearly observed at night. These results closely resemble results obtained by Sheppard [1] and agree with expected high-latitude ionospheric behavior. Skywave delays are larger at night due to the higher overall reflection height of the ionosphere.

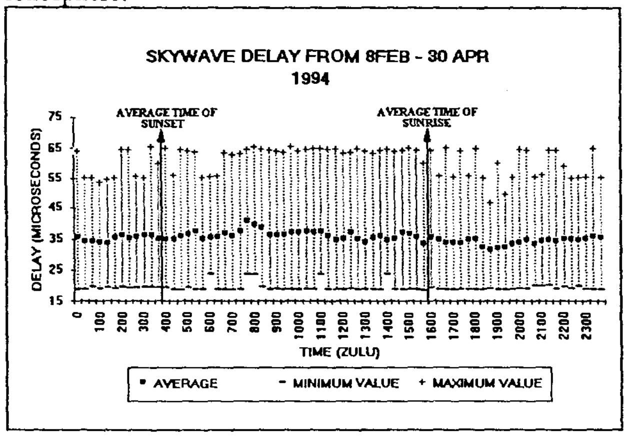

Figure (4.2) Average Skywave Delay from February through April 1994

Based on an average daytime skywave delay of 33.97μsec and an average nighttime skywave delay of 36.33μsec, ionospheric reflection heights were estimated to be 54.31km by day and 56.56km by night. Reflection height estimations were calculated using skywave delays, the distance between Port Clarence and Fairbanks, phase-factor corrections, the speed of light, and a spherical model of the earth. These results show that ionospheric reflection heights are much lower in this part of the world as compared to lower latitude regions (approximately 18km lower during the day and 33km lower at night) [5]. In addition, diurnal changes in skywave delay are much less pronounced in this region.

4.2 TD, ECD, and SNR Data

Figures 4.3, 4.4, and 4.5 show average plots of TD, ECD, and SNR from February through April 1994.

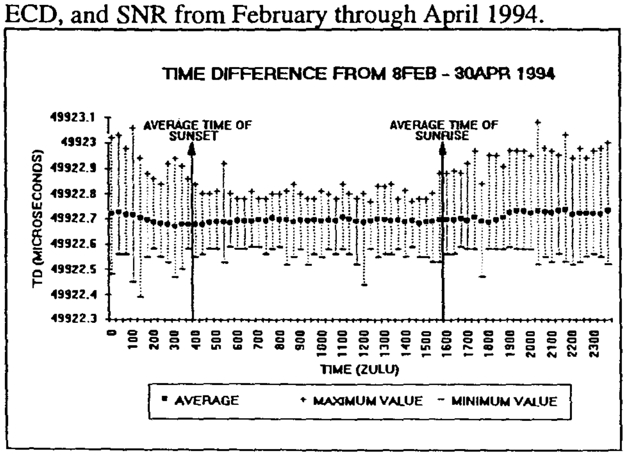

Figure (4.3) Average Time Difference vs. Time from February through April 1994

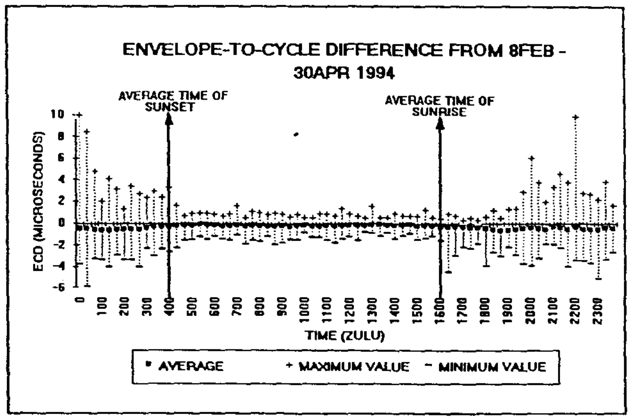

Figure (4.4) Average Envelope to Cycle Difference vs. Time from February through April 1994

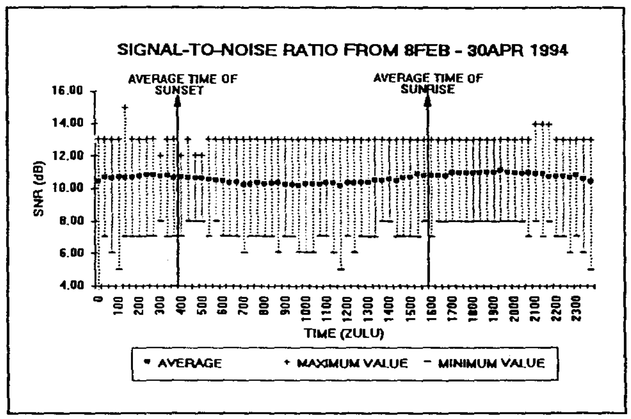

Figure (4.5) Average Signal to Noise Ratio vs. Time from February through April 1994

As shown in figures 4.3 and 4.4, TD and ECD tend to be at a maximum (maximum deviation from the mean for the case of ECD) during the day. TD variations seen in figure 4.3 are most probably due to the accuracy of the JET receiver clock (± .1 μsec) or changes in the refractive index of the near-earth atmosphere. Ground conductivity changes would cause a more gradual and steady change in TD and changes due to the terrain over which the Port Clarence signal propagates remain the same for each transmission. TD seems to follow skywave amplitude and is maximum at times when skywave delay is small. This change in TD is, however, relatively small and did not affect the availability of the Port Clarence signal.

Large positive or negative ECD's tend to correspond to large skywave amplitudes. Abrupt changes in skywave amplitude cause ECD to flip from either positive to negative or from negative to positive. When skywave delay is small and relatively smooth or constant, ECD tends to be more negative, and when skywave delay fluctuates, ECD tends to be more positive. As is the case with skywave-to-groundwave ratio, abrupt changes in skywave delay also cause ECD to change sign. Figures

4.4 Station Port Clarence Unusable Time

Figure 4.11 shows the relation between unusable blink time at station Port Clarence and the times of sunrise and sunset from February through April 1994. As shown by the figure, virtually one hundred percent of blink occurrences were during the day and tended to "follow" the times of sunrise and sunset. These results were similar to results obtained by Sheppard [1].

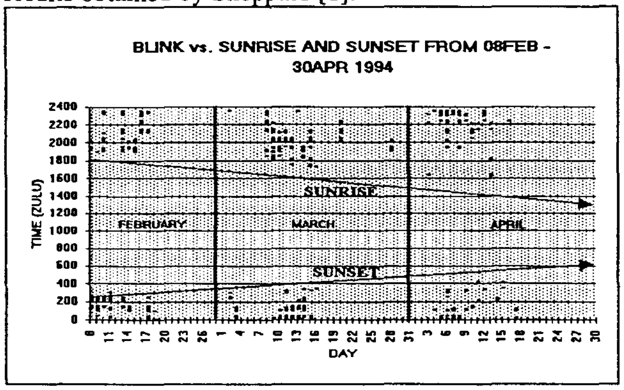

Figure (4.11) Blink vs. Sunrise and Sunset

Blink times closely followed diurnal variations of skywave parameters, and groundwave amplitudes did not fluctuate from day to day. From this observation, it is believed that unusable time at station Port Clarence is due to skywave interference and not groundwave attenuation. The same conclusion was reported by Sheppard, Peterson, and Gross [1,2] during the original study using 1993 groundwave and skywave data in this area. Based on this conclusion, poor station performance shown in figure 2.1 does not reflect actual *station* performance , but shows how uncontrollable skywave signals reduce the availability of the Port Clarence navigation signal.

Figure 4.12 shows a cumulative plot of skywave-to-groundwave ratio versus skywave delay. This figure has been broken up into times during blink (bold print) and times during normal operations (light print) at station Port Clarence.

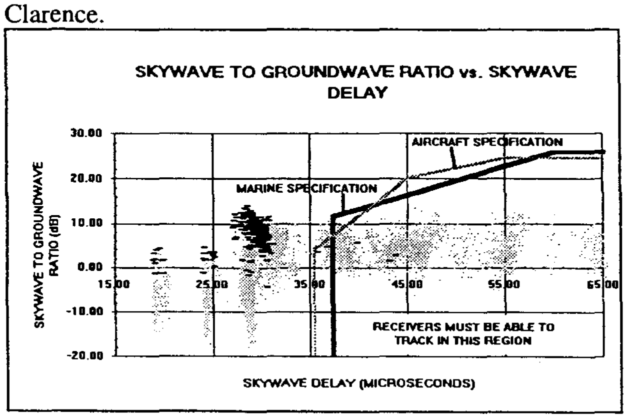

Figure (4.12) Cumulative Results of Skywave-to-Groundwave Ratio vs. Skywave Delay

(Note - the ability of the skywave data acquisition system to accurately estimate skywave delay is greatly reduced when skywave-to-groundwave ratio falls below approximately -3 dB.)

As shown in figure 4.12, blink is most probable when skywave amplitude is large and skywave delay is small. Table 4.1 shows approximate "thresholds" summarizing these conditions.

SKYWAVE PARAMETERS	BLINK CONDITIONS
Skywave-to-Groundwave Ratio	> +2 dB
Skywave Delay	< 31 μsec

Table (4.1) Most Probable Skywave Conditions which Cause Blink

Figure 4.12 also includes minimum Loran-C receiver performance specifications for both maritime (dark line) and aviation (light line) use [1,12]. The plot shows that using these performance specifications, receivers may not be able to track the Port Clarence signal at many times when skywave-to-groundwave ratio and skywave delay fall above and to the left of these lines. This figure shows that the Port Clarence signal was only blinked when the minimum receiver specifications were not met (except for only three cases). This illustrates that the station acted properly to start blink in these situations.

When observing station Port Clarence unusable time, K-index values show a certain pattern on days when the station's navigation signal is unusable. Figure 4.13 shows a comparison of one week of K-index data when the Port Clarence signal was (top plot) and was not (bottom plot) usable. The bottom plot represents 7 consecutive days of data when blink occurred at least once during the day, whereas the top plot represents 7 different consecutive days of data when no blink was recorded.

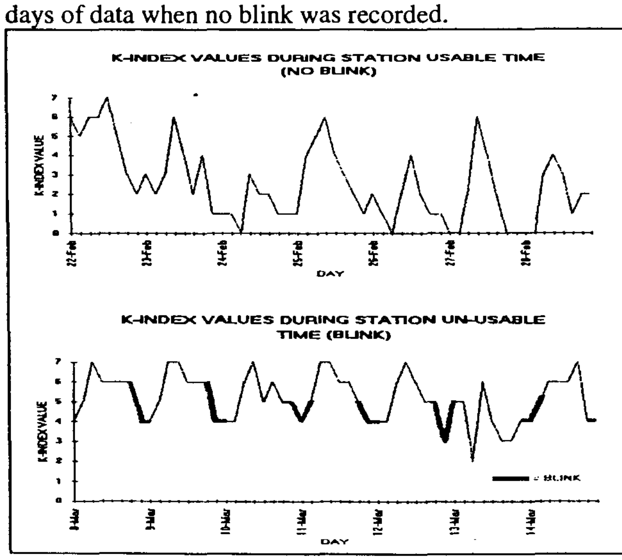

Figure (4.13) K-Index Values During Station Usable and Unusable Time

The data shown in figure 4.13 shows that blink occurred on days when the K-index was elevated from zero for the entire day (fluctuated from 3 to 7). Blink did not occur when the K-index went below 2 at least once during the day. A large variation of K-index values during the day tended to correspond to very few blink conditions from February through April 1994. In nearly all blink conditions, the K-index level was elevated and did not go below 2 or 3 at any time during the day. The bottom portion of figure 4.13 also shows that on days when blink occurred, it occurred when K-index values were at a daily minimum.

Figure 4.14 shows the College A_k index values from February through April 1994 and illustrates days when blink occurred.

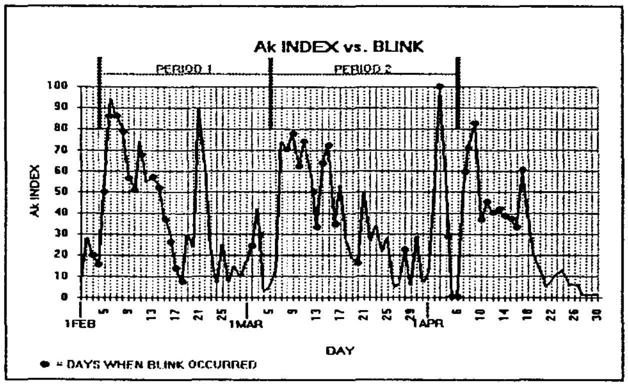

Figure (4.14) A_k Index and Days when Blink Occurred

As shown by the figure, station Port Clarence blinked it's navigation signal on most days when the A_k index was above 40, although there were many times when the station did blink below this A_k value. Assuming that the A_k index curve is somewhat periodic as discussed in section 4.3 and shown by the wide vertical lines in the figure, days when the Port Clarence navigation signal was unusable tend to follow this periodic pattern. From February through April 1994 blink occurred at approximately 15 day intervals - 15 days of blink ⇒ 15 days of no blink ⇒ 15 more days of blink, and so on. This periodic pattern of blink occurrences can also be clearly seen in figure 4.11. Figure 4.14 also shows that blink occurred most frequently during the beginning of each period when the average A_k level was elevated and in a falling transition. Table 4.2 shows average College A_k values for all data, data during no blink conditions (no blink from 0000-2400 GMT) and data when blink occurred at least once during the day.

	AVERAGE A_k VALUE
TOTAL AVERAGE (all data)	39.93
NO BLINK DAYS	21.57
BLINK DAYS	50.90

Table (4.2) A_k-Index on Blink and No-Blink Days

This table shows that blink is more probable on days when the A_k index is large. It is believed that elevated A_k index values correspond to a more "active" and more pronounced nighttime aurora, leading to sudden large daytime skywave amplitudes when the aurora subsides.

Blink occurrences shown in these figures seem to take place only at times when the auroral oval is not present anywhere between Port Clarence and Fairbanks (supported by the fact that blink only occurs during the day) ***and*** when the A_k index is elevated (normally the first 15 days of each 29-day A_k cycle). It is believed that when an enhanced aurora (elevated A_k) appears at sunset and disappears at sunrise (approximately) a significant change in skywave amplitude will be observed. The sudden decrease in ionospheric absorption when the auroral oval subsides could result in large daytime skywave amplitudes, cause ECD to go out of tolerance during the day, and make daytime blink much more probable. Absorption of the Port Clarence skywave signal when the oval is located on top of the Fairbanks monitor site appears to be greater than D-region absorption caused by solar daytime ionization. Although the auroral oval can be associated with more intense reflective properties in the D-region of the ionosphere, studies in Fairbanks area have shown that D-region absorption of Low-Frequency (LF) skywaves is more common than enhanced reflection of these signals [13]. Larger daytime skywave-to-groundwave ratios, in addition to much smaller daytime skywave delays in this region of the world, create the necessary conditions to make blink highly probable.

Results have shown a significant decrease in the amount of station Port Clarence unusable time as seasons changed from winter to spring. Table 4.3 shows minutes of station Port Clarence unusable time from February through May 1994.

MONTH (1994)	TOTAL UNUSABLE TIME (MINUTES)
FEBRUARY	**2820**
MARCH	**2994**
APRIL	**1462**
MAY	**250 (APPROXIMATE)**

Table (4.3) Station Port Clarence Unusable Time from February - May 1994

It is believed that the number of blink occurrences decrease from winter to summer primarily due to the reduction in daytime skywave amplitudes as shown in figure 4.15. A decrease in daytime skywave amplitude can be attributed to more intense summer ionization of the D-region. Due to this overall increase in skywave absorption and the extremely long days (daytime aurora do exist, but are uncommon [3]), the auroral oval most likely does not play a significant role during the summer. In addition,

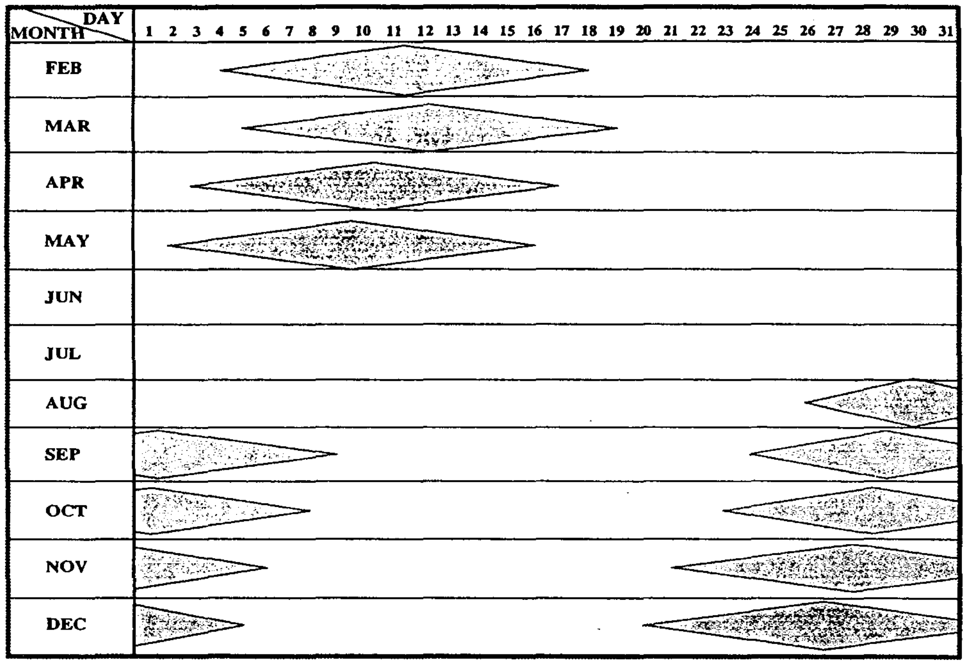

Table (5.1) 1994 Blink Prediction Table

station blinked it's signal only when skywave parameters were outside of the minimum receiver specifications. The CSECD of -0.3μsec with a threshold of ± 1.5μsec worked well when compared with these specifications. It is highly recommended that the monitor be moved to another location closer to the Port Clarence transmitter. The skywave data acquisition system should then be used to determine new coverage area limits, and Fairbanks should not be included in this area.

Based upon the regular occurrence of daytime blink during winter months on this baseline and taking the ***present*** advertised coverage area limits into account, it is recommended that users be warned about the limited availability of the system during winter days between sunrise and sunset.

The skywave data acquisition system has proven to be an extremely valuable tool for the evaluation of skywave interference on the Port Clarence-to-Fairbanks baseline. Correlating skywave parameters with geomagnetic K and A_k-index data proved to be very difficult. First, data was impossible to obtain in "real time" even with the SESC SELVAX system available on the INTERNET. K-index data for the College and Sitka observatories was hand-scaled and monthly data arrived by mail approximately twenty days after the end of each data month. In addition, three-hourly K-index data did not allow for the close correlation of skywave parameters at particular times during the day. In the future, raw H and D component magnetogram data instead of three-hourly K-indices would allow for the correlation between magnetic activity and specific blink occurrences during the day.

