THE WILD GOOSE ASSOCIATION

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Reference #__________

The International Loran Radionavigation Forum

Proceedings of the Twentieth Annual Technical Symposium

October 1 - October 3, 1991
Williamsburg, Virginia

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The International Loran Radionavigation Forum

Twentieth Annual Convention and Technical Symposium

October 1 - October 3, 1991
Fort Magruder Inn and Conference Center
Williamsburg, Virginia

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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. Named after the majestic bird that navigates thousands of miles with unerring accuracy, the Canada Goose, the WGA was organized in 1972. Its membership includes professional engineers, program managers, scientists and operational personnel from all segments of government, industry, academic and research institutions, and the loran user community throughout the world.

Table of Contents

Foreword

This was the Twentieth Anniversary of the Wild Goose Association, and it was fitting that this Technical Symposium reflected the growth of the Association and our loran community throughout the world. It came at a time in history when there were both severe economic recession and threats of war present, but also at a time when there were never before imagined such changes in social and political structure.

In the background were the reversal by the United Kingdom on its decision to participate in the Northwest European Loran-C System, new expansion of Loran-C in the Far East, and the recent dedication of the U.S. mid-continent chains. The good news seemed to outweigh the bad, however, and a better perspective developed on the situation as we heard the technical presentations and talked informally with one another. Indeed, the theme of the meeting, "Bridging the Gap", was being worked out. We saw how Loran-C was used in Operation Desert Storm to supplement the Global Positioning System (GPS) coverage and in precessing aircraft inertial navigation systems, in an area devoid of landmarks. It was also evident, by new faces in the crowd, that the automatic vehicle location (AVL) industry has a renewed interest in Loran-C due its ability to work where GPS will not. We were disappointed, however, that the Soviet delegation and several other overseas visitors that had been with us in Long Beach in 1990 were unable to join us this year in Williamsburg.

Dr. Frank Tung of the Volpe National Transportation Systems Center set the theme for the Symposium with his Keynote Address. It was heartwarming to see the significant attendance by the U.S. Coast Guard personnel who actually operate the loran system for us, and was most appropriate that Rear Admiral Ecker was able to address us during the first luncheon. Phil Boyer, President of the Aircraft Owners and Pilots Association (AOPA), did an excellent job in giving us his personal insight on the importance on having Loran-C in the cockpit.

Special thanks go to all of our authors for the excellent technical program. We also thank the sponsors who made possible our well-stocked Hospitality Suite, and the exhibitors, coordinated by William Parks of NavCom, who displayed some of the newest loran technology. Bob Frank and his committee did a commendable job developing the awards which were such an important part of the Banquet. Of course the Symposium would not have been possible without the significant corporate support of NavCom Systems, Inc. and its President and CEO, Elijah "Zeke" Jackson. Mrs. Mary Jackson, NavCom's Vice President and a very busy lady, personally organized the company's staff support and directed the Spouse's Program. This was the first time we used the convention services of NavTech Seminars. Carolyn McDonald, President, made sure all wheels ran smoothly and took the pressure off the convention organizers. Ruth Scull played her usual backup role, keeping her husband on track as well as being responsible for much of the early planning and organization.

This year we changed WGA Presidents. Captain Jim Culbertson, USCG (Ret.), has done an excellent job leading the Association over the past two years. Both of us have known Jim both in this capacity as well as professionally and know he will be missed. Dr. Bob Lilley, our newly elected President, is well known to the Loran-C community. Bob has served admirably the past three years as Editor of the Goose Gazette.

Next year we will be traveling to Birmingham, England for the 21st Technical Symposium, August 23-26, 1992. We are looking forward to seeing you in Europe.

Dave Scull **Dave Olsen**

Guest Speakers

Keynote Address
Tuesday, October 1

Dr. Frank C. Tung
Deputy Director
Volpe National Transportation Systems Center
55 Broadway, Kendall Square
Cambridge, MA 02142

Luncheon Speaker
Tuesday, October 1

Rear Admiral William J. Ecker
Chief, Office of Navigation Safety
and Waterway Services
U.S. Coast Guard Headquarters
2100 2nd Street, S.W.
Washington, DC 20593

Banquet Speaker
Wednesday, October 2

Phillip P. Boyer
President
Aircraft Owners and Pilots Association
421 Aviation Way
Frederick, MD 21701

Technical Sessions and Papers

Session 1
INTERNATIONAL ACTIVITIES

Chairman: Edward L. McGann, *Megapulse, Inc.*

Session 2
GOVERNMENT ACTIVITIES

Chairman: Maurice "Mike" Moroney, *Volpe National Transportation Systems Center*

Session 3
LAND AND MARINE
TECHNOLOGY AND APPLICATIONS

Chairman: Captain Henry E. Marx, *Landfall Navigation*

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[1]*The author was unable to attend the Symposium. Paper was synopsized by the session chairman.*
[2]*Unavailable for publication in the proceedings of the Long Beach symposium. Presented here for reference.*

Session 4
TECHNOLOGY AND SPECIAL APPLICATIONS

Chairman: David H. Amos, *Synetics*

Session 5
PROPAGATION AND SIGNAL ANALYSIS

Chairman: Dr. Robert H. Miller, *II Morrow, Inc.*

Session 6
AVIATION TECHNOLOGY AND APPLICATIONS

Chairman: Chester "Chic" Longman, *Air Navigation Consulting*

[1]*Manuscript not available. Dr. Miller summarized activities and showed a short video.*

Session 1
INTERNATIONAL ACTIVITIES

Chairman: Edward L. McGann, *Megapulse, Inc.*

Ed has been involved with Loran-C since the mid-1960's. He has presented a number of papers on the subject and has worked on the design of various Loran-C equipment and the implementation of Loran-C systems in many parts of the world. Expansion of Loran-C world-wide has been his continuous goal.

Ed is currently Executive Vice President of Megapulse in Bedford, Massachusetts. He is a Director and former Vice President of the Wild Goose Association and received the President's award for service to Loran-C. He is a member of the Institute of Navigation and was a committee member on the National Ocean Industries Association. Ed holds a Bachelors and Masters degree in Electrical Engineering from the University of Lowell in Massachusetts.

Papers

[1]*The author was unable to attend the Symposium. Paper was synopsized by the session chairman.*
[2]*Mr. Funtikov's remarks were unavailable for publication in the proceedings of the Long Beach symposium and are presented here for reference.*

LORAN-C FOR MARITIME USE
THE CURRENT WORLD WIDE SITUATION

N.F. Matthews, Secretary General

International Association of Lighthouse Authorities (IALA)

Abstract

The paper describes the progress being made World Wide in the introduction of Loran-C and Chayka.

In particular the possible consequences of the withdrawal of the UK from the NW European Group are discussed.

The progress of the Far East Group - USSR, China, Japan and Republic of Korea - is highlighted.

N.W. EUROPE

As most people will be aware, the planned Loran-C coverage of NW Europe waters had reached a final stage of negotiations when the UK Minister of Transport finally decided to retain the Decca system for marine navigation in UK waters after 1997.

This latest pronouncement completely reverses an earlier decision made in April 1990 to adopt Loran as a part of a joint regional system of marine radionavigation for North West Europe and the North Atlantic for which the UK had been successfully negotiating with eight other countries - Canada, Denmark, France, Germany, Iceland, Ireland, the Netherlands and Norway - for an International Agreement to run a common Loran system providing coverage of the area.

This sudden and unexpected withdrawal of the UK from the North West European Loran-C Policy Group without any adequate prior notification dismayed the international members of the policy group with whom the UK had been in negotiation over a long period of time.

Most opinion considers that the decision to retain Decca is operationally and technically flawed. It is most certainly not in the best long term interests of land, sea or air navigation.

In the very short term there are some minor benefits resulting from the decision to retain Decca after 1997. It avoids the cost of users having to replace existing Decca equipment. However, most Decca sets in use today would probably require replacement before 1997 in any event.

The adoption of Loran as the future back-up aid in Europe would give a new lease of life to equipment manufacturers and a high degree of equipment standardisation. Additionally, it will give the obvious advantages of increased range, a wider range of land, sea and air use and of providing a regionally based and independently controlled system.

The decision to retain Decca raises several doubts. Whilst appreciating the financial aspects are important, finance is not the sole or most important criterion. It is nevertheless extremely disturbing to see that overall costs played such a significant and biased part in the decision making process.

Also of significance were the vested interests, extensive lobbying, and various emotive issues presented in the press (frequently totally inaccurate), by the fishing and manufacturing groups in particular.

What is going to happen now ?

Well the other countries involved have begun to study whether they can go it alone, and whether the financial conribution due from the UK can somehow be absorbed.

This matter will be dealt with in a subsequent paper.

Now for better news.

The Far East

The author has recently returned from Japan where he chaired the 2nd meeting of the "Far East Loran-C/Chayka" Group, known as FELT, from 14th-10th September 1991.

The FELT Group comprises Japan, China, Korea and the Soviet Union and the first meeting was in Moscow in March 1991. Great progress was made towards an agreement to run cooperative chains in Chayka and Loran-C throughout the area.

The principal reason for this progress was that the four nations that came to the meeting wanted to agree. The second meeting in Tokyo enabled most of the technical problems to be solved leaving only some details outstanding for the next meeting.

With regard to coverage, it was agreed that this would be dealt with in two stages. The first stage (see Fig.1) is the coverage of the area enclosed within the solid line by 5 chains.

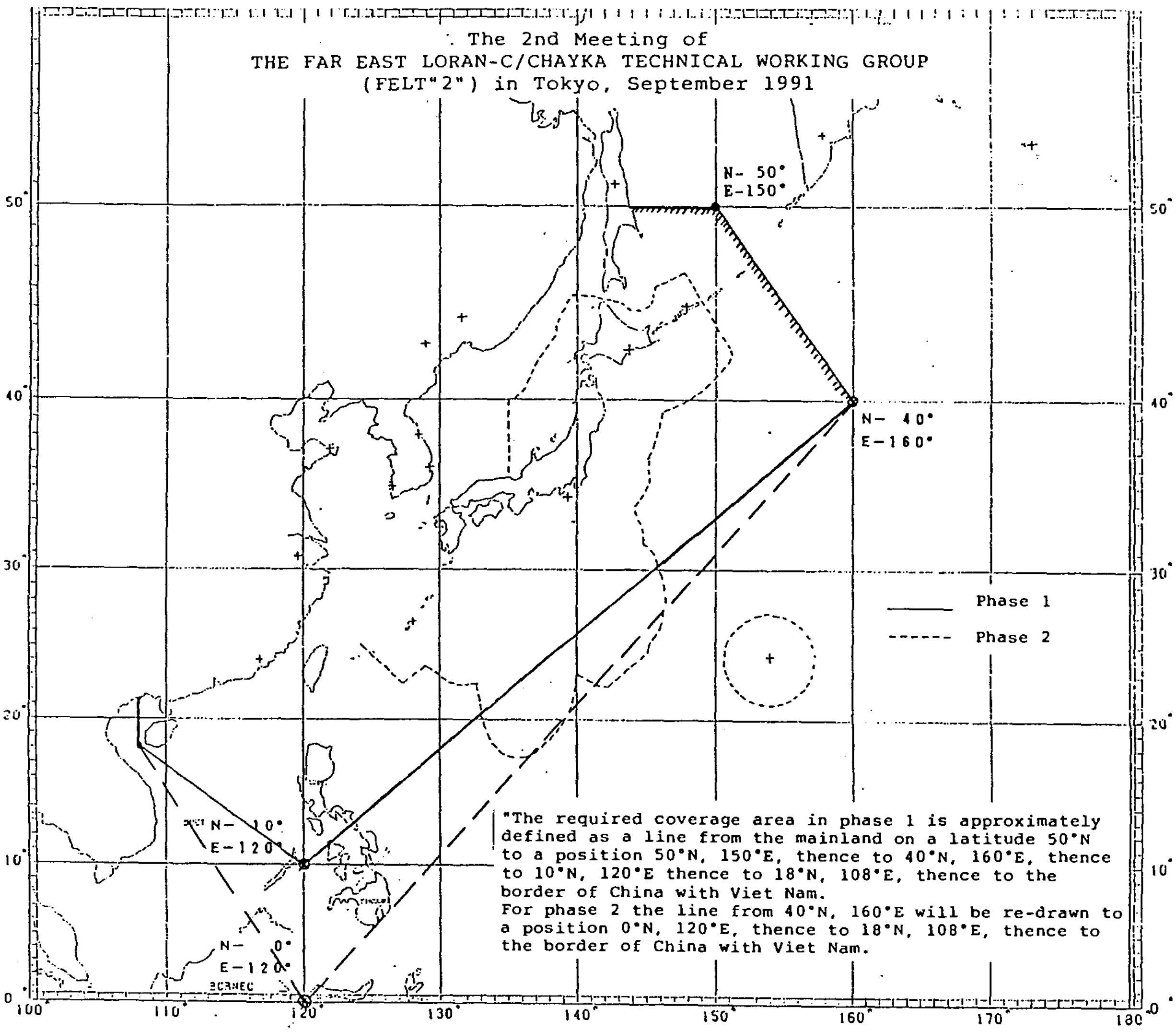


Fig. 1 - Definition of required area of coverage

The second stage inside the dotted line will require a further chain maybe in cooperation with the Philippines. Japan wants this additional area so that their entire Economic Zone is completely covered.

The target completion date for Phase 1 is 1st January 1995.

At some future stage, consideration may be given to attempting to interest Indonesia, as Japanese shipping is greatly concerned about navigational safety in the Malacca Straits.

The Agreement worked out is quite neat inasmuch as each of the four concerned countries will have at least 1 master station on its own soil, and each chain will have stations in at least 2 countries. A truly cooperative effort (see Fig. 2).

The Japanese Government is currently in negotiation with the US Government concerning host nation operation and the terms on which the stations operated by the US Coast Guard can be handed over.

STATION (NATION)	LOCATION WGS-84	POWER (kW) RATE #1	POWER (kW) RATE #2	CHAINS B	C	D	E	F	G	REMARK
Petropavlovsk (USSR)	E157° 41' 42.90 " N 53° 07' 47.50 "			○						◎ : MASTER ○ : SECONDARY
Alexandrovsk (USSR)	E142° 42' 04.95 " N 51° 04' 42.80 "			◎						
Okhotsk (USSR)	E143° 05' 22.90 " N 59° 25' 02.00 "			○						
Ussuriisk (USSR)	E131° 38' 23.40 " N 44° 31' 59.70 "			○	○					
Hokkaido (JAPAN)	E143° 43' 09.799" N 42° 44' 37.217"			○		○				
Nii-Jima (JAPAN)	E139° 16' N 34° 24'				○	◎				
Marcus Island(JAPAN)	E153° 58' 53.786" N 24° 17' 08.026"					○				
Gesashi (JAPAN)	E128° 08' 56.999" N 26° 36' 25.110"				○	○				
Pohang (R O K)	E129° 20' 27.833" N 36° 11' 05.921"				◎	○				
Kwangju (R O K)	E126° 32' 27.295" N 35° 02' 23.996"				○		○	○		○
Helong (CHINA)	E129° 14' N 42° 35'						○			China to select whether Kwangju is in chain E or chain F
Rongcheng (CHINA)	E122° 28' N 37° 12'						◎	○		
Xuancheng (CHINA)	E118° 44' N 30° 56'						○	◎		
Raoping (CHINA)	E117° 02' N 23° 35'							○	○	
Hexian (CHINA)	E111° 43' N 23° 58'								◎	
Chongzuo (CHINA)	E116° 53' N 23° 43'								○	

Fig. 2 - Plan of chain configuration

With regard to the timing standard for the chains it was agreed that :

1. The master stations of all chains to be synchronized to within $\pm$ 2.5 μs of UTC, by 1st January 1995;

2. Experience gained in operating the chains should permit the tolerance to be reduced to $\pm$ 0.2 μs, in the longer term.

It was also agreed that :

3. In principle, System Area Monitoring (SAM) should be used as the means of ensuring that the tolerances of the transmitters are maintained;

4. An out of tolerance baseline will be indicated to users by "blinking". In this regard the USSR undertook to study introduction of "blink" to the Chayka stations of Chain B;

5. The Agencies providing the master station of a chain will be responsible for preparing detailed plans of the control and communication arrangements proposed for the chain in time for the meeting in May 1992.

As regards geodetic datum it was recognized that although the nautical charts of the different countries were based on different geodetic datums, there was a need for all the stations in the radionavigation service to use a common reference datum, from which corrections for any other datum could be derived, if necessary.

It was therefore agreed that :

6. The positions of all transmitters would be defined in WGS 84 coordinates;

7. The positions of some, or all, of the transmitters may also be described in the coordinates of local geodetic datums, such as the Krasovskiy (1942) datum, WGS 72, the Tokyo datum or others as required by administrations.

Concurrently with the technical discussions, FELT 2 developed an Agreement to be signed by all parties.

To avoid political problems and long delays, it was decided that the Agreement should be an inter agency Agreement rather than an Agreement between Governments, that is to say :

Maritime Safety Agency	for Japan
Korea Maritime and Port Administration	for Rep.of Korea
Internavigation Committee	for USSR
Aids to Navigation Division, Ministry of Communications	for China.

To avoid many of the pittfalls that faced NW Europe in its cost sharing agreement, it was decided that each administration would bear all the costs pertaining to transmitters on their soil.

To ensure the smooth running of the operation, a Council will be established comprising one member from each of the four Administrations. The Council will meet once a year and the language of the Council will be English. Each Councillor will be responsible for his or her travelling expenses, and the Chairmanship of the Council will be rotated among the 4 members.

The Chair will be responsible for organising and hosting the next meeting and will be responsible for any incidental expenses during the one year term of office.

Finally it was decided that as it is an inter agency Agreement, IALA would act as the depositary organisation.

The next meeting, FELT 3, will be held at IALA Headquarters in May 1992 when it is hoped that all outstanding matters will be cleared up.

It is planned that the Agreement will be formally signed by the four countries in September 1992 in Moscow.

The Far East situation has been dealt with at some length for the reason that it can be considered as a model of international cooperation in the radionavigation field. It involves four countries with very different backgrounds. It poses some difficult technical questions, financial problems and political problems.

All these matters were sorted out because the four Administrations concerned really wanted to cooperate with one another for the benefit of the International Maritime Community.

At this point, a special word of thanks to the US Coast Guard is appropriate. A number of officers gave unsparingly of their time and effort to help in the solution of many of these problems, and the countries concerned and IALA owe them a debt of gratitude.

The Mediterranean and the Iberian Peninsula

The existing US Coast Guard Mediterranean Chain comprises 4 stations, one in Spain, two in Italy and one in Turkey.

Discussions up to now have been greatly hampered as it had not proved possible to interest Turkey in maintaining the Kargaburun station after the US withdrawal at the end of 1994.

With no station in Turkey, Italy would have no coverage to the East which is in fact their main area of interest.

However, quite recently the Turkish Authorities have intimated that they have now decided to take part in the discussions so the situation is much more hopeful. The next meeting of the group is in November 1991.

The Mediterranean discussions also have another dimension as the USSR is keen to link Chayka Chains with the Mediterranean Chain to ensure coverage of the Black Sea.

At the same time, France is discussing with Spain and Portugal coverage of the entire Iberian or Spanish Peninsula by utilising its stations at Lessay and Soustons.

These discussions are proceeding well.

Other areas of Europe

Apart from the general NW European situation which is dealt with in another paper, Norway and Germany are having discussions with the USSR with a view to improving Loran-C/Chayka coverage in the Baltic and North of Norway. These bilateral and trilateral discussions are proceeding well.

The European Community is keenly interested in all these developments as the Commission can visualise complete coverage of the European area if all these plans come to fruition.

USA and Canada

All members of the Wild Goose Association are well aware that the Mid Continent Gap is now dealt with and that Loran-C can look forward to a rosy future in this area.

The US Coast Guard and the USSR Internavigation Committee are carrying out exciting joint operations following the signing of an agreement in 1988 to establish a joint Chayka/Loran-C chain in the Bering Sea. More details of this work will be found in other papers.

Canada is currently concerned by the NW European situation as it is keen to have coverage across the North Atlantic. Much depends upon the decision of Iceland as to whether this can be realised.

South America

Venezuela is carrying out serious studies as to the needs and viability of coverage in their area. IALA was approached for an opinion and they were informed that IALA policy is to pursue the furtherance of Loran-C/Chayka coverage.

South Africa

South Africa is studying the introduction of Loran-C principally for land users.

Middle East

The Saudi Chains are still in operation and are considered to be a valuable aid to navigation in Saudi waters and those of neighbouring countries.

India

The two Indian Chains are under construction and are expected to come on stream soon.

IALA POLICY

To strenghten the efforts of those seeking to implement Loran-C and Chayka the IALA Council passed a resolution at its meeting in April 1991.

This resolution reads as follows :

IALA Policy on terrestrial navigation systems

The International Association of Lighthouse Authorities :

CONVINCED that there will be a requirement for a terrestrial radionavigation system, to complement global satellite navigation systems for the foreseeable future;

CONSIDERING that to reduce costs to users and providers and to maximise the usefulness of the system, a standard terrestrial radionavigation system should be adopted where possible;

RECOGNIZING that the inter operability, long range, high availability and accuracy of the Loran-C and Chayka systems, make these the preferred systems for adoption as a standard, world wide terrestrial radionavigation system;

HAS ADOPTED A POLICY to support and encourage cooperative efforts between member nations to expand and improve Loran-C and Chayka coverage throughout the world, including the establishment of joint Loran-C/Chayka chains, wherever this is practicable.

So it can be seen that although there has been some set back in NW Europe due to the decision of the United Kingdom, elsewhere we are making slow but sure progress towards our goal of wide coverage of the world by a terrestrial based system that will be complementary to the satellite systems now being put into place.

The North West European Loran-C System
A New Update

Andreas Stenseth
Norwegian Defense Communications and
Data Services Administration (NODECA)
(Chairman, Loran-C Policy Group)

On the 19th of June this year, the Norwegian Parliament unanimously consented to Norway becoming party to the International Agreement concerning the establishment and operation of the Civil Loran-C Navigation System in North West Europe and the North Atlantic. The draft Agreement was the result of 3 to 4 years of staffing under the direction of the Loran-C Policy Group consisting of official representatives from Canada, Denmark, Germany, France, Iceland, Ireland, The Netherlands, Norway and the United Kingdom, with the U.S. Coast Guard, the International Association of Lighthouse Authorities (IALA) and the Commission of the European Communities (EEC) as active observers.

The next day — the 20th of June — we were informed by telefax from the Department of Transport in London that the UK withdrew from the Policy Group as a consequence of having chosen DECCA as their future terrestrial radionavigation system. The UK decision was taken without any prior consultations with other members of the Policy Group and disregarded the international impact of the decision.

The rest of this brief will concentrate on the consequences of the UK withdrawal, for the programme presented you at the 19th Annual Technical symposium at Long Beach, last year, and the near term activities we are engaged in to promote this programme without UK participation. The coverage diagram presented in Long Beach is shown in Figure 1.

Consultations following the UK withdrawal led to a meeting of the Loran-C Policy Group. This meeting was held in IALA's Headquarters in Paris 17-18 July. All members of the Policy Group except the UK were represented. The meeting concluded as follows:

- The Group agreed to continue the work towards a NW European Loran-C system, if necessary without UK participation. Some members were however, not in the position to commit their country at this stage.

- Alternative configurations presented at the meeting demonstrated that required coverage can be maintained without transmitter station(s) in the UK.

- It was agreed to send a letter signed by the Chairman to the Department of Transport, London, asking for a meeting with the Secretary of State for Transport offering UK reentry into the group on modified terms. Draft copy was endorsed.

- The Coordinating Agency Office (CAO) to take over the administration of the International Agreement and propose the amendments necessary to take account of the UK withdrawal. As part of this work the CAO will propose a new cost sharing formula.

- It was decided not to invite new members to the Group at this point in time; EEC, IALA and USCG continue as permanent observers.

- A Working Group was established to propose new configurations and cost them, and terms of reference were approved.

- A Work Programme for the activities leading to the signing of a revised International Agreement before January 1992, was agreed.

- The authorization for continued operation of the Coordinating Agency Offices to 1 January 92 was granted.

The Working Group established by the Policy Group met at the Delft University of Technology 20-23 August. The Group was tasked to propose new configurations without

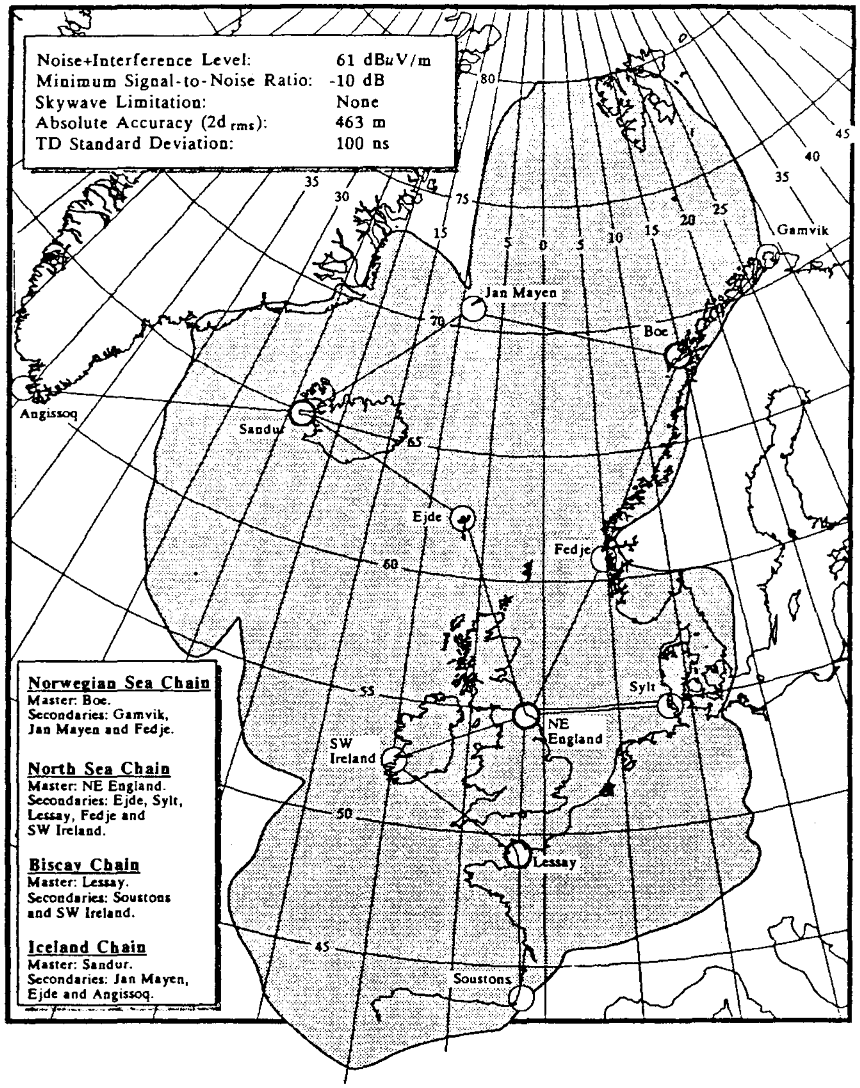


Figure 1. Coverage Diagram Presented in Long Beach

station(s) in the UK and savings which would make contributions from member nations, less UK, comparable with what they were expected to pay under the previous arrangement. Finally, the Group was asked to discuss possible modifications to parameters determining the coverage area of a given configuration. It was this last item that most dramatically changed the situation and led to solutions we should be able to live with; so let us take a closer look at what happened.

First of all you must realize that the signal-to-noise ratio which Loran-C receivers experience in Europe is generally not limited by atmospheric noise, but by carrier-wave interference. This is not accounted for in defining the coverage area in NW Europe today, with the result that present coverage diagrams give overly optimistic results.

Realizing this, the former Technical Working Group in 1990 initiated a study on the prediction of Loran-C coverage and performance. The actual job was given to the University of Wales in Bangor on contract with the Coordinating Agency Office.

In parallel, a research project was initiated in cooperation with the Delft University of Technology, taking advantage of their knowledge of continuous wave interference and their computer facilities, to find optimum Group Repetition Intervals (GRI's).

These two Universities cooperated closely, and the preliminary results were presented to the Loran-C Working Group at Delft in August. These results were used as the basis for the proposals to be recommended for consideration by the Policy Group.

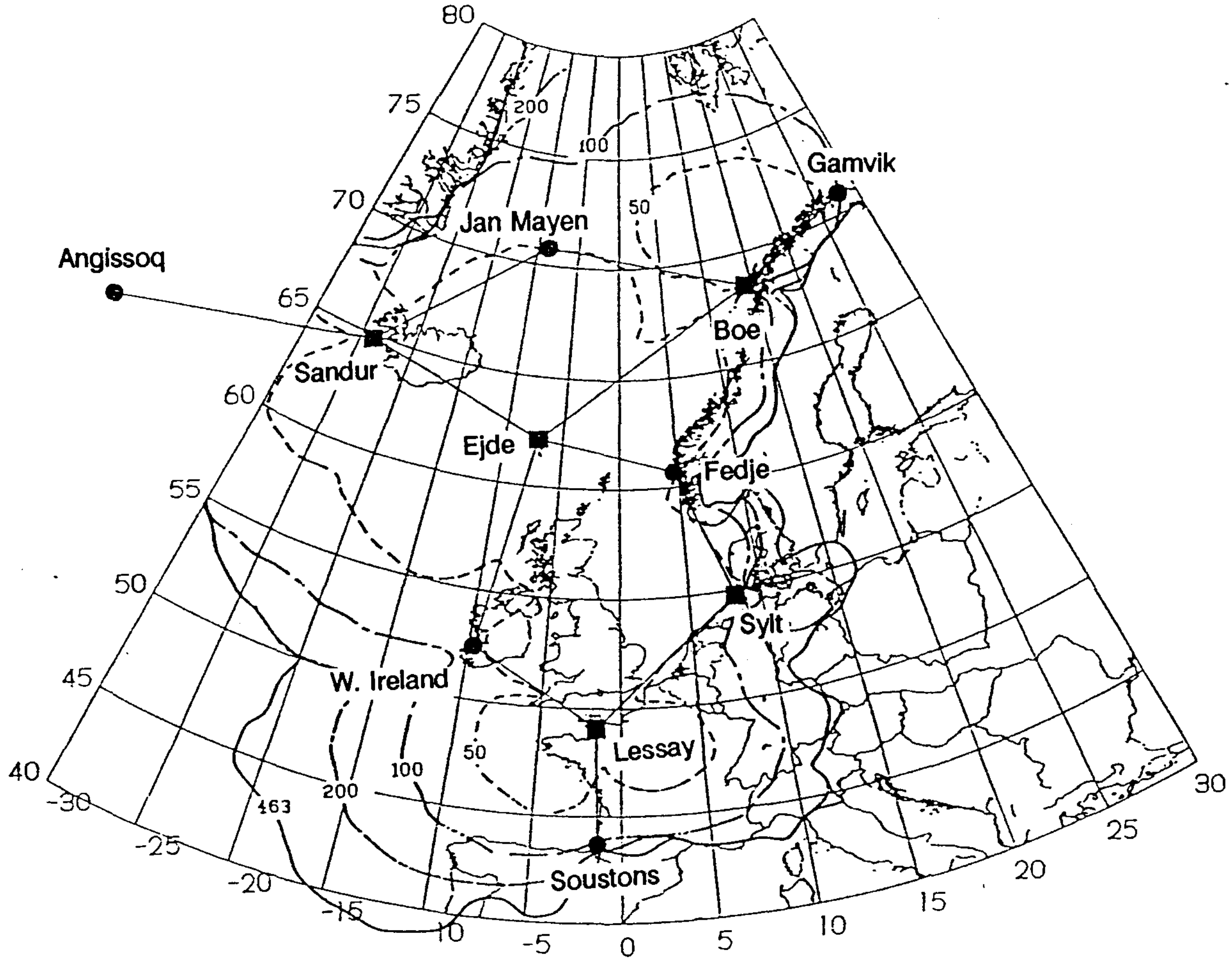


Figure 2. Coverage of Alternative 1

In the Working Group the following explanation was given:

- Previous coverage predictions have taken no account of specific interfering signals, therefore GRI selection had no effect. With the introduction of the signal-to-Interference Ratio (SIR), the GRI becomes very important because it can have a great influence on the number and severity of synchronous interferers. Thus, it is possible to select an "ideal" GRI, within certain constraints, to produce the minimum coverage limitation due to interference.

- During this discussion, one GRI was used throughout: 7777. This is a good GRI in terms of avoiding synchronous interference, but no attempt was made to select the "ideal" GRI for each chain area. This is a lengthy process and is part of a study being carried out by the University of Delft. Therefore, the SIR limits shown may be considered to be pessimistic and will be improved upon in practice.

- The use of the same GRI for all chains has no effect on coverage prediction. In reality, each chain would of course have a different GRI.

On this basis, the alternative coverage diagrams presented in Figures 2 and 3 were adopted. Actually, Alternative 1 has been improved subsequent to the Delft meeting by using a better GRI and it is the latest version which is presented here. The difference being that the station in Ireland, which in the first version was moved further north to meet Irish requirements, is back at Loop Head.

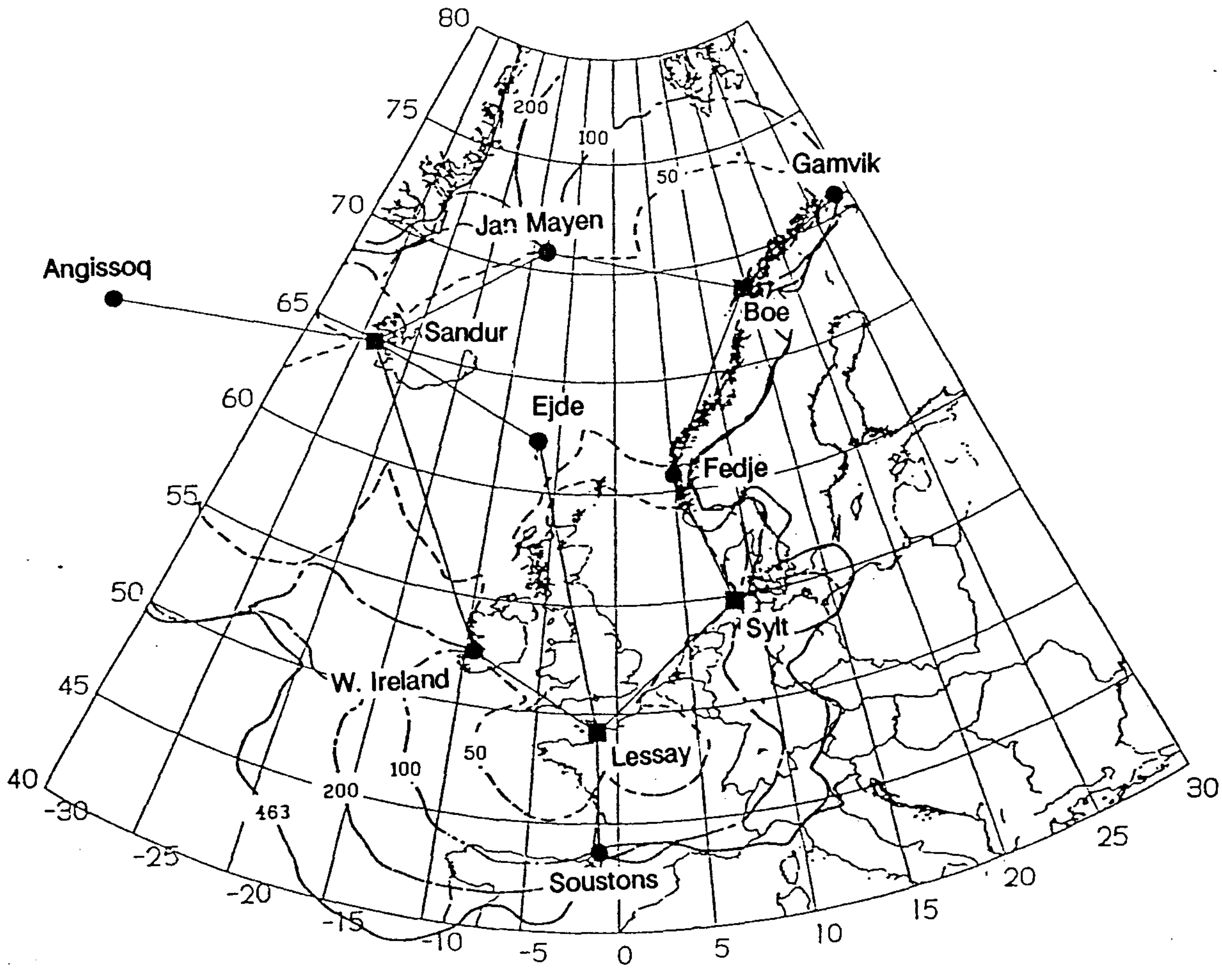


Figure 3. Coverage of Alternative 2

The conclusion so far is therefore that the loss of a transmitter station in the UK will have only marginal effect at the edge of the coverage area towards the east.

A problem which is not so easily solved, however, is the economy of the system since the UK was expected to contribute more than the cost of one station in the UK. The Working Group was therefore tasked to look at possible savings. One important element in this regard is a new technical development which makes it possible to increase power output from each Half Cycle Generator (HCG) and hence reduce the number of HCG's necessary to obtain a given output from the antenna. Further savings are proposed by reducing the number of control and maintenance centers for the entire system to one of each, in addition to a few smaller items. The gap is, however, not fully closed and it is yet to be seen if the recommended solutions and the new cost estimates will be adopted by the Policy Group and indeed by the nations involved.

To take a stand on the Working Group's proposals, the Policy Group will meet in Oslo in the late October/early November timeframe. If at that meeting a solution is recommended for further political consideration in each of the member countries, the next milestone will be the signing of an International Agreement committing all signatories to go on with the project. This will have to happen in early February 1992 at the latest to meet national requirements in some countries and to be able to take over the USCG stations in the area by 1 January 1995 which is the deadline for U.S. Loran-C engagement in NW Europe.

So much for the coverage and economy of the system.

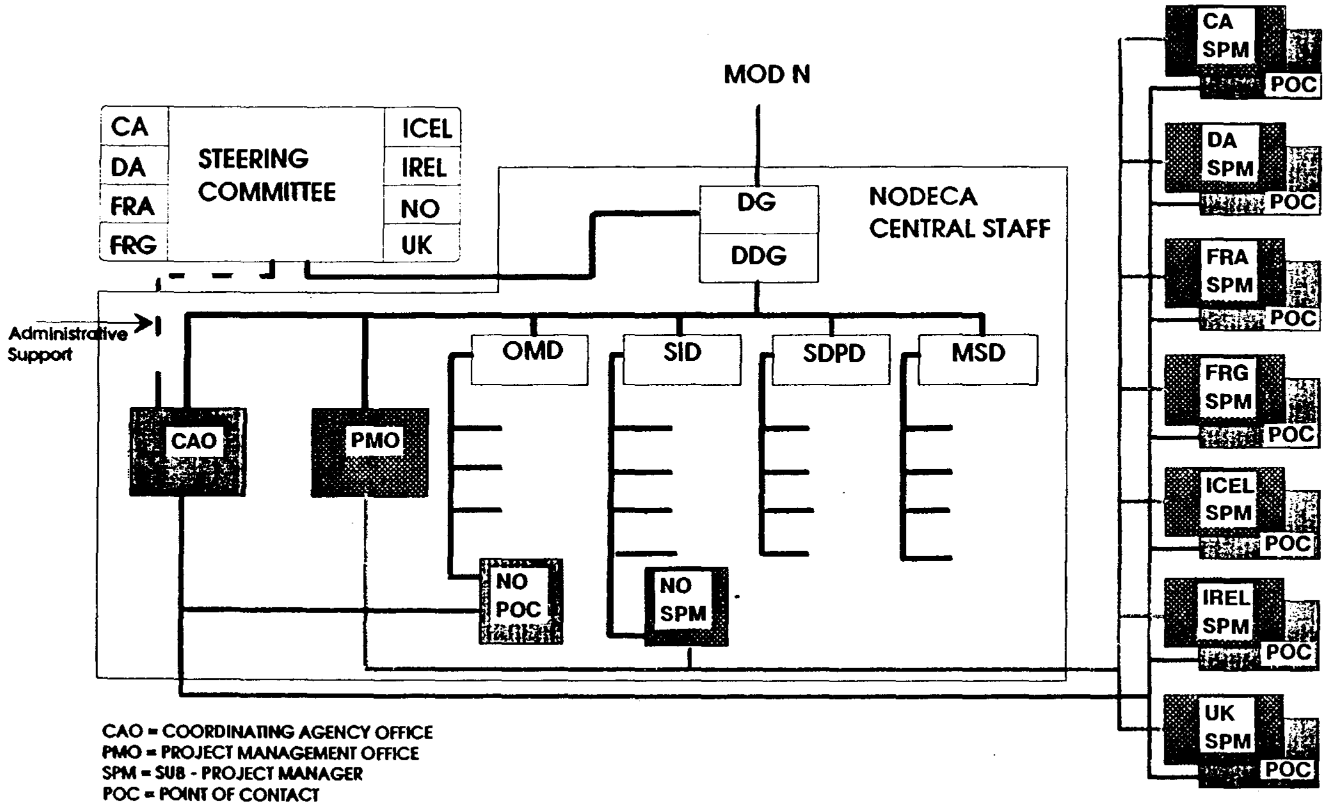


Figure 4. NW European Loran-C Organization

As a prerequisite for continued planning, the Policy Group, at its Paris meeting, also authorized the Coordinating Agency Office and the Project Management Office to continue at present level until 31 December this year. This implies that the management organization in operation at the time of the UK withdrawal is still in operation preparing for both the coming meeting of the Policy Group and for the contract negotiations with the vendors. As some of you will remember from previous briefs, the NW European Loran-C Organization is as shown in Figure 4.

In my opinion, the slow progress towards a NW European Loran-C system is partly due to the fact that GPS is approaching operational status. It is also true that the GPS syndrome has hit some countries harder than others and introduced uncertainties as to the need for Loran-C. In this regard it is very encouraging to note the development within IALA of a formal policy supporting Loran-C on a world-wide basis, has been agreed. Also, the position of the Commission of the European Communities strongly supports the Loran-C concept for the whole of Europe. Finally, the Soviet interest in cooperating with the NW European countries towards a common system based on cooperation between Loran-C and Chayka is of great importance. This is particularly important for Germany and Norway since these countries will not be able to fully cover the areas of interest within the NW European system.

There is no change in the Norwegian policy as presented at last year's symposium and recorded in the proceedings from that symposium. However, an International Agreement excluding the UK will have to be approved by the Parliament before Norway can become party to the Agreement.

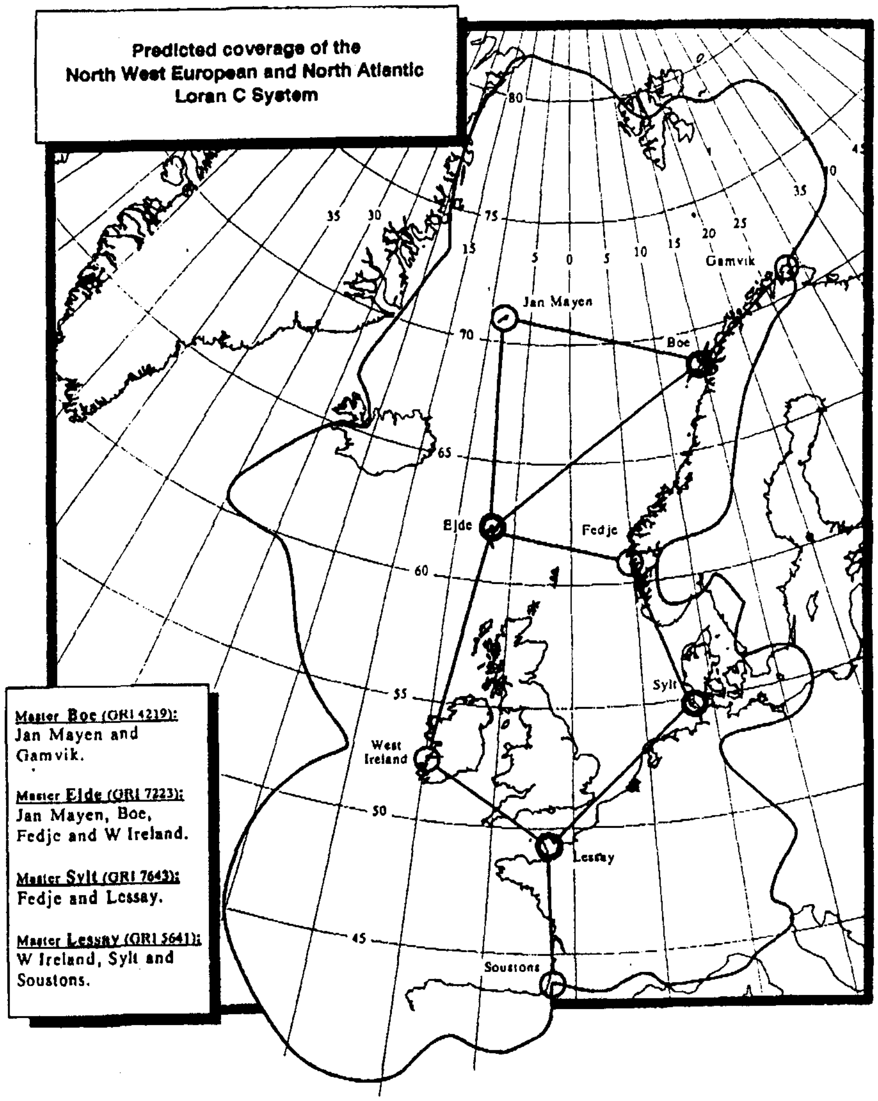


Figure 5. Coverage diagram resulting from Loran-C Policy Group meeting in Oslo, 3–5 December 1991

Addendum

The coverage diagram resulting from the Loran-C Policy Group meeting in Oslo, 3–5 December 1991, is shown in Figure 5.

ANDREAS STENSETH

Mr. Stenseth has been involved in Loran-C since the early 70's, when he was responsible for Host Nation operation of USCG-funded stations. He was Chairman of the Loran-C Working Group from 1984 to 1985, and since 1990 has been Chairman of the Loran-C Policy Group investigating the possibility of establishing a regional Loran-C system in North West Europe. Mr. Stenseth is presently holding a position as Deputy Director of NODECA.

Mr. Stenseth has a background as a Telecommunications Engineer and is a graduate of the Norwegian Institute of Business Administration.

REVIEW OF LONG-RANGE RADIONAVIGATION SYSTEMS DEVELOPMENT IN THE USSR LONG-WAVE RADIONAVIGATION SYSTEMS THE SPHERES OF EMPLOYMENT

A. G. FUNTIKOV

Modern long-range radionavigation systems went rather a long and complicated way of development. Their appearance and improvement were predetermined by significant rise in number of marine vessels and aircrafts at the beginning of the century, by increasing requirements to ensure their safe navigation, and also by some demands of military tasks.

First stage of radionavigation systems development was connected with a series of practical works in creating domestic radio means to provide air and marine navigation. They were fulfilled in the 20-es. To such radio means domestic angle-measuring systems worked out by Soviet engineers V. I. Badgenov, J. A. Myasoedov, M. M. Zelent and other specialists may be attributed.

At the end of 30-es the development, and the construction of powerful stationary ground radio beacons were carried out to provide airplane flights. Long-range sector radio beacons used for marine navigation were also developed. Essential drawbacks restricting the use of indicated radio beacons were small accuracy and limited range of operation.

Further progress of aviation and fleet demanded the development of principally new long-range radionavigation systems. Group of Soviet scientists headed by academicians Z. J. Mandelschtam and N. D. Papalexi worked out the principles and made the patterns of equipment of distance-measuring and difference-distance-measuring radionavigation systems.

The author's certificate was issued to engineer A. M. Rubchinsky in 1938 for working out difference-distance-measuring radionavigation systems with pulse radiation. The patterns of difference-distance-measuring systems with continuous radiation were worked out by a group of specialists under the guidance of B. M. Konoplev and E. J. Schegolev. In the early fifties chief designer A. S. Poltorak represented for tests pulse-phasic long-wave radionavigation systems (European chain) operating at frequency of 100 kHz. The trial was conducted by the state commission headed by A. V. Belyakov. In 1957 under the leadership of V. P. Chkalov he took part in the flight of 10000 km in total length from Moscow across the North Pole to the USA. The commission marked that obtained accuracies were comparable with American "Loran-C" system. Home system covered with radionavigation field eastern and western parts of European territory of the USSR and it's southern and northern parts after constructing two additional stations and also the regions of inland and adjacent seas. The range of operation was 1600-1800 km. It should be noted that the stations of European chain after a number of modernizations are continuing to operate up to now. It's radionavigation field permits to determine the position practically to all the types of mobile objects having onboard receiver with no worse than 500-600 m accuracy without corrections on propagation. Beginning with the end of 50-es the main stress was laid on further increase of the long-wave system's chains and on the establishing of VLF stations. As a separate direction one may distinguish the development of radionavigation system with multi-frequency signal format. It operates in a frequency range of 64-92 kHz. It is intended in general to provide radionavigation services for marine users. Taking into account the limits of the report and also that the topic of our consideration is Soviet long-wave radionavigation system of "Loran-C" type I'll dwell just upon them.

At present there ar four stationary chains of long-wave radionavigation system in the USSR. It is similar to "Loran-C" system and is called "Chayka".

These chains are:

European chain consisting of 5 stations, located at Brjansk, Petrozavodsk, Slonim, Simferopol and Sjizran. It's group repetition interval is 8000.

Northwestern and Northern chains consisting of 5 islands, Teriberka. The group repetition intervals are 4970 and 5960.

Far Eastern chain consisting of 5 stations, located at Aleksandrovsk-Sakhalinsky, Petropavlovsk-Kamchatsky, Ussriysk, Kurilsk and Okhotsk. It's GRI is 7950.

In 1990-1991 the USSR and the USA are going to establish joint Soviet-American chain, which will be comprised at the first stage of 3 stations, located at Attu Island (USA), Kamchatka Peninsular (USSR) and Sakchalin Island (USSR).

Soviet chains have master, several secondary stations and also monitors. Frequency standards with relative instability in the order of 10 are installed at master and some secondary stations. This provides enough operation stability for radionavigation determination.

Besides, ground stations have powerful transmitter, transmitting and receiving antennae, control and synchronization equipment and subsidiary equipment.

First patterns of transmitters were designed on electronic tubes. But vacuum-tube transmitters are complicated in maintenance and their efficiency is unsatisfactory. The last plays crucial role in creating high power stations.

In later pasterns key-type tiratron transmitters were used. They are distinguished primarily by efficiency and simplicity. The transmitter consists of the modules, generating power in order of 600 kW. Under addition of power in the input of antenna unit the total power amounts several megawatts.

According to radiating power ground stations are divided into high, average and small power stations. The value of radiating power depends not only on the power of transmitter but also on the design of transmitting antenna.

Soviet designers have developed several classes of long-wave transmitting antennae. They include multi-mast umbrella antennae with the height about 200-250 m. Such antennae are differed by rather high cost. At the same time they have good electric characteristics and the efficiency achieves 60%. Stub antennae on the single mast with grounded base have less cost. However, to achieve the efficiency of more than 50% for such antennae it's necessary to build masts of about 460 m high.

In accordance with Soviet specialists' opinion the optimal transmitting antennae according to the criterion "efficiency-cost" are umbrella antennae with one insulated mast, 250 m high. Such antennae under rather low cost allow to obtain the efficiency of about 40%. Special features of antenna's curtain and mast's supply with the means of mechanization permit to change to some extent promptly the electric characteristics of antenna system.

To cover small local regions by "Chayka" coverage area umbrella antennae on four 52 m masts are used.

The efficiency of such antennae is units of percents however their cost is low.

Control and synchronization equipment provides forming the pulses of transmitter's starting and also supporting the synchronization accuracy. The responsibility of system synchronization is laid on the master station, which measures the time interval between secondary station signal arrival and the master signal emission. Instrumental error of signal arrival measurement is about 0.05 mks.

The shape of radiating signal is monitored with the help of sensor which is a current transformer and a special forming circuit. In the case of deviation of signal parameters from nominal values the disbalance of half-cycles of the signal monitored from the sensor occurs. This disbalance should not exceed 25% which is equivalent to envelope-to-cycle difference less than 1 mks. So the requirements to the tolerances of radiated by key transmitters signal shape are rather strict.