Rocket sounding of the ionosphere in the vicinity of the College observatory would be beneficial in determining the ionospheric characteristics during certain times of the day and of the year. Although research is in progress in this area, data is difficult to obtain at the time it is needed.

Data on the position and activity of the auroral oval would also be extremely valuable in this region. No daily records of any kind were available. Daily records of auroral position and activity would be valuable in supporting our premise that the winter auroral oval plays a significant role in the enhancement of daytime skywaves transmitted from station Port Clarence and received at the Fairbanks monitor.

In addition to research performed in this region of the world, skywave measurement at other Loran-C stations could provide valuable information. A comparison of the average reflection heights of the ionosphere and the strength of skywaves, using comparable transmitter-to-receiver distances, could provide valuable information to the "uniqueness" of skywave propagation in high-latitude/auroral regions of the world.

Bian and Last [15] proposed new techniques which could enable skywave detection by Loran-C receivers. Spectral and cepstral analysis used to measure skywave delay and amplitude appear to be very promising tools in an effort to produced adaptive Loran receivers which could adjust their sampling point according to skywave interference conditions. Another advantage of cepstral analysis is that no *a priori* knowledge of the groundwave is required to estimate skywave parameters. This eliminates the need for a groundwave template, which should be frequently updated to ensure accuracy of skywave estimation. Skywave data and estimation results used for this thesis as compared to results obtained using the spectral and cepstral analysis methods could produce some very interesting results. Future research in this area could possibly eliminate receiver errors caused by skywave interference.

6.0 Acknowledgments

I would like to thank Dr. Albert Frost, my thesis advisor, for his comments, suggestions and enthusiasm during my research and thesis preparation. I would also like to thank CAPT Ben Peterson, Dr. Keith Gross, LT Eric Chamberlain, and ETCS Robert Erickson at the U.S. Coast Guard Academy for suggesting an interesting research topic, providing necessary project funding, answering *numerous* questions about the set-up and operation of the skywave data acquisition system, and supplying all logistical needs during the research. In addition, LT David Watkins and ET1 Tim McBride from Kodiak, AK supplied all necessary monitor site data and provided much needed insight to the problem at hand.

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8.0 Biography

Alan Arsenault is a Lieutenant in the U.S. Coast Guard and is presently assigned to the Navigation Systems Branch at the Coast Guard Electronics Engineering Center. He has completed tours as Operations Officer on the USCGC BRAMBLE and as a Project Officer in the Electronics Technology Division at Coast Guard Headquarters. LT Arsenault received a BSEE degree from the U.S. Coast Guard Academy in 1988 and a MSEE degree from the University of New Hampshire in 1994.

Rational Modelling Techniques for the Identification of Loran-C Skywaves

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Abstract

At the 1992 WGA Symposium, Bian and Last proposed a new concept of receiver design which adaptively adjusts the sampling point to its optimal value in a constantly-changing skywave interference environment. They demonstrated the feasibility of FFT-based techniques in estimating the skywave delays of Loran-C signals. This paper presents a new and higher-resolution technique for the identification of Loran-C skywaves based on spectral analysis using rational transfer function models. The paper explains briefly the principle of frequency estimation using rational techniques and identifies a new class of high-resolution algorithms. It also 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 performance of techniques of this kind when used to estimate Loran-C skywave delay is evaluated by computer simulation and compared with earlier results.

1 Introduction

Propagation of the low-frequency (100 kHz) Loran-C groundwave pulses for navigation is exceptionally stable. Unfortunately, components of the signal also reach the receiver via the ionosphere, arriving later than the groundwave pulses and interfering with them. Loran-C receivers minimise skywave contamination by processing samples of received pulses taken early on their rising edges, prior to the arrival of the skywave components. It has been shown that this technique has unexpected limitations due to the effects of the bandpass filters in receivers [1]. As a result, many receivers are designed to take samples sufficiently early to cope with the minimum skywave delay, which is experienced only rarely. They pay the price of too low a signal amplitude at the sampling point. A receiver which could always sample just early enough to avoid skywave contamination would therefore be an attractive proposition.

At the 1992 WGA Symposium, Bian and Last [2] proposed a new concept of receiver which adaptively adjusts its sampling point to the optimal value in a constantly-changing skywave interference environment. They demonstrated the ability of two signal processing techniques to estimate the arrival times of the groundwave and skywave components: spectral-division and cepstral methods, both of which are based on Fourier analysis. The limited resolution of these methods in both the time and frequency domains has prompted further research. One alternative approach, the 'eigendecomposition method' was described in the 1993 WGA Symposium [3]. A second promising alternative, described in this paper, is the use of 'rational model-based' methods.

It will be shown that the problem of estimating the arrival times of the groundwave and skywave components of a Loran-C signal is analogous to that of isolating the components of a composite signal in the frequency domain. Consequently we can take advantage of recent advances in frequency-domain signal-processing techniques. The principle of frequency estimation using these techniques will be explained, and a relatively-new class of high-resolution algorithm identified. It will be shown that this 'model-based' approach [4-7] provides better frequency resolution than the earlier FFT-based methods and that it works equally successfully at low signal-to-noise ratios.

The organisation of the rest of the paper is as follows. Section 2 presents a mathematical model of the received Loran-C signal in the time and frequency domains for use in skywave delay estimation. Section 3 reviews the spectral-division technique based on Fourier analysis and discusses its principal limitations. The principles of the new model-based techniques, their advantages and limitations, will be discussed in Section 4. The performance of these techniques under noisy conditions will be demonstrated by computer simulation in Section 5.

2 Signal Model

It was shown in [2] that the received Loran-C signal may be represented in either the time domain or the frequency domain. This composite signal consists of the groundwave and skywaves, plus noise and interference. The signal model used in estimating skywave delay assumes that the skywaves pulses have the same shape as the groundwave but that they are delayed in time and scaled in amplitude. Therefore, the composite signal $x_c(t)$ can be expressed in the time domain as:

$$x_c(t) = x_g(t) + \sum_{n=1}^{N} k_n x_g(t - \tau_n) + e(t) \qquad (1)$$

where $x_g(t)$ is the groundwave signal and $e(t)$ is the total noise and interference. The amplitude and delay of the n-th skywave component relative to the groundwave, are represented by k_n and τ_n, respectively.

By taking the Fourier Transform of equation (1), we obtain the equivalent representation of the composite signal in the frequency domain:

$$X_c(f) = X_g(f) \left[1 + \sum_{n=1}^{N} k_n e^{j2\pi f \tau_n} \right] + E(f) \qquad (2)$$

where $X_c(f)$, $X_g(f)$ and $E(f)$ are the Fourier Transform of $x_c(t)$, $x_g(t)$ and $e(t)$, respectively.

Equations (1) and (2) constitute the signal model which will be used in estimating the Loran-C skywave parameters. This model is valid for both Fourier and model-based techniques.

3 Fourier-based Techniques

There are two techniques based on Fourier analysis for skywave delay estimation: spectral-division and cepstral analysis. Full details are presented in [2]. In this paper we will concentrate on spectral-division analysis because of its superior performance, especially at the lower signal-to-noise ratios (SNRs).

As shown in [2], we start by dividing the spectrum of the signal by the spectrum of a standard Loran-C pulse. This is the 'spectral-division' concept. We then return to the time domain by taking the Inverse Fourier Transform of the result. In the time domain we observe impulses at the arrival times of the groundwave and skywave components. This process can be represented mathematically as

$$F^{-1}\left\{\frac{X_c(f)}{X_0(f)}\right\} = k_g \left[\delta(t) + \sum_{n=1}^{N} k_n \delta(t-\tau_n) \right] + F^{-1}\left\{\frac{E(f)}{X_0(f)}\right\} \qquad (3)$$

where F^{-1} represents the Inverse Fourier Transform operator, $X_0(f)$ is the spectrum of the normalised standard Loran-C pulse $x_0(t)$; k_g is a constant related to the amplitude of the groundwave. Equation (3) thus illustrates the principle of the FFT spectral-division technique for estimating the arrival times of skywave components.

Computer simulation has demonstrated the ability of this method to detect skywaves and estimate their arrival times at SNRs higher 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 is equivalent to an SNR at the antenna of -23 dB. These figures may be compared with the SNR value of 27 dB after processing, or -10 dB at the antenna. This is the SNR adopted by the US Coast Guard (USCG) as their minimum value in predicting the coverage of Loran-C chains. They estimate that it results in 100 ns (rms) TD measurement error. Thus the spectral-division method appears to operate successfully at values of SNR 13 dB below the USCG minimum.

This FFT-based spectral-division analysis is computationally efficient and robust, but it has certain performance limitations, notably its resolution. They result from the need to filter the signal in the frequency domain via a window of limited width, especially at low SNRs [8,9]. The conflicting requirements of SNR, window width and resolution have prompted a search for higher-resolution estimation techniques.

4 Model-based Techniques

A relatively-new class of frequency analysis technique looks promising here: these are the 'model-based' techniques. A major reason why they are used for spectral estimation is their excellent frequency resolution compared with the classical FFT-based methods [10]. We will first explain these frequency-domain analysis methods and then show how they may be applied to the Loran-C skywave analysis problem.

It is well known that many real-life discrete random processes are approximated by a rational transfer function model. In this model, the input sequence $\epsilon(n)$, which is assumed to be a white noise process with zero mean and variance σ^2, and the output sequence $x(n)$ are related by the following linear difference equation [11,12]

$$x(n) = -\sum_{k=1}^{p} a_k x(n-k) + \sum_{k=0}^{q} b_k \epsilon(n-k) \tag{4}$$

This process is known as '*autoregressive moving average (ARMA)* model of order (p,q)' and is usually denoted as ARMA(p,q). Estimation of p and q can be interpreted as the determination of the number of poles $a_k's$ and zeros $b_k's$ of the system defined by (4).

The system function $H(z)$ between the input $\epsilon(n)$ and output $x(n)$ for the ARMA model is the polynomial transfer function defined as

$$\begin{aligned} H(z) &= \frac{B(z)}{A(z)} \\ &= \frac{1+\sum_{k=1}^{q} b_k z^{-k}}{1+\sum_{k=1}^{p} a_k z^{-k}} \end{aligned} \tag{5}$$

The model-based spectrum estimation procedure consists of two steps. Given the data sequence $x(n)$, $0 \leq n \leq N-1$, we first estimate the parameters a_k and b_k of the model. Then, using these parameters, we estimate the power spectral density (PSD) from the expression [10-12]

$$PSD_{ARMA}(f) = \sigma^2 \frac{|1+\sum_{k=1}^{q} b_k e^{-j2\pi fk}|^2}{|1+\sum_{k=1}^{p} a_k e^{-j2\pi fk}|^2} \tag{6}$$

This is the general ARMA form; there are two simplified forms of the model, one employing only the numerator, the other the denominator. To obtain the first, all the $b_k's$ are set to zero and the resulting model has a system function $H(z) = 1/A(z)$ and its output $x(n)$ is called an '*autoregressive (AR)* process of order p' and denoted as AR(p). In the second, $A(z) = 1$, so that $H(z) = B(z)$, and the output $x(n)$ is called a '*moving average (MA)* process of order q' and denoted as MA(q).

In general, the MA model requires more coefficients when representing a narrow spectrum than the AR model [11]. The AR model (and of course the full ARMA model) also have the sharp peaks required for high-resolution spectral estimation. The AR model is thus simpler than ARMA while retaining good resolution and, consequently, is by far the most widely used for spectral estimation. AR parameters can also be estimated in a variety of computationally-efficient ways. Furthermore, determining the order of the model is relatively straightforward in the AR case [11,13].

4.1 Determining the Parameters for the AR Model

The AR parameters required to compute the PSD in accordance with equation (6), can be calculated from the autocorrelation function $r_x(k)$ by using the *Yule-Walker (Y-W)* normal equation [10-12]. The autocorrelation estimate $r_x(k)$ is defined as

$$r_x(k) = \frac{1}{N} \sum_{n=0}^{N-1-k} x(n)\, x^*(n+k) \tag{7}$$

and the Y-W equations which relates the parameters of the AR model to these autocorrelation estimates, are given by

$$r_x(m) = \begin{cases} -\sum_{k=1}^{p} a_k r_x(k) + \sigma^2 & m = 0 \\ -\sum_{k=1}^{p} a_k r_x(m-k) & m \geq 1 \end{cases} \tag{8}$$

In matrix form, these equations are compactly expressed as

$$\begin{bmatrix} r_x(0) & r_x(1) & \dots & r_x(p-1) \\ r_x(1) & r_x(0) & \dots & r_x(p-2) \\ \vdots & \vdots & \ddots & \vdots \\ r_x(p-1) & r_x(p-2) & \dots & r_x(0) \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_p \end{bmatrix} = - \begin{bmatrix} r_x(1) \\ r_x(2) \\ \vdots \\ r_x(p) \end{bmatrix} \quad (9)$$

Therefore the AR parameters can be found by solving this set of linear equations, and the white noise variance σ^2 can be obtained from the following equation

$$\sigma^2 = r_x(0) + \sum_{k=1}^{p} a_k r_x(k) \quad (10)$$

By using a reasonable model order and substituting the AR parameters in equation (6), we obtain sharp peaks at the corresponding sinusoidal frequencies.

4.2 Relevance to Loran-C Skywave Analysis

The result of the spectral-division operation (Section 3) was an expression in the frequency domain which was then converted to the time domain by the use of an Inverse Fourier Transform. An alternative (and possibly preferable) route from the frequency to the time domain is provided by the use of an ARMA, or AR, approach. We analyse the results of the spectral-division, $X_c(f)/X_0(f)$, and calculate the AR parameters from this frequency domain expression as shown in (Section 4.1). The corresponding time-domain representation is then given by equation (6); it is this which contains the skywave delay information as, for example, in Fig. 3b.

4.3 Determining the Order of the AR Model

In this subsection we discuss briefly how to estimate the order (p) of the number of poles of the system under investigation when receiving noisy data. This must be done before parameter estimation can be performed. Because the best choice of order p is not generally known *a priori*, it is necessary in practice to postulate several values. If the value chosen is too low, there will be insufficient poles to represent the spectrum adequately. Too high a choice of order will usually result in spurious peaks in the estimated spectrum. There are a number of alternative criteria for selecting the order [11], and various opinions as to the best. The most commonly-used criteria are the *Akaike information criteria (AIC)*, developed by Akaike [14].

The AIC determine the order by minimising a function developed from an information-theory viewpoint. The AIC for a *p-th* order model is given by

$$AIC(p) = -ln\ \sigma^2 + 2\left(\frac{p}{N}\right) \quad (11)$$

The order selected is the one that minimises the AIC estimate in this equation.

The optimum order of p to be used when employing the AR technique for Loran-C skywave estimation is a compromise: too low a value gives poor time resolution, too high leads to spurious peaks. Unfortunately, the optimum order also changes with the received Loran-C signal, depending on its strength, signal-to-noise ratio and on the skywave delays. No single value of p is suitable under all conditions and so the skywave detection system must continuously recalculate the optimum value of this parameter.

5 Performance Evaluation

Sections 3 and 4 explained the principles of the FFT spectral-division and AR techniques for estimating skywave delay. This section evaluates the performance of the new AR algorithm under noisy conditions by means of computer simulation. Typical results are presented and compared with those obtained by the earlier FFT spectral-division method.

5.1 Simulation Arrangements

All simulations were written using the advanced software package Pro-Matlab [15] and run on a Sun work-station. Fig. 1 shows a functional block diagram of the simulation program.

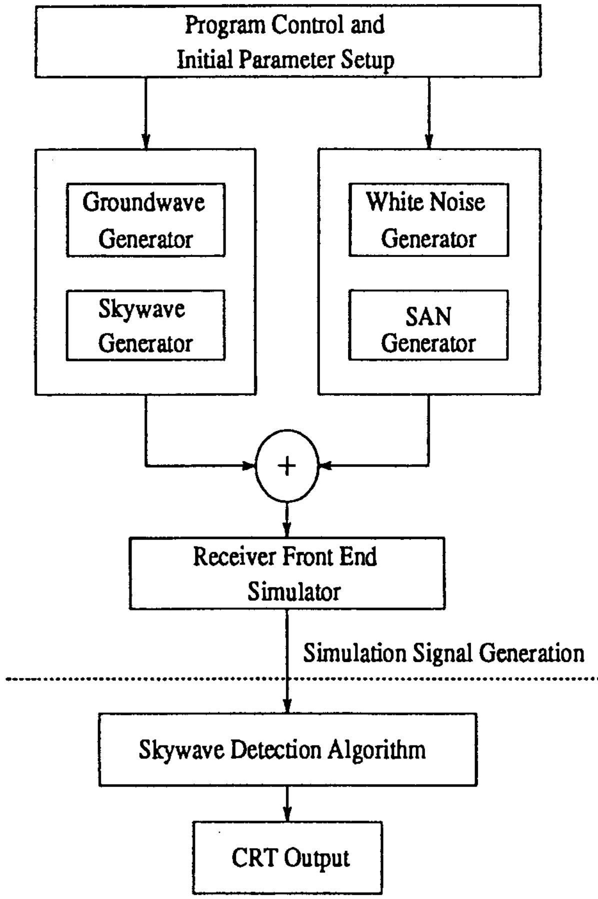


Fig. 1 Functional block diagram of programs to simulate the operation of the proposed skywave detection techniques under noisy conditions [2].

The Program Control block sets up the initial parameters for the other functional blocks and controls their operations. Simulated Atmospheric Noise (SAN) is generated in accordance with the standard defined in the Loran-C Minimum Performance Standards (MPS) practice [16,17], added to the separately-generated Loran-C groundwave and skywaves, and fed into the Front End Simulator block. Finally, the filtered composite signal is applied to the Skywave Detection Algorithm which analyses it to determine the arrival times of the skywaves.

Block diagrams of the simulations of the FFT spectral-division and AR analysis methods are shown in Figs. 2a and 2b, respectively. This shows clearly that the only difference between them is that the IFFT operation has been replaced by the AR modelling algorithm.