Main units of long-wave ground station equipment have the reserve of 100%. This allows to provide all-year-round work with short switchings from maintenance checkup.

The possibilities of long-wave radionavigation systems and the fields of their employment are determined by accuracy characteristics which depend on a number of factors including propagation peculiarities, ground stations arrangement, synchronization errors of secondary stations, the errors of hyperbolic coordinate transformation and some factors of different national and artificial interferences.

As the study of consequences of each factor's influence is the subject of many scientists I'll only note that taking into account all these factors with propagation errors in the first place, one may reach the potential possible accuracy of long-range radionavigation systems which is about several dozens meters.

The spheres of long-range radionavigation systems employment are different. They are used:

- as means for marine, air navigation and the means of monitoring land objects;
- as correcting device for autonomous inertial systems;
- to transmit the signal of the universal time;
- to investigate propagation conditions;
- in geodesy and other branches of science and technology.

In conclusion I'd like to fall upon the plans of future development of long-range radionavigation systems.

Vast geography of the USSR, great spaces of adjoining seas and oceans, most varied relief require to develop for our country the systems which allow to provide maximum covering of the territory under minimum expenses and with enough high accuracy. It is "Chayka" and "Loran-C" which are the systems of such sort.

At least up to 2005-2015 years we plan further employment and improvement of long-wave radionavigation systems and also their wide use on the basis of composite processing and information from different navigation sensors of user's onboard integrated equipment including the sensors of satellite systems.

CONFERENTION OF RADIONAVIGATION SYSTEMS DEVELOPMENT IN THE USSR

Vice-Chairman of "Internavigation" Committee and its research centre
Director Mr. V. I. Denisov

The USSR in it's approach to the solving the problems of radionavigation provision is striving for maximum possible satisfaction of user's requirements and creation of conditions of safe navigation for marine, air and land users under any arising conditions in any region of the Earth.

To our mind in practice, the special place is occupied by long-wave radionavigation "Chayka" and "Loran-C" systems. High technical, operating and economic features distinguish these systems among others. We consider that their potentials are not exhausted yet:

1. One of the perspective directions of increasing coverage area is the connection and amalgamation of "Chayka" and "Loran-C" stations in new chain. We don't still exclude establishing additional stations, which construction on condition of sharing expenditures by all interested countries in our option will not meet particular difficulties.

On the initiative of the USSR and the USA this work has been already launched. The results of last meeting of mentioned countries' delegation in Moscow from 11 till October 16, 1990 confirmed that technical, operating and organizing problems of establishment of these systems joint chains may be resolved;

2. There exists the possibility to increase considerably the accuracy of mobile objects positioning by further improving the differential method of radionavigation parameters measuring; by increasing the accuracy by synchronizing radio signal of transmitters to common time scale; by decreasing the instrumental error of user's receive equipment;

3. Contemporary level of technology development provides the use of circular method for radionavigation parameters determination.

Realization of this method would allow to increase essentially the coverage area and to raise position accuracy.

Consideration of technical, operating and economic features of existing radio aids to navigation including satellite navigation systems shows that no one of them presently doesn't meet completely user's requirements and is not universal.

Employment of GLONASS and GPS systems is limited by their availability, high cost of receiver equipment (what restrains it's installation on small-sizes objects), great operating expenses.

Employment of "Omega" system and the similar Soviet VLF land communication stations is limited by low position accuracy, insufficient for solving the large class of navigation problems.

In particular I'd like to dwell upon the use of "Chayka" and "Loran-C" systems. Long-termed experience of their operating showed their high efficiency. Therefore, actively supporting the work on creating our own satellite navigation system GLONASS and it's further combining with GPS we consider that the prospects of using "Chayka" and "Loran-C" systems may be divided into three stages:

1. Period of self-contained use of "Chayka" and "Loran-C" systems and their combining.

These systems will be widely employed by the users of overwhelming majority of the countries during the nearest 15-20 years. The foundation of such statement is as follows:

radionavigation field of these systems covers the regions with most intensive marine and air navigation (Europe, America, Far East, northern parts of Atlantic and Pacific Oceans);

high accuracy of position determination (the same order as satellite system accuracy) providing the solving of great class of navigation tasks and real possibilities to improve it;

existence of large number of users equipped with receivers of these systems (about hundreds thousand);

lower cost (2-3 times in comparison with satellite systems equipment) of on-board equipment, which stipulates the possibility to install it practically on all classes of mobile objects including small-sized ones;

more little (in comparison with satellite system) operating expenditures;

potential possibilities to improve the characteristics (about the ways of realization it was said above).

2. Period of integrating "Chayka"/"Loran-C" systems with GLONASS/GPS satellite systems (to tie ground and satellite systems signals to common time scale).

It's possible to provide reliable radionavigation service for users only with the help of using satellite and "Chayka"/"Loran-C" systems in combination (especially during the period of deployment of satellite navigation systems and saturation of user equipment stock).

In our opinion "Chayka"/"Loran-C" systems will be used even after complete deployment of GLONASS/GPS satellite systems:

to complement satellite systems,

to transmit the differential corrections to users.

3. Period of "Chayka"/"Loran-C" operation in united system of positioning and timing.

The results of recent years investigations revealed the trend to bring closer the methods of position and time measurements with simultaneous expansion of the composition determined parameters.

However, at present the tasks to carry out position and time measurements are solving on the basis of separate using aids to navigation and synchronization (of universal time).

Hence it is necessary to combine navigation (land and space) and synchronization means in a united system of position-timing provision.

I'd like to note that first steps on positioning and timing system creation are already in progress.

"Chayka"/"Loran-C" combining;

linking the stations of these systems to common time scale;

consideration of GLONASS/GPS combining issues.

Concluding consideration of "Chayka"/"Loran-C" future I'd like to notice that the showed stages of systems use don't represent any time sequence. They have both horizontal and vertical links.

On the basis of all mentioned above we express confidence that "Chayka"/"Loran-C" radionavigation systems will find the employment still in XXI century.

THE CHINESE LORAN-C SYSTEM: ACHIEVEMENT & PROSPECT

Gan Guoqiang, Yan Jiaping,
Wei Qianzi, Bao Wuwei
XIAN RESEARCH INSTITUTE OF NAVIGATION TECHNOLOGY

ABSTRACT This paper presents the development of the Chinese Loran-C Radionavigation System of recent years. With the descriptions in detail, the paper puts forward the configuration of chains, the way of synchronization and control, the method of noise calculating, the fix accuracy and the coverage of the Chinese Loran-C system. The paper then, with the introduction of three chains; one already established in the South China Sea, the other two new chains being built, made analyses on the results of some actual tests. Finally, prospect of the development of the Chinese Loran-C system is made.

1. INTRODUCTION The first Loran-C chain along the coast of China was completed in 1988. The results from the inland tests and the marine tests show that all of the main technical characteristics—including the fix accuracy, the coverage and the signal availability of the chain in the South China Sea—reached the design requirement. The chain passed the National technical appraisement in August 1990.

Now China is building other two Loran-C chains along the coast of Northeastern China. Test transmitting of signal is expected at the end of 1992 or a little bit later.

According to a contract signed with the Government department concerned, the Xian Research Institute of Navigation Technology (XRINT) is in charge of all the technical duties of Loran-C project, including the configuration of chains, the location selection of transmitting station and monitoring station, the giving of electric requirement on civil engineering, the laying out, production, purchase, installation and debugging of the equipment, and the calibration and check up of the system, etc. Besides, the Institute is responsible for the development and production of the user's equipment and the provision of ASF correction data within the coverage.

Up to now, the three Loran-C chains are mainly for the navigation positioning service of marine users. And they began to make themselves attractive to other quarters of China, especially to air users who noticed the possibility of en-route navigation and non-precision approach by Loran-C system. Plans of extension of chains of Loran-C stations to cover the main air ways of inland China are being discussed.

The paper will make a comprehensive introduction to the Chinese Loran-C system, including the system design, the configuration of chains, the method of synchronization and control, the layout of equipment, etc. In addition, in the light of some test results of the chain of the Southern China, the paper will also make some analyses on the fix accuracy, the coverage and other system performances. The sampling method of atmospheric noise and the definition of coverage which are different from the USCG traditional method are introduced in detail. In the end, the prospect of the Chinese Loran-C system is made.

2. CONFIGURATION OF CHAINS The configuration of chains of the Loran-C system along the coast of China mainly concerns about the following aspects:

- all of the stations located on the Chinese territory,
- to meet the users' requirements in the accuracy and the coverage,
- to cut down the cost by building the minimum numbers of stations possible,
- to take account of the working and living conditions of the stations selected,
- to control the civil engineering cost to as low as possible.

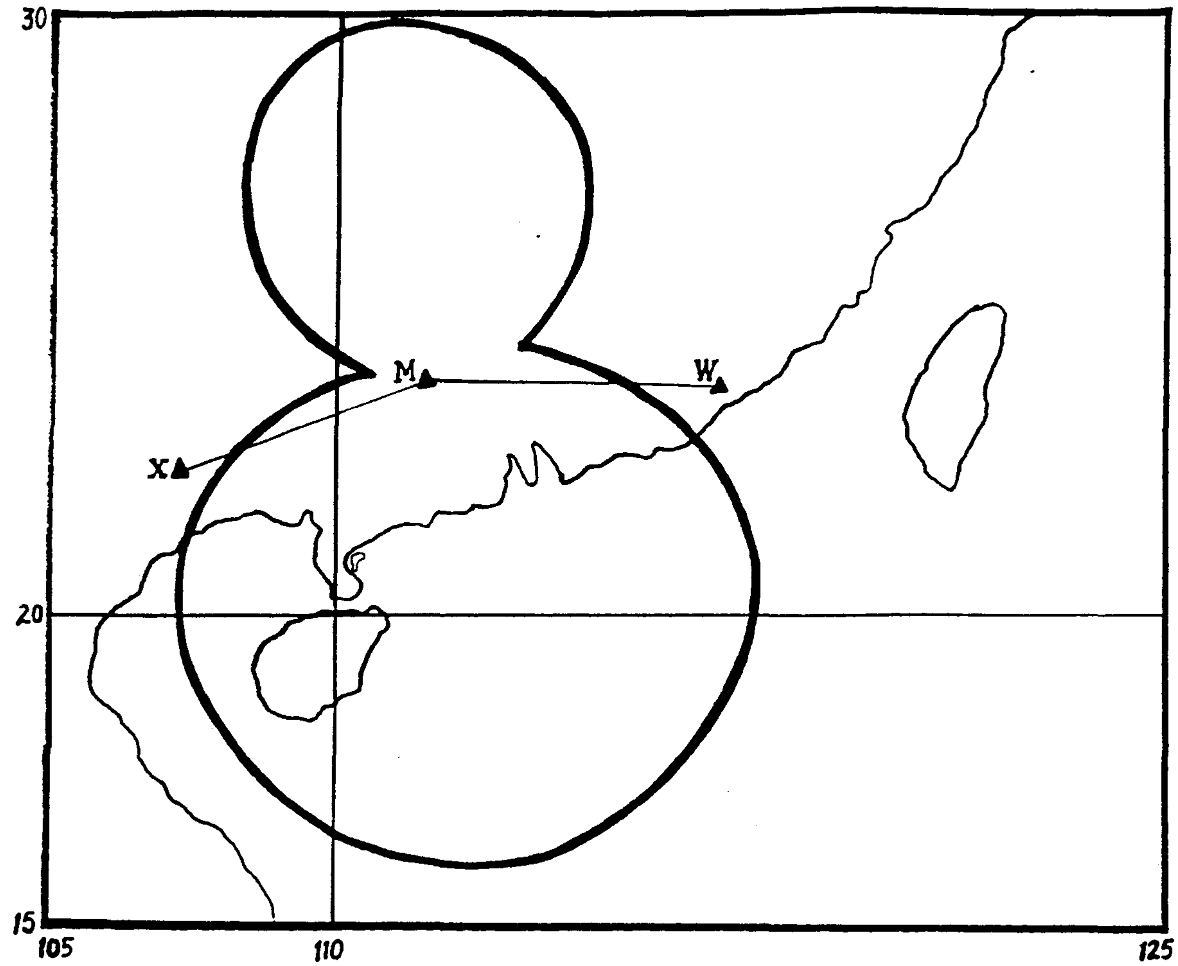
The coverage requirement was determined based on sea areas during daytime or nighttime respectively, and measured according to the maximum distance from the main coveraging direction to the master station.

South Sea	daytime	1000 nautical miles
	nighttime	900 nautical miles
Northeast Sea	daytime	1300 nautical miles
	nighttime	1000 nautical miles

After considering all the requirements, together there are 6 transmitting stations designed along the Chinese coast with 3 dual-rated to form 3 chains. Every chain is aided by a system area monitor (SAM) and a Control Center. The actual configuration is shown as follows. (see Figure 1).

The Control Center of each chain is collocated at the Master Station. The configuration of chains is limited by the geographical conditions of China. There are two reasons to account for the little bit shorter baselines of the South Sea Chain. One is the requirement for the coverage range to reach the 8° of northern latitude to the South, which prevents the Master station from being located far away inland. Another is the limit for the two Secondary stations located to the east and the west to stretch more, because to the east of the Raoping Station is the sea, to the west of the Congzuo station is the mountain areas and to the south is the boundary line.

Figure 1a. South Sea Chain



图为罗兰c地波覆盖区 信噪比 1:3; 重复精度(95% 2dRMS)1/4 NM; 大气噪声 正区: 61.5 dB uv/m 背区: 57.3 dB uv/m 。

图 例:

▲ 发射台 M 信 都 W 饶 平 X 崇 左 Y

台站符号	坐	标	编码延迟 / 基线长度	发射功率
M	111 43.0E	23 58.0N	0 /0.0	1200KW
W	116 53.7E	23 43.4N	0 /0.0	1200KW
X	107 13.3E	22 32.6N	0 /0.0	1200KW

Figure 1b. East Sea Chain

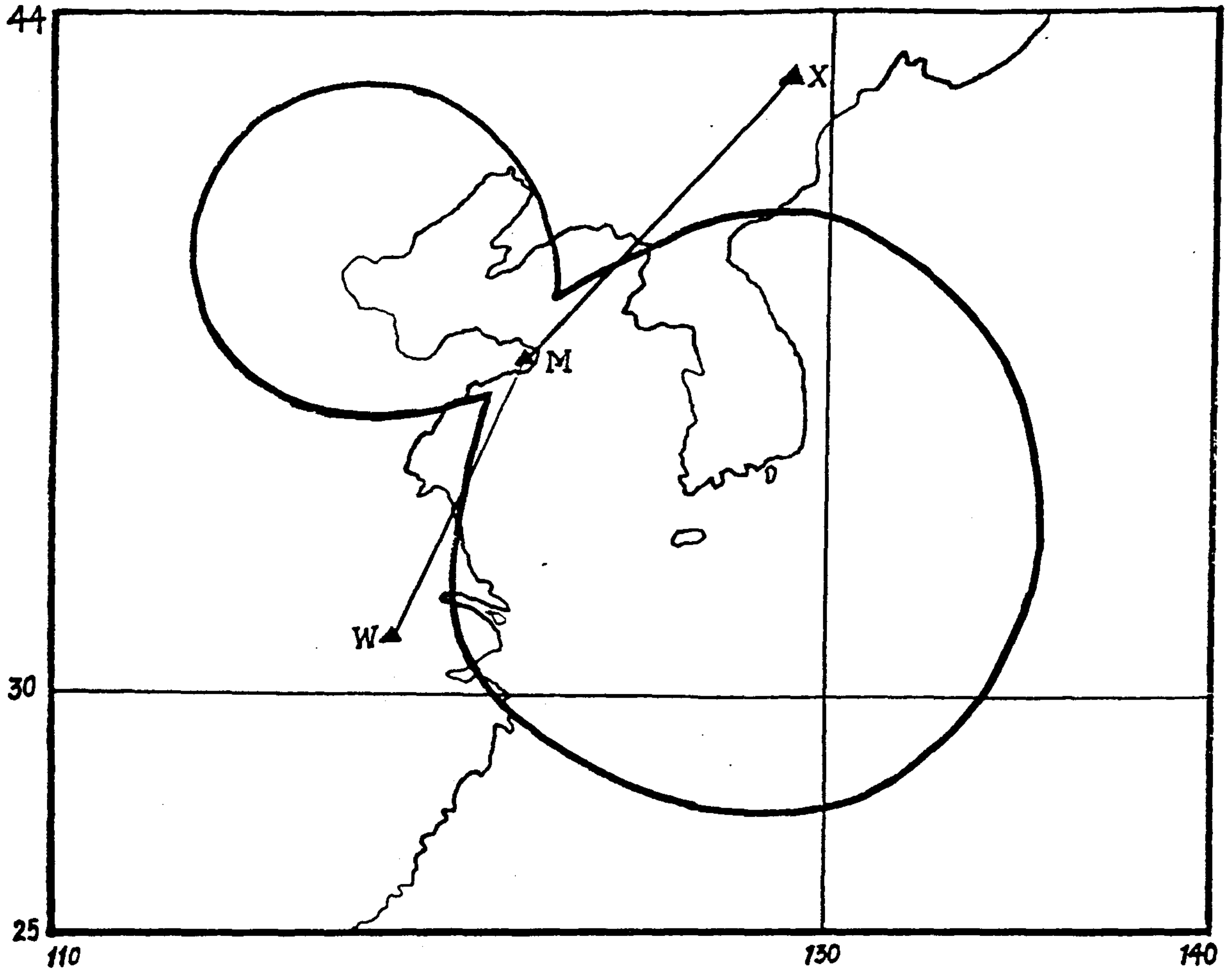
图为罗兰c地波覆盖区　信噪比 1:3;　重复精度(95% 2dRMS) 1/4 NM;　大气噪声　51.4 dB uv/m 。

图 例:

▲ 发射台　　M 宣 城　　W 饶 平　　X 荣 成　　Y

台站符号	坐	标	编码延迟 / 基线长度	发射功率
M	118 52.0E	31 04.0N	0 /0.0	1200KW
W	116 53.7E	23 43.4N	0 /0.0	1200KW
X	122 20.4E	37 04.3N	0 /0.0	1200KW

Figure 1c. North Sea Chain



图为罗兰c地波覆盖区 信噪比 1:3; 重复精度(95% 2dRMS) 1/4 NM; 大气噪声 48.8 dB uv/m。

图例:

▲ 发射台 M 荣成 W 宣城 X 合龙 Y

台站符号	坐标		编码延迟 / 基线长度	发射功率
M	122 20.4E	37 04.3N	0 /0.0	1200KW
W	118 52.0E	31 04.0N	0 /0.0	1200KW
X	129 06.0E	42 43.0N	0 /0.0	1200KW

Compared with the South Sea Chain, the length of the baseline of the East Sea Chain and the North Sea chain are more appropriate. But, the included angle of the baselines appeared to be large due to the convex shape of the Chinese eastern continent.

The three Loran-C chains along the Chinese coast mentioned above can cover most sea areas of China. But around the Raoping station, which will be the secondary-secondary-dual-rated for the South Sea Chain and the East Sea Chain, there is a part of the sea area which lacks satisfactory coverage.

South Sea Chain

M. He County,	Simplex	
Guangxi Prov.	included angle	160°
X. Congzuo County,	Simplex	
Guangxi Prov.	baseline	486 km
W. Raoping County,		
Guangdong Prov.	Duplex	
	baseline	528 km
SAM. Taishan County,		
Guandong Prov.		

East Sea Chain

M. Xuancheng County,	Duplex	
Anhui Prov.	included angle	170°
W. Raoping County,	Duplex	
Guangdong Prov.	baseline	837°
X. Roncheng County	Duplex	
Shandong Prov.	baseline	739 km
SAM. Nanhui County,		
Shanghai		

North Sea Chain

M. Rongcheng County,	Duplex	
Shandong Prov.	included angle	166°
W. Xuancheng County,	Duplex	
Anhui Prov.	baseline	739 km
X. Helong County,	Simplex	
Jilin Prov.	baseline	852 km
SAM. Shandong Prov, (undecided)		

3. SYNCHRONIZATION AND CONTROL

As is the method adopted by USCG, the Chinese Loran-C system operates in the free synchronization method controlled by SAMs. Every transmitting station is equipped with a time-frequency rack (TFR) to supply the transmitter with time and frequency standards. The time-frequency rack consists of 3 FTS-4050 cesium beam atomic frequency standard units (CBFS), 3 phase microstepper, 3 XKP phase recorders of R/S Company of Germany and 2 frequency conversion controllers. The TFR is equipped with an AC-DC automatic switching power with which it can operate for 45 minutes to ensure the reference not to be lost when AC failure occurs. The composition and the connection of the TFR are shown in Figure 2.

The function of the frequency conversion controller is the integrating and phase locking of the 3 cesium beam atomic frequency standard units and the 3 phase microsteppers. Among the 3 CBFS units, there is one master standard, the other two serve as secondary standards locked to the master one with the accuracy of ± 2 ns. When the master one breaks down, the switching will happen automatically with phase error less than ± 4 ns.

Up to now, the transmitting timing of the master stations of the Chinese Loran-C chains has been in the state of free transmission, do not connected with any other time standards. The Chinese national time standard already established in relationship with UTC is kept by the Chinese Academy of Sciences. So there are no technical difficulties for the Chinese Loran-C system in establishing a relationship with the UTC.

The holding accuracy of the time difference at the SAM with respect to CSTD is better than 70 ns, measured by the following formula:

$$(\sigma^2 + (\overline{TD} - CSTD)^2)^{1/2} < 70 \text{ ns} \tag{1}$$

where

σ	is the standard deviation of SAM observation time difference (TDI), ns;
$\overline{TD}$	is the mean of TDi, ns;
CSTD	is the control standard time difference of the SAM, ns;
CSTD	is determined during the calibration of the system.

The measurement of the emission delay (ED) of secondary stations adopts the method of baseline extension, the method of clock transportation and the method of the common viewing of a single GPS satellite.

The information monitored by the SAM includes TD, ECD, SNR, and etc., which are sent to the Control Center by means of single-side band data transmission (SSB). The LPA command for the secondary station is sent out by the Control Center, and is transmitted to the transmitter RCU of the secondary station through SSB. Then the transmitter will carry out the command automatically.

The designed synchronous accuracy of the South Sea chain is 100 ns. The LPA's threshold is ± 50 ns, and the synchronous alarm's is ± 100 ns.

Apart from SAM, each transmitting station is aided with a set of synchronous monitoring equipment (SME) to monitor and to help to control the synchronization of the system. This set of equipment consists of a timing receiver (similar to Astron-2000C) and other necessary aids. The height of the receiving

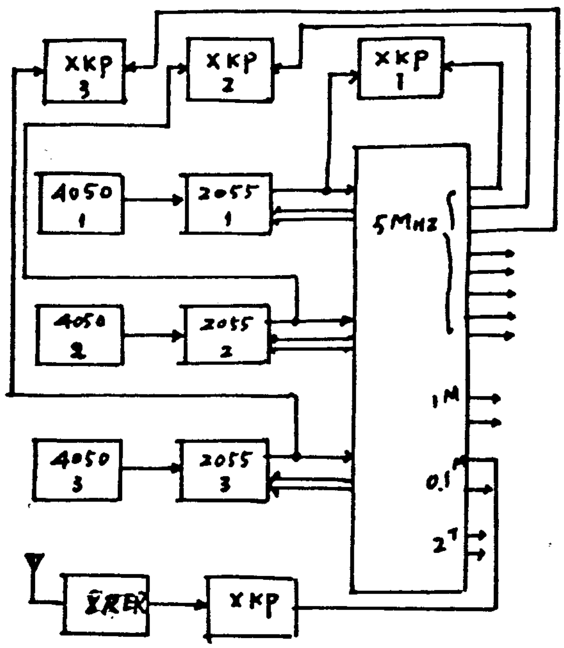


Figure 2. Time Frequency Rack (TFR)

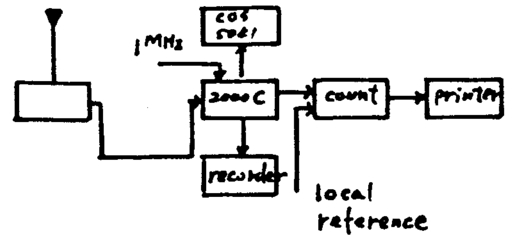


Figure 3. Synchronous Monitoring Equipment (SME)

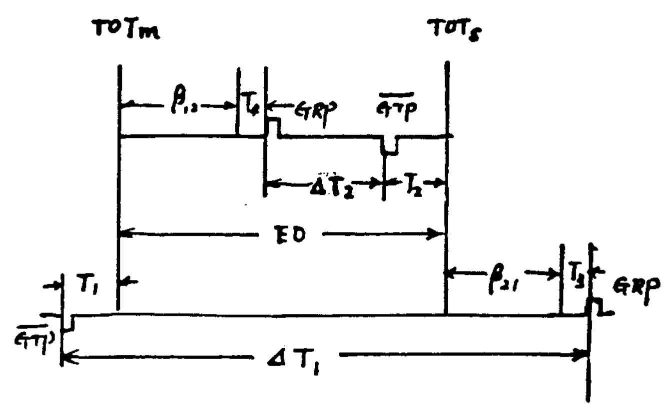


Figure 4. SME Time Relation Chart

antenna is 16 m, and it is located about 550 m from the transmitting antenna. The block diagram is shown in Figure 3.

The SME assists SAM to monitor the transmitting signal from the stations far away, check their phase code, measure the time differences between the local reference (GTP) and the reference of the far aways' (GRP) tracked by the timing receivers, calculate and calibrate the frequency shift of the atomic frequency standard of the master and secondary stations.

Figure 4 is the time relation chart measured by SME. And the results measured by the master and secondary stations are expressed respectively:

$$\Delta T_1 = T_1 + ED + \beta_2 + T_3 \tag{2}$$

$$\Delta T_2 = ED - T_2 - \beta_1 - T_4 \tag{3}$$

where

ΔT_1 and ΔT_2 are the results measured by SME of the master and secondary station respectively, which are called the pseudo-time-differences of the both,

T_1 and T_2 are the exceedances of LTU with respect to TOT in time respectively,

T_3 and T_4 are the overall delays of the receiving channel of the master (secondary) station respectively,

β_1 and β_2 are the signal transmitting time from the master (secondary) station to the secondary (master) station respectively.

If the difference between the forward transmission and the reverse transmission of the baseline is ignored and with T_{12} and T_{34} — the differences in the channel delay of the transmitting and receiving between the master and secondary station — measured, that is:

$$\beta_1 = \beta_2 \tag{4}$$

$$T_{12} = T_1 - T_2 \tag{5}$$

$$T_{34} = T_3 - T_4 \tag{6}$$

Then we have

$$ED = \frac{1}{2}(\Delta T_1 + \Delta T_2) - \frac{1}{2}(T_{12} + T_{34}) \tag{7}$$

From the formulas above, it is clear that the synchronization of the system can be monitored roughly by the transmitting station's own SME.

4. ATMOSPHERIC NOISE ESTIMATION

Based on "World Distribution and Characteristics of Atmospheric Radio Noise" of the CCTR's report No. 322, the noise of atmosphere is estimated. To take the South Sea Chain for example, the method of noise sampling is shown. The representative spot chosen is the Taiping Island in the South Chain Sea. The sampling is made according to 24 time blocks a year respectively, with the noise bandwidth 25 kHz.

To meet the user's requirement, the Service Probability of daytime and nighttime is defined respectively:

$$P_1 = \frac{1}{12} \Sigma\, P_1(E_{N1}) \tag{8}$$

$$P_2 = \frac{1}{12} \Sigma\, P_2(E_{N2}) \tag{9}$$

where

P_1 and P_2 is the Service Probability of daytime and nighttime of a full year respectively;

$P_1(E_{N1})$ and $P_1(E_{N2})$ are the time probability with F not exceed E_{N1} (day) and E_{N2} (night). F is the medium of the hourly noise within No., four-hour time block;

E_{N1} and E_{N2} are the noise sampling on 12 time blocks of daytime and nighttime respectively.

The predicated noise of 90% Service Probability are:

South Sea Chain	daytime	59.5 dBuv/m
	nighttime	62.5 dBuv/m

The method for the sampling of atmospheric noise adopted here is slightly different from the traditional way of USCG which makes the sampling according to the noise mean with the same time probability (95%) of each of the 24 time block a year, that is:

$$E_0 = \frac{1}{24} \Sigma\, E_m(95\%) \tag{10}$$

This way of noise sampling doesn't mean that the atmospheric noise of more than 95% of time a year is equal to or less than E_0. The time probability of E_0 is not directly viewed. With the Service Probability adopted, the average time probability (not over E_{N1} and E_{N2}) is directly viewed.

In fact, the results of the noise sampling of both 90% of Service Probability and 95% of mean probability (USCG) are very close. For the chain in the South Sea, the calculation result of $E_0(95\%)$ is 61.5 dBuv/m, similar to 61.0 dBuv/m of the means of $E_{N1}(90\%)$ and $E_{N2}(90\%)$.

5. FIX ACCURACY AND COVERAGE

This coverage of Loran-C system in the Chinese coastal areas is limited by SNR and fix accuracy. The SNR adopted in making the chart of coverage is -14dB. The limit value of fix accuracy (dRMS) is 1.2 nautical miles.

The parameters taken in SNR calculation are the atmospheric noise of 90% of Service Probability.

The propagation path conductivity:

Seawater	5 V/m
Land	(3-5) x 10^{-1} V/m

The radiation power of transmitting station (peak power) is 1200 KW.

The SNR calculated in Millington method between 700-1300 nautical miles from the transmitting station are shown in the following table:

6. ACTUAL TEST RESULTS

The offshore tests for the covering range of the South Sea chain were carried out many times from 1988 to 1990. The result is satisfactory. The receivers adopted in the tests are the XN-800 and XN-8000 Loran-C receivers made by the Xian Research Institute of Navigation Technology. The reference ship position is given by MX-4400 GPS receivers of Magnavox Company.

Table 2 gives part of the results from the tests carried out in the Summer of 1989. The test areas given by the table do not exceed 100 nautical miles in size.

Table 1

SNR (dB)	South Sea		North East Sea	
R(NM)	Day Time	Night Time	Day Time	Night Time
700	-3.5	-6.5	10.4	-1.1
800	-6.7	-9.7	6.8	-4.7
900	-10.4	-13.4	3.1	-8.4
1000	-14.4	/	-0.9	-12.4
1100	/	/	-5.14	-16.6
1200	/	/	-9.6	/
1300	/	/	-14.3	

The parameters adopted by the fix accuracy calculation are:

the synchronous error for the transmitting station: 0.1 us,

ASF errors: 0.2 us,

the errors of time difference measured by the receivers:

When SNR > -9.5 dB	0.15 us ,
when SNR > -14 dB	0.30 us .

Table 2

Test Area	n	Test Sea Area	X(m)	(m)	drms(m)
A	22	22° -21° N, 100° E	148.8	44.9	155.5
B	43	14° -15° N, 111° E	244.1	124.2	273.8
C	27	13° -14° N, 111-112° E	864.6	243.4	898.2
D	100	11° -12° N, 114-116° E	877.0	644.5	1088.5
E	45	10° N, 115° -116° E	1435.6	926.3	1708.5
F	34	9° N, 114° -115° E	1278.0	923.1	1576.5
G	28	8° N, 114° -116° E	1542.0	1089.0	1888.7

where

X is the mean of the distance error of the Loran-C positioning with respect to the reference

σ is the root-mean-square value of the Loran positioning with respect to the mean, representing the repeated accuracy,

drms is the root-mean-square value with respect to the reference, representing the absolute accuracy.

Most of the data in the above table were attained in the night time (23:00 - 3:00) with ASF preliminary correction data applied.

Skywave interference is a major factor in limiting the maximum operation range of the South Sea chain. Between 8° ~ 9° of northern latitude, there are cycle identification-alarm and slide cycle in receivers, where the amplitude ratio of skywave to groundwave exceeds 15 dB during night time. After modification of XN-8000 Loran receiver, the anti-skywave-interference ability of it improved a lot. Meanwhile, it can operate well in the condition of -14 dB SNR.

The analyses of the error distribution for the location points show that there exists some shift for the major axis's direction of the actual error ellipse with respect to the theoretical orientation, with the reference position being the origin. The results from the tests in most of the areas seem to show that Y secondary's timing error is a bit bigger.

7. FUTURE DEVELOPMENT The operating of the South Sea chain gains a lot of the users' favor. And the construction of the East Sea chain and the North Sea chain are undergoing without a hitch. The civil engineering of the two chains are to be completed in 1991 on the whole and two transmitting antennas are to be installed within the same year expectedly. The equipment—including the solid-state transmitter—for the new chains, are made by the Xian Research Institute of Navigation Technology. The test transmitting of the signals of the new chains are expected to begin at the end of 1992 or a little bit later.

The future development of Chinese Loran-C system includes the expanding of the coverage and the opening up of the application.

It is very promising for Loran-C to expand its coverage, and to supply air users with en-route navigation and non-precision approach within the inland China. Various plans concerning the inland configurations of chains are being brewed and discussed. The Loran-C stations along the coast have laid a solid foundation for the inland expanding of coverage. Several stations added (2-3) will satisfy the air coverage for the main economic zones of China. And the coverage for the whole inland China needs only 9-10 stations added basically. Still, the coverages of the coastal Loran-C need to be perfected, especially the coverage at the joint between the South Sea chain and the East Sea chain, which matters much for the connection of the coverage of the Loran-C chains (9970) of the Far Eastern Pacific with the Loran-C chains of the Chinese coastal areas. The filling of the gap will greatly benefit the marine navigation for the whole area.

The opening up of the application for Loran-C system has a very bright future in China. It is of great value for: the attaining of high positioning accuracy of 50 m by Differential Loran-C at the areas like the mouth of Zhujian and Changjiang with heavy traffic; the connection of the transmitting time of the master station of Loran-C with the national standard time or even with UTC, thus providing time service by Loran-C corresponding with the national standard time or even with UTC.

8. CONCLUSION China attaches great importance to the development of Loran-C Radionavigation System. Apart from the established South Sea chain (it has passed the national technical appraisement already, with the main technical characteristics of the desired requirement achieved), there are two new chains being founded. China is also working hard in the expanding of the coverage of Loran-C and the opening up of the application.

Loran-C Research Activities in Italy

S. Leschiutta E. Rubiola

Politecnico di Torino, Dipartimento di Elettronica
c/so Duca degli Abruzzi 24, I-10129 Torino, Italy

Summary

Research activities performed in Italy about Loran-C are not widely known, being most of the documentation written in italian language. The aim of this paper is to present a summary of some of these activities, for the period 1970–1990.

1 Introduction

Loran-C research in Italy was performed in a number of Laboratories for different reasons; in some cases for institutional ones, such as at the Istituto Idrografico della Marina (Navy Hydrographic Service) in Genoa, or the Istituto Universitario Navale (Naval University) in Naples. In other instances the activities were promoted for radio propagation studies, metrological applications and land navigation, mostly in the Turin area, at I.E.N., the italian equivalent of the National Institute for Science and Technology and at the Turin Technical University, named Politecnico.

This paper presents a summary of the activities performed in the two latter Institutions for the period 1970–1990. Most of the papers are in italian and are available at the author's address.

This summary is presented divided by different topics — metrology, propagation, experiments and constructions, measurement campaigns, differential use and land navigation — and it is extended also to some activities performed about Omega.

2 Metrological Use of Loran-C signals

In the period 1970–1985, the utmost accuracy in remote Time and Frequency comparison was secured by the metrological use of Loran-C signals [1,2,3,4]. Consequently routinely measurements were performed on the absolute arrival times of Master and X plus Z slaves of the Mediterranean Sea chain; for some periods the Sylt station, the southernmost slave of the Norwegian Sea chain, was also monitored for the same purposes [5,6].

In order to have an independent time check, for some period a TV time comparison method was installed at the Master Station Sellia Marina in order to link the local master clock with the atomic clocks used in Torino.

The readings of the italian Time scale UTC(IEN) were and still are transferred to BIH (now BIPM) in Paris, for the construction of the international Time Scale UTC, via Loran-C only since 1970 and also via GPS since 1985 [7].

The technical setup that was used for metrological and propagation research pourposes is given in Fig. 1; Omega signals were received and Loran-C and Omega simulators were used to assist the calibrations of the receivers [8].

3 Propagation and coverage area research

Propagation studies were performed in order to derive the ASF directly from geological charts. The distribution of conductivity in Italy is indeed very irregular, and in some cases the theoretical value was checked using a caesium clock traveling in a car.

For instance in 1975 a journey from Turin to Sellia Marina, the Master station of the Mediterranean Sea Chain, about 1500 km, the propagation time was measured and a *theoretical* position of the antenna, as seen from Turin, was calculated. This latter determination was performed taking, out of the Fresnel region, absolute time of arrival data versus the *true* geometric distance from the transmitting antenna. By a linear regression on this data, the *electrical* position of

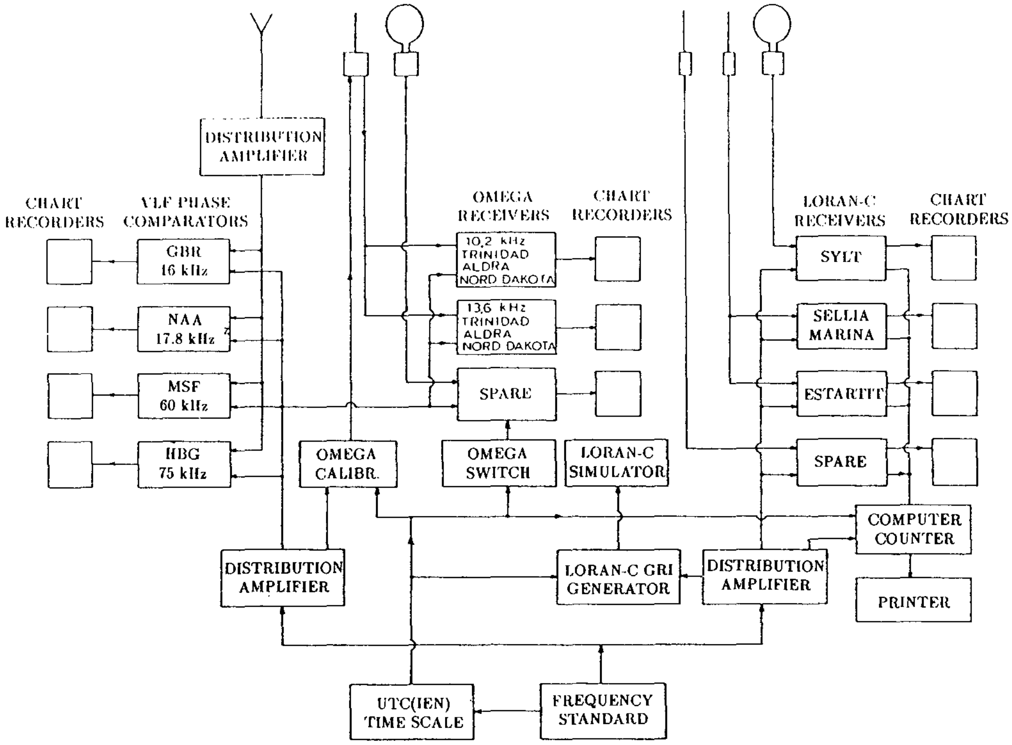


Figure 1: LF and VLF measurement setup at I.E.N.

the antenna was found.

With a portable clock also the propagation time between Turin and Estartit (Spain), the Z station, was measured in 1981.

As a result of this kind of activities, the propagation time (i.e. the ASF for a given location) obtained via careful use of geological data and computation methods, can be established with errors of about 0.2 μs (1σ).

Concerning the Loran-C and Omega propagation, a number of researches were performed, both at IEN [9,10,11,12,13,14,15] and Politecnico [16,17,18,19,20].

Loran-C navigation in towns poses some problems, not all clearly understood; consequently a study is under way [21] with the scope to gain a better understanding on what happens when a pulsed 100 kHz signal is grazing over a town. In our model, the town was treated as a grooved conductive surface, with groves 20 m depth and 15 m wide (the typical sizes of roads downtown in Torino). Only simple cases were insofar considered, and the research is still underway. Anyway, preliminary results can explain some pheuomena encountered when one moves the receiving antenna over a roof and approaches the walls of a building, or the difficulties experienced by the receivers in reaching locking conditions at ground level along a street.

The future of the Mediterranean Sea chain after 1994 [22,23] is not settled and possible alternatives were investigated, Fig. 2. In one case a national chain was studied [24], formed by the existing Master and X slave plus an additional new station to be located in North-East of Italy. On other instances [25] a network covering part of the Eastern Mediterranean was studied.

In both cases the procedure followed was a computer-based evaluation of the following parameters:

- signal strength, using data and methods proposed in the CCIR report 717-1; data of the existing transmitters (power, antennas etc.) was used, and the proposed new stations were assumed to be equal to the existing ones,
- atmospheric noise, using data and methods of the CCIR report 322-2. A single value, 47.5 dB over 1μV/m on a 20 kHz bandwidth was considered representative of the whole area,

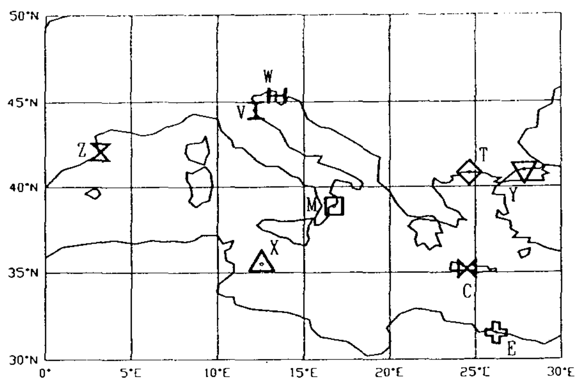


Figure 2: Existing and proposed Loran-C stations in the Mediterranean Area.

- sensitivity, namely the consequence of systematic errors or time jitter on the measured position, in direction orthogonal to the hyperbolae.

It was concluded that a fully national Loran-C navigation system make sense with the existing stations M and X, plus one additional station (W) in North-East of the Country. The sensitivity, i.e. the relation between time difference errors and positioning errors, for this solution is reported in Fig. 3.

The second result is that, if the turkish station Y is to be moved, it should be located in Creta island or in western Egypt (C or E instead of Y, in Fig. 2). This ensures an adequate coverage and partially restores the geometry altered by the deplacement of Y from Matratin (Libya) to Lampedusa island. The consequences on the eastern Mediterranean area are represented in Fig. 4, that reports equal S/N curves for M, X, C and shadowed areas of sensitivity better than 600 and 1000 m/μs.

4 Experiments and constructions

First constructions, back in 1965, were receivers for Loran-C and Omega [26,27,28,29,30,31].

Later an activity was started in order to design a Loran-C like system, able to carry also a coarse and a fine time reference information, giving directly UTC. The system was studied [32], a model of the antenna was tested at 6 MHz and finally an experimental low power transmitter constructed, with a top loaded antenna 42 m high [33]. This research remained at the stage of experiments.

Various problems concerning the better use for Metrology of the Loran-C signals were discussed in a postgraduated thesis [34]. One of the problems, i.e. the calibration of the absolute delay of the Loran-C receivers used in Metrology, promoted the construction of a Loran-C [35] and of a Omega [36] simulators. In booth instruments, the signal is formed by synthesis, using read-only memories.

The Omega simulator can be programmed directly via a PC computer, while the Loran-C device is fitted with an internal microprocessor. In both instruments the carrier phase can be controlled with a resolution between 10 and 100 nanoseconds.

Loran-C receivers suited for metrological purposes are expensive, and consequently a research was performed in order to see if commercial navigation receivers could be used also for metrological purposes [37]. A fake Loran-C signal, locked to the local clock, is injected at the receiver antenna, replacing the weakest station. In this condition the equipment measures the time differences between master and all the secondaries without "realizing" that one of them is locally generated; an external computer evaluates the difference between Loran-C stations and the laboratory time scale. In this application the receiver and antenna internal delays, and consequently their possible variations, are canceled in timing equations.

Comparing timing data with similar ones taken at IEN, differences of ± 50 ns (peak) were observed; this value includes all the instruments involved at IEN and Politecnico, plus some differential propagation effects.

5 Measurement campaigns

A number of campaigns were performed in order to measure the real propagation time; usually a van was equipped with a caesium clock, Loran-C receivers of the metrological type (reception of one Loran-C station only) and navigation receivers.

These measurements were made in order to assist a nation-wide time ordered network for the monitoring on real time of the national power grid.

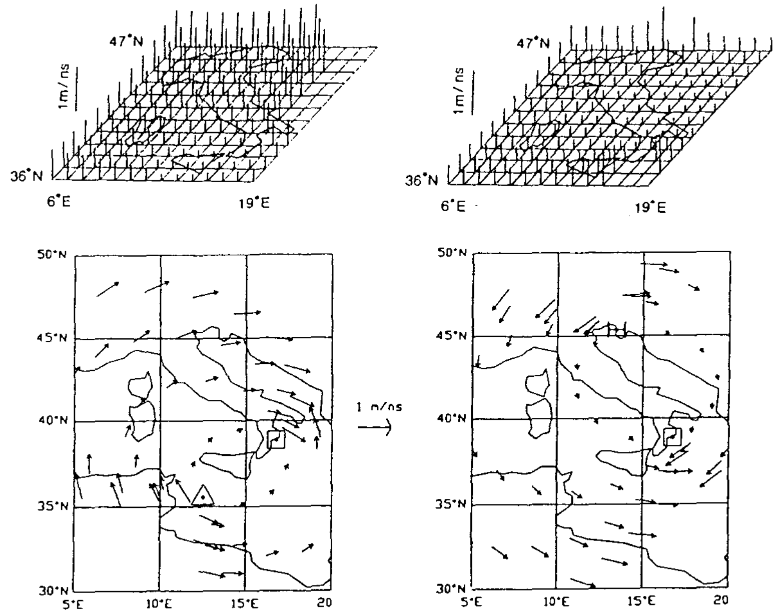


Figure 3: Sensitivity for the couples of stations M–X (left) and M–W (right). **Top:** module, the reference segment is 1 m/ns; all the values above 1.2 m/ns are suppressed. **Bottom:** vectors, module and direction; the angles are not distorted as the map.

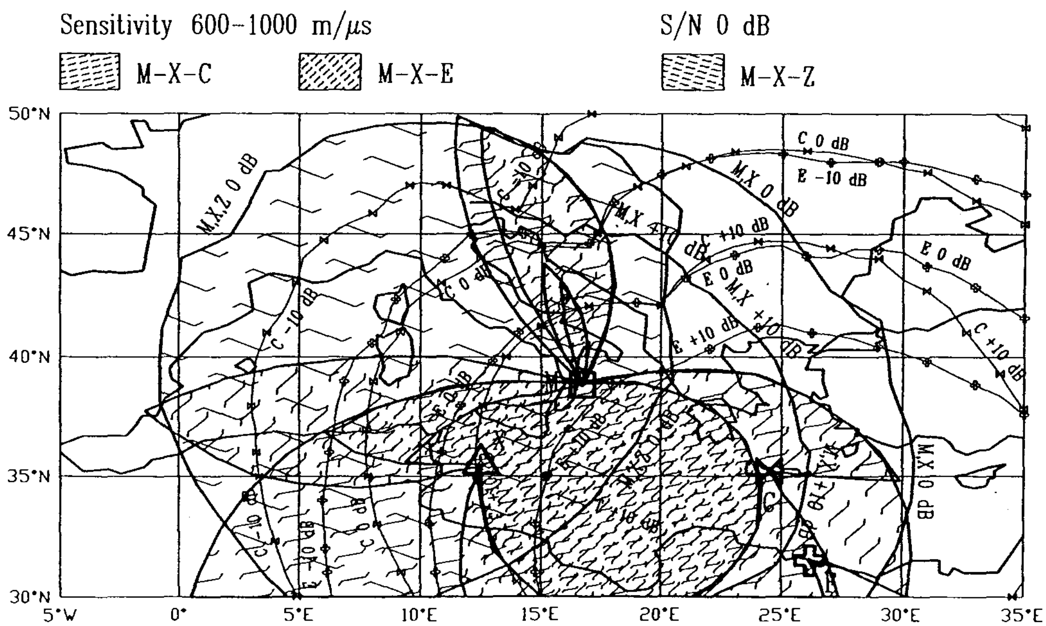


Figure 4: Sensitivity and predicted S/N ratio for two hypothesis of reconfiguration of the Mediterranean Sea chain, in which the Y station is replaced by C or E. The leftmost, about circular, shadowed area represents the coverage of the existing triad M–X–Z. The curves labeled C and E are the equal S/N loca for two of the proposed stations (C-Crete, E-Egypt), while the curves M–X limit the area covered by both of these two stations, to be used in conjunction with one of the proposed transmitters. The other shadowed areas represent the zones in which the sensitivity is less than 600 m/μs (heavy shadow) and 1000 m/μs (light shadow) for the triads M–X–C and M–X–E.

6 Differential use

Limited experience was gained in differential systems. The problem to solve, in a pre-GPS era, was to obtain from a specially equipped plane, the fixes of ground based transmitting stations. The plane was fitted with a digital radiogoniometer, a Loran-C receiver and the data were post-processed in order to locate, via triangulation from the various aircraft positions, the transmitter location.

7 Land Navigation

The possibility to use Loran-C signals for Land navigation was investigated both in towns [38,39,40,41,42], in rural areas [43] and along highways.

The aim of this activity was to have an idea of the amount of the secondary phase errors and of their constancy with time.

The conclusion was, in some extents obvious, i.e. that this navigation system it is not suited in high rise towns (difficult or impossible initial locking) or on hills (large and varying errors), while can offer a solution for land navigation along highways.

Two problems are anyway encountered, the poor geometry in NE of the country and the fact that in some areas of the Italy a large part (in some case up to 50%) of an highway is in tunnels. In the case of "short" tunnels (car travelling time less than about 20 s), the receivers are usually able to recover the signal, but with closely spaced tunnels, the locking is lost.

8 Studies on the quality of the Loran-C service

In land navigation, the positioning requirements are more strict than for sea applications, for two reasons. First, the accuracy requirements are more severe on ground and, second, while in the seas a temporary lack of signals can be easily overcome, since the craft has usually a number of redundant positioning systems, in land navigation three Loran-C signals must be present at any time.

Keeping in mind the requirements of land navigation, some investigations [44] were performed about the "reliability" of the signals, giving the probability to find at least three useful signals. These investigations were conducted using the USNO Bulletins, with the timetable of the planned out-of-operation periods and of the outages and the data phase and amplitude data gathered using the setup presented in Fig. 1.

The mediterranean sea chain was investigated and it was found that for the twelve years period 1979–1990, on the average the signal was useful for about 99.85% of the time.

This kind of analysis is being performed routinely. Some investigations were also performed on the statistics of cycle slips [45] and on the envelope stability [46].

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ABSTRACTS
of Report

of the Head of Soviet Delegation at 19th
Technical Symposium of "Wild Goose" Association
Professor A.G. Funtikov
Vice Chairman of "Internavigation" Committee
Lieutenant-General, Doctor of Technical Sciences

Long Beach, USA, October 22-25, 1990

Dear Mr. Chairman!
Dear Ladies and Gentlemen!

On behalf of the Soviet Delegation I greet immediate technical symposium of "Wild Goose" Association, Mr. Chairman, Council member of board of directors, all participants. Thank you for warm receipt.

Technical Symposium of "Wild Goose" Association represent excellent possibility to meet with leading specialists determining the world main directions of "Loran-C" type radionavigation systems development. Long-wave radionavigation has passed rather a long and complicated way of development. It has proved the undoubted usefulness in the sphere of air, marine and land safe navigation.

The USSR and the USA at the end of 70-es came to the single standpoint about the possibility and expediency of establishment of joint radionavigation chains aimed at covering various regions of the Earth in favor of separate countries of their groups. However, some peculiarities of political and economic situation of that time did not allow to realize in the interests of all interested nations of one or another region.

Each of the sides engages in developing the systems of "Loran-C" type was orientated mainly towards it's own resources. They used to decide the technical problems had been already solved and fulfill elaboration in parallel.

Agreement between the USSR and the USA Governments of May 31, 1988 gave the pulse to scientific and technical cooperation. One may state that within two years after that the specialists of our countries passed more significant way that during previous ten years.

Nowadays our theoretical consideration are turning into the plane of practical affairs. It's enough to say that during 1990-1991 we are to implement the body of works of first stage of Soviet-American agreement and establish the joint Soviet-American "Chayka"/"Loran-C" chain, including the following stations: Petropavlovsk-Kamchatsky (master), Attu (secondary), Aleksandrovsk-Sakhalinsky (secondary). We still have some particular technical problems, but we believe that we'll settle them by joint efforts.