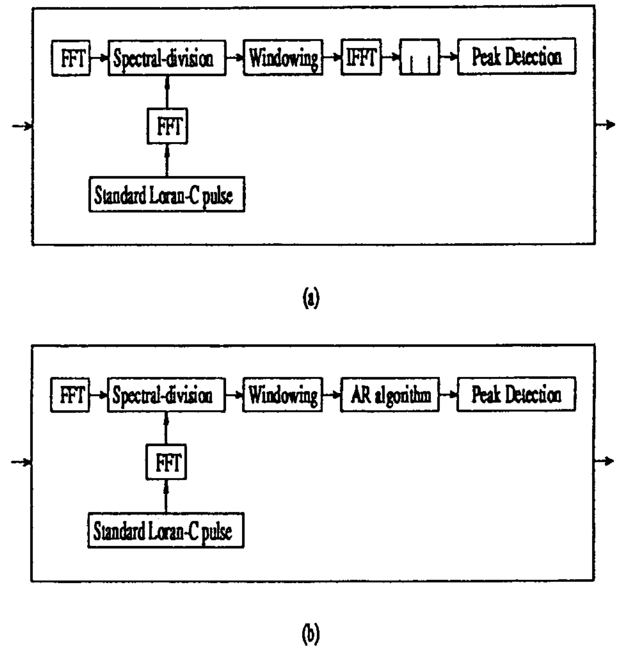


Fig. 2 Block diagram of the simulations of the skywave detection algorithms, (a) FFT spectral-division method and (b) AR model.

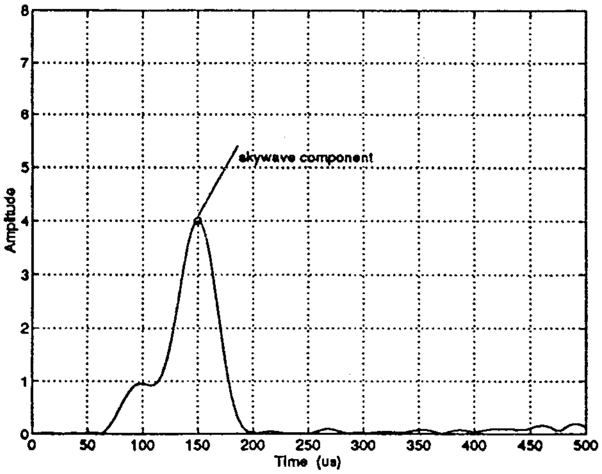
5.2 Simulation Results

Simulation programs have been developed for the Fourier and AR methods described in Section 3 and 4, respectively, and extensive simulations performed. The order for the AR algorithm is obtained by running the program and determining the value of p which gives the minimum AIC. The value of p used in the simulation is 20.

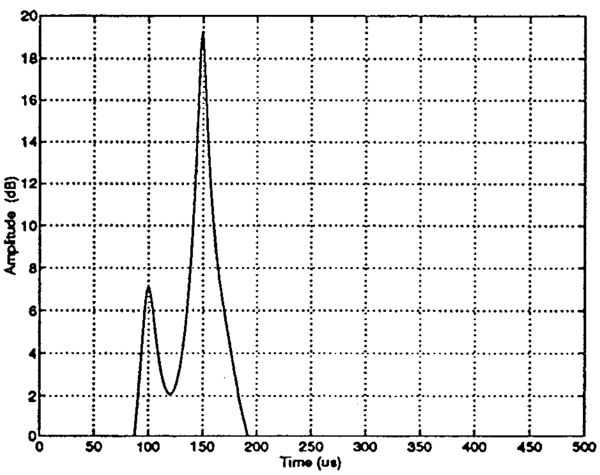
Fig. 3 shows typical results when a groundwave component at 100 μs is followed by a skywave component 50 μs later; the skywave is 12 dB stronger than the groundwave. These results are obtained at an SNR of 24 dB. The AR method clearly provides better resolution and sharper peaks at the groundwave and skywave positions than does the FFT spectral-division.

The results of 100 independent simulations at an SNR of 14 dB (-23 dB at the antenna), are summarised in Fig. 4. Skywave delays estimated by the AR algorithm are represented by circles, and the FFT spectral-division ones by crosses.

The mean value of the AR algorithm estimates is 50.1 μs and their standard deviation 1.9 μs. The FFT spectral-division estimates have a mean of 50.1 μs and its standard deviation 1.8 μs. Therefore at this SNR value, both techniques produced excellent results.



(a)



(b)

Fig. 3 Groundwave and skywave components separated by (a) the FFT spectral-division analysis and (b) the AR algorithm. The peak at 100 μs is the groundwave. The skywave comes 50 μs later. SGR=12 dB and SNR=24 dB.

A paper currently being prepared will compare the performance of the techniques described in this paper with the other high-resolution estimation technique, eigen-decomposition employing the MUSIC algorithm which Bian and Last presented at last year's WGA Convention [3].

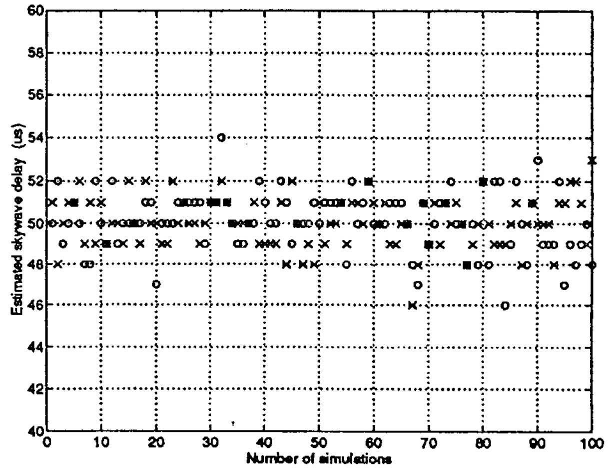


Fig. 4 Skywave delay estimates. The estimates obtained using the AR algorithm are marked by circles and those from the earlier FFT spectral-division method by crosses. Skywave delay=50 μs. SGR=12 dB and SNR=14 dB.

6 Conclusions

Adaptive skywave estimation techniques which can monitor the delays and strengths of skywave components in real time are desirable in Loran-C receivers since they allow an optimal sampling point to be selected. Such techniques should minimise errors due to skywave while maximising signal-to-noise ratios. This paper has proposed an alternative skywave estimation method using rational modelling techniques: a class of high-resolution estimation techniques, based on the AR and ARMA algorithms. The AR technique offers a good compromise between efficiency and complexity and the paper has shown how it may be applied to the Loran-C skywave problem. Simulation results have been presented and compared with those obtained by the earlier FFT spectral-division method. The AR technique has been shown to have sharper peaks and better resolution than the FFT spectral-division method. The price to be paid is the need to recompute the order p and the model parameters continually as the signal and signal-to-noise ratio change.

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Dr. Yi Bian graduated from Department of Precision Instrumentation of Jiao Tong University, Shanghai, China in 1985, with the highest honours of the year. He completed his M.Sc. with distinction in 1987 and continued work on inertial navigation systems as a 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. From 1 October 1992 to 30 June 1994, he was employed as a Post-doctoral Research Fellow by the University of Wales. He proposed, developed, and tested novel signal processing and computer simulation techniques for Loran-C receivers. He also worked on the Loran-C system performance modelling and conducted studies of Loran-C signal propagation characteristics (ASF modelling) for the NW European Loran-C systems. In 1993

he started working on information theory and its applications to (fibre optical, satellite, and data) communications systems. In this context, he discovered a new class of punctured convolutional codes and developed a new generic strategy which makes it possible to conduct realistic performance assessment of coded communications systems at extra-low Bit-Error-Rate regime via computer simulations. Since 1 July 1994, he has been with University College London, UK, as a Research Fellow, working on information theory and its applications to fibre optical communications systems and massive storage (magnetic and optical) systems. He jointly won the WGA Best Paper award of 1993.

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LORAN-C TD DISTORTION MEASUREMENTS AT THE NORWEGIAN COAST

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[1]with the University of Calgary, Department of Geomatics Engineering, during the preparation of this work.

Abstract

Expansion and renewal of LORAN-C in northwest Europe continue. Mapping of ASF corrections is necessary in order to achieve optimal absolute position accuracies with the system.

This paper presents an analysis of TD distortions using DGPS, and methods to achieve this. For this purpose, a data collection system for integrated LORAN-C and GPS measurements was used. The error sources of the data collection system have been investigated, and some proposals for future, larger scale, ASF projects are given. The TD distortion measurements along a section of the Norwegian coast reveal relatively stable TD values in the open sea, while considerable variations are experienced when signals travel partly over land. The TD repeatability is 0.067 μs when returning within two days. The conclusion obtained from the analyses is that a considerable gain in absolute position accuracy can be achieved if position dependent distortions are calibrated.

Introduction

In order to reap the fruits of the expansion of LORAN-C in northwest Europe and extend the user community as much as possible, ASF analysis and mapping is necessary. As an introduction to planned large-scale activities of that kind, measurements of TD distortions have been carried out in a central part of the coastal area of Norway, both in the open sea and in inlets and other narrow waterways [Melgård, 1994]. Data were collected in January 1994 on a ship along a 400 km trajectory, using a time-synchronised differential GPS - LORAN-C calibration system. The same type of tests were also conducted on some roads in the area.

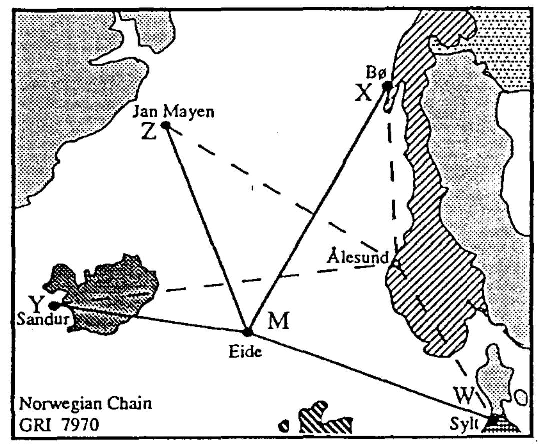

Figure 1. Ålesund was centre of the measurement area

The measurement area

The measurements were carried out along a few sea trajectories in the Møre and Romsdal region in the southwest part of central Norway (Figure 1), between 62 and 63°N and between 5 and 8°E. The measurement area was within a radius of 100 km from the Møre & Romsdal College of Fisheries (MRFH) at Ålesund who kindly supported the campaign by putting the ship "Nordengen" at our disposal. Figures 2 and 3 show the area, which is characterised by a fiord landscape with a large archipelago, sounds and inlets, and a very rugged and mountainous terrain with a ground conductivity of usually 0.3 - 0.9 mS/m.

With the old 7970 chain still in operation, the area of investigation had reasonably good coverage by the X and Z secondaries at Bø and Jan Mayen, respectively, in addition to the Master at Ejde. The directions to these transmitters are also shown in Figures 1 and 2. Distances (in nautical miles) from Ålesund to all transmitters in the chain (Figure 1) are:

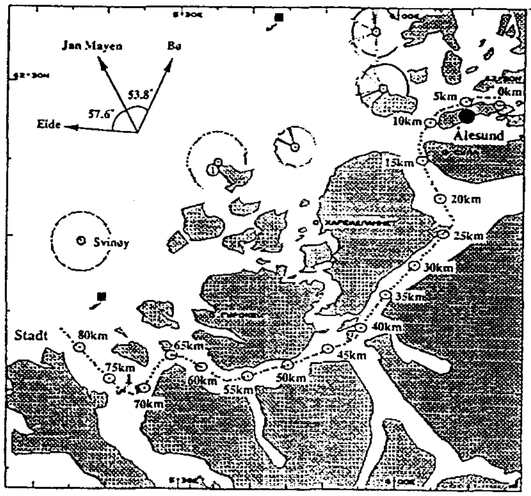

Figure 2. Trajectory map Ålesund - Stadt

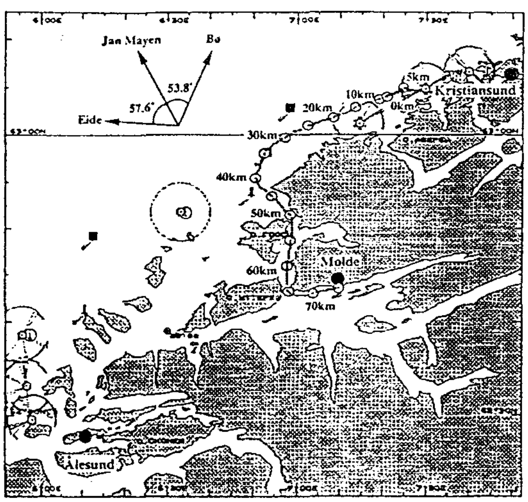

Figure 3. Trajectory map Kristiansund - Molde

M	Eide	368
X	Bø	422
W	Sylt	465
Y	Sandur	805
Z	Jan Mayen	615

Although the Sylt transmitter is not particularly far away, the signal path passes a long way over poorly conducting ground (as bad as 0.1 - 0.01 mS/m), and the signal level is insufficient (Figure 1). Signals from the more distant Sandur have a similar path, and, additionally, Sandur will not be part of the Northwest European LORAN-C System (NELS).

The measurement area is known to yield poor LORAN-C reception because of interference from a close military transmitter at 87 kHz and a DECCA transmitter at 112.26 kHz. The former was kept off, on request, during the measurements, whereas the latter created noticeable noise in the LORAN-C band.

The field measurement system

For the GPS receiver the NovAtel GPSCard™ 951R was chosen, mainly because of its documented tracking stability and good performance in presence of code multipath [Cannon and Lachapelle, 1992] with a portable Toshiba 5200 as host computer. Three LORAN-C receivers were used, two prototypes GM1050 from Geometrix of Tromsø, Norway, and one JET7202 from BFGoodrich, Grand Rapids, USA. It should be noted, however, that the JET7202 was intended for use in North America and had only three notch filters, which is generally considered too few in the European interference environment.

Logging software had to be written especially for this measurement campaign. It was however possible to use general ideas and overall principles from a similar system called LORCAL[2] developed at the University of Calgary [Townsend, 1993, and Lachapelle et al., 1993].

In general terms, the data collection program takes in data from all receivers, adds time tags and stores the data. Data reduction is done in post-mission. The system configuration is shown in Figure 4. Optical disks were used for storage and back-up of data.

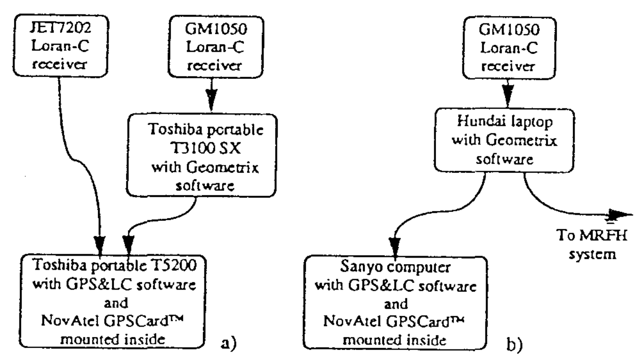

Figure 4. System configuration for data collection

In addition, a data collection system already installed by MRFH on board the "Nordengen" could be used. This system [Kjerstad, 1994] consists of a Magnavox 4200D DGPS receiver, a GM1050 LORAN-C receiver and the data logging software Seacontrol™ developed by the Seatex company in Trondheim. The MRFH system relies on a network of DGPS reference stations distributed all along the Norwegian coast and managed by the Norwegian Mapping Agency. Correction messages in RTCM 2 format are transmitted by LF maritime radio beacons situated in the neighbourhood of the reference stations.

Field measurements

The sea measurements were conducted during three days in the beginning of January this year. Two days were used for the road tests. The weather was very good, partly sunny, around freezing point and almost calm seas. Tidal variations in the area are in the order of 2 m.

The speed of the "Nordengen" during the kinematic measurements was 8.5 - 10 knots (4.3 - 5.1 m/s).

A total of three NovAtel receivers were mounted on the ship, with the antennas in a triangle, so that test data of the ship's attitude could be collected in addition to the LORAN data. Collected data were referenced to GPS time to facilitate post-processing.

Two cars were utilised for the road measurements. The MRFH system described by Figure 4b as well as the system in Figure 4a were used.

The DGPS base station was a NovAtel GPSCard. The antenna was located on the roof of the MRFH building in Ålesund. The receiver was located in an office below, in a computer with a hard drive capacity of 110 MB. The monitor could thus collect data at a 1 Hz rate for at least 36 hours.

A static GPS survey was conducted to find the coordinates of the base station. A known point in the local network, a few kilometers away from the base, was used as reference. Data were collected for two hours with a choke-ring antenna mounted on a tripod. For data reduction, two software packages developed at the University of Calgary were used. The coordinates of the base station were determined by SEMIKIN™, and the DGPS positions of the remote receiver were achieved by using C³NAV™ (e.g. Cannon and Lachapelle, 1992). The expected accuracy of the base-station position is at the cm level.

LORAN-C data reduction

Processing tools for the LORAN-C data reduction had to be developed. The LORCAL[2] programs mentioned above were modified and served as a basis for other software development. A flowchart of the processing is shown in Figure 5.

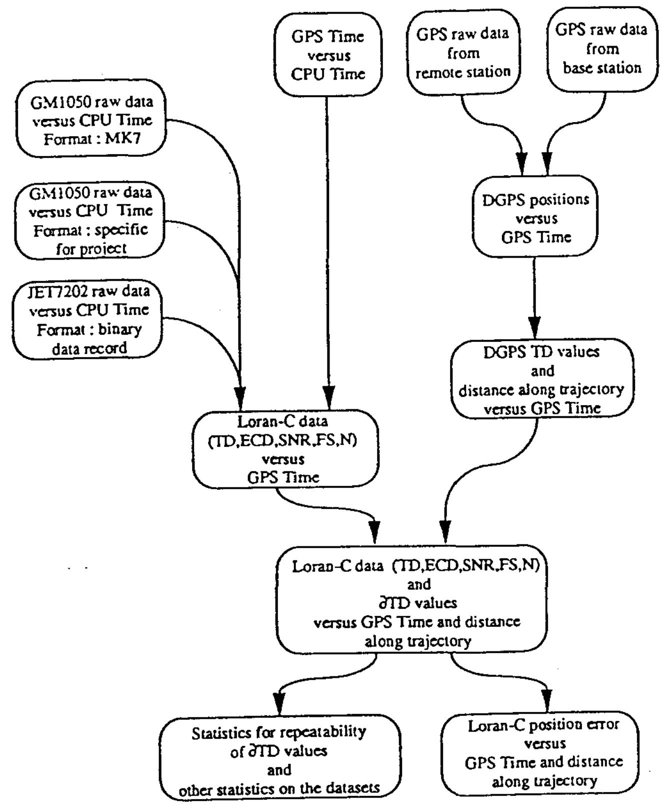

Figure 5. Flowchart of the LORAN-C data reduction

The DGPS TD values were obtained from the corresponding distances on the WGS84 ellipsoid.

General analysis tools

Processing and analysing large amounts of data create a need for displaying graphs fast and easily. A problem found in most graph generating programs is that input in a specific format is required, and that only limited amounts of data can be handled. A graphing program was developed to avoid these problems. The major advantage of that program is that it accepts raw-data outputs from most processing programs and displays a graph for the selected data columns almost immediately. Besides, there is no upper limit for the size of the data file.

Simple programs for computing statistics of the data sets were also developed.

Results

DGPS analysis

Before presenting the results of the LORAN-C measurements, we would like to give a very brief report about the DGPS performance as a reference system in this case.

DGPS performance was analysed using static as well as kinematic measurements. Static measurements in the harbour of Ålesund revealed differences in multipath sensitivity between the NovAtel and Magnavox receivers (as expected because of differences in correlator techniques). These differences added to differences caused by the Magnavox receiver being used for in-situ corrections in quasi-real time, but in reality with latencies of 3 - 30 seconds, and the NovAtel receiver being used for post-processing. Therefore, attenuated SA effects might have caused fluctuations of the Magnavox DGPS position. The resulting standard deviations in both latitude and longitude static measurements, 0.4 m for NovAtel and a little more than 3 m for Magnavox, should be construed with this in mind.

In the kinematic (i.e. on board the moving ship) measurements, another source of error adds to those present in the static measurements, namely the time tagging. The Magnavox measurements were tagged with the local computer time, whereas the NovAtel data were referred to GPS time. The total mean and rms differences between the outputs of the two receivers in kinematic use were in the order of 1 m and 8 m, respectively. This is still considerably better than the LORAN-C expected accuracy, so DGPS used as described is well suited as a reference system.

Static LORAN-C harbour measurements

Altogether, 38 hours of static LORAN-C data were collected in the harbour just northeast of Ålesund. A measurement result was accepted as good if the deviation from the mean was less than 5 μs. Statistics of the results of the JET7202 show a mean value of 15369.91 μs for TDX (Bø) and 64735.84 μs for TDZ (Jan Mayen). The DGPS value for TDX is 15369.00 μs. The corresponding LORAN-C standard deviations were 0.085 and 0.144 μs, respectively. The samples were accepted as good in 99.7 and 97.4% of all cases, respectively.

No significant diurnal fluctuations could be seen from the TDZ plots. A slow fluctuation of about 0.12 μs in the TDX mean could be observed, however. This difference is ascribable to the longer land pass of the Bø signal (Figure 1).

LORAN-C sea (kinematic) measurements

Noise, field strengths and signal-to-noise ratios

The noise along the trajectories Ålesund - Kristiansund, Kristiansund - Molde and Molde - Ålesund was stable at the 73 dB level (referred to 1μV/m) for both receivers (Figures 2 and 3). Close to Stadt (Figure 2), a clear noise maximum was registered because of the proximity of the DECCA station there. This is clearly demonstrated by the frequency spectrum measured at Stadt (Figure 6) as compared to the spectrum measured at Molde (Figure 7). The spectral components of the DECCA slaves, red at 112.26 and green at 127.3725 kHz, are seen as high spikes. The spectra were obtained by using an FFT program supplied with the GM1050 receiver by Geometrix.

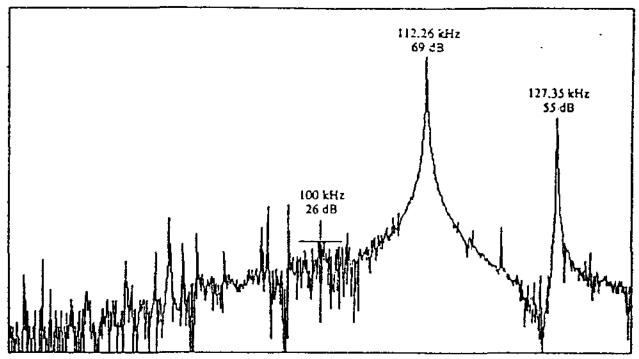

Figure 6. Frequency spectrum at Stadt, 5 January 1994

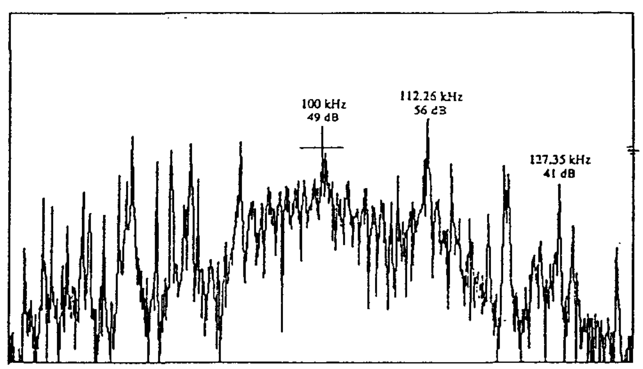

Figure 7. Frequency spectrum at Molde harbour, 6 January

Measured field strengths were 61 - 63 dB for the Master, 54 - 60 dB for the X transmitter and 49 - 53 dB for the Z transmitter, all referred to 1μV/m and measured with the JET7202. Both receivers showed typical SNR values for the Master 6 dB above those of X and 12 dB above those of Z.

TD distortions

The TD distortions were obtained by subtracting the calculated GPS TD from the measured (by the JET7202) LORAN-C TD. The GPS TD is given by the difference in distance to the transmitters divided by the velocity of light in vacuum and added the emission delay. No attempt has been made to model and remove the primary and secondary factors from the measured distortions.

The resulting δTD values were obtained from the mean TD's of 100 m sections along the trajectories. Graphs for some different trajectories and transmitters are shown in Figures 8 - 12. (The small gaps in the graphs were caused by a failure (by the measurement team) to block the automatic search mode of the receiver.)

The LORAN-C HDOP values in the measurement area were about 2.6. Thus, the μs values in the graphs can be translated into distances in metres by multiplication by 390.

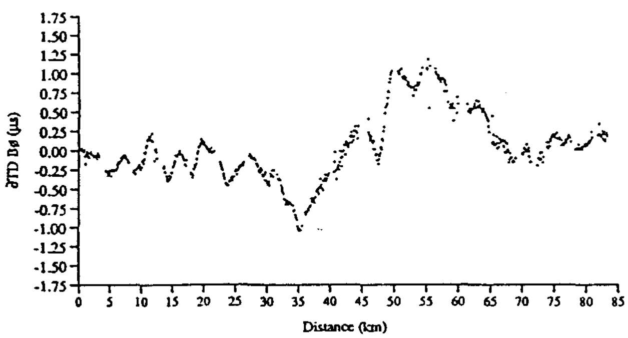

Figure 8. δTDX from Ålesund to Stadt

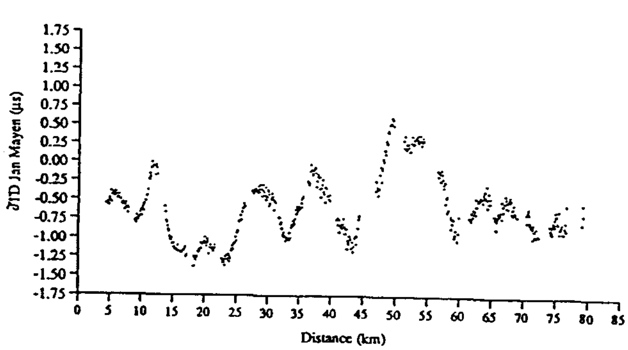

Figure 9. δTDZ from Ålesund to Stadt

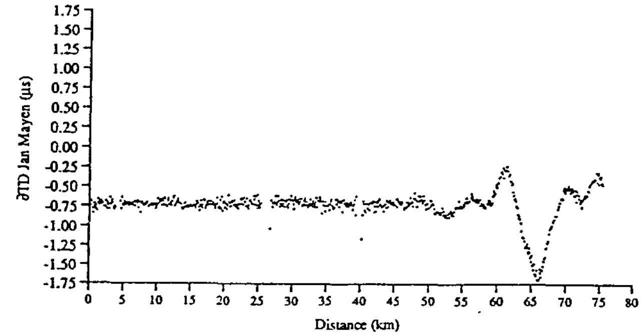

Figure 10. δTDZ from Kristiansund to Molde

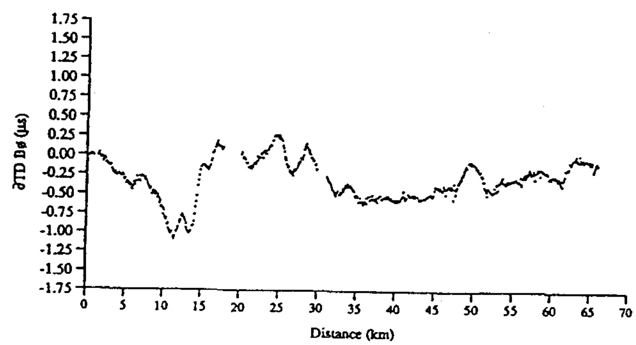

Figure 11. δTDX from Molde to Ålesund

Some comments should be tied to the above graphs. As soon as the ship enters inlets and inland waterway sections, considerable variations of the δTD values are noticed. These are in the ranges of -1 μs to 1 μs for TDX (Bø) and -1.75 μs to 0.5 μs for TDZ (Jan Mayen).

In general, the measured TD values have significant position-dependent distortions as soon as the signals travel partly over different kinds of land. This is as expected for this type of geography [e.g. Lachapelle et al., 1994]. The distortions are considerably larger than the expected repeatability of LORAN-C (30 - 50 m [Forssell, 1991]) due to rapid ASF variations.

The δTD does not reveal the magnitude of distortion along the signal path to the respective transmitter, but only the total distortion difference. Therefore, it is difficult to draw conclusions about the relationship between the terrain along the signal path to individual transmitters and the measured δTD fluctuations. The actual distortion related to each transmitter can however be found by time-of-arrival (TOA) measurements.

Repeatability of measured δTD values

During the measurements, the ship passed through some areas twice or more times. Then, δTD values were compared if the trajectories were separated by less than 500 m in DGPS positions. Comparison of a total of 1000 points gave rms values of 0.067 μs for both TDX and TDZ. Thus, good agreement between TD measurements in the same area was observed.

Road measurements

These measurements were executed along a 70 km section east of Ålesund. The road section winds through a wide variety of terrain. It goes inland among hills, follows along a lake and turns again towards the coast, along fiord arms.

Sadly enough, the results from both days and with both LORAN-C receivers turned out with noisy measurements and a low percentage of signal availability. The data sets were unfortunately not suitable for further TD distortion analysis.

Future measurements

ASF mapping is planned for the whole NELS area. In view of this, the undertaking presented in this paper is just an introduction. For the large-scale measurements, an efficient methodology is being developed. This implies TOA instead of TD measurements, which requires the use of precision time transfer (e.g. GPS common view, capable of accuracies of a few ns), and post-processing with precise ephemerides. By using DGPS in this way, single-point ship trajectory determination at the 1 m level (rms) should be obtainable in both coordinates. A very good ASF model has to be developed in order to minimise the required amount of data and measurement points for driving the model for continuous coverage of the area in question.

Conclusions

The data collection system proved to be a flexible and feasible approach to TD distortion measurements.

An optimally performing LORAN-C receiver is crucial for accurate measurements.

Noise measurements show the degrading influence of DECCA transmissions. This is reflected by reduced accuracies in all LORAN-C measurements. An increased number of notch filters might have improved the results of the JET7202.

The TD distortion analysis reveals relatively stable TD values in the open sea, whereas considerable variations are experienced when signals travel partly over land. An extreme example of such a variation is a change in δTD for Jan Mayen of 1.4 μs en route to Molde harbour along a distance of only 5 km.

Both the comparison of TD values obtained with different LORAN-C receivers and the repeatability analysis confirm the correctness of the results. When returning to the same area hours or up to two days later, the agreement in measured TD is 0.067 μs rms (about 26 m position error).

The results clearly show that calibrating LORAN-C can give a considerable accuracy gain. This is particularly important in coastal approach (landfall) and along coastal and inland waterways where the largest distortions are observed and accurate navigation of ships is a demand.

Mapping of ASF corrections is necessary to achieve optimum absolute position accuracies. TOA measurements are required for analyses of the individual signal paths.

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Dr. Gérard Lachapelle is a professor in the Department of Geomatics Engineering of The University of Calgary where he is responsible for research and teaching related to positioning, navigation and hydrography. He has been involved with GPS developments since 1980, and with Loran-C since 1989.

Analysis of High Latitude Loran-C Abnormalities in Alaska: Relationships to Solar Activity and Other Factors and Modification of Operational Decision Procedures

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1.0 Abstract:

Detailed analysis of Alaskan Loran-C abnormalities indicates relationships with various types of solar activity resulting in better control procedures. Solar activity and other data including flares, geomagnetic activity and other GOES satellite data from July 1992 through July 1993 is compared with over 250 Loran-C abnormalities resulting in blink during the same period. Results indicate that most Loran-C blink periods can be related to daytime, geomagnetic activity, elevated electron/magnetic flux, and extensive flare activity. However, the converse is not always true. Large solar related often occurs with no detected Loran-C abnormalities. In addition, some 7960 chain blink periods resulting from nighttime 7960-M ECD out of tolerance indications on the AUSTRON 5000 primary monitor receiver could not be related to solar or other factors. Although separate JET receiver data also shows increased nighttime 7960 ECD and TD variations, expected amplitude changes at an AUSTRON 2000 receiver located only 27 miles from the AUSTRON 5000 receiver did not occur. Close examination and subsequent modification of the primary AUSTRON 5000 monitor site and equipment did not indicate obvious equipment causes for the variations. Additional analysis of AUSTRON 2000 amplitude and timing tracks for 9990-Y and 7960-Z indicated concrete confirmation criteria for abnormalities on these baselines. This analysis of abnormality and solar data resulted in simplified procedures for verifying Alaskan Loran-C abnormalities and deciding whether or not to blink secondary signals. The new procedures focus more on verifying coverage area effects and less on solar activity data.

2.0 Introduction:

From the period 1 July 1992 through 31 July 1993 there were over 250 periods of blink unexplained by transmitting station or local noise problems totaling 15,168 minutes or about 2.64% unavailable time. Most of this blink was due to out of tolerance pulse shape of the 7960-Z Port Clarence signal monitored at Fairbanks, AK (11,262 minutes), or related to abnormal pulse shape of the 7960-M Tok signal monitored at Kodiak, AK (3,711 minutes). 152 minutes of the reminder were due to out of tolerance 9990-Y Port Clarence signal shape monitored at Adak, AK and the other 43 minutes were most likely due to 9990-X and 9990-Z monitoring problems.

These extended and frequent abnormalities were studied to verify relationships to solar activity and modify and simplify Loran-C control decisions if possible. This paper will:

1) Discuss analysis of over 250 blink periods showing relationships with solar activity.
2) Discuss the 7960-Chain blink periods resulting from apparent 7960-M ECD out of tolerance.
3) Briefly discuss confirming 9990-Y and 7960-Z abnormalities using AUSTRON 2000 amplitude and timing information.
3) Discuss the resulting improved control decision making process.

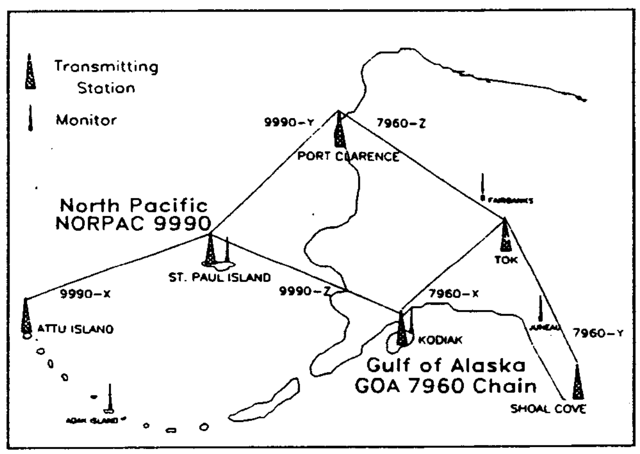

Figure 3-1. Alaskan Loran-C Chains, Stations, and Monitors

3.0 Background:

Although Alaskan Loran-C chains differ from others due to their high latitude location and difficulty with locating monitors at optimal locations, we use the same far field control method common to all US chains.[1] Figure 3-1 gives an overview of the two operational Alaskan Loran-C Chains, Gulf of Alaska (GOA) with Group Repetition Rate (GRI) of 7960 and North Pacific NORPAC with a 9990 GRI. The coverage areas include latitudes from 45 to 65 degrees North Latitude. As indicated by monitor locations, US Loran Chains use coverage area far field monitor information to maintain signal timing and verify correct signal shape and format. These monitors are preferably located in the main coverage area close to the center of baselines or in areas of heavy Loran-C use. As shown in Figure 3-1, Primary ALPHA-1 (A-1) and Secondary ALPHA-2 (A-2) monitors for GOA and NORPAC Chains are not often located near baseline centers and sometimes not even in the coverage area. The primary reason is that few locations in Alaska have the required power and support personnel available. Of interest in this study, the A-1 and A-2 monitors for the 7960-Z Tok-Port Clarence baseline are in Fairbanks and Kodiak, the A-1 and A-2 monitors for 7960-M signal are in Kodiak and Juneau, and the A-1 and A-2 monitors for the 9990-Y baseline are Adak and St. Paul, respectively. Juneau is the only monitor located close to a baseline center. The Kodiak A-2 location used to monitor the 7960-Z baseline is outside the coverage area.

The various solar activity data studied was obtained from weekly Preliminary Report and Forecast of Solar Geophysical Data reports and individual geomagnetic activity sensor data, all provided by the Space Environmental Services Center (SESC). The SESC provided individual geomagnetic sensor data from 1 July 1992 though 31 July 1993. The rest of the data was taken from the weekly Geophysical Data Reports covering 1 July 1992 through 18 April 1993. The various types of solar activity examined were: geomagnetic, flare, electron flux, magnetic flux, x-ray, and proton activity along with SESC alerts and warnings.

Geomagnetic activity is a ground based measurement of how the Earth's magnetic field varies.[2] Maximum geomagnetic activity is measured in nT for 8 daily three hour periods at a number of global ground locations. The raw data is converted to a "K" index using a lookup table designed to correct for natural differences between monitor sites. K values for individual sites are recorded as well as planetary "K_p" values combined from of high and low latitude individual K indices. 8 a_k indices for an individual site are also combined to give a 24 hour "A_k" index and individual A_k indices are combined to provide a planetary A_p index. In this study planetary and individual Alaskan K indices at College (near Fairbanks), Anchorage, and Sitka were examined.

Weekly reports include flare class, optical information, and beginning, end and peak times.[3] Flares are classified as A, B, C, M or X according to the peak x-ray intensity. For example, an M class flare may range from 10^{-2} to less than 10^{-1} erg cm^{-2} s^{-1}. C class flares are the next magnitude lower, for example, a C1.2 flare would have a peak x-ray intensity of 1.2×10^{-3} erg cm^{-2} s^{-1}. This study examined time, peak value, and duration of the highest three classes, C, M, and X. Location of the flare on the sun's surface and other details were not examined.