Solving the problem of covering with radionavigation field the northern Pacific on the basis of Soviet-American "Chayka"/"Loran-C" chain we also consider it necessary to undertake efforts to increase "Chayka"/"Loran-C" coverage area in southern Pacific too on the basis of cooperation with countries from Asian region.

In September, 1990 the first international meeting "Radionavigation - Eastern Waters-90" was held in Japan. The representatives of Japan, the USSR, China, Korea and the USA were present. Soviet delegation was headed by Mr. V. I. Denisov, Vice-Chairman of "Internavigation" Committee.

The general view of radionavigation provision in Eastern Waters was examined, the ways for possible cooperation between the countries of the region were outlined, the agreement about establishment of international working group on coordinating the works was achieved (in March 1991 the second international meeting took place in the USSR).

We also undertake activities in the same direction with the countries of Western and Northern Europe.

Regarding the questions of radionavigation provision in different regions of the Globe, being the supporters of such radionavigation systems as "Chayka"/"Loran-C", nevertheless it's necessary to notice, that technical progress doesn't stand still. Today we have come up to such level of technical means development when together with local ground radionavigation systems the global satellite systems as "Chayka"/Loran-C", nevertheless it's necessary to notice, that technical progress doesn't stand still. Today we have come up to such as GLONASS (USSR) and NAVSTAR (USA) are under development and they are taking worth place.

At the same time conducted investigations showed that the only use of systems such as "Chayka"/"Loran-C" or GLONASS and NAVSTAR can not provide the required reliability of radionavigation services for all classes of mobile users and in the first place air ones. In our opinion the most effective solution of radionavigation provision problem is the combined use of satellite navigation systems of GLONASS and NAVSTAR type and landbased systems of "Chayka"/Loran-C" type. In this case the resulting availability of radionavigation signals or the probability of radionavigation provision under combined use of two systems might be about 0.99999.

At present in our country the works on development and manufacturing of the signals from ground and satellite radionavigation systems are in progress, i.e., realizing the possibility of combined use of ground and satellite systems. The question of cooperation with foreign companies in development and manufacturing of such equipment is considering. To our mind development of integrated equipment is the only possibility to reach the level of information reliability, which is enough to ensure the decision of tasks such as aircraft landing on unequipped airdrome, ship navigation harbor, geodetical surveying and so on.

Concluding I want to emphasize once more our optimism in estimation of both the existing groundbased radionavigation systems of "Chayka"/Loran-C" type and the newly developed satellite ones such as GLONASS and NAVSTAR and the perspectives of their use as well.

Session 2
GOVERNMENT ACTIVITIES

Chairman: Maurice "Mike" Moroney, *Volpe National Transportation Systems Center*

Mike is the Chief of the Center for Navigation at the Volpe National Transportation Systems Center (VNTSC) of the U. S. Department of Transportation (DOT). In this capacity he has been responsible for numerous navigation systems studies and developmental programs sponsored by DOT modal administrations. His recent areas of concentration have been the LORAN for Aviation Program conducted for the Federal Aviation Administration, and LORAN/GPS interoperability studies mandated by Congress. Before joining DOT, Mike was a project leader with NASA working on the Lunar Excursion Module for the Apollo Program.

A Registered Professional Engineer in Massachusetts, Mike is a graduate of Boston College and has an MS from Long Island University. He was given the DOT Superior Achievement Award for his efforts at the Transportation Systems Center, and was honored by the Institute of Navigation with the Norman P. Hays Award for his outstanding contributions to the field of navigation. As a result of his vital contributions to the development of Loran for approach use in the National Airspace System, he was made the recipient of the Medal of Merit from the Wild Goose Association.

Papers

THE 1990 DOT/DOD FEDERAL RADIONAVIGATION PLAN: Plans and User Projections for Loran

Elisabeth J. Carpenter
John A. Volpe National Transportation Systems Center
Cambridge, Massachusetts

Abstract

The Federal Radionavigation Plan (FRP), published jointly by the U.S. Department of Transportation and the U.S. Department of Defense, is the official source of Federal Government radionavigation policy and planning. The FRP, by direction of Congress, has been revised and published biennially for over a decade. The FRP addresses all Federally-provided civil and military common-use systems; however, the focus of this paper is on civil user plans and projections for the LORAN system.

There is presently extensive use of LORAN by the civil marine and aviation communities, and usage growth in these areas, as well as for terrestrial applications, is expected through the next decade. The Department of Defense requirement for LORAN will cease by the end of 1994 as GPS becomes operational; however, due to the extensive current use and projected growth rate among civil users, LORAN service will continue to be provided to civil domestic users beyond the year 2000.

Most current domestic research and development activities involving LORAN are for aviation applications and are funded by the Federal Aviation Administration; this includes activities related to 1) integration of LORAN into the National Airspace System, and 2) integration and interoperability of LORAN with other radionavigation systems.

Current plans for the FRP call for two user conferences to be held before the end of 1991, and for publication of a new FRP by the end of 1992.

Introduction

The Federal Radionavigation Plan (FRP) is the official source of information on U.S. policy and operating plans for present and future Federally provided radionavigation systems. The objectives of Federal radionavigation policy are to support national security, provide safety of travel, and promote efficient transportation services. In support of these objectives, the FRP provides the integrated Federal policy and plan for all common-use civil and military radionavigation systems; provides a means for addressing radionavigation requirements and identifying common-use systems and applications; outlines an approach for consolidating radionavigation systems; provides government radionavigation system planning information and schedules; defines and clarifies new or unresolved radionavigation system issues; and provides a focal point for user input.

The FRP is prepared and published jointly by the U.S. Department of Defense (DOD) and the U. S. Department of Transportation (DOT). A Memorandum of Agreement (MOA) between the two agencies, initiated in 1979 and renewed in 1984 and 1990, requires coordination between DOD and DOT for navigation planning and publication of a single DOD/DOT radionavigation plan. The MOA recognizes that DOD and DOT have joint responsibility to avoid unnecessary overlaps or gaps between military and civil radionavigation systems and services. Both agencies have radionavigation system responsibilities that, while stemming from different missions, often have significant commonality. The FRP was first published in 1980 as part of a Presidential Report to Congress, prepared in response to the International Maritime Satellite Act of 1979. The plan is now published biennially as a stand-alone document.

DOT is responsible for ensuring safe and efficient transportation. Radionavigation systems play an important role in carrying out this responsibility. The two main elements within DOT that operate radionavigation systems are the United States Coast Guard (USCG) and the Federal Aviation Administration (FAA). The agency responsible for coordinating radio-navigation planning within DOT is the Research and Special Programs Administration (RSPA). Other elements in DOT have ongoing or periodic interests in radionavigation planning. DOD is responsible for developing, testing, evaluating, implementing, operating, and maintaining aids to navigation and user equipment required for national defense, and ensuring that military vehicles operating in consonance with civil vehicles have the necessary navigational capabilities.

Figure 1 shows the structure of the navigation planning function within DOT. In coordination with the DOD radio-navigation planning function (Figure 2), the members of the navigation working group produce an updated and agency-approved version of the FRP every two years. The long-term goal is to establish, through an integrated DOD/DOT planning and budgeting process, a cost-effective and user-sensitive mix of systems for the post-2000 time frame. Liaisons are maintained with the civil users, the international community, and other concerned government agencies during the consultation, review, and recommendation cycle.

Each edition of the FRP includes a statement of current DOD/DOT radio-navigation planning policy and a definition of DOD/DOT responsibilities. The plan then discusses civil and military user requirements for air, land, marine, and space phases of navigation; current and projected use of Federally-provided radionavigation systems; and Federal research, engineering, and development (R, E and D) activities in radionavigation. Radionavigation systems covered in the FRP include LORAN, Omega, Very High-Frequency Omnidirectional Ranging (VOR), VOR/Distance Measuring Equipment (DME), Tactical Air Navigation (TACAN), VORTAC (VOR/TACAN), Instrument Landing System (ILS), Microwave Landing System (MLS), Transit, radiobeacons, and the Global

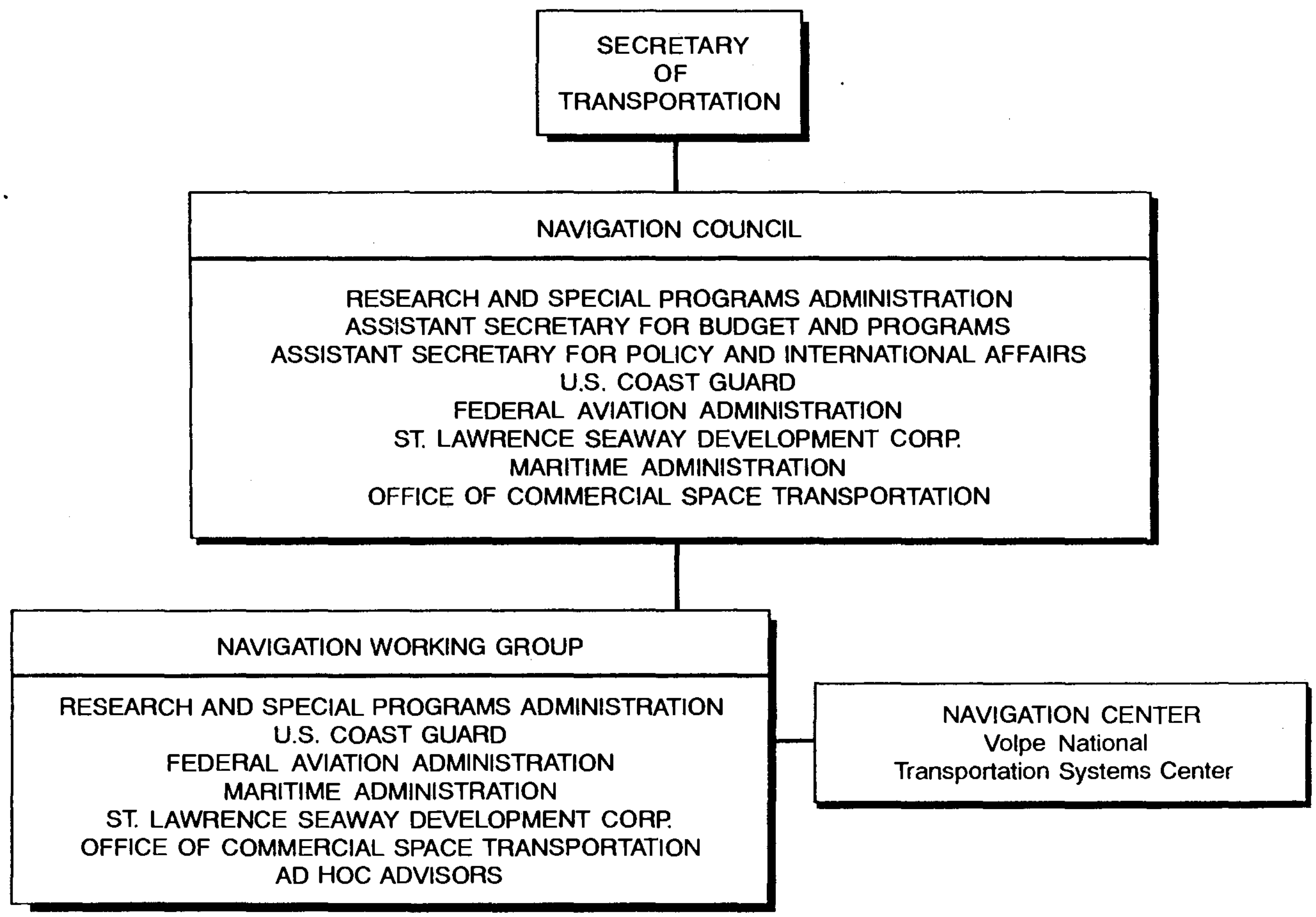

Figure 1. DOT Navigation Management Structure

Positioning System (GPS). The following sections focus on plans and projections for the LORAN system, as defined in the 1990 FRP. As the DOD requirement for LORAN will terminate in 1994, the focus will be on civil use of LORAN.

LORAN System Usage and Operating Plan

System use. There is presently extensive use of LORAN by the civil marine and aviation communities, and growing terrestrial use, due to increased coverage and the lowered costs of LORAN receivers. LORAN is designated as the official Federally-provided radionavigation system for U.S. coastal areas. LORAN is also used in the ocean phase of navigation and may have applications in the harbor/harbor approach phase. For aviation applications, LORAN has been certified as a supplemental navigation aid for en route navigation in U.S. airspace. It may also be used for oceanic en route navigation where applicable and work is proceeding on enabling LORAN to be used as nonprecision approach aid. Terrestrial use of LORAN is a relatively new and growing area. Land uses now include monitoring vehicles involved in interstate, commercial, and emergency services; in the transportation of hazardous material; and in a variety of vehicle control/dispatching functions.

Current and projected use of the LORAN system is shown in Table 1. Maritime users obviously comprise the largest percentage of LORAN users; however, projections of user growth in this segment beyond the year 1993 were not available for the current FRP. Use of LORAN by the aviation community and land users is expected to grow steadily at a moderate rate. Although no figures are provided for growth of LORAN use among land users beyond the year 1994, some moderate growth may be expected in this area over the next decade, as LORAN is one of the radionavigation systems being investigated for land navigation and radiolocation applications.

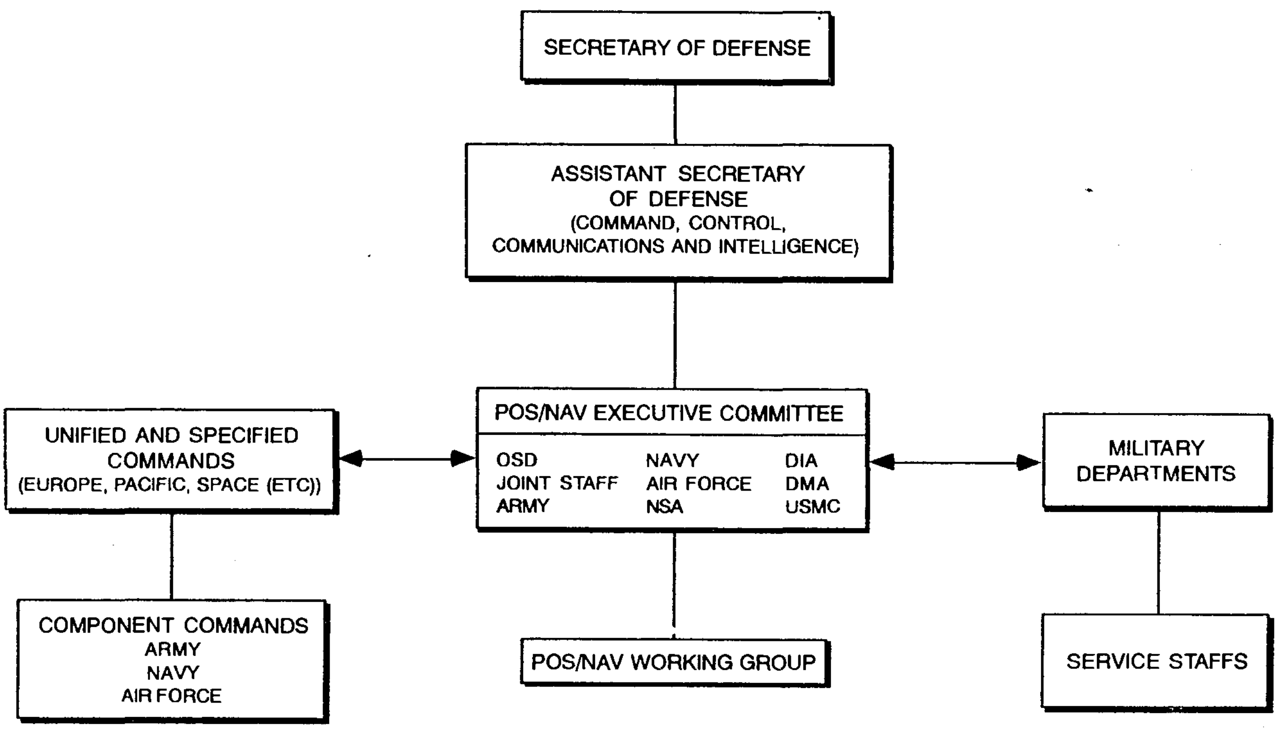

Figure 2. DOD Navigation Management Structure

In the international arena, Canada, as a partner nation with the U.S., operates four Canadian stations; in conjunction with stations in the U.S. and Greenland, three Canadian chains are formed. There are plans to expand LORAN for maritime use in Northern Europe, and for development of a potential Joint U.S./USSR Chayka/LORAN Chain in the North Pacific. France, the People's Republic of China, and Saudi Arabia have their own loran chains. Several other countries, including Venezuela and India, are considering plans for loran chains.

Operating plan. Under current plans, the DOD requirement for LORAN will terminate in 1994 after GPS becomes operational. The domestic (CONUS) LORAN system will continue to be operated beyond the year 2000, with no specific phase-out date for civil use.

In terms of domestic enhancement of the LORAN system, the U.S. Coast Guard is pursuing a LORAN equipment recapitalization program. Older transmitters in Alaska will be replaced through 1993 to result in only two transmitter types to be maintained in the U.S. and Canada after overseas U.S. operations are terminated. Timing and control equipment is being redesigned to make use of new technologies while meeting expanded requirements for integrity, time synchronization, and economy of operation. In addition, the FAA-sponsored mid-continent expansion of the LORAN system will provide coast-to-coast LORAN coverage in the U.S. Further expansion to provide coverage to the Caribbean, Eastern Hawaii, and Northern Alaska is not cost-beneficial.

As LORAN has been designated by the FAA as a supplemental system in the National Airspace System (NAS), the FAA plans to fully implement LORAN in the NAS by approving non-precision approaches at selected airports that have adequate LORAN coverage. Local LORAN monitors will be deployed throughout the NAS to provide the calibration values required for nonprecision approaches. In terms of standards and certification for LORAN, the FAA and the USCG are preparing a National Aviation Standard for LORAN which will specify aviation requirements for user and provider systems; Advisory Circular AC 20-121A and Technical Standard Order TSO-C60b have been prepared by the FAA; and RTCA Special Committee No. 137 has issued a Minimum Operational Performance Standard (MOPS) for LORAN receivers. Efforts will continue to improve master station synchronization with Coordinated Universal Time (UTC).

A policy change in the 1990 FRP is the specific mention of the shutdown of the Central Pacific chain and the possible host-nation continuation of service at foreign stations. On the international front, the DOD requirement for LORAN will cease at the end of 1994, resulting in either closing overseas chains that support DOD or transferring them to operation by host nations. Several Northern European nations and Canada are

Table 1. LORAN Projections

FACILITIES/ USERS	CALENDAR YEARS													
	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
U.S./CANADIAN FACILITIES	26	30 [1]	30	30	30	26 [5]	26	26	26	26	26	26	26	26
U.S. OVERSEAS FACILITIES	16	16	16	16	16	0	0	0	0	0	0	0	0	0
U.S. CIVIL AVIATION USERS [2]	79,500	80,000	80,500	81,000	81,500	82,000	82,250	82,500	82,750	83,000	83,250	[3]		
U.S. CIVIL LAND USERS [4]	20,000	22,000	24,200	26,600	29,300	[3]								
CIVIL MARITIME USERS (WORLDWIDE) [2]	450,000	470,000	490,000	[3]										
DOD USERS	700	500	500	450	250	[3]								

[1] *Increased to provide conterminous U.S. coverage.*
[2] *Includes non-DOD Federal users.*
[3] *Data beyond this year are not available.*
[4] *Civil land users include survey, timing and other applications.*
[5] *Central Pacific chain shut down.*

developing an agreement concerning a mutual cost-sharing arrangement to take over and continue operation of USCG LORAN stations in Northern Europe after the DOD requirement ends. In the Mediterranean area where several stations are located, Spain and Italy have indicated interest in taking over operation of these stations. Korea has taken over ownership and operation of the stations in their country previously owned and operated by the U.S. Air Force. In addition, the U.S. and the USSR have agreed to establish a jointly-operated LORAN/Chayka system to provide service in the north Pacific Ocean and the Bering Sea.

Civil use in the continental U.S. will not be affected by the cessation of the DOD requirement for LORAN.

LORAN Research and Development (R&D) Activities

LORAN R&D. According to the 1990 FRP, the bulk of LORAN-related R&D activities are for aviation applications and are funded by the FAA. As mentioned above, development of LORAN non-precision approaches will continue for appropriate airports. The FAA will continue to address use of LORAN to supplement the existing VOR/DME system for remote areas and for helicopter IFR operations.

System interoperability. A particular areas of interest is interoperability and integration of LORAN with other radio-navigation systems. The benefit of this is that radionavigation systems may sometimes used in combination with each other or with other systems in such a manner that the strengths of one system supplement the weaknesses of another. The increased performance potentially offered by integrated and/or interoperable systems is an area that could benefit from increased emphasis.

Integrated navigation receivers combine the signals from multiple sensors to determine position and/or velocity. Systems have the potential to be interoperable if the time references of different systems can be related to one another in a known manner. LORAN is in the process of being more closely coordinated with UTC, which could result in better synchronization with GPS.

In 1989, the FAA and the USCG completed studies of GPS/LORAN interoperability in response to a request from Congress to the FAA. The FAA plans to continue investigations of GPS/LORAN integrated operations and interoperability. Ongoing work includes development of receiver avionics which combine signals from GPS with LORAN signals to take advantage of the periodic coverage as the GPS constellation builds up. Through VNTSC, Ohio University has been doing this work on hybrid LORAN/GPS receivers, which is now in the flight test stage. These systems have a real potential to contribute to the development of multisensor navigation systems that can have major beneficial impacts on the safety, reliability, and efficiency of national and international transportation. Studies on combined MLS use with GPS and LORAN for various aviation applications have been ongoing at The Analytic Sciences Corporation (TASC) through VNTSC.

Terrestrial applications. There are no specific activities planned by DOT agencies for using existing radio-navigation systems in terrestrial applications. However, this area of development is being watched with interest by DOT organizations.

Planned Activities

The two-year planning cycle for the 1992 FRP started in January 1991. Open meetings for radionavigation systems users to attend and provide their input have been planned for November, 1991 in Alexandria, Virginia, and December 1991 in Seattle, Washington. The next edition of the FRP will be published by December 1992. The radionavigation planning and review cycle will be continued until GPS is fully operational and it has been determined how to meet users needs with the optimum radionavigation systems mix.

Acknowledgements

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Biography

Elisabeth Carpenter joined the technical staff of the Volpe National Transportation Systems Center/Center for Navigation in August, 1990. Since that time, she has worked on Federal radionavigation planning, LORAN projects, and satellite integration planning for the Federal Aviation Administration. Prior to her employment at VNTSC, she was a member of the technical staff at the Jet Propulsion Laboratory in Pasadena, CA., where she worked on system requirements for space station and advanced technology development and applications. From 1985 to 1987, she managed the Mobile Satellite Program for the National Aeronautics and Space Administration in Washington, DC. She earned Bachelors and Masters degrees in Physical Geography from the University of California (Los Angeles and Davis) and is a member of AIAA, the Association of American Geographers, the Institute of Navigation, and the Wild Goose Association.

Radionavigation Policy Planning In Today's Dynamic Environment

Edward L. McGann
Megapulse, Inc.

ABSTRACT

The multitude of forces acting on the navigation planning community has never been experienced before. Expanding user communities now using Loran-C face the choice of staying with Loran-C or going to GPS. Political, financial, and military considerations have changed the near-term prospects for GLONASS and the strategic lessons learned in the Gulf activities have refocused the question of—should the US provide GPS to the world? The author looks at Chayka/Loran-C expansion in terms of affordability and effectiveness and raises the consideration of a peaceful, non-threatening satellite configuration meeting most user requirements in inter-operable modes with GPS/Chayka which can be internationally accepted and supported such that GPS can be free to serve its primary US interests military mission.

DISCUSSION

In the distant past coastal bonfire keepers colored the flames of their beacons with special materials so that mariners navigating nearby could distinguish one beacon from another and thus safely traverse the shore or approach a harbor. Information on the color or other characteristics defining a certain beacon and its associated location was passed by any means available throughout the concerned maritime community. Horns were blown in specified patterns and pillars and buoys were colored in distinctive ways, the patterns of which were also disseminated throughout the potential user community so as to assist in the safe and effective movement of vessels in the various areas. On land similar markings and directions evolved — the High Road, the Low Road, this path for westward traffic, this one for eastward traffic marked by symbols which over time become standardized and recognizable even by illiterate transporters on international trade and emigration routes because their symbolism and meaning was of fundamental importance to the safety and effectiveness of movement of the people and goods involved in these transport activities. Safety — effectiveness — the fundamental precepts of navigation practices then and now. And how were these issues defined and the requirement quantified? Were there "navigation system user conferences"? Indeed there were! Discussions were regularly held among the merchant princes and those bodies controlling national aids-to-navigation. And the day-to-day users alongside the governmental providers regularly discussed these navigation issues — most appropriately one would believe in wayside and dockside pubs and hostels — communicating the concepts and ideas to their respective corporate and bureaucratic entities. Probably there were not many manufacturers or lobbyists or lawyers or "research" organizations living off research and development funds in those times as there are now. As has been true throughout history there were, most probably, bureaucrats who sought ways to enhance their power, travel more broadly and set themselves up for future profitability. There were also, in those times, many determined, competent, well meaning participants in the process especially users and providers but including some bureaucrats and even an occasional politician.

Moving on to modern times there came long after the depth rope and compass — the alternatives: radar, sonar and electronic positioning and aid-to-navigation systems to complement the historic charts and visual and audio navigation aids. The mid-twentieth century saw the evolution of all of the aforementioned new technologies and while local users and authorities struggled to define local standards — such as one set of altitudes for east/west flights and another for north/south flights — international organizations wrestled with the even more difficult tasks of attempting to reach accord on each issue with due regard for: individual national standards which often independently evolved in orthogonal directions, manufacturers equipment performance specifications which are many times not in concert with one another; issues of national sovereignty and price — and as always — the promise of better technologies capable of replacing everything else available currently and which are just around the corner according to their well funded proponents. And, of course, proponents of developing systems have always had the advantage. Promises are much easier to sell than proving the factual performance of existing systems which always necessarily includes some limitations. Then too, at least in the United States, programs in their evolutionary phase are eligible for research and development funding — so they can buy their own supporters in the universities and research groups which rely on such funding. Systems already in operation are denied such financial and political support on the premise that if a system is operational, it has fulfilled its potential so just let it run. No doctoral thesis explorations are sponsored for the enhancement of operational systems nor is there many attendees at technical symposia. And certainly the mundane, effective working systems do not attract exploitive pulp press exposure.