Electron and magnetic flux are included in the Weekly Geosynchronous Satellite Environment Summary page of the weekly SESC Forecast.[3] This data is from the GOES-7 satellite. The electron flux is a plot of 5 minute average electron flux in electrons cm^{-2} sec^{-1} sr^{-1}. The magnetic field is a plot of 5 minute average H component values in nT measured parallel to the Earth's rotation axis and denoted Hparallel. As Mr. Joe Kunches at SESC notes, the electron flux sensor is often affected by proton as well as electron activity. In contrast, the magnetic field sensor is not usually affected by proton activity and provides valuable secondary data during high proton activity as well as sudden geomagnetic events.

The x-ray and proton data examined are also taken from SESC weekly forecast GOES satellite information.[3] The proton plots are GOES-7 5 minute averages of proton flux in protons cm^{-2} sec^{-1} sr^{-1} for energy levels of greater than 1, 10, 30 and 100 MeV energy thresholds. The x-ray plots are 5 minute averaged x-ray flux in watts m^{-2} measured by GOES 7 and GOES 6 satellites. X-ray plots include separate plots for 0.5-4.0 and 1.0 to 8.0 Angstrom wavelength energy. The x-rays are classified according to 1-8 Angstrom band energy levels.

Alerts and warnings in the SESC weekly reports and Polar Cap Disturbance (PCD) warnings by the Omega Navigation Systems Center (ONSC) were also examined. The SESC warnings included high energy proton events, high K and A levels, high energy flares, radio noise bursts etc.[2] ONSC warning messages for the 6 Polar Cap Disturbances during the period studied were also examined.

The exact cause and effect relationships between solar activity and Loran-C abnormalities do not appear to be well known. The Coast Guard Academy "Port Clarence Skywave Interference Study" and further research by LT Arsenault at the University of New Hampshire seem to clearly verify that the immediate cause of the Loran-C abnormal pulse shapes result from skywave interference.[4] During my transmitting station visits in Alaska I also observed frequent skywave interference on AUSTRON 2000 oscilloscope displays during day and night. The skywave amplitude and delay were worst on long land baselines such as 7960-Z Tok-

Port Clarence and 7960-Y Tok-Shoal Cove. The mechanisms that result in earlier and more frequent skywave interference are not well known. In general, the solar activity data provides an indication of x-rays, electrons, and protons coming from the sun and some idea of how the Earth's magnetic field is affected. Many theories indicate that particles entering near the Earth's poles, sunlight, x-ray activity, magnetic field variations and other activity probably add energy and 'energize' Ionospheric layers, enhancing the lower D layer more often and to a greater extent at higher latitudes.[5,6,7]

4.0 Analysis of Blink Periods and Solar Activity:

A general review of solar related activity revealed frequent relationships between daytime, high latitude K-indices, planetary K indices and GOES electron flux. Alaskan Loran-C abnormalities were compared to Sitka, Anchorage and College geomagnetic sensor K indices for the entire 1 July 1992 through 31 July 1993 period. The SESC weekly report data were compared for a somewhat shorter period of 1 July 1992 through 18 April 1993. The over 200 separate blink episodes for this shorter period were divided into 112 groups of related periods within the same day or time frame.

Figure 4-1 shows the distribution of blink periods during the year versus time of day. The distribution demonstrates that almost all blink periods occur during the daytime and more blink occurs from fall through spring with fewer periods in the summer. The great majority of nighttime events resulted from 7960-M ECD out of tolerance indicated by the Kodiak monitor. Many daytime periods also occur near sunset with few at sunrise.

In almost all cases blink periods corresponded with one or more high latitude K indices occurring either during or within 12 hours of the abnormality. Of the 112 groups examined, K-4 geomagnetic activity occurred during the same 3-hour period 70 times and within 12 hours in another 33 occasions. Of the remaining 9 periods no high latitude geomagnetic data was ivailable for Sitka, Anchorage, or College sensors n 7 cases. In only 2 of 112 cases was there no orrelation between blink and geomagnetic ctivity and these cases were in the beginning of ie extended 7960 chain blink in mid-December 992.

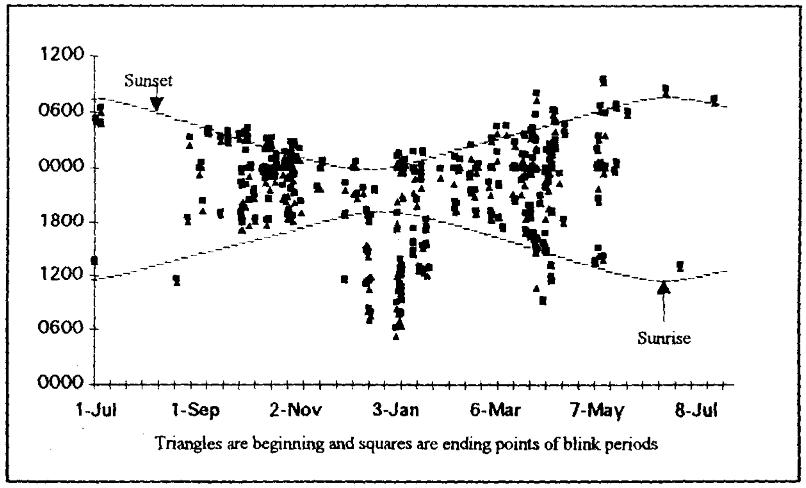

Figure 4-1. Blink Periods vs. Sunrise and Sunset
1 July 1992 to 31 July 1993

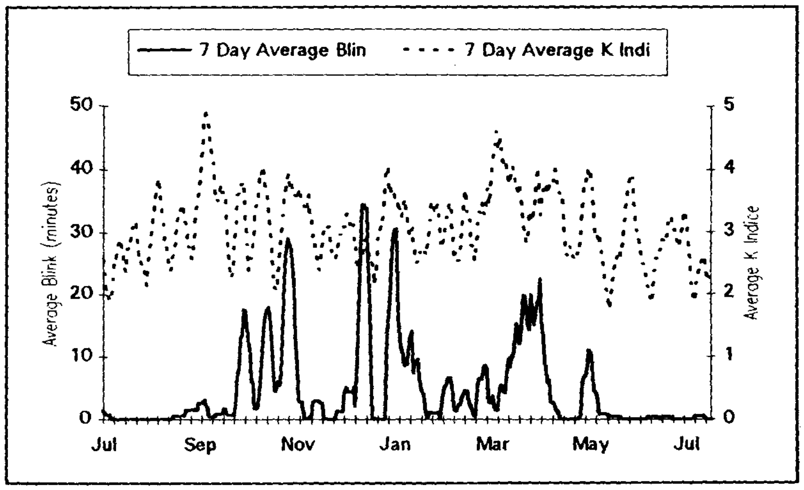

Figure 4-2. Blink vs. Average Geomagnetic Activity
7 Day Average, 1 July 92 - 31 July 93

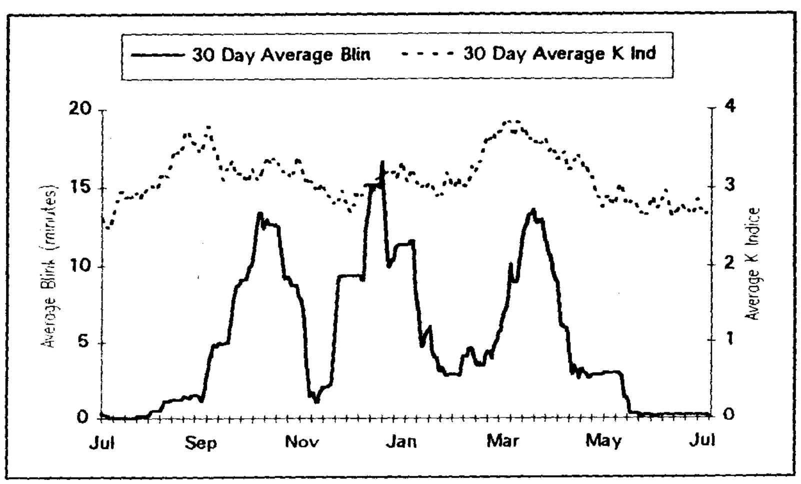

Figure 4-3. Blink vs. Average Geomagnetic Activity
30 Day Average, 1 July 92 - 31 July 93

Another indicator of a relationship between geomagnetic activity and Loran-C abnormalities is apparent by comparing longer running averages of blink and geomagnetic activity levels. Figures 4-2 and 4-3 compare 7 and 30 day average plots of geomagnetic activity and blink. The lowest geomagnetic activity occurs in the summer time when abnormalities are also at a minimum. Also, blink periods are usually grouped near peaks of geomagnetic activity.

Planetary geomagnetic activity correlates somewhat also, even though this index is a combination of high, middle and low latitude sensor values. In 50 of 112 cases K4 or higher planetary indices occurred during blink periods and in another 38 cases K4 or higher occurred within 12 hours. Planetary geomagnetic levels correlated with blink in 4 of the 7 cases where data was unavailable at College, Anchorage, or Sitka sensors.

GOES electron/magnetic flux also correlates with blink activity. In 79 of the 112 cases either high levels of electron flux or peaks in magnetic or electron flux occurred at the same period as blink. If additional spike occurrences in electron or magnetic flux activity are included then a total of 87 out of 112 groups of blink periods correlate.

Clustered flare activity also correlates with blink periods. In 63 cases there were many flares occurring around the blink periods. The majority of the flares were lower energy C class flares.

Somewhat surprisingly, even higher energy individual flares did not correlate well with individual blink period times. It was thought that an X class or strong M class flare occurrence would result in signal abnormalities and blink periods within 15 to 30 minutes after flare detection. However, this analysis suggests that while high energy and longer duration flares often occur within the general time frame of abnormality periods, they usually cannot be correlated with the beginning time of a specific blink period. Of the 5 X Class flares with greater than 10^{-1} erg cm^{-1} s^{-1} peak energy during the July to April period analyzed, one did not occur near any blink period, two others including a very high energy X-9 flare occurred after blink periods had already begun and only two occurred within an hour or so before blink periods began. An analysis of 107 M class flares between 10^{-1} and 10^{-2} erg cm^{-1} s^{-1} peak flux revealed no consistent correlation with the beginning of blink. Actually, slightly more than half of the M class flares occurred after blink periods began rather than before. In 1989 during peak sunspot activity it did appear that Loran abnormalities often occurred before flare detection.[5] It may be that direct correlation of flare and abnormality times is closer at lower latitudes where X-rays have a more direct path through the ionosphere. So, although abnormalities frequently occur around clusters of flare activity at high latitudes, flare timing does not seem to coincide closely enough with abnormalities for use in confirming decisions to blink.

While abnormalities resulting in blink almost always occur during periods of solar activity, there are many periods of high solar activity that do not result in blink. For example, in the 396 day period studied there were 270 days where the averaged Sitka, College, and Anchorage K indices were K-4 or higher sometime during a 24 hour period. Blink occurred in only 108 of these 24 hour periods. For planetary K values the 292 day period from 1 July 1992 through 18 April 1993 had 153 days with a K-4 or higher value while blink occurred during only 75 of these days. While blink often occurs during periods of large clusters of flare activity there are may cases of frequent flares with no blink.

Electron flux data seems to give much fewer 'false' positives. In the July 92 to April 93 period there were 136 days with GOES electron flux over $1x10^3$ electrons cm^{-2} sec^{-1} sr^{-1}. Of the 114 days with blink during this period 93 were within 48 hours of 108 different high electron flux periods. Of the 21 blink days not accounted for, 15 of the blink periods were during night time chain blink related to 7960-M ECD out of tolerance. 5 were only another day from high flux and only 1 period did not coincide at all. Looking at the days with high electron flux but no blink, many of these periods occurred in the summer months of July and August. Most others occurred during periods of higher GOES proton activity in the range of $1 \ x10^1$ protons cm^{-2} sec^{-1} sr^{-1}. As noted earlier, the GOES electron flux detector may have been affected by proton storms.

The probable relationship between solar activity and Loran-C abnormalities is further strengthened by the fact that most of the exceptions during the period analyzed were during the apparent 7960-M ECD out of tolerance occurrences in mid December 1992 and January 1993.

To summarize, there seems to be a correlation between Loran-C abnormalities and daytime, sunset, flare, geomagnetic and electron/magnetic flux activity. However, solar activity is not always a reliable indicator of when Loran-C abnormalities may occur.

5.0 7960-M ECD OUT OF TOLERANCE Analysis:

The 7960-M ECD out of tolerance periods were studied and reviewed closely resulting in a change in policy to blink secondary signals only if other AUSTRON 5000 or AUSTRON 2000 receivers verified user area effects.

The 1992-93 blink periods resulting from nighttime 7960-M ECD out of tolerance indications on the Kodiak monitor were lengthy, affected a large area, and were unusual in nature. The blink total was 3,711 minutes, almost 25% of the combined 13 month total for all Alaskan baselines. The major portion of these chain blink periods occurred from 16 to 19 December, 4 to 7 January, and 20 to 24 January with additional shorter periods on 14, 16 and 18 January. Since the Master signal was out of tolerance, all three secondary station signals of the 7960 Chain were blinked affecting the entire Gulf of Alaska and Interior Alaska coverage areas.

This chain blink was unusual because it occurred almost entirely during night hours, resulted from slow 7960-M ECD variation indications only on the Kodiak primary A-1 monitor, and the ECD varied slowly in both positive and negative directions. These blink periods were the only unexplained abnormalities that occurred during darkness. The 7960-M secondary A-2 monitor located at Juneau showed no ECD variations. The Kodiak ECD tended to start shifting shortly after sunset often taking more than an hour to move out of tolerance. Although the ECD moved out of tolerance in a negative direction more often, it also went out of tolerance in a positive direction. While daytime 7960-Z abnormalities also usually resulted from out of tolerance ECD, the variation periods were generally shorter and resulted from positive going out of tolerance ECD in only 4 of over 200 blink periods.

Later detailed review of the 7960-M ECD abnormalities was puzzling with little independent verification of actual signal variations but also no clear signal ECD movement.no ECD variations it is located near the middle of the 7960-Y baseline well away from the Kodiak primary monitor located only 27 miles from the secondary end of the 7960-X baseline. The Kodiak monitor is also used to monitor 9990-M and 9990-Z signals and indicated no abnormalities with these other signals. The only other Kodiak tracks that

No AUSTRON 2000 receiver data from transmitting stations clearly indicated signal ECD variations. The clearest AUSTRON 2000 indication of ECD variation would be changing signal amplitude tracks as the half cycle amplitudes increased or decreased equipment related explanations. AUSTRON 5000 monitor receiver from other primary and secondary monitors in Juneau, Fairbanks, St. Paul and Adak all showed no unusual signal variations. While the Juneau secondary 7960-M monitor receiver showed varied were 7960-X,Y and Z TD tracks. These tracks tended to move only during larger 1.0 microsecond or more 7960-M ECD variations. These TD tracks varied in a matching pattern closely related to master ECD movement but with no secondary ECD variations, indicating that the TD variations most likely resulted from master with skywave or other interference. Although AUSTRON 2000 tracks vary often at Alaskan stations none correlated at all closely with the chain blink periods. In particular, 7960-M ECD variations indicated by the Kodiak monitor should be verifiable by AUSTRON 2000 receiver indications at the 7960-X transmitting station only 27 miles away at Narrow Cape. But, no significant amplitude variations occurred during any of the night time blink periods. In contrast, daytime 7960-M ECD out of tolerance conditions on the Kodiak monitor were accompanied by large 0.5 volt or more changes in the Narrow Cape AUSTRON 2000 Amplitude values. Daytime 7960-Z abnormalities are usually accompanied by 0.3 volt or more variations in the Tok AUSTRON 2000 amplitude tracks.

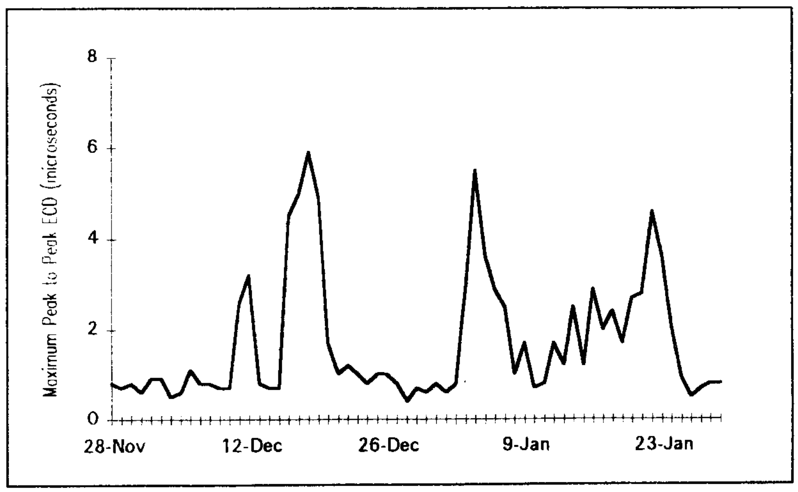

Figure 5-1. Kodiak Monitor 7960-M ECD
Maximum Peak to Peak Variation
28 Nov 1992 to 29 Jan 1993

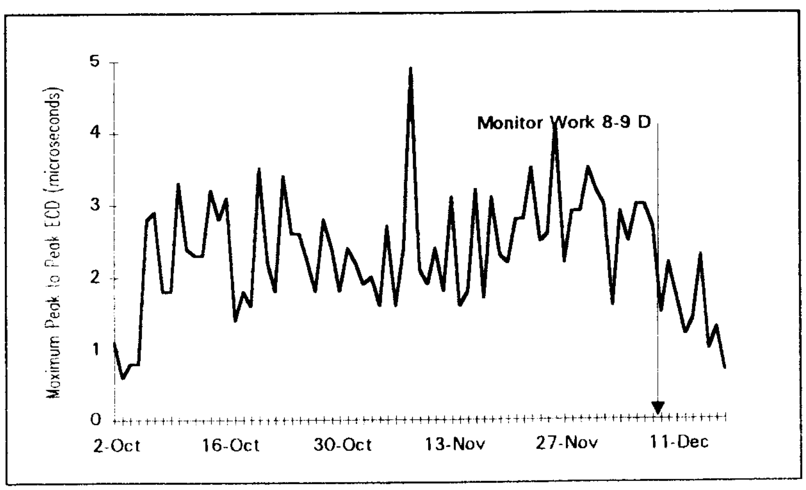

Figure 5-2. Kodiak Monitor 7960-M ECD
Maximum Peak to Peak Variation
2 Oct to 17 Dec 1993

Larger than normal 7960-M ECD fluctuations also occurred for a long period in the fall of 1993 as well as during the chain blink periods in 1992-93. Figures 5-1 and 5-2 plot maximum 7960-M peak to peak nighttime ECD shifts for the two periods. In 1992-93 the ECD variations occurred closely around the periods of 7960 chain blink while the fall 1993 variations occurred from October through December.

Throughout the period from 1992 to 1994 equipment inspections and modifications did not clearly indicate equipment causes for the indicated 7960-M ECD variations. When the out of tolerance periods first began to occur inspection of the Kodiak monitor site did not reveal any improper connections or other out of ordinary items other than apparent skywave interference on the CRT display. However, frequent or continuous visible skywave interference during both day and night time particularly on longer Alaskan land baselines is not unusual. Also in January 1993 the monitor antenna coupler and several receiver components were switched with no apparent effect. The 7960-M ECD fluctuations again occurred during the fall of 1993. The monitor antenna was switched out December 8 with no apparent effect. The 7960-M ECD fluctuations seemed to already have begun decreasing before the antenna switch as annotated in Figure 5-2. As an additional measure in the winter of 1994 the entire Kodiak monitor AUSTRON 5000 receiver was replaced by Loran Station Kodiak and another detailed inspection was performed by the Pacific Area Maintenance and Logistics Command. Although the fluctuations had since subsided, no other changes in signal tracks or Control Standard ECD or TD values was evident. The detailed inspection revealed a few discrepancies, the most important being a grounded notch filter chassis. Normally the notch filter ground is left floating. Although no changes in monitor performance were obvious these equipment changes may have resolved the problems. However, we will have to wait through the fall of 1994 and winter of 1995 to see if 7960-M fluctuations re-occur.

Some independent JET receiver data recorded on Kodiak may substantiate increased variation of 7960-M ECD during late fall night time periods. A JET 7202 receiver connected to an 18" whip antenna on the roof of the Loran Station Kodiak Control Station building

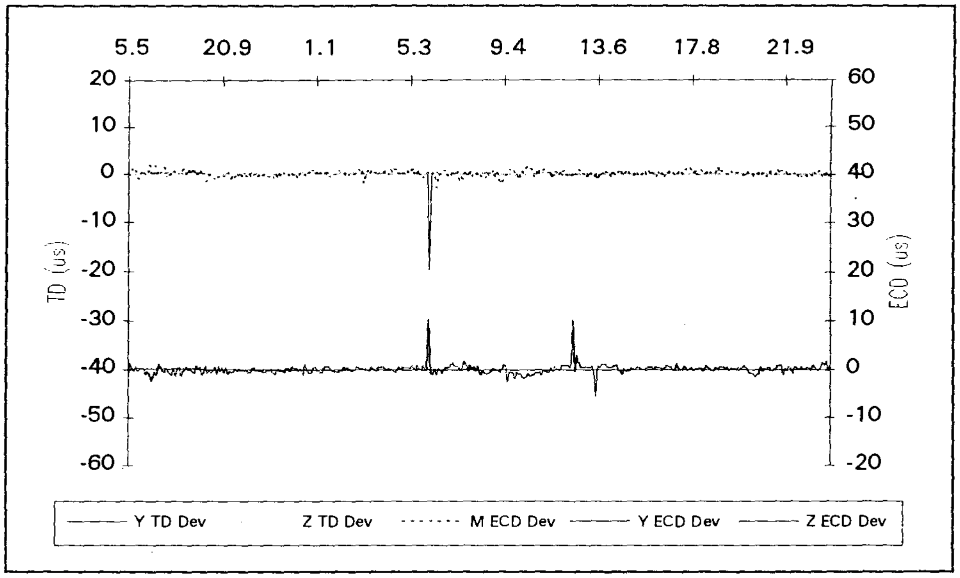

Figure 5-3. 9990 TD and ECD Deviation
from average value.
Jet Receiver at Kodiak, AK:
0530Z 1 May to 2400Z 2 May 93

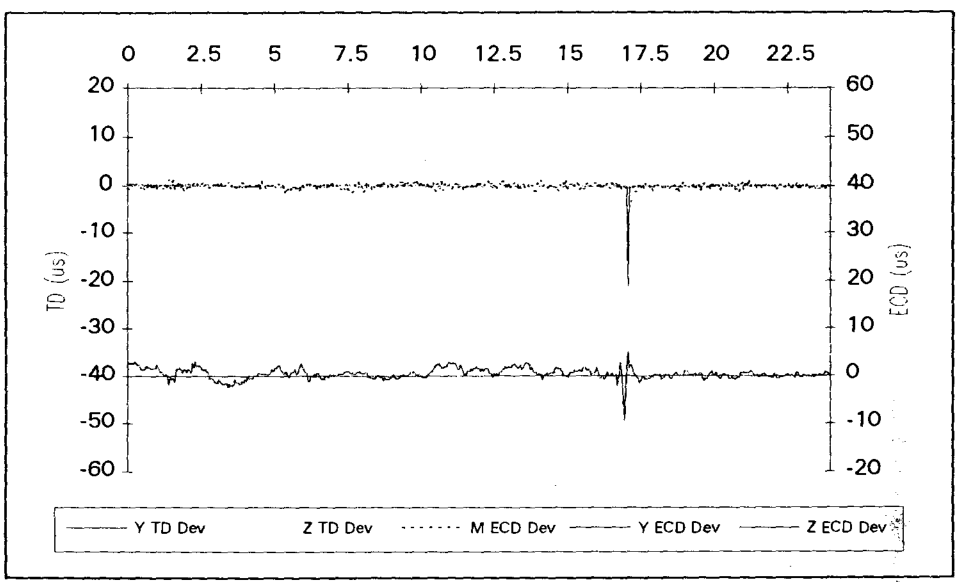

Figure 5-4. 9990 TD and ECD Deviation
from average value.
Jet Receiver at Kodiak, AK:
0000Z 16 Oct to 2400Z 16 Oct 93

located about 8 miles south of the monitor site recorded TD, ECD and signal strength data to an IBM compatible computer. Figures 5-3 through 5-6 show 9990 and 7960 TD and ECD information for a typical May and October time period. The antenna installation on the roof was not optimal with several other antennas and objects also on the roof.

While not conclusive, the plots do seem to indicate relatively more receiver difficulty with 7960 than 9990 and more variation at night than during daylight hours. Note that the 9990 plots show almost no variations in either May or October. Also note the much longer 7960 variations in October as compared to May. These 7960 variations occurred during nighttime rather than daytime hours.

Other interesting plots in Figures 5-7 and 5-8 show Signal-to-Noise Ratio (SNR) and signal strength variations with season. In Figure 5-7 the longer nighttime periods correlate directly with lower SNR values. The Figure 5-8 plot shows correspondingly shorter SNR decrease during the short summer nights. The signal strength also appeared to vary with season with lower values in October through January and higher values in April and through the summer.

Because the detailed review was inconclusive but no user coverage area effects could be verified, in the winter of 1993 policy was changed to blink secondaries during 7960-M ECD out of tolerance on the Kodiak monitor only if verified by AUSTRON 2000 receiver amplitude and timing tracks.

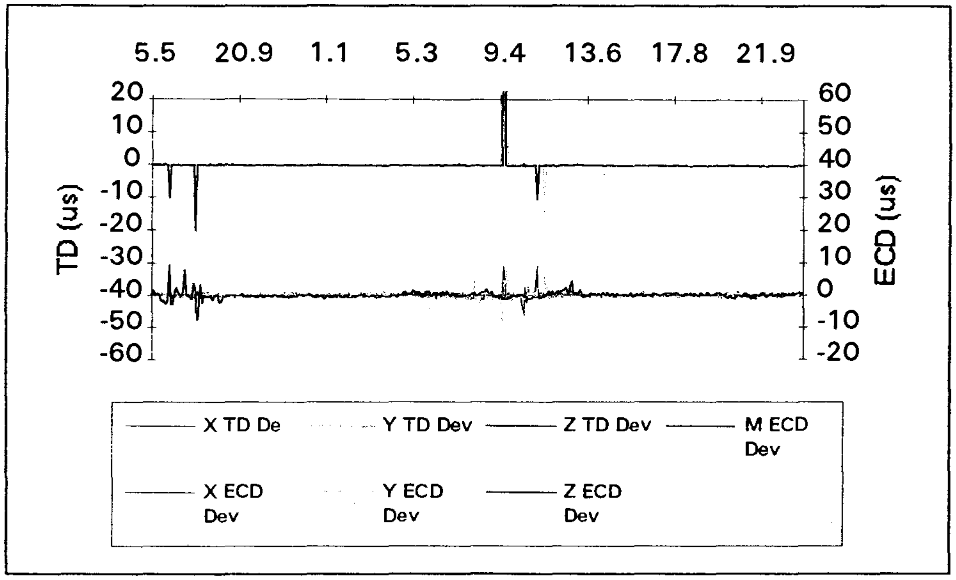

Figure 5-5. 7960 TD and ECD Deviation from average value. Jet Receiver at Kodiak AK: 0530Z 1 May to 2400Z 2 May 93

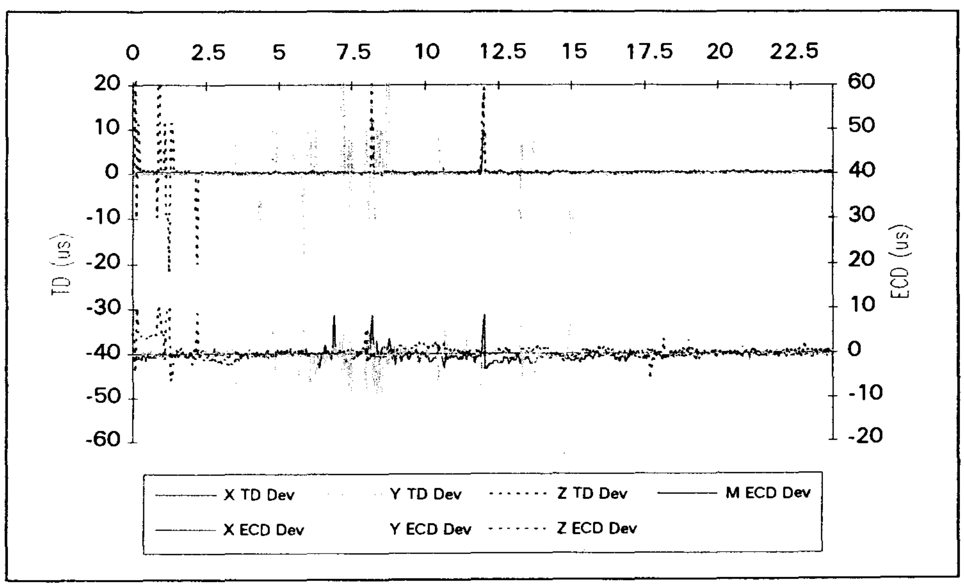

Figure 5-6. 7960 TD and ECD Deviation from average value. Jet Receiver at Kodiak, AK: 0000Z 16 Oct to 2400Z 16 Oct 93

6.0 9990-Y Abnormality Analysis:

The six 9990-Y blink periods due to abnormalities correlate well with solar activity but confirmation by amplitude and track movement at the St. Paul master station varies indicating that assigning Adak as primary A-1 monitor for 7960-Y ECD and TD should perhaps be re-examined. These blink periods occurred on 10 September 1992 and 23 March, and 7, 8, 11, 12 April 1993. All six periods corresponded to solar activity as noted above. All periods showed characteristic ECD movement on primary A-1 monitor and/or secondary monitor tracks. The St. Paul AUSTRON 2000 amplitude movement was only large during the 7 and 8 April cases at about -0.4 volts. In the other cases amplitude movement matched the blink periods but was only about +/- .2 volts at most. Likewise, AUSTRON 2000 timing tracks varied by about 160

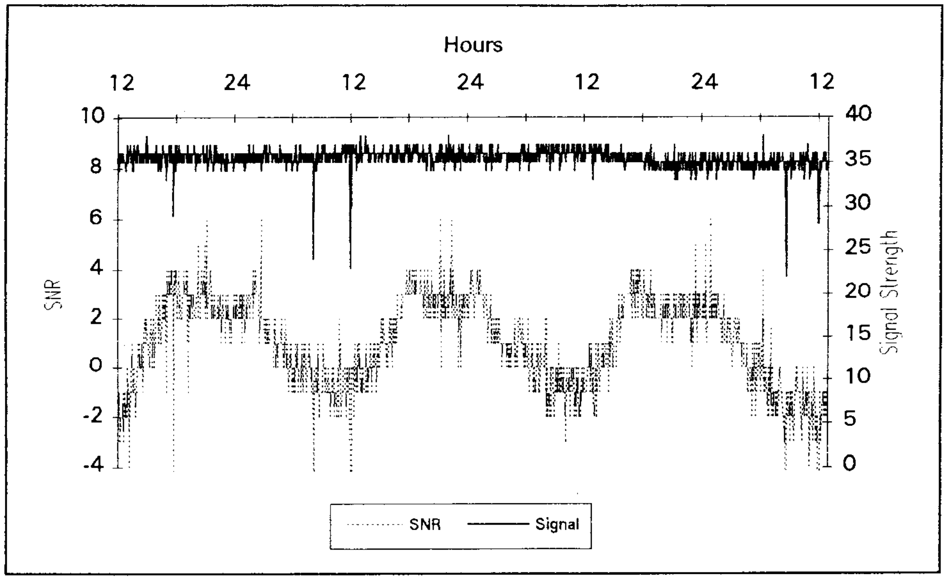

Figure 5-7. 7960 SNR and Relative Signal Strength
From Jet Receiver at Kodiak, AK:
1200Z 18 Oct to 1200Z 21 Oct 93

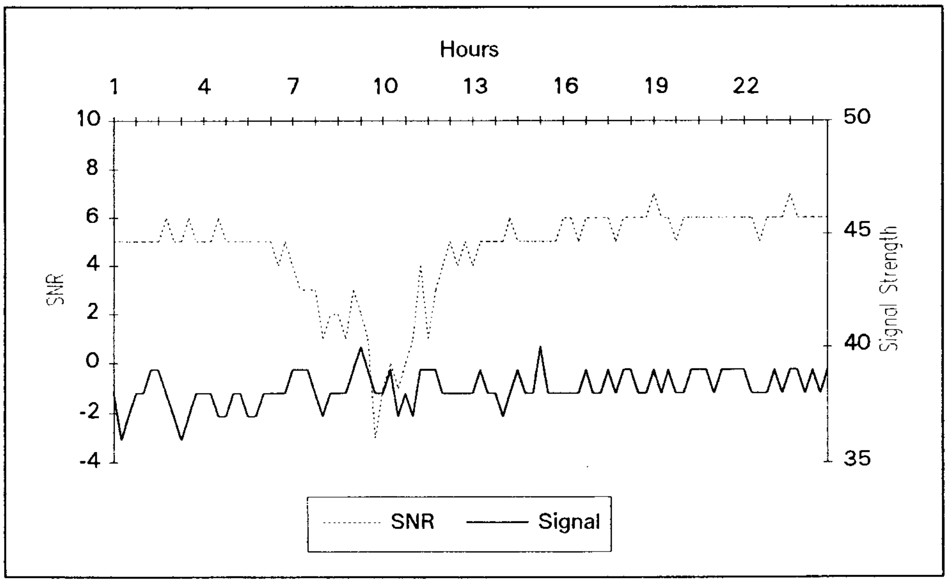

Figure 5-8. 7960-M SNR and Relative Signal Strength
From Jet Receiver at Kodiak, AK:
0100Z 3 June to 0100Z 4 June 93

nanoseconds on 7, 8 April and only 50 to 60 nanoseconds during the other blink periods.

Although the Adak A-1 monitor is in the extreme coverage area for the 9990-Y baseline its remoteness may make it susceptible to skywave interference that does not substantially affect the majority of the coverage area. Figure 3-1 shows that Adak is quite far from Port Clarence. The additional distance not only results in more ground wave attenuation but tends to reduce the skywave delay as well. As a result, skywave interference may affect Adak before the effects are seen between St. Paul and Port Clarence. This increased susceptibility seems to be confirmed by the six abnormality periods examined.

Whether or not to switch from Adak to St. Paul for A-1 monitor is a close call. The other Attu 9990-X and Kodiak 9990-Z baselines do provide slightly better geometry in the Adak area and through the mid-Aleutians. On the other hand, it may be better to 'tie down the grid' for 9990-Y closer to the Aleutian Islands where more hazardous reefs and stronger currents exist. Finally, the overall amount of 9990 blink is generally low. Of a total 152 minutes in a 13 month period switching primary monitors would only have saved between 39 and 79 minutes of blink.

7.0 AUSTRON 2000 Confirmation of 7960-Z Abnormalities:

Along with this study, Tok AUSTRON 2000 amplitude and timing tracks were examined and rules for confirming pulse shape abnormalities were determined. Copies of Tok AUSTRON 2000 receiver tracks for the 7960-Z signal from Port Clarence were compared with Alpha monitor tracks. In all cases, abnormalities resulting in out of tolerance ECD corresponded to a 0.3 volt or greater shift in AUSTRON 2000 amplitude. Although more variable, AUSTRON 2000 timing usually shifted greater than 150 nanoseconds. These results show that AUSTRON 2000 can confirm abnormality effects. However, it is important to realize that the magnitude of AUSTRON 2000 amplitude and timing shifts will vary depending on signal strength, location and noise. For example, Shoal Cove AUSTRON 2000 tracks for monitoring the 7960-M signal are frequently unusable even during good conditions while most St. Paul AUSTRON 2000 tracks are typically very steady.

8.0 Resulting Changes in Policy:

The combined results of this study were used to simplify control shift and blink decisions to emphasize watchstander confirmation of non-equipment related abnormalities by other Alpha monitor AUSTRON 5000 or transmitting station AUSTRON 2000 information. The policy for blinking signals during non-equipment out of tolerance conditions is still to blink anytime the effects are confirmed to affect more than a single localized monitor location. When an A-1 primary monitor indicates an out of tolerance condition control is shifted to the A-2 secondary only if no confirmed coverage effects exist.

The confirmation process has been simplified by this study. Previously, watchstanders checked other Alpha monitor data, transmitting station AUSTRON 2000 data and called the SESC for flare, geomagnetic proton activity data. Under old procedures confirmation by AUSTRON 2000 tracks required comparing timing number shift magnitude and direction of both master and secondary receivers. Only AUSTRON 2000 data from Tok and Kodiak transmitting stations is immediately accessible via the Remote Operating System (ROS). Data from other transmitting stations must be obtained via personnel at the station. Also, AUSTRON 2000 data is sometimes unusable during high noise periods frequently experienced at Port Clarence, Shoal Cove and Tok. Finally, significant levels of the various solar activity required for abnormality confirmation were not well defined.

The new control decision procedure only requires watchstander confirmation by either Alpha monitor or single station AUSTRON 2000 data. Watchstanders at control station Kodiak check the locally and remotely available data first for confirmation. If other Alpha monitor information does not provide confirmation then a single station's AUSTRON 2000 amplitude and timing numbers may be used. If AUSTRON 2000 data is not available remotely then control watchstanders contact transmitting station personnel, such as in the case of a 9990-Y abnormality. Control watchstanders only gather solar activity data from the SESC watchstander if no Alpha monitor or AUSTRON 2000 data provides confirmation. In this case the watchstanders will contact the Chain Coordinator immediately with all data and plan to shift control unless otherwise directed.