Before we leave history, it should be understood that in those days whatever policies evolved, they were the work of professional navigators and service providers and were relevant for the specific local geographic areas concerned and then coordinated over wider areas when possible.

From the aforementioned historical entry, let us consider how US navigation policy has evolved over the past two decades, what might happen in the coming years, how these activities and the advent of new world spanning technologies might impact on international navigation policies and finally to focus on policy determination procedures: identifying a need, defining the required performance criteria, examining the relevant operational, legal, financial and political aspects and involving by the necessity for an open, public process which recognizes that the navigation policies of today are not concerned with a few local professional, closely involved individuals or groups but rather a broad-based community of navigation system users who in the main know nothing of the technical operational details or limitations of the navigation system on which they are depending. Making the issues even more difficult are radio-aid-to-navigation systems provided by one country or one organization which are potentially capable of providing some services worldwide. This capability raises new issues never before faced in navigation policy discussions such as international liability, political influence by the supplying nation on others, and the fair and equitable distribution of capital and operational costs among the nations drawing benefits from system or systems provided by other and sometimes geographically remote countries. Todays' considerations moreover still must address the political, technical and economic confrontations of one nation or groups of nations against the others.

Technological advances, while bringing significant benefits, set in motion all types of trade-offs and modifications to past policies and practices. More accurate long range or wide area navigation aids for instance permit safe operation closer to shore in maritime operations thus reducing the range requirements on visual and audio aids in critical coastal areas and harbor approaches which in turn leads to such operational benefits as reduced electrical power input and the resultant lower capital cost/operating costs — but it also mandates changes in shipboard procedures and in the legending of applicable charts. In certain areas new, more efficient systems can lead to the demise of older configurations. In many cases the changes are coming about so rapidly that it is difficult for all parties to coordinate the necessary actions even with the best of intentions. In the case of radio aids-to-navigation the situation is simply chaotic — in a large part due to the lack of recognition of the magnitude and importance of the issues by the responsible authorities. A whole new high level appreciation of the issues is needed which should in turn then lead to the establishment of the organizations and procedures much more appropriate to deal with these matters than the ineffective processes in place today which are at best structured to address the needs of the navigation community a generation ago. At the worst many countries have no organization addressing these issues and major new and evolving user communities such as those with vehicle location systems are completely without representation even in the United States whose planning document — the Federal Radionavigation Plan (FRP) is looked at as the world standard.

Returning for the moment to the pre-World War II era we remember that radio beacons were the extent of radio aid-to-navigation systems for both maritime and aviation activities. These were installed and operated whenever the close knit user community decided they were needed if the required funding was available. World War II saw the introduction of the Decca Navigator and Loran-A systems. Their implementation reflected two widely different policies. Loran-A was parochially installed in the US, Canada and Japan and later initiated into the Peoples Republic of China essentially by governmental initiatives without any corporate based driving force simply based on wartime experiences. The Decca Navigator system as a proprietary, patented system was marketed worldwide — particularly successfully in Northwest Europe, Canada, India, Japan and South Africa. The user communities of those pre-semiconductor days were limited by user equipment price rather than national policy decisions which continued to be made essentially by the tight knit user/provider community. The 1970s saw the regional worldwide development of much more affordable user equipment which then expanded the user community from the traditional large merchant vessels and larger fishing vessels into the smaller commercial vessels and indeed into the recreation market where such use could vastly improve safety and reduce USCG costs by reducing "Sunday evening" recovery calls. To address the situation and faced with the prospect of choosing between Omega, Loran-C, Loran-A and Decca Navigator (as well as some less known prospects) so as to define the final system, the USCG convened the so-called "Polhemus Panel" — chaired by the respected navigator William Polhemus. This panel — for perhaps the only time in navigation policy planning to date — set out first to define the users and the operational requirements for each segment of operations — open waters, harbor approaches, etc. More importantly this panel established the procedures whereby proponents of each candidate system addressed questions to the others and answered the questions of the others in what might be described as a "fight to the finish" — all in public and on the record. In the end all systems proponents agreed that Loran-C was the correct choice based on the technical, operational, cost and benefit considerations. Loran-C was designated as the official radio aid-to-navigation system for CONUS navigable waters. The marvelously foresighted USCG proponents were correct in their projections of the benefits that solid state technology would bring to the users and today Loran-C is the most widely used radio-aid-to-navigation system in the world. Incidentally if one would like evidence of the pain of untimely navigation system planning and policy take the time someday to talk to the folks of Canada who followed the "head-fakes" of the US during the 1960s flirtations with

Loran-A, Decca and Omega. From the Canadian viewpoint, the US choice of Loran-C — to which our friendly neighbors also concurred — must only have been received by a — "I hope this is the last one" acceptance. Through the 1970s, of course, the FAA grandly ignored the prospect of Loran-C in the derivation of its National Air Space Plan (NASP). Only the pressure of a rapidly growing general aviation user population — in spite of any official acceptance — and the technical data collections/and presentations of Texas Instruments (bless them even if they are no longer in the Loran-C community) grudgingly dragged the FAA into the Loran-C community.

In the same 60s and 70s time period OMEGA was implemented as was TRANSIT — why argue about their value even now when both have some real applicability, the operating costs are relatively small and in the case of OMEGA — the costs have come to be shared by a number of countries. Most of the initial incentives were from the US DOD but there have been significant civil applications. Few policy considerations arose until recently concerning these systems.

Also in the 1970s came the concept of a satellite-based navigation system to satisfy the worldwide requirements of the US military and its allies — shortly thereafter followed by a similar concept in the Soviet Union for achieving their purposes. A most interesting prospect — being able to precisely locate all cooperating military units anywhere in the world using the most advanced technology. How well it fit into the military-industrial complex prime project profile. And politically all those satellites represented a significantly enlarged launch manifest requirement which justified a larger space shuttle fleet — and more launch complex and control facilities and more astronauts etc. But, as usual, all DOD programs compete for funds and in this environment some DOD elements raised issues as to the performance acceptability of NAVSTAR/GPS — it was not self contained on the individual military platforms — it was vulnerable to enemy attack and electronic countermeasures — it would not work through an ionosphere ionized by a nuclear blast — it would not work in valleys, cities or under foliage — and it would give the enemy as much advantage as it gave friendly forces. But its proponents — both military and industrial — rose to the occasion and reconfigured the system reducing the number of satellites (note they were later again increased) thus reducing cost, added nuclear detection capability (increasing both the DOD priority and the ranking on any enemy hit list). Finally it was portrayed that this satellite based system would replace and/or negate any other position fixing/navigation systems both for military and civilian purposes — or so said the proponents. In the absence of any statutory policies and procedures the political process of Washington, D.C. prevailed and the posture of the proponents was accepted by no less a technical and operational authority than the Office of Management and Budget which then mandated the establishment of a procedure to bring into concurrence the navigation policies of both the DOD and the DOT and set forth a schedule within which the GPS would replace all existing and proposed systems — hence the Federal Radionavigation Plan (FRP). And you thought this momentous document came about through the knowledgeable and virtuous efforts of the professional navigation community to give creditable guidance to US navigation policy evolution. The first edition of the FRP did indeed set forth a schedule of replacement and shutdown which, of course, has since been shown to be completely without justification — however, this totally erroneous — but politically official proclamation has confused and delayed the implementation and acceptance of radio navigation systems worldwide over the past decade. Each subsequent issue of the FRP has moved away from the initial posture reflecting first its intrinsic lack of credibility and then the realities of the real-world implementation schedule of satellite systems and the recognition of their real performance characteristics and thirdly the enormous expansion and acceptance in the interim period of other navigation systems and technologies — particularly those of Loran-C. Navigation policy and certainly US commercial export business have however, been negatively effected over the past decade by the overly optimistic and oftentimes blatantly untrue presentation of the GPS political future and its projected performance.

Just a few more points of commentary — in the early 1980s at the time of the tragic Korean Airline (KAL007) incident over Soviet territory, President Reagan declared that the US would make the GPS available to the international civil aviation community on the basis that if KAL007 had this navigation capability the incident would never have happened. Does anyone really believe that the aircraft was lost? Do we think President Reagan had such an in depth grasp of all national programs that he immediately saw the potential application of GPS to avoid future similar incidents? To be callous, this regrettable incident was used by the DOD supporters of GPS as well as very interested industrial interests placed in White House advisory roles to promote the GPS in a way that cloaked President Reagan's statement and Congress' later affirmation as a humanitarian gesture — but the US radionavigation policy has been skewed since that time by that baseless promulgation.

Note there were no performance, policy, legal, economic assessments leading up to this posture — just a grotesquely, opportunistic action. And it goes on. Last month FAA Administrator Busey announced to the ICAO conference on Future Air Navigation Systems (FANS) that the US would provide the GPS signals without direct charges to the international user community for ten years after 1993 as an affirmation of President Reagan's "commitment". As involved members of the navigation community are any of us knowledgeable of the in-depth legal, economic, political and operational considerations which must have proceeded this promulgation? Certainly satellite-based communications/positioning systems have a role in the future of international aviation but why should US taxpayers bear the burden — and the potential liabilities? If the projections are that international airlines will save $5.5 Billion annually why should US taxpayers pay over $1.0 Billion annually to support the system for the world. Even tiny Australia projects an $800 million internal market and a $1.2 Billion export market for its GPS products based on freely provided GPS signals. How about some of profitability being returned to the US taxpayer? And the same goes for each other benefitting country — particularly Japan.

On another issue we remember that in 1982 the USCG issued a Federal Register notice indicating their intent to install a differential Loran-C system in Valdez harbor stating that its R&D work had shown that such a system would be effective for vessel traffic management and safety and that the implementation would be simple and would be in concurrence with the definition of Loran-C as the official radio-aid-to-navigation system for US navigable waters and its recognition as such in our legal system. Unfortunately the notice concluded with the comment that no further actions would be taken if the associated cost benefit analysis did not show it to be the desirable course of action — and, of course, nothing was implemented. So much for cost/benefit analysis! Presently the USCG is moving to implement a differential GPS in Valdez. Why not Loran-C or GPS/Loran-C? According to the USCG they have to do it quickly (there were over 8000 transits in that area over a decade of time before the Exxon Valdez incident), R&D funds are only available for GPS (as mentioned earlier, operational systems do not qualify) and differential Loran-C might not do the job (their own 1982 Federal Register comments notwithstanding). There was apparently no consideration that Loran-C is an officially and legally recognized system — GPS is still at the "use at own risk" developmental stage or that RTCM specification #104 defines the signal format for dissemination of both differential GPS and differential Loran-C. One would not be concerned if this were only an isolated installation but it is projected by the USCG procurement request as a forerunner of the standardization not only of national VTS but of harbor/harbor entrance installations and quite possibly of dependent surveillance for all US navigable waters. Note that how things have degenerated to no Federal Registration announcement — no public comments in spite of the fact that eventual VTS harbor/harbor entrance issues could effect or benefit many times more current Loran-C users than could have been effected in 1982.

In both the above examples the fact that there might be user interests have been completely ignored and public comment has not only not been sought but has been completely and deliberately circumvented.

Are there other issues — certainly! Go to a GPS Civil User Conference — which is paid for by US taxpayers in addition to the fact that the same taxpayers have paid for the $15 Billion development/deployment cost and will continue to pay the $1.0 Billion plus yearly operating costs of the GPS. Listen to the demands — and demands they are demands — of representatives of other non paying countries as to what they want from GPS. See the US GPS policies being pressured by a few US business interests — whose long term prospects are questionable — and a large group of survey people whose concerns ought not to bias navigation policy unless they have an overwhelming requirement or concern (and by the way why should we not restrict precise GPS signals for survey purposes to only wholly owned US companies — we pay for it, we should get the benefits).

To summarize the author urges that before we get to any further US "policy" statements let us try to realize how they effect users and manufacturers — and to a lesser extent system operators — and let's get the interested parties involved. Right now those who have the least concerns and investment are making the policy decisions — such as they are.

If you do not believe you — as navigation professionals — are out of the loop let me ask you —

1) Have you seen the analysis defining why TRANSIT cannot be continued or transferred to a mon-military organization — US or international?

2) Have you reviewed the report defining which prospective new user communities GPS will serve or the ones it will replace on an operationally acceptable and economically beneficial basis?

3) Did you see the analysis examining the continuation or not of OMEGA operations?

4) Are you involved in the assessment of whether Microwave Landing Systems (MLS) should indeed replace Instrument Landing Systems (ILS) or whether both should be replaced by differential GPS?

5) Have you ever made a comment on the FRP and been completely ignored? Not only wasn't your comment examined or explained — it usually wasn't even acknowledged and by a damn site was not incorporated. This comment is not a reflection on the people now involved but rather on the process. Compare today's process with the Polhemus Panel where all the questions got answers — in public.

In conclusion, it is author's opinion that the present radio navigation planning process is conducted at far too low a political level considering its huge impact on users, manufacturers and administrations. It is grossly under recognized, under funded and understaffed. As a result US policies are responsive (and untimely) not directive and heading and are often driven by foreign interests. If you do not believe this assertion — come to the next conference held to elicit public commentary on the FRP. Held for only one or two days within the biannual preparation period of the next FRP edition, such sessions are notable for the absence of any high level DOT/DOD/FAA/USCG representative.

So as to overcome this serious policy-making shortcoming, it is recommended that the US which realistically provides almost all navigation technology and candidate systems (excepting GLONASS) must establish at the visible and responsible level (DOT Under Secretary) an office for civilian navigation policy planning and implementation and further that on the international level a navigation/position fixing policy forum be established perhaps within the United Nations structure — so as to oversee and guide the evolution of future policies with applications to land, sea and air operations.

Author's biography. Mr. Edward L. McGann has been involved with Loran-C since the mid-1960s. He has presented a number of papers on the subject and has worked on the design of various Loran-C equipments and the implementation of Loran-C systems in many parts of the world. Expansion of Loran-C world-wide has been his continuous goal. Mr. McGann is currently Executive Vice President of Megapulse, Bedford, MA, USA. He was a Director and former Vice President of the Wild Goose Association and received the Presidents award for service to Loran-C. He was a member of the Institute of Navigation and was a committee member of the National Ocean Industries Association. Mr. McGann holds a Bachelors and Masters degree in Electrical Engineering from the University of Lowell in Massachusetts.

A Program Status Report on the NAVSTAR Global Positioning System (GPS)

CDR Dennis R. McLean, USCG
Deputy Program Manager for DOT
USAF Space Systems Division/MZT

ABSTRACT

The Joint Program Office at the US Air Force Space Systems Division has the responsibility for the development, test and deployment of all three program segments - Space, Control, and User of the Global Positioning System (GPS). Once fully operational the twenty-one satellites and three active spares will provide continuous, worldwide position, velocity, and time data to a wide variety of military and civilian users, with a fundamental aim of becoming the primary navigational system for all military and civil aircraft for the US and its allies. The NAVSTAR GPS program has entered the production phase in all three segments. The Space Segment is launching Block II satellites, GPS logistical support transferred to Air Force Logistics Command in October 1987, and operational responsibility for space vehicles transferred to the Air Force Space Command in may 1990. User Equipment is in Limited Rate Initial Production. This paper will present the status of the GPS as it transitions into the operational phase of the program.

BACKGROUND

Since the early 1960s, the Air Force, Army, and Navy have actively pursued the idea that all weather global positioning and navigation could be performed using RF signals transmitted from space vehicles. Such a system could meet the needs of a broad spectrum of users and cut cost by reducing the proliferation of specialized equipment responsive only to particular mission requirements. The Air Force was appointed as the executive service for the GPS program by the Secretary of Defense, and as such manages the overall program from the NAVSTAR GPS Joint Program Office (JPO), located at HQ Space Systems Division (SSD), Air Force Systems Command (AFSC) at Los Angeles AFB in El Segundo, CA. In this case, manages is defined as "design, develop, acquire and place into orbit the operational GPS satellites; establish an Operational Control System (OCS) to maintain the GPS satellites on orbit; and design, procure, and maintain User Equipment (UE) for the US military and our allies".

The development and acquisition of GPS has so far taken place in three general phases. The first phase was devoted to validating GPS concepts, the second to full-scale engineering development of its three segments, and the third to production deployment. A fourth phase will begin once GPS reaches its Full Operational Capability (FOC) milestone.

The US military services, as well as representatives from the Defense Mapping Agency, the Department of Transportation, the North Atlantic Treaty Organization, and Australia maintain active participation at the JPO.

GPS was designed to be a passive, survivable, continuous system which will provide any suitably-equipped user with three-dimensional position, velocity, and precise time information. The high levels of accuracy provided by the Precise Positioning Service (PPS), will be denied to unauthorized users, but the reduced accuracy Standard Positioning Service (SPS) is available free of charge to any worldwide user.

The GPS segments are Space, Control, and User. Space Segment consists of the planned constellation of twenty-one GPS satellites, also known as Space Vehicles (SVs), and three active spares. Segment responsibilities encompass satellite development, production, and launch. The orbits of the constellation had been optimized to support the UE test program, but were rephased in 1990 to maximize the orbits on a worldwide basis.

The OCS of the Control Segment consists of three Ground Antennas (GAs) - Ascension, Diego Garcia, and Kwajalein, five Monitor Stations (MSs) - the GAs plus Colorado Springs and Hawaii, the Prelaunch Compatibility Station (PCS) at Cape Canaveral, and the Master Control Station (MCS), resident with its collocated MS at the Consolidated Space Operations Center (CSOC) at Falcon AFB near Colorado Springs, CO.

The User segment consists of families of UE sets and their associated support equipment. A Limited Rate Initial Production (LIRP) contract was awarded in 1986 as a result of the Joint Resource Management Board (JRMB) Milestone IIIA decision. A Full Rate Production decision is possible as early as January 1992.

SPACE SEGMENT STATUS

Of the initial eleven prototype Block I satellites, ten were successfully launched into 63 degree orbit planes. Five of these remain useable for GPS test missions. The oldest of these, Navstar-3 or Pseudo-Range Noise Number 6 (PRN-6) was launched in 1978. Twice per year now, during ecliptic periods, its power system cannot always provide continuous power and it must be shut off. The other four are continually operational.

The Block I SVs were launched into 63 degree inclined orbits and do not fit within the defined Block II SV constellation. Plans are to rely on the Block I SVs to augment the coverage provided by the growing complement of Block II SVs until such time that twenty-one of the Block II SVs are on orbit.

The first of the Block II, or operational satellites, PRN 14 or II-1, was launched on 14 February 1989. The Block II SVs included subsystem design enhancements from the Block I SVs plus necessary changes to support the full operational GPS system requirements. Significant Block II enhancements include:

* Radiation hardened electronics.
* 180 days worth of navigation message storage.
* Full Selective Availability (SA) and Anti-Spoofing (A-S) capabilities.
* Automatic detection of certain error conditions for security.

When fully deployed, the on-orbit GPS constellation of twenty-one operating BLOCK II SVs plus three active spares will be arranged with four SVs in each of six nearly circular orbital planes. The orbital planes have an inclination angle relative to the equator of 55 degrees and the SVs will have an average orbit altitude of 20,200 km relative to the surface of Earth. This is the semi-synchronous altitude where a complete orbit takes about one-half sidereal day to complete and the SVs therefore follow a ground track which repeats every sidereal day (approximately 23 hours, 56 minutes).

The spacing of the SVs in their orbit planes has been selected so as to maximize the probability that at least four SVs with good Dilution of Precision (DOP) will always be visible to users at every location on Earth.

Since that February 1989 launch of the first Block II SV, Space Segment has launched eleven more. PRN 23, II-10, was the first of the Block IIA "heavyweight" satellites. It experienced a solar array drive failure on orbit in December 1990 due to a design anomaly. Air Force Space Command (AFSPACECOM) and the JPO developed procedures to control the solar panels manually to ensure the satellite remains a productive asset to the overall constellation. The launch schedule was delayed until the cause of the failure was found and fixed in follow-on SVs. PRN-24, the second of the "heavyweights", was launched 3 July and has completed testing.

Due to the Shuttle Challenger tragedy and the subsequent unavailability of the Space Transport System (STS) for GPS satellite launches, a contract was awarded to McDonald-Douglas in 1986 for production of medium launch vehicles (MLVs). Twenty MLVs were procured on this contract. The SSD has since purchased ten additional MLVs via the competitive bid process to provide sufficient launch vehicles to reach a full constellation by the second quarter of FY 1993.

To ensure the continued availability of an operational worldwide GPS, the JPO awarded a contract, after a full and open competitive process, to General Electric Astro-Space Division in 1989 for twenty Block IIR (R for replenishment) satellites with delivery to begin in 1995. The Block IIR SVs have the capability to autonomously navigate (AUTONAV) themselves and can essentially generate their own 50 Hz navigation message data. The navigation message is part of the Space-to-User Interface often referred to as the GPS "Signal-in-Space" or SIS. (The GPS SIS comprises the PRN sequence Time of Arrival (TOA) ranging code, the L-band RF carrier waves, and the 50 Hz navigation message data streams.) The Block IIR SVs will contain crosslink ranging and on-board navigation data processing capabilities. The concept is that each SV periodically will measure the distance to other SVs. Then each SV will transmit measurement corrections to the other SVs, and they will transmit these data to the ground if commanded. Finally, each SV will compute corrections to pre-loaded navigation messages provided by the OCS. The satellites will have seven months of broadcast ephemerides uploaded only once per month by the OCS. This AUTONAV capability allows the Block IIR satellites to maintain full SIS accuracy for at least 180 days without Control Segment support. AUTONAV will also provide significant improvements in both the reliability and integrity of the broadcast SIS. The first launch of a Block IIR SV is currently scheduled not earlier than 1995.

The GPS SVs were initially launched into orbits with emphasis on maximizing coverage in the vicinity of Yuma, Arizona to support the military UE testing done in that area, and to support the operational test effort for both the Block II SVs and the Control segment. When this initial testing was completed, the JPO developed plans to rephase - or adjust spacing within the orbital planes. This effort was carried out by AFSPACECOM.

Rephasing began on 15 March, 1990, and by the middle of December 1990, the existing SVs were relocated to provide initially two-dimension and ultimately three-dimension worldwide coverage for users. Without this rephasing and with a full constellation of twenty-one satellites, fifty percent of the world would have at least one-half hour a day when Dilution of Precision (DOP) would exceed ten, an indication of poor satellite geometry. Rephasing decreased that to only about five percent of the world, a considerable improvement.

Operational turnover of the GPS Space Vehicles (operations, planning, and maintenance) from the JPO to AFSPACECOM took place in May 1990. AFSPACECOM took responsibility for OCS mission software, sustaining engineering (modifications to hardware and software to maintain the capability of the system), launch, and on-orbit operations (including constellation buildup/replenishment planning). The JPO retained control of development engineering (acquisition of hardware and software to support major new requirements), early orbit operations, integrity of on-orbit SVs after turnover, and operational responsibility for any major anomaly recovery operations.

CONTROL SEGMENT STATUS

The Control Segment was the first segment of the GPS to undergo Program Management Responsibility Transfer (PMRT) from the JPO. Logistic support of the OCS of the Control Segment transferred to the Joint Service Systems Management Office (JSSMO) at AF Logistics Command (AFLC) on October 1987. AFLC at Warner-Robins Air Logistics Center (WR-ALC) took control of hardware maintenance, system software maintenance, and logistics sparing at that time. The JPO provided system software maintenance for AFLC until operational turnover of the space system to AFSPACECOM in May 1990.

Development of the Operations Capability (OPSCAP) Reporting and Management System (ORMS) began in September 1987. The ORMS provides GPS operators and US military commanders with system status information and will generate documentation in support of GPS missions. The complete military ORMS should be fully operational by early 1993. Some information provided by the system is already available to users via distribution nodes. A Notice Advisory to Navstar Users (NANU) has been developed that contains all critical information (health status, planned outages or tests, etc.) about individual SVs and the constellation in general. These NANUs are transmitted to government and certain civil users. The Coast Guard has taken over the responsibility to make the information in the NANUs available to the civil community. Their computer bulletin board and telephone recorded message service started on 20 March 1990. GPS status information is published in the Notice to Mariners by the Coast Guard and is also provided to users via NAVINFONET by DMA.

USER SEGMENT STATUS

The GPS UE is now a Low-Rate Initial Production (LRIP) program extended through fiscal year (FY) 1992. The rationale behind awarding an LRIP contract as opposed to one for full-rate production was two-fold. On one hand, the observed reliabilities of the various UE sets during Initial Operational Testing & Evaluation (IOT&E) were not up to their full specification values and it was therefore necessary to improve the quality of the winner's equipment prior to entering full-rate production. By taking the LRIP approach, the required manufacturing and design improvements could be made in a production line environment and a period of Reliability Demonstration Testing (RDT) conducted to ensure that the full specification values would indeed be met. On the other hand, the delay in the start of deployment of operational NAVSTAR satellites caused by the Shuttle Challenger tragedy meant there would be little need for full-rate production quantities of UE sets until the early 1990s, and so the LRIP option schedule could be sized to support both the needs of the RDT effort and those users with particular early-on requirements.

New contracts for UE for FY91 and FY92 were awarded after a full and open competitive bid process was completed. A Full Rate Production decision for an additional 25,000 sets is expected at the Defense Acquisition Board IIIB (DAB IIIB), presently scheduled for January 1992. Second sources have been developed for built-to-print production of the two-channel and five-channel Rockwell-Collins receiver designs (to Canadian Marconi and SCI Technology), and a contract was awarded for production of a non-development item (NDI) "off the shelf", manpack receiver. NDI contracts have been completed for alternate GPS fixed reception pattern antennas (FRPAs), controllable reception pattern antennas (CRPAs), and control display units (CDUs).

In addition to using second-source contracting for cost reduction, the JPO has explored several other innovative alternatives to gaining the maximum utility at minimum cost. First and foremost, it has been encouraging other qualified manufactures to participate in the GPS UE program by way of NDI procurements. This approach is based on buying commercial-type UE sets instead of military specification (MILSPEC) ones whenever their performance is adequate to satisfy one or more military mission needs. The cost of any militarization or other special development needed is borne by the potential NDI vendor prior to submitting samples for evaluation.

UE in-plant testing is ongoing for performance and environmental qualification. Production and integration units have been delivered from all contractor plants, and emphasis has been placed on adherence to the UE delivery schedules. Integrations are underway at service depots by contractor and government personnel for aircraft and helicopters in each service, aboard ships, and in numerous other ground vehicles belonging to the services. The first flight of an F-16 with a production phase GPS receiver occurred in June 1988, and since that time hundreds of test with GPS receivers have been performed by all services in a myriad of air, sea, and ground vehicles.

The UE program has focused on Initial Operational Test and Evaluation (IOT&E) and operational readiness planning. The test program included reliability growth testing, test-analyze-and-fix (TAAF), and technical test and operational analysis (TT & OA) prior to formal IOT&E. A variety of test platforms from the US services and the international community have been employed in the program.

GPS underwent the ultimate test during Operation Desert Shield, and Operation Desert Storm recently in Southeast Asia. Reports indicate that the system performed admirably.

SYSTEM LEVEL ISSUES

The GPS JPO organized a DAB IIIB Steering Committee to ensure all necessary actions are completed prior to the time for a full rate production decision at the DAB. Some issues that will be resolved prior to the DAB include threat validation, life-cycle-cost estimation, production and deployment scheduling, logistics, producibility, and communications security (COMSEC) matters.

The policy of implementation of Selective Availability (SA) and Anti-Spoofing (A-S) for the operational NAVSTAR GPS has been established by the Department of Defense (DoD). The SA feature consists of the intentional introduction of errors into SIS along with encrypted deterministic correction parameters which allow certain users to remove the effects of those errors. SA thus allows limiting the positioning/navigation accuracy achievable by users who are unable to decrypt the deterministic SA correction parameters. SA is always "on", but the level of errors added to the SIS may be set to Zero.

The A-S feature allows the P-code portion of the SIS to be encrypted. The encrypted P-codes are known as the "Y-codes". This Y-code capability is needed in the military environment wherein the potential threat exists that an adversary might use a deception jammer (i.e., a broadcast beacon which mimics the SIS) to spoof the UE set into tracking the deception jammer signals instead of the actual SV-transmitted signals. Since the deception jammer cannot autonomously generate the Y-codes needed to mimic the SIS, spoofing is thereby prevented when the A-S protection is applied. Unlike the SA feature, A-S may be either "on" or "off". Current policy dictates that SA and A-S will be enabled on all operational Block II satellites after the system has been declared fully operational.

In terms of user reaction to SA and A-S, there are two categories both of user and of UE sets. Users are divided into those who are authorized to receive the special cryptographic variables (CVs, also called "keys") needed to decrypt the deterministic correction parameters and to encrypt the P-codes, and those users who are not authorized to receive the CVs. UE sets are divided into those that have cryptographic logic built into them to do the decryption/encryption processing (PPS-capable UE) and those UE that do not (SPS UE).

The division of users and their UE sets into categories based on SA/A-S corresponds to a like division in terms of the SIS interface itself. The two aspects of the SIS interface are:

* Standard Positioning Service (SPS). The SPS aspect is the limited accuracy service available to all users of the SIS interface. No keys or cryptographic logic are required to access the SPS. The effect of SA and A-S on the SIS are felt. The SPS is intended primarily for civil GPS users.
* Precise Positioning Service (PPS). The PPS aspect is the full accuracy service available only to authorized users of the SIS interface. Both keys and cryptographic logic are required to access the PPS. The effects of SA and A-S on the SIS are counteracted. The PPS is intended for US and allied government agencies and their military forces and, if in the national interest, to selected civil GPS users.

On 25 March 1990, in keeping with national policy, all Block II satellites began broadcasting navigation messages at accuracy levels consistent with the SPS. The introduced level of error into SIS was temporarily reduced in September 1990, for the Gulf conflict. A higher level of error was reestablished in July 1991.

During constellation build up, the system operational configuration will be driven by the need to complete system or UE testing. After full operational status is achieved, nominal SPS will be operated with SA on the Block II SVs at the 100-meter [2drms, (at least 95%)] level or better, as dictated by DoD policy and as stated in the Federal Radionavigation Plan (FRP). SPS signals are broadcast in the clear and are available to all users.

The four GPS formal system accuracy specifications are composite statistical numbers. In no special order, they are:

* The PPS user 3-dimensional (spherical) position accuracy shall be 16 m SEP (Spherical Error Probable) or better.
* The PPS user velocity accuracy in any dimension shall be 0.1 m/sec RMS (root-mean-square) or better.
* The PPS user time accuracy with respect to UTC shall be 100 nsec one sigma or better.
* The SPS user 2-dimensional (horizontal) position accuracy shall be 100 m 2 drms (twice the distance root mean squared) or better.

The SPS 2-dimensional (2-D) specification is given at the 2 drms probability level (95-98%) because it enables the civilian user to directly compare GPS with other radionavigation systems described in the FRP. As an example, Table A-1 of the 1990 FRP: Loran-C System Characteristics (Signal-in-Space), describes the predictable accuracy (2 drms) at 0.25 nm (460m) for Loran-C based upon the Geometric Dilution of Precision (GDOP) factors at the user's location within the coverage area.

SUMMARY

The GPS program is nearing its fully operational phase. It has evolved into a highly accurate (16-meter, three-dimensional position accuracy), world-wide, all-weather navigation system applicable to the needs of both the military and civil communities. Block II operational satellite launches began in February 1989 and will continue at approximately five per year until a full constellation is in place. The OCS, the most mature of the segments, will continue to develop its operational capability. In addition to the LRIP MILSPEC UE set production, NDI efforts currently under way will provide alternatives in GPS UE set technology, design, and capabilities. The UE program will enter into Full Rate Production after a positive decision from the DAB at milestone IIIB. UE integration planning is underway on a wide variety of platforms and will expand into hundreds of host vehicle candidates over the next few years. GPS could be fully operational by early 1993 and will provide state-of-the-art position, velocity, and time information for radionavigation or precise positioning to an unlimited number of properly equipped users anywhere on the ground or sea, in the air, and out in space.

Consequently, GPS has been selected by the United States Government to supplement and/or replace other radionavigation systems currently in use. To support this selection, the DoD has determined that all GPS UE-equipped military aircraft will use the PPS for flight in U.S. national air space and will require its use in any other direct combat support operations. Furthermore, the DoD and DoT have established a policy to guarantee civil access to the GPS. The SPS users will be able to determine their positions to within 100 meters (2 drms) once the system becomes operational. Selected civil users may also qualify to get PPS access to the full system accuracy. This overall DoD policy on civil access was established to balance the national security needs against the practical requirements of civil aviation, maritime, and ground-based users.

ACRONYMS

AFLC	Air Force Logistics Command
AFSC	Air Force Systems Command
AFSPACECOM	Air Force Space Command
A-S	Anti-Spoofing
AUTONAV	Autonomous Navigation Capability
CDU	Control Display Unit
COMSEC	Communications Security
CRPA	Controllable Reception Pattern Antenna
CSOC	Consolidated Space Operations Center
CV	Cryptographic Variables
DAB	Defense Acquisition Board
DoD	Department of Defense
DMA	Defense Mapping Agency
DOP	Dilution of Precision
DoT	Department of Transportation
FRP	Federal Radionavigation Plan
FRPA	Fixed Reception Pattern Antenna
FY	Fiscal Year (01 Oct to 30 Sep)
FOC	Full Operational Capability
GA	Ground Antenna
G-DOP	Geometric Dilution of Precision
GPS	Global Positioning System
IOT&E	Initial Operational Test and Evaluation
JPO	Joint Program Office
JRMB	Joint Resources Management Board
JSSMO	Joint Service System Management Office
LRIP	Limited Rate Initial Production
MCS	Master Control Station
MILSPEC	Military Specification
MLV	Medium Launch Vehicle
MS	Monitor Station
NANU	Notice Advisory to Navstar Users
NATO	North Atlantic Treaty Organization
NDI	Non-Developmental Item
OA	Operational Analysis
OCS	Operational Control System
OPSCAP	Operational or Operations Capability
ORMS	OPSCAP Reporting and Management Sys
PCS	Prelaunch Compatibility Station
PMRT	Program Management Response Transfer
PPS	Precise Positioning Service
PRN	Pseudo-Range Noise
PVT	Position, Velocity, and Time
RMS	Root Mean Square
RTD	Reliability Demonstration Testing
SA	Selective Availability
SEP	Spherical Error Probable
SIS	Signal-in-Space
SPS	Standard Positioning Service
SSD	Space Systems Division
STS	Space Transport System
SV	Space Vehicle
TAAF	Test-Analyze-and-Fix
TOA	Time of Arrival
TT	Technical Test
UE	User Equipment
USCG	US Coast Guard
UTC	Coordinated Universal Time
WR-ALC	Warner Robins - Air Logistics Center

ABOUT THE AUTHOR

Commander McLean is a Coast Guard Aviator with over 3500 hours flight time in fixed wing and search and rescue aircraft. After his 1970 graduation from the U.S. Coast Guard Academy and a tour afloat he completed Naval Flight Training, winning his wings in 1972. He was stationed at various Coast Guard Air Stations including two tours to the Antarctic with the Polar Operations Division. He served as the Head of the Flight Safety Program at Coast Guard Headquarters in Washington, D.C., before becoming the Executive Officer of Coast Guard Air Station Los Angeles. He is a graduate of the Naval War College and Air War College programs.

Commander McLean assumed duties as the Deputy Program Manager for the Department of Transportation to the Navstar GPS Joint Program Office of the Space System Division at Los Angeles Air Force Base in March 1991, and transferred to that position full time in July.

The Role of Loran in Desert Shield and Desert Storm

Calvin Culver

Micrologic, Inc.
Chatsworth, California

ABSTRACT

Approximately 15,000 loran receivers were used in the Persian Gulf conflict. Most of these were purchased from August, 1990 to March, 1991, and were of the least expensive commercial type. Survey questionnaires were sent to loran manufacturers and individual military users, requesting information on loran procurement and use. The responses to these questionnaires are presented, along with excerpts from unsolicited letters from military personnel. Loran users in the war were very enthusiastic, with several stating that loran was the most important piece of navigational equipment they had used, that it was critical to the accomplishment of their missions, and that it was responsible for saving many lives.

INTRODUCTION

At the beginning of Operation Desert Shield in August, 1990, U. S. military organizations began buying quantities of commercial loran and GPS receivers. The early loran purchases appear not to have been centrally coordinated, but were the result of many small purchases by individuals, platoons, and regiments. Later, a central procurement was initiated, which led to the purchase of a large number of lorans by the U. S. Army.

A number of newspaper and magazine articles appeared in early February, 1991 describing the use of GPS in the conflict. (1,2) Little concerning the use of loran has been published.

From August, 1990 to April, 1991, Micrologic delivered approximately 11,000 loran receivers of all types to military customers. The units delivered up to January, 1991 displayed position in time differences and latitude/longitude only. After that, the ability to input and output coordinates in UTM (Universal Transverse Mercator) and MGRS (Military Grid Reference System) was added to all military lorans supplied by Micrologic.

GATHERING INFORMATION ON LORAN USE IN THE CONFLICT

During the course of Operations Desert Shield and Desert Storm, Micrologic received 20 unsolicited letters with return addresses, from servicemen who had used the lorans in Saudi Arabia and Iraq.

To gather further information on the use of loran, a questionnaire soliciting information on the number and type of loran receivers supplied for the conflict was sent to thirteen loran manufacturers. This questionnaire stated that any information provided would be published in a Wild Goose Association paper to further public awareness on the existence and use of loran. Respondents were offered the option of being anonymous.

Two responses were received, one anonymous and one from Furuno, USA, Inc. The information from these responses, plus information from Micrologic, is summarized as follows:

NUMBER AND TYPE OF LORAN RECEIVERS KNOWN TO BE DELIVERED
TO MILITARY CUSTOMERS DURING DESERT SHIELD AND DESERT STORM

LORAN TYPE	NUMBER
Marine	2123
Handheld	9397
Airborne	584
Remote Sensor	0
Total	12104

It seems certain that other manufacturers also delivered loran receivers to military customers, and that a substantial number of loran receivers were already in use in Saudi Arabia and Kuwait prior to the outbreak of hostilities. A reasonable estimate would appear to be 3000 such receivers. This would lead to the conclusion that approximately 15,000 loran receivers were used by the United Nations Allies in the battle to liberate Kuwait.

Survey questionnaires were also sent to the twenty known individual military users of loran in the Persian Gulf. Each person was sent two questionnaires asking for their detailed experience and opinions regarding loran and GPS. They were requested to give the second copy to someone else who had used radionavigation systems in the conflict. Seven responses were received from the original 20, and 4 questionnaires were returned from new people.

The eleven responses to the questionnaires are reproduced in this paper, edited only to correct grammar and to remove references to brand names. Excerpts from the unsolicited letters are also included, with similar editing. There are no omissions of negative opinions of loran, or positive opinions of GPS.

CONCLUSIONS

Approximately 15,000 loran receivers and 12,000 GPS receivers were used by the United Nations Allied forces in operations Desert Shield and Desert Storm. Most of these were commercial units purchased in great haste, because the U. S. Department of Defense had not previously procured nearly enough radionavigation receivers to fight a war of this type.

Most of the lorans used were of the least expensive commercial type, with an estimated average cost of $600. The estimated average cost of the commercial GPS units used was $3,800. (1,2). Thus the total expenditure for loran and GPS units was about $9.0 million and $45.5 million, respectively.

The loran receivers were used for navigation by foot soldiers, HMVEEs, trucks, tanks, ships, helicopters, and fixed wing aircraft. Individual soldiers were very enthusiastic in their praise of loran, and several have stated that the loran was the most important piece of navigational equipment used, crucial to the accomplishment of the mission, and was responsible for saving many lives and large amounts of time and money.

The evidence indicates that loran played an equal if not larger role in the Gulf war than GPS, at far lower cost.

THE PROSPECTS FOR FUTURE MILITARY USE OF LORAN

The prospects for future military use of loran appear to be slim to none. Many people have argued in the past decade that loran should be retained as a low cost backup system to GPS, for military purposes. That position has been rejected by the U. S. Department of Defense, and the phaseout of all DOD use of loran is scheduled for December 31, 1994. (3) The exemplary performance of loran in the Gulf War seems unlikely to change that position.

There will probably be some military use of loran by countries in the Middle East and Far East, for at least several decades.

RESPONSES FROM THE USER SURVEY QUESTIONNAIRE

Billy L. Reus
HSC-3-101 AVN REGT
101st ABN DIV (AASLT)
Ft. Campbell, KY 42223-5000

PURPOSE OF NAVIGATION: Precise point locations in the desert terrain, which seem to change daily.
VEHICLES: HUMMVs and helicopters
OPINION OF LORAN: It was great! Easy to use, accurate, and a big time saver in convoy movement, site locations.
LORAN-GPS COMPARISON: none
HOW IMPORTANT WOULD LORAN BE TO YOU IN ANOTHER CONFLICT? Very important, it is extremely worthwhile.

SSG James W. Klein
HHC 3/32 AR, 1st CAV DIV
Ft. Hood, TX 76544

PURPOSE OF NAVIGATION: I was the lead element of my scout platoon, and the rest of the task force based from our platoon. Loran was used for all movement.
VEHICLES: Hummer (M1026)
OPINION OF LORAN: Very useful in a flat, featureless environment with inaccurate maps, more so at night.
LORAN-GPS COMPARISON: The loran takes a little longer to lock on but the GPS only works if the satellites are overhead.
HOW IMPORTANT WOULD LORAN BE TO YOU IN ANOTHER CONFLICT? Very important. As a scout for the battalion, the rest of the unit depends on us to give them accurate information and to guide and lead them to their objective.

Thomas D. Mayfield III
410 Hogan Dr.
Copperas Cove, TX 76522

PURPOSE OF NAVIGATION: For use in general navigation during all movements in Saudi Arabia and Iraq. I used lat/lon and km. I picked a lat/lon from the 1:250,000 map and navigated to the points.
VEHICLES: M1A1 tanks, M998 Hummer
OPINION OF LORAN: It was extremely useful! Without it I would have been lost, literally!
LORAN-GPS COMPARISON: I felt the loran was more useful in many respects. It was handier and less dependent on the availability of satellites. One loran transmitter did however become unserviceable for a period of time. The GPS was more accurate. I found on several occasions that for precise position determination I had to use the GPS (EG, for shifting of artillery) For navigation, however, the loran was close enough. Given the relatively low cost of the loran relative to the GPS, these things have a good prospect for use in the Army. The two main problems are access to transmitters worldwide, inland, and that MGRS is absolutely necessary. A possible solution to the transmitters is to develop portable transmitters the Army could place in position as units move forward into areas not covered by existing loran transmitters.
HOW IMPORTANT WOULD LORAN BE TO YOU IN ANOTHER CONFLICT? (not answered.)

1SG Martin D. Matney
166 Ashley St.
Ft. Bragg, N.C. 28307

PURPOSE OF NAVIGATION: To locate battle positions for anti-armor defenses and to locate phase lines and attack positions after crossing our line of departure into Iraq.
VEHICLES: HUMMV M998, 5 ton truck
OPINION OF LORAN: The loran was extremely useful in the accomplishment of our mission in Saudi and Iraq. Due to the lack of terrain features in the desert, finding planned positions or one's own location would have been next to impossible without the loran.
LORAN-GPS COMPARISON: I found the loran much easier to use than the GPS. Also the GPS was slower in acquiring satellites during daylight hours.
HOW IMPORTANT WOULD LORAN BE TO YOU IN ANOTHER CONFLICT? The loran would be very important. As an infantryman, knowing your exact location at all times in any type of terrain can never be overemphasized.

Perry J. Matthews
1479 Whisperwood Dr.
Columbus, GA 31907

PURPOSE OF NAVIGATION: Tactical navigation in combat - mostly at night.

VEHICLES: UH60A Blackhawk Helicopters
OPINION OF LORAN: Loran signals were degraded by the altitudes we normally flew (10-50 feet AGL). Also several of the Saudi Stations were unreliable.
LORAN-GPS COMPARISON: With good signal strength and geometry loran and GPS signals matched within 1/8 mile.
HOW IMPORTANT WOULD LORAN BE TO YOU IN ANOTHER CONFLICT? Loran was good as a low cost backup navigation system. A purpose built aviation unit with a better antenna would have been better - but for the money the loran did very well. <Mr. Matthews was using a battery powered handheld loran for helicopter navigation. (editor)>

John F. Czuhajewski, SFC
HHC-3-32 Armor Scout Platoon
Ft. Hood, TX 76544

PURPOSE OF NAVIGATION: We were the recon platoon for the battalion. We used the loran to mark routes, to identify logistic points (fuel, water, food), to fix targets for artillery, to fix positions for MEVEVAC, and to fix link-up points for the platoon.
VEHICLES: HUMMV 4X4. Battalion also had one loran per tank company.
OPINION OF LORAN: Critical. We used them on every mission. We could have used the compass-azimuth method of navigation, but with the loran the time and speed of our mission was greatly enhanced.
LORAN-GPS COMPARISON: Loran is a great piece of equipment, but it did not have military grids. <Early equipment did not have grid coordinates. By the time of Desert Storm, MGRS and UTM coordinates were being supplied. (editor)> We broke both antennas. We need a flexible antenna. We also used coaxial cable attached to the base of our radio antenna, and the unit worked great. We had a hard time getting AA batteries. We need a 24 VDC adapter to military vehicles. In N. Saudi Arabia (Neutral Zone) and Southern Iraq the unit read one degree off in latitude, but we learned to compensate for it. The loran was easy to use. Thirty people learned to use it in about four hours. It gives soldiers a sense of security to know where they are. We never experienced that lost feeling. The loran was highly reliable. We abused our two units, and they are still working after eight months of abuse.
HOW IMPORTANT WOULD LORAN BE TO YOU IN ANOTHER CONFLICT? Very important. Critical. We had only two units for the platoon, with ten vehicles. We need one per vehicle.

Bruce E. Bulger
494 Wyn Drive
Newport News, VA 23602

PURPOSE OF NAVIGATION: Point A to B navigation, timed passage through air defense passage points, target position fixing, locating refuel locations, pre-flight planning, aircraft avoidance through accurate route structuring, search and rescue.
VEHICLES: OH58, UH-1, AH-1 helicopters, HUMVEE, Hemett, 2 1/2 ton army trucks
OPINION OF LORAN: We were lucky. Even though the chain was adequate (8990), station 24 was erratic, presumably from jamming. We off tuned to station 39, at the cost of accuracy, and continued to operate deep inside Iraq. We could not count on the transmitters being there.
LORAN-GPS COMPARISON: The military will turn to GPS, but for a low cost navigation solution for most situations was a viable alternative. Cost is the difference.
HOW IMPORTANT WOULD LORAN BE TO YOU IN ANOTHER CONFLICT? Electronic navigation ranges from critical importance in desert or over water operations to nice-to-have in areas with accurate maps and easily identified terrain features. In order to be the best equipped force in the world, everything that moves needs a way to fix an exact location.

Mark D. Corrigan
A co 3 battalion 160th Special Operations Aviation Regiment
Hunter Army Airfield, GA 31409

PURPOSE OF NAVIGATION: We used the unit in conjunction with 1:250,000 scale maps for basic navigation and position fixing.
VEHICLES: OH-58 (Bell 206) helicopter
OPINION OF LORAN: After we modified the antenna and mounted it on the outside fuselage, the loran was an indispensable piece of navigation equipment.
LORAN-GPS COMPARISON: The GPS did not have an external antenna, so it was awkward to use. The advantage of the GPS was that it gave your position in MGRS and the loran only gave lat/lon.
<early lorans had only lat/lon - later ones were provided with MGRS. (Editor)>
HOW IMPORTANT WOULD LORAN BE TO YOU IN ANOTHER CONFLICT? With the UTM/MGRS modification, the loran would be a mandatory piece of equipment.

Ernest J. Nickles
CW2, U. S. Army OH-58 A/C Instructor Pilot
Box 1022
E-TRP 4/7 Cavalry
APO NY 09076

PURPOSE OF NAVIGATION: To eliminate navigation worries, and key on winning the battle and surviving.
VEHICLES: OH-58 Kiowa helicopter
OPINION OF LORAN: Excellent. The only stumbling block encountered was finding an optimum mounting position and antenna, which were easily obtained because of the versatility of the loran. We fabricated a mount on the side of the instrument panel. The antenna was a three foot piece of copper wire taped to our chin bubble.
LORAN-GPS COMPARISON: Not really. We had one GPS, and at the time I was very content with the loran.
HOW IMPORTANT WOULD LORAN BE TO YOU IN ANOTHER CONFLICT? Very. But I wish that the Army would purchase a helicopter installation kit.

Steven F. Flankey
7229 Shady Grove Lane
Fayetteville, NC 28314

PURPOSE OF NAVIGATION: I used the loran extensively to fly air routes and to find field sites. I would be given the field site location in grid coordinates and then convert them to lat/lon. Although the loran would accept grid coordinates, I found that it was more accurate using latitude/longitude.
VEHICLES: OH-58C Kiowa helicopter
OPINION OF LORAN: The loran was extremely useful for navigation in the desert. It also helped to speed up

pre-mission planning. I relied heavily on the loran and was very satisfied with its performance in Iraq.
LORAN-GPS COMPARISON: I did use the GPS some. I found the loran to be just as accurate as the GPS.
HOW IMPORTANT WOULD LORAN BE TO YOU IN ANOTHER CONFLICT? I would like very much to have a navigation system such as loran or GPS incorporated in my aircraft.

Charles C. Blankinship
5895 Waccamaw Ct.
Fayetteville, NC 28314

PURPOSE OF NAVIGATION: To fly troops and supplies to predetermined coordinates in the deserts of Saudi Arabia, Iraq, and Kuwait.
VEHICLES: UH1H helicopter
OPINION OF LORAN: The loran saved the U. S. Army many thousands of dollars in wasted hours of flight time.
LORAN-GPS COMPARISON: Loran has a little less accuracy but this proved to be no real problem.
HOW IMPORTANT WOULD LORAN BE TO YOU IN ANOTHER CONFLICT? I already have waypoints set up for the Hospital, refuel and rearm points, and friendly airfields.

EXCERPTS FOR UNSOLICITED LETTERS

"You cannot believe how difficult it is to fly hundreds of miles over a terrain that has few features to identify on a 1/250,000 map. ... I only wish we could have had the loran 5 months ago when we arrived. ... We have installed the loran on tops of MRE (meals - ready to eat) cardboard boxes beside the copilot seat. A long wire antenna is strung from the nose of the helicopter to the skid gear. Looks funny, but works."

"I was notified on Aug. 15, 1990, that I was being reassigned to the 101st Airborne Division. ... I went shopping, and purchased two loran units. Let me tell you they are life savers! ... The maps are very tough. You could use a shopping bag with lines on it just as well. ... My Brigade Commander saw me plotting waypoints and asked what I had. After a brief demonstration, he was interested. Later that week he ordered 100 units for the Brigade. Many people now sing the praises of loran."

"The loran has become an important part of the "Scorpion" Battalion's daily military operations. Often it is our primary navigating tool in an area where terrain association and map quality are poor at best."

"I am writing from my HMMWV, somewhere in Northern Saudi Arabia. I know exactly where I am, thanks to the loran. Unfortunately, I am borrowing the Colonel's, and may have to return it soon. While I can, and do, and will accomplish my missions of establishing liaison, coordinating fire support, and shepherding my troops, with a compass and map, I have been able to do all these things faster, better, and more safely since I got to use the loran."

"I am an OH58 helicopter Instructor Pilot in an Air Cavalry Troop. ... Although the antenna required some modifications, I must admit that the loran has become the single most important piece of navigational equipment in the aircraft. ... The loran has become indispensable for the type of combat tactics that we employ."

"Other units had tried the loran, but complained that it didn't work in the cockpit. I was skeptical. After reading the Operator's manual, I was able to fabricate an antenna that gave me excellent reception while I wore the loran on my leg. After some experience, I was able to accurately navigate to any location here in the deep desert. Previously, I was not able to navigate accurately."