Solar data is still of interest and the Chain Coordinator should review weekly solar forecasts. However, solar activity information is no longer used for immediate confirmation since no correlation with available flare, geomagnetic, or proton activity has been shown to be accurate within 30 minutes or so of the blink periods. This study does provide some clear guidelines for what SESC weekly forecast information may be important for the Chain Coordinator to monitor and review after abnormality periods.

As a result, control station watchstanders now have a well defined confirmation process which only requires immediately available data in about 90% of signal abnormality cases. What appears to be excessive nighttime chain blink due to 7960-M ECD out of tolerance is eliminated because other Alpha monitor and AUSTRON 2000 data usually do not provide confirmation.

9.0 Conclusions:

This study shows likely relationships between daylight, geomagnetic activity, elevated electron/magnetic flux and clusters of flare activity and Loran-C abnormality periods resulting in blink. The results also allow simplified, well defined control station watchstander blink and control shift decisions. Later Chain Coordinators have valuable background for additional comparisons between abnormalities and blink. Further work should be done regarding nighttime 7960-M ECD abnormalities and a change in primary A-1 monitor for the 9990-Y ECD and TD parameters from Adak to St. Paul might also be considered.

10.0 Acknowledgments:

I greatly appreciate help provided by Loran Station Kodiak, other Loran Station personnel and Chain Coordinator Assistants ET1 Tim McBride and ET1 Karl Brand during this study. This study could not have been accomplished without assistance and equipment provided by the CAPT Ben Peterson, Dr. Keith Gross, LT Eric Chamberlain and other Coast Guard Academy Electrical Engineering Section staff.

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Biography:

Dave Watkins served in the Coast Guard for 12 years including tours as Information Systems Center Project Manager and Coast Guard Academy Electrical Engineering Instructor. LT Watkins was most recently the Coordinator of Chain Operations for the Gulf of Alaska and North Pacific Chains, including development of Russian-American Chain operational procedures. He received a BSEE degree from the U. S. Coast Guard Academy in 1982 and an MSEE degree from the University of Michigan in 1985. Dave Watkins is presently pursuing a career in project engineering and management in telecommunications and electrical engineering.

EXPERIMENTAL STUDY ON LORAN-C PULSE DISTORTION

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Abstract

In August, 1994, a pulse distortion measurement system was installed at KOBE University of Mercantile Marine by which Loran-C pulse wave was received and processed; the wave shape was observed and the distortion measure was calculated. Since the level of distortion in the pulse shape varies with the propagation path, ECD at Japan Maritime Safety Agency's (JMSA) 9970 monitoring stations were simultaneously observed to help evaluate a stability of transmitted pulse shape. In this paper we present some analytic and experimental results on the Loran-C pulse distortion measures.

1 INTRODUCTION

In 1993, JMSA took over Loran-C Northwest Pacific Chain (GRI: 9970) from USCG (USA). New chain configuration was decided taking into consideration an efficiency of the Asia Pacific Area GNS and the operation starts in October, 1994. We analyze the received pulse shape in the present chain configuration, which is intended to be utilized in future to evaluate the new configuration.
At 19th WGA meeting, we showed that the Loran-C pulse distortion changes with propagation path and proposed the method for ASF correction which utilizes distortion measure called CHACLE and is illustrated by simulation. We also showed that the measurement technique for the proposed measure and its performance in a noise environment[1]. The purpose of our study then was firstly to improve the absolute accuracy of Loran-C to be the same level as that of GPS, and secondly to make possible the high availability and reliability of the either system being used to complement each other.
Now that the GPS system is completed, the Loran-C system is regarded by and large as a system to complement GPS. For overall safety of the navigation, it is still important for the Loran-C system to establish the better ASF correction method. The exact calibration of Loran-C pulse distortion measure needs some elaboration in the measurement system due to the effects of an atmospheric and manmade noise, a characteristics of the propagation path and a lack of information on the transmitted pulse. In this paper, the Loran-C pulse shape measurement system at KOBE (KUMM: Kobe Univ. of Mercantile Marine) is described and some results of the experiment with this system were reported.

2 MEASUREMENT SYSTEM

The measurement system consists of two parts; hardware and software. The hardware structure is to receive and record the pulse wave, and the software is to process recorded pulse wave form to estimate various pulse distortion measures.

2.1 HARDWARE STRUCTURE

Figure 1 shows a block diagram of the hardware used in this experiment, which is expected to ensure the precise pulse shape recording.
In the Loran-C receiver, the pulse which is used to trigger signal for A/D conversion is generated synchronizing at SSP(standard sampling point) of the first pulse of the master station pulses. The RF signal coming in from antenna and coupler (of bandwidth wide enough for Loran-C RF signal) is converted to a digital signal with 16bits resolution and 100MHz sampling frequency at the above SSP timing.
The digital signal thus converted is then accumulated up to

500 times and then taken its average. This average of 500 pulses is then recorded in the hard disk as a received Loran-C pulse shape. It takes about 2 hours to accumulate 500 signals due to the low S.N.R.(signal-to-noise ratio) of each received pulse (below 0dB). Fig.2 shows one example of the recorded wave shapes from Y station.

2.2 CALCULATION FLOW

Figure 3 shows the block diagram of the software structure of the present system which estimates the pulse distortion measures. Now a recorded pulse is filtered digitally by software; the signal processed by band pass filter (FIR filter with center frequency of 100kHz and cutoff frequency of 20kHz) becomes a signal with reduced noise component and eventually with less distortion, by which zero crossing times are to be determined. Figure 4 shows an example of the BP filtered signal, which is to be used to estimate following three pulse distortion measures.

1. ECD(Envelop to Cycle Difference):
   The bandpass filtered signal is filtered again, this time, by low pass filter with the same cutoff frequency as the BPF above. With this filtering, an envelope of the pulse is reproduced. Then seven sampling points, i.e. SSP, 3 points each before and after SSP with intervals of 2.5 microsecond in between, are obtained, with which ECD is estimated by least square error method.

2. CHACLE (Change of Half Cycle LEngth):[1]
   Half cycle length before and after SSP is measured and used to calculate CHACLE following the equation below.

   CHACLE = (half cycle length after SSP) - (half cycle length before SSP)

3. Phase Modulation Term:[2]
   Phase shift is calculated from in-phase and quadrature component of the lowpass filtered signal. For that purpose 100 phase data are collected from this signal in the vicinity of SSP, and then estimated the phase modulation term at SSP by least square method. As being considered that the phase shift thus calculated at the SSP has a strong correlation with CHACLE, we could use one pulse distortion measure to correct the ASF.

3 EXPERIMENTAL RESULTS

3.1 OUTLINE OF EXPERIMENT

In August and September of 1994, the experiment was done to evaluate the present measurement system. Transmitter and receiver configuration is shown in Fig.5. The measurement system was installed and measured pulse wave shapes

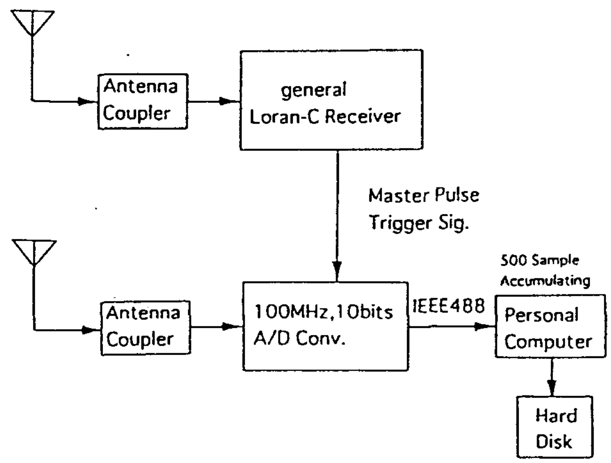

Figure 1: Harweare Block Diagram

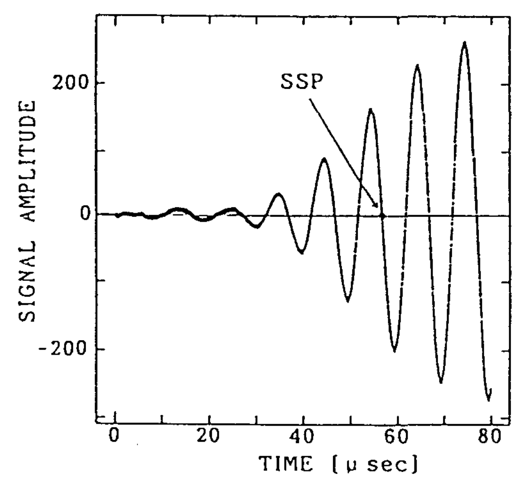

Figure 2: Recorded Wave Shape

Table 1: Results at Transmitters and Monitor Stations

Transitter	M			X			Y		
monitor	Dist. [n.m]	ECD [μ sec]	S/N [dB]	Dist [n.m]	ECD [μ sec]	S/N [dB]	Dist [n.m]	ECD [μ sec]	S/N [dB]
KOBE	671.4	-1.4	-2.0	567.9	-1.9	-8.0	643.9	1.2	0.0
TITIJIMA	145.4	3.4	11.8	893.7	2.8	-2.64	767.2	3.1	1.5
KATUURA	621.0	0.2	3.5	430.1	0.4	4.4	839.2	1.4	-1.6
HEKURAJIMA	812.2	2.0	-5.7	374.8	0.2	4.8	842.2	2.1	-4.1

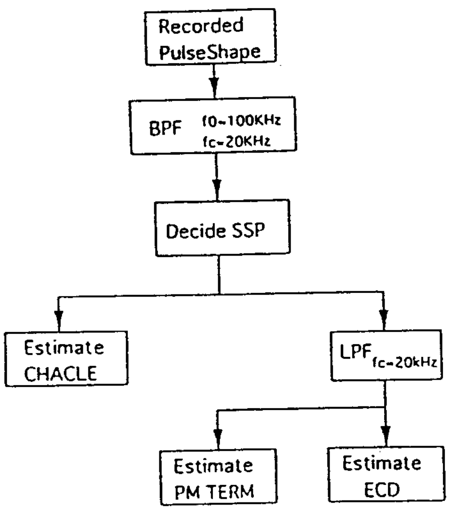

Figure 3: Softweare Block Diagram

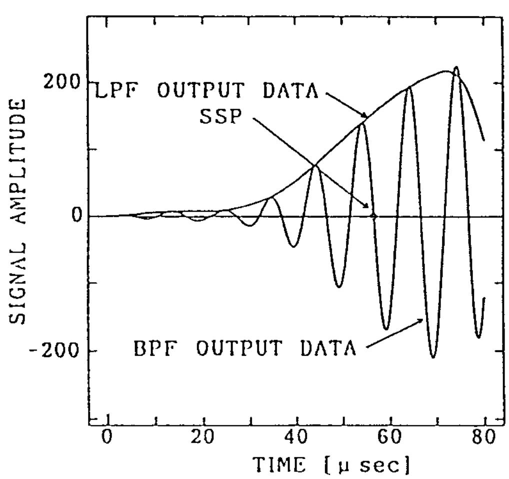

Figure 4: BPF and LPF Filtered Wave Shape

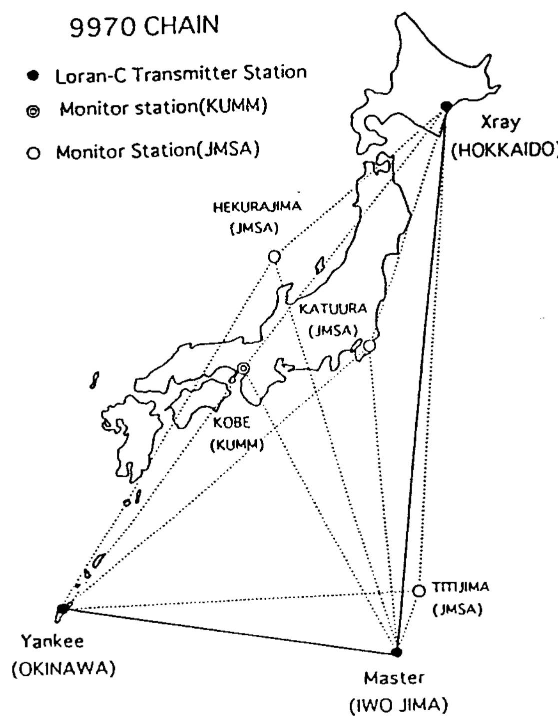

Figure 5: Transmitter and Monitor Configulation

at Kobe(KUMM). At three other JMSA Loran-C monitoring stations, ECD, SNR and other characteristics were measured of the transmitted signals from all stations in 9970 chain.
On the 9th through the 13th of August, the master's pulse was measured at KUMM ,while at JMSA stations the above characteristics of the pulse signals from all stations were measured. On August 25 through 31, the pulse shape from Y station was measured at KUMM and so was the one from X station on September 6 through 9.

3.2 SSP

As was mentioned in the section before, SSP was determined for the pulse signal after being processed by bandpass filter. Figure 6 through Figure 8, each shows the variation of SSP and its distribution for master, X and Y station pulses, respectively. Table 1 is the analyzed results on the recorded pulses. The variance of SSP for the master pulse is smaller than the ones for the others because a trigger signal for A/D converter is made synchronous to the master pulse SSP; Hence the variance of SSP for the master depends heavily on the accuracy of a receiver clock. So it is expected that the variation of SSP for the master pulse can be made smaller when the receiver has more stable clock and the number of accumulation is increased. Consequently the repeatablity of the time measurement could be improved.
Factors that supposedly affect the magnitude of variation of SSP are the S.N.R., characteristics of the propagation path, accuracy of the transmitter and receiver clocks and etc., and the variation of SSP for master pulse has about 0.1 microsecond smaller than the variations of SSP for pulses from others. For the more accurate SSP and wave shape measurement, it is found essential to have trigger signals synchronized with each transmitted pulse signals.

3.3 ECD

An example of the experimental results on ECD for the master pulse received in different places is shown in Figure 9. One was estimated at KOBE and the others were observed at JMSA monitors. This figure shows that the ones observed at JMSA monitors are more stable than the one estimated at KUMM. The reason may be the difference in the way obtaining ECD.
Figure 10 shows the estimated ECD at Kobe, and it is noted that the higher the S.N.R., the more stable the estimated ECD. The S.N.R. recovers only +27dB. From the result on ECD in Gaussian noise environment[2], more than about 30 dB is to be necessaries to suppress the standard deviation of ECD variation below 0.1 microsecond. Although there is another disturbing factor as well in addition to noise, the result on the data by averaging of 500 pulses is shown.
Figure 11 shows the relationship between the variation of ECD in five days average and the distance from transmitter to the receiver. The straight line indicates the change

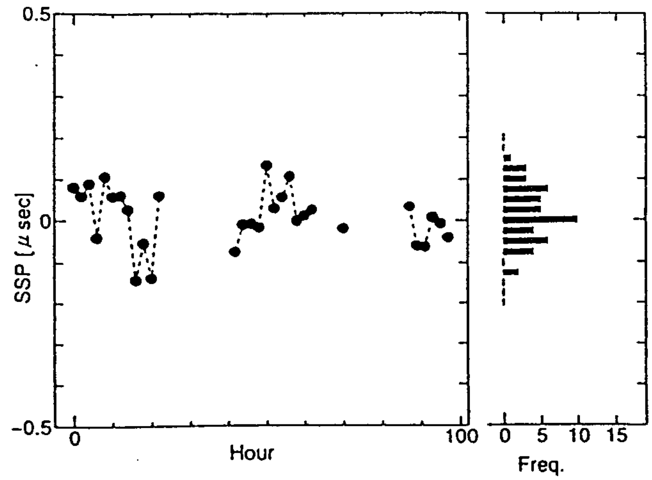

Figure 6: SSP for M Pulse

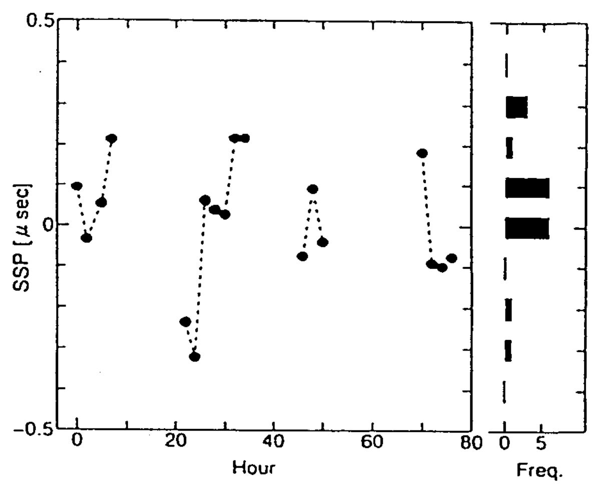

Figure 7: SSP for X Pulse

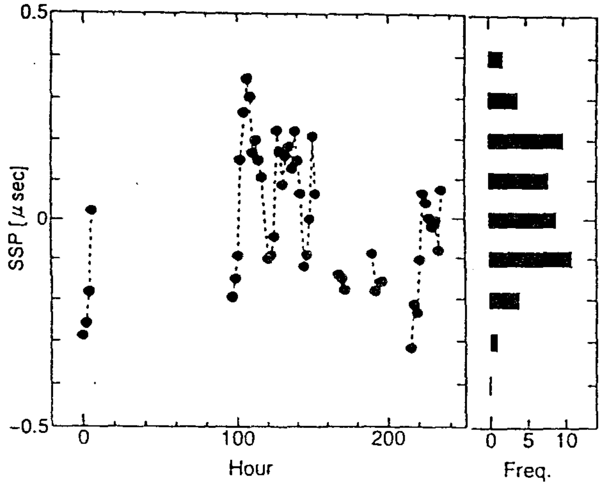

Figure 8: SSP for Y Pulse

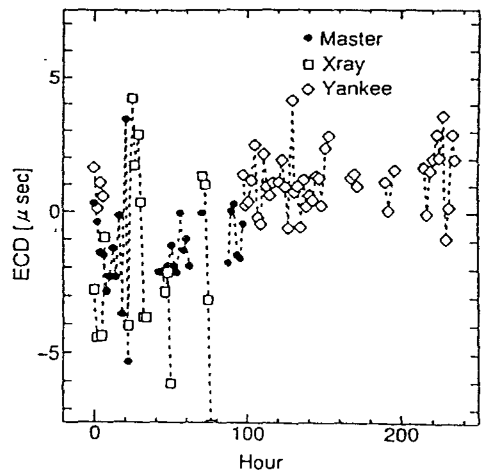

Figure 10: Variation of ECD at KOBE

of ECD with the propagation distance over the sea. Each propagation path to TITIJIMA from M, X and Y station is over the sea water only and the paths to the other receiving locations include the path over land. The effect by over-land path was not clear from this result only. Since TITIJIMA is close to the master station, it is considered probable that the signal data received in TITIJIMA is affected by the radiation of the master station.

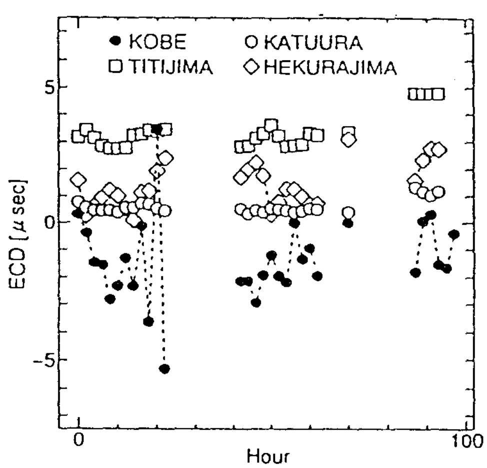

Figure 9: Variation of M ECD

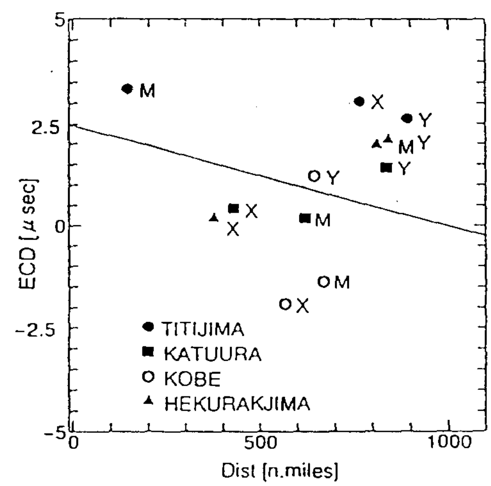

Figure 11: ECD vs. Propagated Distance

3.4 CORRELATION between CHACLE and PM TERM

To improve the ASF correction, the better pulse distortion measure should be introduced. Taking into account the linearlity of the modulation effect during the propagation, phase modulation is considered to be better than amplitude modulation. So we had already proposed the phase modulation measure named CHACLE, but CHACLE is not easy to measure because a variation of the CHACLE is smaller than ECD. Loran-C receiver in our use has 20 MHz clock; an accuracy of only 50 nsec, on which acquisition timing of the pulse depends. Consequently CHACLE is to be measured only within this 50 nsec accuracy. The pulse distortion measure CHACLE at KOBE is estimated and shown in Fig.12. PM TERM which has the same effect of a phase modulation was estimated and the result is shown in conjunction with CHACLE in Fig.12. Figure 13 shows strong correlation between CHACLE and PM TERM.

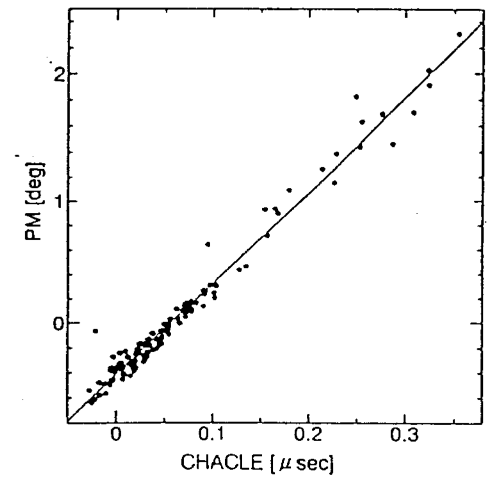

Figure 13: Correlation between CHACLE and PM TERM

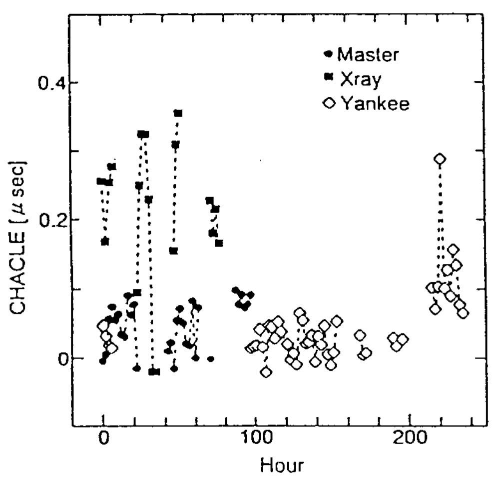

Figure 12: Variation of CHACLE at Kobe

4 CONCLUSIONS

This paper shows the experiment on pulse distortion measures done by the proposed measurement system and its result as well. In this experiment the received pulse was accumulated and then filtered by BPF of bandwidth wide enough for the pulse signal of 9970 North West Pacific Chain. Wide-bandwidth BPF has advantage of giving little distortion to filtered signal and its disadvantage is a low noise immunity. To secure correct pulse shape, therefore, the BPF was made to accommodate wide bandwidth and accurate phase linearlity and the pulse was accumulated in large quantity to cope with noise immunity. How the resulted pulse fluctuates with the number of pulse accumulated was not checked but 500 was selected as the number for accumulation taking into account the expected signal and noise enhancement and 20 kHz as BPF bandwidth.

Pulse shape measurement system we introduced proved to be useful and practical for ASF correction purpose but only in limited terms at present. This however can be a first step forward to our final goal. In the immediate future this measurement system is to be improved for more accuracy, and with further experiments the relationship between ASF effect and pulse distortion measure is to be applicable to ASF correction hopefully.

ACKNOWLEDGMENTS

The author wish to express my thakfullness to Prof. Yuichi MIYOSHI of KOBE Univ. of Mercantile Marine for many helpful suggestions and to a group of the Radio Aids Division of JMAS for providing monitor data.

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General Assembly

Adopted Resolution

International Loran Association

(formerly the Wild Goose Association)

23rd Annual Convention and Technical Symposium

The theme of the 23rd Annual Convention and Technical Symposium held in Newport, Rhode Island, USA on November 1-3, 1994 was "The Role of Loran in a Global Navigation World". After considering the presentations, panel debate and informal discussions that took place, the Association adopted the following Resolution:

Resolution

Recognizing:

1. That the United States Department of Defense is withdrawing its overseas Loran-C commitments effective December 31, 1994; and

2. The United States Department of Transportation and the United States Coast Guard are considering the cessation of Loran-C operation in the USA, under budgetary pressure to reduce expenditure;

And noting:

1. That with the encouragement of the United States, other international administrations have assumed responsibility for maintaining and increasing Loran-C/Chayka coverage worldwide,

2. That many administrations have, or are developing radionavigation plans which include Loran-C and Chayka in their radionavigation mix of systems; and

3. That the Loran-C system is cost effective when used either as a stand-alone system, or in conjunction with satellite systems, while providing many other benefits;

Bearing in mind:

1. That there are in excess of one million Loran-C users in the aviation, marine and land navigation communities, and

2. That Loran-C is employed in critical timing and synchronization applications and is the backbone of timing for many telecommunication networks within the United States;

Resolves:

1. That the United States Department of Transportation be urged to endorse a policy for providing a mix of dissimilar wide-area terrestrial and satellite positioning systems, and

2. That Loran-C operation be continued as the major component of this mix.

Recommends:

That this resolution be brought to the attention of the Department of Transportation, Assistant Secretary for Radionavigation Plans and distributed to administrations worldwide which are responsible for radionavigation plans, policy and implementation.

Awards

Datamarine
PRECISION MARINE INSTRUMENTS

TO: WGA Board of Directors
FROM: Frank Cassidy
DATE: October 28, 1994
SUBJ: 1994 Awards Committee Report

Awards Committee: Frank Cassidy, Chairman
Jim Carroll
Vern Johnson

Awards Summary:

A) Medal of Merit: Contribution of exceptional nature, awarded to a person or persons
Engraved medallion on white and blue ribbon with framed citation signed by the President

B) Best Paper Award: On any aspect of loran, awarded to a person or persons:
i) A WGA member or non-member in a WGA publication
ii) A WGA member in any other publication
Trophy with engraved plaque

C) Student Paper Award: On any aspect of loran, awarded to a student or students
Framed certificate signed by the Awards Chairman

D) Service Award: Awarded to persons who distinguish themselves in the service of the WGA
Framed certificate signed by the Awards Chairman

E) President's Award: Awarded to person(s) or an organization as designated by the WGA President, consent of the Board of Directors is required
Engraved brass plaque

1994 Award Winners: Citations and Certificates attached

DATAMARINE INTERNATIONAL, INC. 53 PORTSIDE DRIVE, POCASSET, MA USA 02559-1030
(508) 563-7151 FAX (508) 564-4707

Awards Chairman **Frank Cassidy** (Datamarine)
prepares to introduce this year's winners.

A difficult task, exceptionally well done, Frank.

Best Loran Paper Awards

"A Statistical Evaluation of the Effects of CW Interference on the Performance of Loran-C Receivers"

Dr. David Last with Dr. Yi Bian

"High Efficiency Loran-C Interference Spectrum Analysis By Synchronous Sampling"

Dr. Yi Bian with Dr. David Last

Dr. Last accepts the awards on behalf of his co-author.

Best Student Paper Awards

"Optimum Loran-C Signal Processing: First Experimental Results"

Richard D. J. van Nee

Delft University of Technology

"Optimum Loran-C Signal Processing: First Experimental Results"

Hein J. Andersen

Delft University of Technology

President ***Dale Johnson*** *presents the awards.*

The Wild Goose Association
Medal of Merit

presented to

Edward L. McGann

For his tenacity and tireless effort in the establishment and continued support of Loran-C as the primary United States radionavigation system and its adoption worldwide.

In the early 1970s he made a substantial contribution to the campaign to establish Loran-C as the system of choice for the United States' Coastal Confluence Zone. For more than two decades his regular presence in government offices in Washington has provided a constant reminder to Congressmen and policy makers of the technical advantages and cost effective benefits of the Loran-C asset created by its adoption in 1974. As a frequent traveller to many States of the world he has carried this message with perseverance and patience, many times confronted with State political change and uncertainty.

Holding managerial positions with Megapulse, Inc., he has been, and remains an ardent supporter of Loran-C and commercial variations of the system. Through some difficult times and with personal sacrifice, his efforts have contributed significantly to the extensive worldwide Loran-C coverage that exists today.

Presented this Second day of November, 1994

Dale Johnson, President

The Wild Goose Association
Medal of Merit

presented to

William F. Roland

For his many technical and managerial contributions to the establishment of Loran-C as a primary worldwide radionavigation system while serving with the United States Coast Guard and in private industry.

During his service with the Coast Guard he made significant original technical contributions to Loran-C technology, including work on the optimal selection of Group Repetition Intervals to minimize cross-rate interference. In the early 1970s he was an active participant in developing the case for the selection of Loran-C as the radionavigation system of choice for the United States' Coastal Confluence Zone and was a key member of the WGA committee formed to develop the Loran-C system characterization. As the Coast Guard's technical representative he was responsible for the contracts to develop the solid state transmitter and the first low-cost Loran-C receiver.

Following retirement from the Coast Guard, and as President of Megapulse, Inc. he is providing technical and managerial guidance to the company's Loran-C programs and contributes to the WGA Committee for a Balanced Radionavigation Policy.

Presented this Second day of November, 1994

Dale Johnson, President

Wild Goose Association

President's Award

Presented to

John M. Beukers

For tireless dedication and outstanding achievement in promoting Loran as an international navigation system

November 2, 1994

Wild Goose Association

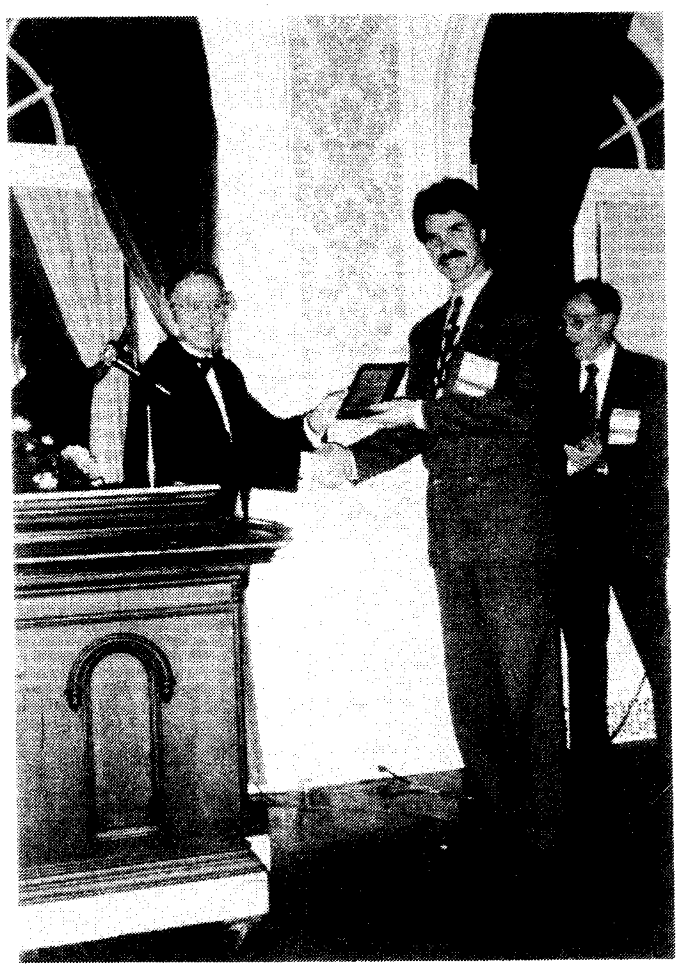
President's Award

Presented to

G. Linn Roth

For outstanding work in leading the drive to petition Congress and the Department of Transportation to keep Loran in operation as a valuable navigation asset

November 2, 1994



Wild Goose Association

President's Award

Presented to

George Quinn

For long years of dedication, support and technical contributions to Loran in the National Airspace System

November 2, 1994

1994 WGA Service Awards

John Illgen

as Chairman of the 1993 Annual Meeting

James Alexander

as Co-Chairman of the 1993 Annual Meeting

Dr. David Last

as International Co-Chairman of the 1993 Annual Meeting

Walt Dean

as the Chairman of the 1993 Technical Symposium

Dr. Durk van Willigen

as the Co-Chairman of the 1993 Technical Symposium

James P. van Etten

as Chairman of the Awards Committee

Norman Matthews

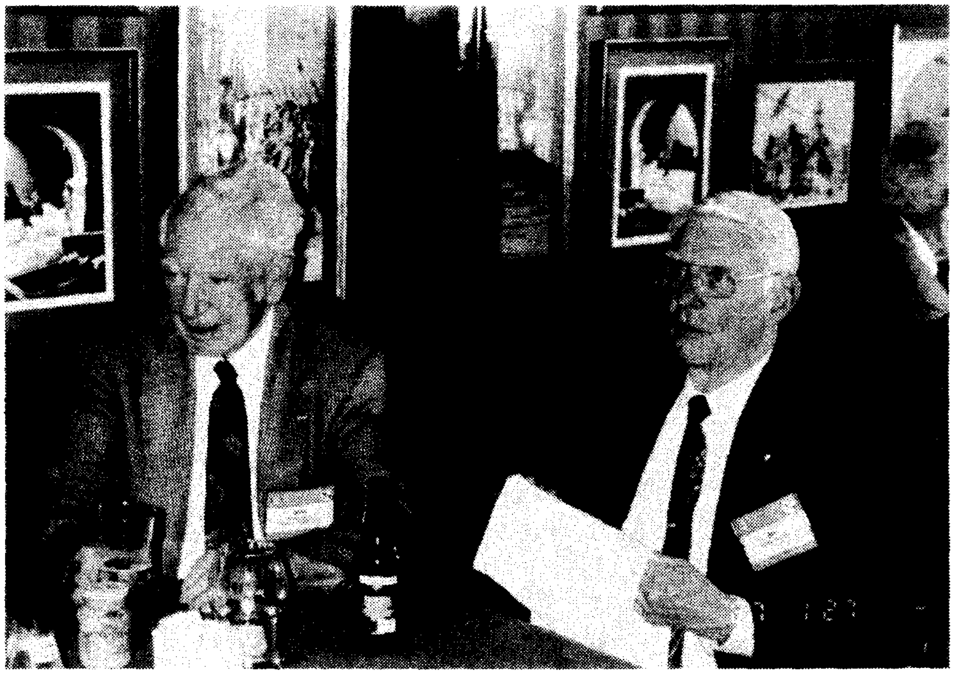
for his continued support for Loran on the international scene

Social Events

Conference general chairman
Bahar Uttam opens the festivities
at the annual banquet

A relaxed moment during the convention for technical chairman Dave Amos and guest Debbie Bellemore.

The lovely colonial-style ballroom at the Viking Hotel was the site of the annual banquet. Good company and excellent food...



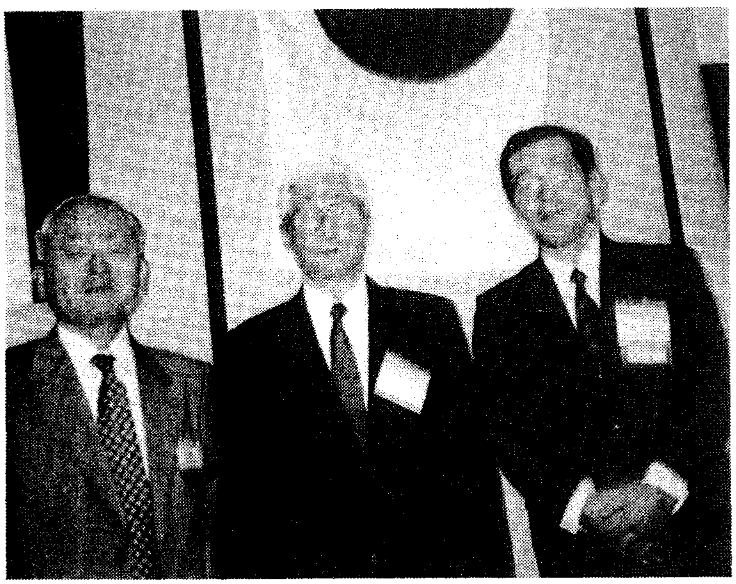
Walt Dean and Jim van Etten enjoy a luncheon gathering in the pub room of the Viking Hotel

Dave Watkins and Tommy Thomas get ready at the speakers' breakfast.

Bill O'Halloran, Bahar Uttam, Karen Van Dyke and Ed McGann with a photo opportunity during a break.

More socializing (and maybe a *little* shop talk)!

A good time is had by geese ...
... ganders ... oh, well ...



Medal of Merit winners, international participation, Bill Polhemus and friends; they're all part of a successful WGA meeting!

The Wild Goose Association
P.O. Box 556
Bedford, Massachusetts 01730