"I was a bit skeptical when our supply officer made a local purchase of some handheld lorans for backup navigation during our deployment in Saudi Arabia. ... We are authorized GPS, but a little research showed us that there was very unreliable satellite coverage, especially at night, when we fly most. So almost out of desperation, we got a loran. We went with a handheld, so we wouldn't have to get an airworthiness release. Most of us sort of scoffed at it, but I'm writing to tell you it works like a champ. Most of the pilots don't even keep it up front. It's so easy to use we usually let our crew chief or Medic give us range and bearing from the back of the bird allowing us to keep our hands up and outside. Very important when flying over the dunes at almost 200 knots. And the accuracy, even very far inland and at low altitudes has been superb. We use a wire "U" shaped antenna, placed with suction cups in the pilot's chin bubble."

"I personally had the opportunity to use a loran with lat/lon to UTM Grid conversion feature, and was extremely pleased with the accuracy and ease of use. Speaking from personal experience as an Army Aviator assigned to fly over vast areas of emptiness with virtually no terrain features to navigate by, the loran is indeed a life saver."

"All of the lorans worked flawlessly and were instrumental in the success of my battalion in performing its combat mission. In the featureless terrain of the Saudi and Iraqi desert the lorans made it possible for aircrews to accurately navigate and perform missions effectively, like adjustment of artillery fire, aerial reconnaissance, attack helicopter, and Air Force ground attack target handoffs. I personally used loran in both my aircraft and vehicle and found it to be a life saver. It proved to be rugged, versatile, and adaptable to the harsh desert environment. Additionally, it proved to be simple to operate. Many of my men, with little instruction, quickly became proficient in its use. ... Loran certainly made a difference in the Gulf War for me and the Army Aviators of 3-101 Aviation Regiment."

"The loran that was issued to me the day before the attack proved to be an excellent piece of equipment. The success of our mission weighed heavily on the accuracy and reliability of the loran. ... Back in the early 70s, when I was in the Scout Platoon in Germany, I used to dream of such equipment. The Army has GPS's, that work from satellites. But they are undependable during the daylight hours. I found that the loran was easier to use, and even with the signal degradation due to the distance from the transmitters, was more accurate once adjusted for a given area. ... Loran made the liberation of Kuwait that much easier."

"I had so much confidence in my loran, that it allowed us to get to the battle in a very timely manner, and quickly react to areas where our firepower was needed immediately. The loran never did us wrong once. I logged 150 hours of combat time in 3 months, and didn't get lost once. It allowed us to concentrate on the mission, and probably saved many lives. Our unit didn't lose one person, pretty good. If you understand the mission of a Scout Pilot, then you know we had a lot on our hands and navigation is usually our worst nightmare. Not in this battle, thanks to loran. By the way, my unit came in contact with the enemy heavily about 8 times within 4 days, and have had many confirmed kills on tanks with our Cobra Attack Helicopter."

ACKNOWLEDGEMENTS

This paper would have been impossible without the efforts of the Armed Forces Personnel who took their time to write letters and fill out the questionnaires. They are the Authors. They deserve our gratitude for the sacrifices they have made.

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About the Author

Calvin Culver received BS and MS degrees from MIT in 1964, and the Sc.D. degree in 1969, also from MIT. He has worked on the design and development of navigation systems at the MIT Instrumentation Laboratory, Litton Systems, Teledyne Systems, and Micrologic. He is currently Chairman of Micrologic.

Participation of State Aviation Agencies in the Loran-C Approach Program

Paul E. Burket
Former Administrator
Oregon Aeronautics Division

James L. Bland
Manager, Airport Services
Virginia Department of Aviation

The following paragraphs summarize key points made by the co-presenters. In lieu of a prepared paper the authors plan to publish and distribute their paper independent of the formal conference proceedings.

The National Association of State Aviation Officials (NASAO) as a whole, and the agencies of a number of states in particular, have been actively working with the FAA/RSPA/USCG/DOT, several receiver manufacturers, and a number of users and user organizations such as AOPA, since at least as far back as 1985. As a result of actions set in motion in 1984 by then FAA Administrator Donald A. Engen, we have seen several important developments leading toward full implementation of Loran approaches into the National Airspace System. One of the more significant occasions was completion by the Coast Guard last May of the mid-continent Loran expansion project. This involved installation of four additional transmitters which will ultimately result in availability of "approach quality" Loran signals throughout the majority of the conterminous United States. Coupled with this major achievement is completion of the nationwide (plus Alaska) network of Local Area Loran Data Collection monitors to collect precise information on signal variations to be used in forecasting Time-Difference corrections for users of the system. Another significant event was the commissioning of ten public-use Loran approaches in November 1990. Unfortunately, these were subsequently NOTAMMED out of use, primarily because there was not a certified aircraft receiver in existence that could legally use them.

The states collectively remain strongly interested and committed to the Loran approach program as the only practical, realistic means available to provide adequate access to the system of public-use airports existing in each state. All-weather access would increase utilization of these facilities and expand the possibilities for economic growth and development in many locations that may never see an instrument approach procedure using a standard ground-based navigational aid.

To illustrate how states are involved and how they see Loran as being useful to them, Jim Bland, Virginia Department of Aviation, outlined the several ways in which his agency is preparing for, and envisions the benefits of, Loran approaches. The Commonwealth owns and operates a rather extensive system of navaids comprised of twenty-seven NDB's, nine Localizers, five DME's and two Outer Markers. To enhance the usability of these facilities, and in anticipation of additional approaches with the implementation of Loran, they have developed a system of twenty-three AWOS installations and a satellite-based weather dissemination system encompassing twenty-five airports. Terminals of the latter can also be used by pilots to file flight plans. Virginia is looking forward to the availability of Loran approaches to enhance their state air transportation system.

In conclusion, it was pointed out that a major impediment to the approach program is lack of a certified aircraft receiver. NASAO is quite concerned over fairly recent developments in the program. It was pointed out that FAA is in the process of setting up a "Loran-C Receiver Certification Conference" in Washington, DC very soon to "obtain input from manufacturers and users as to the direction the Loran-C approach program should go from this point". Everyone receiving notification is strongly urged to attend and participate.

PAUL E. BURKET

Retired from full-time state government service in January 1990 after having served 17 years as Administrator of the Aeronautics Division, Oregon Department of Transportation. Previous experience had been with the Nebraska Department of Aeronautics and with the Lincoln, Nebraska Airport Authority, after having served twenty-two years active duty with the U.S. Air Force as a pilot and staff Officer. Holds additional aeronautical ratings as navigator and bombardier with civil commercial certificate as aircraft and rotorcraft pilot with over 5,000 hours flying experience. Presently operates a small aviation consulting firm and acts as advisor to the Oregon Aeronautics Division on matters related to Loran-C.

JAMES L. BLAND

Manager of the Airport Services Division, Virginia Department of Aviation. Professional Civil Engineer. Has been with the Department for twenty years and manages all programs of financial assistance for airport development in the Commonwealth. This includes facilities and equipment such as Navaids, AWOS, Lighting and other visual aids.

Session 3
LAND AND MARINE TECHNOLOGY AND APPLICATIONS

Chairman: Captain Henry E. Marx, *Landfall Navigation*

Henry grew up on an island in Long Island Sound in Greenwich, Connecticut and spent his youth sailing throughout New England. He holds a B.S. in Economics and Finance from the University of Hartford and an MBA from the University of Connecticut. Henry also graduated from the Navy Submarine School in Groton, Connecticut, and holds a 50 Ton Auxiliary Sail Masters License. He has spent some time on oil tankers and presently delivers yachts along the east Coast.

Henry spent ten years as a manager with Pitney Bowes in Stamford, Connecticut, then moved on as a member of the corporate controller's staff at Combustion Engineering, and finally to the American Gas & Chemical Company in Northvale, New Jersey as vice president and plant manager.

In 1982, Henry took over Landfall Navigation, a small retail chart agency, and has built it into one of the largest nautical chart and marine safety equipment stores in the country. In addition to these retail services, Henry teaches a number of navigation courses each year — including a day-long seminar on Loran-C navigation — and has produced the very successful marine educational video: *LORAN-C — A Navigator's Approach*.

Papers

[1]*Manuscript not available. Dr. Miller summarized activities and showed a short video.*

Direct Comparison of LORAN and GPS in Vehicle Location Applications

G. Linn Roth, Ph.D., President
Kendall E. Post, Vice President of Engineering
LOCUS, Incorporated

ABSTRACT

Direct, side-by-side comparisons were made between technologies in an automatic vehicle location (AVL) application. These technologies were: (1) conventional multichain LORAN receivers currently used in commercial AVL systems; (2) 3-channel and 6-channel GPS receivers; and (3) single chain Linear Averaging Digital (LAD)-LORAN prototype receivers from LocUS.

Receivers were mounted on a specially equipped vehicle to insure optimal operation of each system, and data were simultaneously logged on a computer. Output of each receiver was logged every 10 seconds, and routes included urban and rural (i.e. open) areas. Test results suggest GPS receivers provide more accurate representation of vehicle routes than LORAN systems, but LORAN can provide continuous coverage in areas where GPS receivers do not operate. Results also demonstrate 6-channel GPS receivers provide more continuous coverage than 3-channel GPS receivers. Finally, results suggest GPS and LORAN technologies are complementary, and a combined LORAN/GPS system would give accurate and continuous coverage in many environments where neither technology is wholly adequate.

Introduction

This study compares the performance of different receiver technologies in an automated vehicle location (AVL) application.

Receivers were mounted on a specially equipped vehicle providing excellent, uniform operating conditions for all systems, and data were simultaneously recorded from each receiver. Such side-by-side comparisons are the most objective way to evaluate performance under real-life conditions.

METHODS

Receivers: Four different types of navigation receivers were used for these tests. One was a 6-channel GPS receiver from a commercial vendor; one was a 3-channel GPS receiver from a commercial vendor; one was a multichain LORAN receiver from a commercial vendor; and one was a single chain prototype from LOCUS.

The 6-channel and the 3-channel GPS receivers were continuously tracking units. All GPS units were configured to accept data with an angle of elevation of 3 degrees or greater and a GDOP of 10 or less.

Duplicate receivers of each type were available to check optimum operation of each system.

Vehicle: A 26 foot recreational vehicle (RV) was used for the tests. The RV is equipped with a gas generator and regulated power supply, which was used for all receivers. An aluminum roof deck was used to mount all antennas, and cabling was run via a conduit to an interface panel in the van's interior.

The base of each antenna was mounted about 13'6" above road level, which is more than twice the mounting height used on an automobile AVL system. This higher mounting effectively provided a greater viewing angle to the GPS receivers in urban environments, but probably had no impact in open, rural areas. For this reason, we believe the urban GPS data shown here illustrate somewhat better performance than would be achieved from a GPS receiver mounted on a car.

Acquisition and Display: Data were simultaneously acquired from all receivers via an 8-channel RS-232 board by an AT compatible PC running a LOCUS data acquisition program. Data were acquired from each receiver every 10 seconds, and the complete data stream was logged to a hard disk for later display and analysis.

Only position valid (i.e. unflagged) data points issued by each receiver are shown. In order to clarify routes determined by each receiver, sequentially acquired points (i.e. points acquired within ten seconds or less of one another) are connected by a line. Data points not issued sequentially (i.e. more than 10 seconds apart) are not connected by lines.

Static Test: A continuous, 55-hour static test was run on the 3 and 6-channel GPS receivers and the LAD-LORAN prototype with the RV parked in an open area on LocUS' lot. Data acquisition was as defined above, except a 30 second acquisition interval was used. The test was run from approximately 7:30pm on September 5 to 2:30am on September 8.

Calibration: There were no means available to calibrate these systems or compare data issued to geodetically defined positions. All data shown are simply latitude/longitude plots of positions issued by each receiver and, therefore, give some indication of the relative performance of these systems under identical conditions.

Selective Availability: It is our understanding a "low level" of Selective Availability (S/A) was on during each of the tests reported here, and dates and times for each test are listed. However, LocUS has no means of quantifying the level of S/A or the effect of any other DoD procedures during these tests. GPS receiver results only include data each receiver reported as good.

RESULTS

Rural Route: The following data illustrate receiver performance on an open, rural interstate highway during a 36-hour period in August 1991 (Figures 1 & 2). Data were acquired on a drive from Madison to LaCrosse, Wisconsin, a distance of about 130 miles. LaCrosse is located on the Mississippi River.

The return trip was from Prairie du Chien to Madison. Prairie du Chien is also located on the Mississippi River, and no data were recorded between LaCrosse and Prairie du Chien. (LocUS work unrelated to this comparison testing precluded data gathering in this section of the route.)

State of Wisconsin enlarged area, and heavy line showing test route.

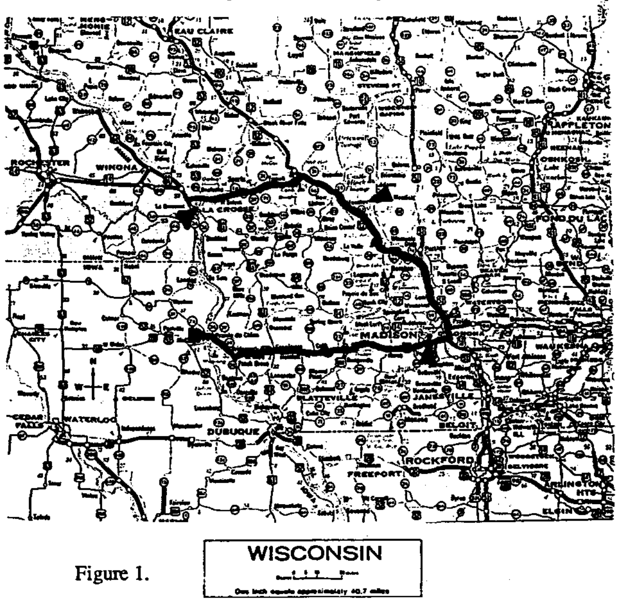


Figure 1.

For the initial Madison/Mauston segment of the trip, six satellites at elevation angles of 15-64° were visible at the start, and five satellites at elevation angles of 14-65° were visible at the end. For the Mauston/LaCrosse segment of the trip, four satellites at elevation angles of 16-63° were visible at the start, and 6 satellites at elevation angles of 3-45° were visible at the end. For the Prairie du Chien/Madison segment of the trip, five satellites at elevation angles of 14-85° were visible at the start, and four satellites at elevation angles of 22-26° were visible at the end.

It is clear from Figure 2 that GPS and LORAN receivers were able to operate over most of this rural route, and appear to trace the route reasonably well. However, there was a segment of the trip just west of Mauston (shown in Figure 3) where there were many gaps in the data generated by the 3-channel GPS receiver. During this approximately 30-mile segment, the receiver indicated it was tracking between 2 and 4 satellites. An identical receiver produced similar data during this entire route. Note that the short gap in the commercial LORAN receiver data followed a short lunch stop and power-down, and was due to its typical 3-5 minute delay to lock-on after power-up.

From these data, and similar trips not shown here, all receivers appeared to function reasonably well in open environments. In general terms, the GPS receivers seemed to define the route more accurately, while the LORAN receivers provided better continuity of coverage. Although we cannot quantitatively define the absolute accuracies provided by each system, it seems likely that the performance of each system would be sufficient for an AVL system operating mostly in an open or rural environment, such as on interstate highways. For example, any of these navigation systems would probably be adequate for a trucking fleet operating in the continental U.S., particularly given the increased LORAN coverage provided by the SOCUS and NOCUS chains.

<u>Urban Routes</u>: The route driven during urban data acquisition runs is shown in Figure 4, where the heavy line indicates the route on a standard city map of Madison. It is from LocUS headquarters near the airport, along a residential section by the lake, around a square surrounding the state capitol building, and with the exception of one segment with one way streets, back to LocUS along the same route. Madison is a city of about 180,000, and in regard to operation of an AVL system, could be described as a "light urban" environment.

Figure 2. Test run route shown on expanded view of data for each receiver from Madison to Mauston, Mauston to LaCrosse, then Prairie du Chien to Madison.

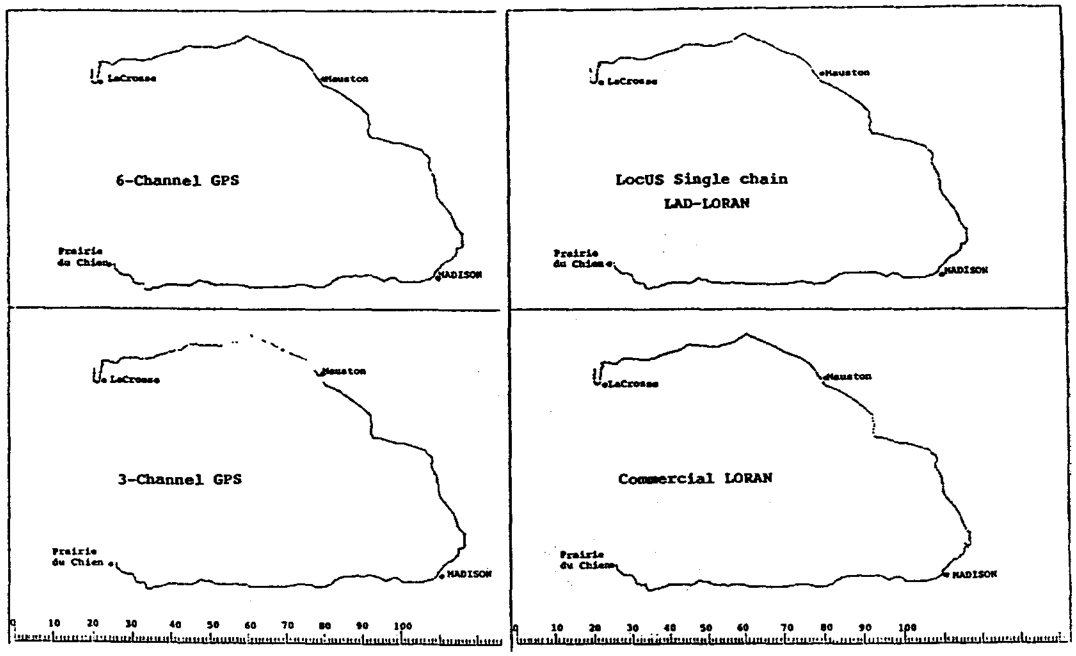
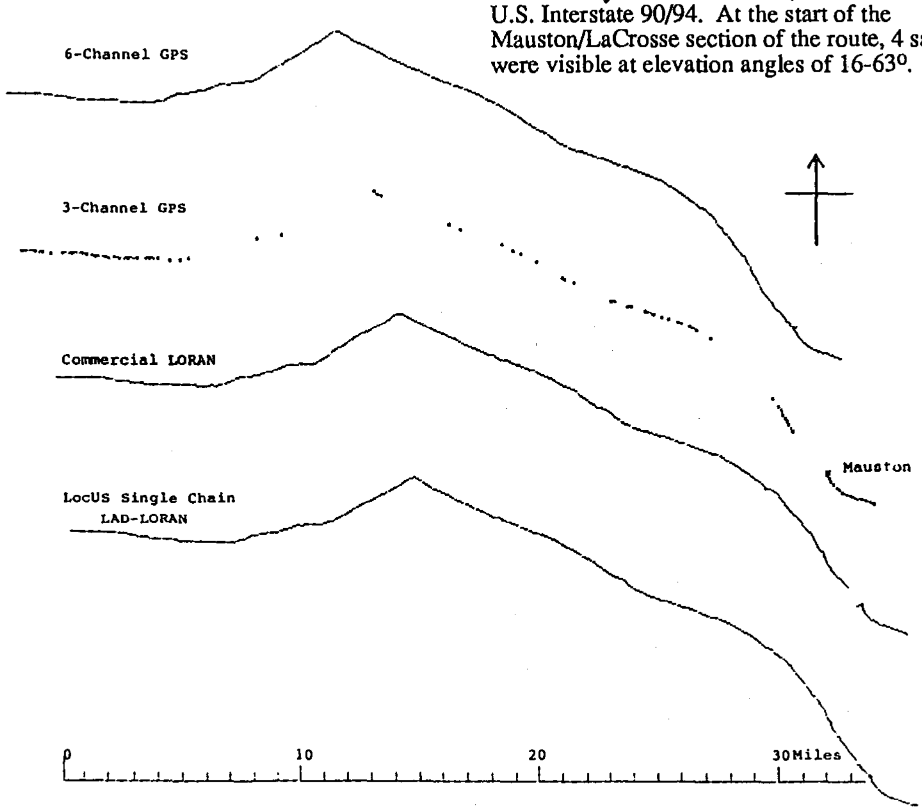


Figure 3. Expanded view of data generated by each receiver immediately west of Mauston, Wisconsin along U.S. Interstate 90/94. At the start of the Mauston/LaCrosse section of the route, 4 satellites were visible at elevation angles of 16-63°.



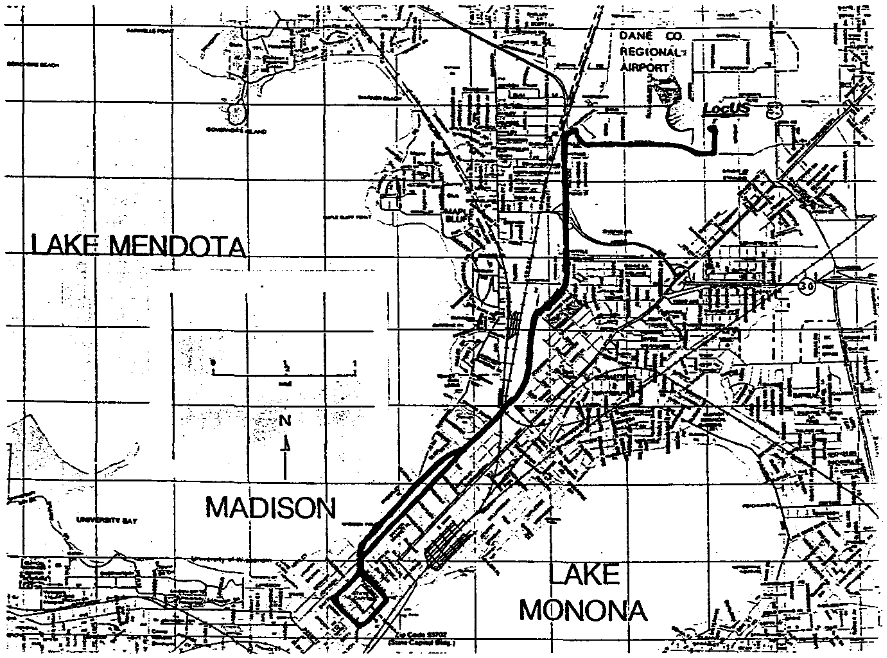


Figure 4. City of Madison and enlarged area with heavy line showing test route.

The route chosen encompasses different types of districts within the city. Streets by LocUS' headquarters and the airport are open, with occasional power lines running alongside the road. The route by the lake is more residential, with 2-3 story homes and some trees bordering the streets. Around the capitol and city square are a few open areas and some streets bordered by 8-12 story buildings. All data shown were obtained within the last six weeks, and before each run, all units were simultaneously powered up.

The first test was done on August 26, and data acquired are illustrated in Figure 5. At the beginning of the run, six satellites were visible with elevation angles from 5-61^{o}, and at the conclusion of the run, five satellites were visible with elevation angles of 16-64^{o}.

(see Figure 5)

From these data, it appears the 6-channel GPS receiver generated an accurate definition of the route, with the exception of some data gaps around the square. The 3-channel GPS receiver had data gaps at other segments in the route in addition to the route around the square. The commercial and LAD-LORAN systems provided continuous coverage throughout, but did not appear to generate as accurate a definition of the route as the GPS receivers. The LORAN systems also showed some grid distortion due to power lines near the beginning/end of the route, and the commercial system had an initial data gap due to lock-on time from power-up (note missing segment of approximately 1 mile at start of route).

Figures 6, 7 and 8 show data obtained from three subsequent trips over the same route.

Figure 5. First test run. Note gaps in GPS data for 6-channel (a) and 3-channel (b) receivers. Note power line grid distortion for multichain (c) LORAN and LAD-LORAN (d) receivers. Note initial data gap for multichain (e) LORAN receiver due to slow acquisition time from power up.

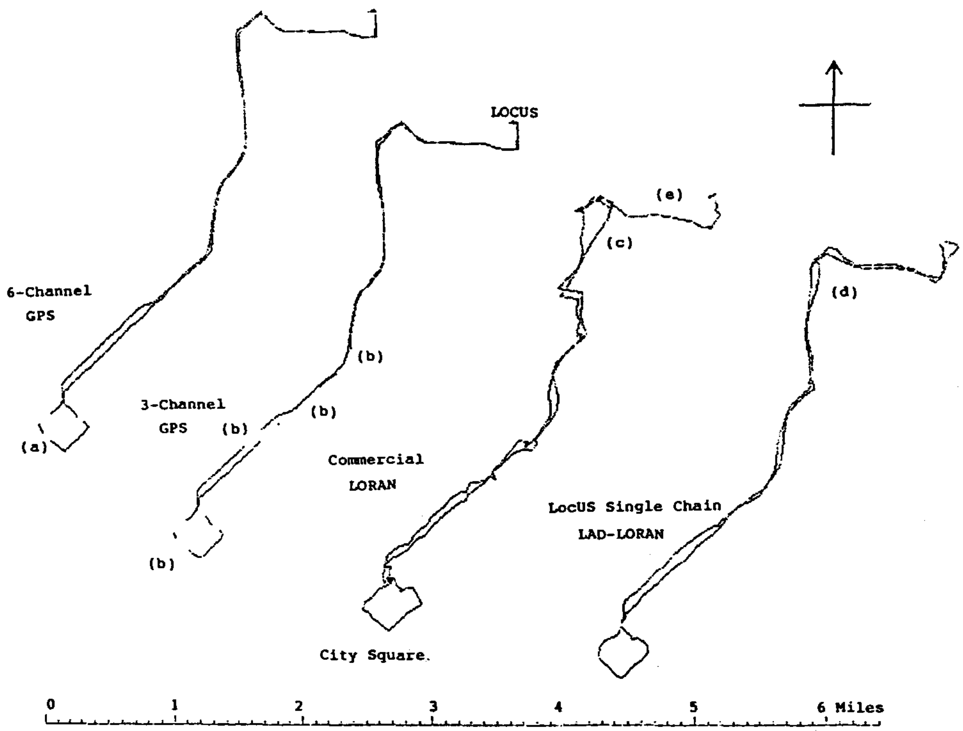


Figure 6. Second test run. Note gaps in GPS data for 6-channel (a) and 3-channel (b) receivers. Note power line grid distortion for multichain (c) LORAN and LAD-LORAN (d) receivers. Note initial data gap for multichain (e) LORAN receiver due to slow acquisition time from power up.

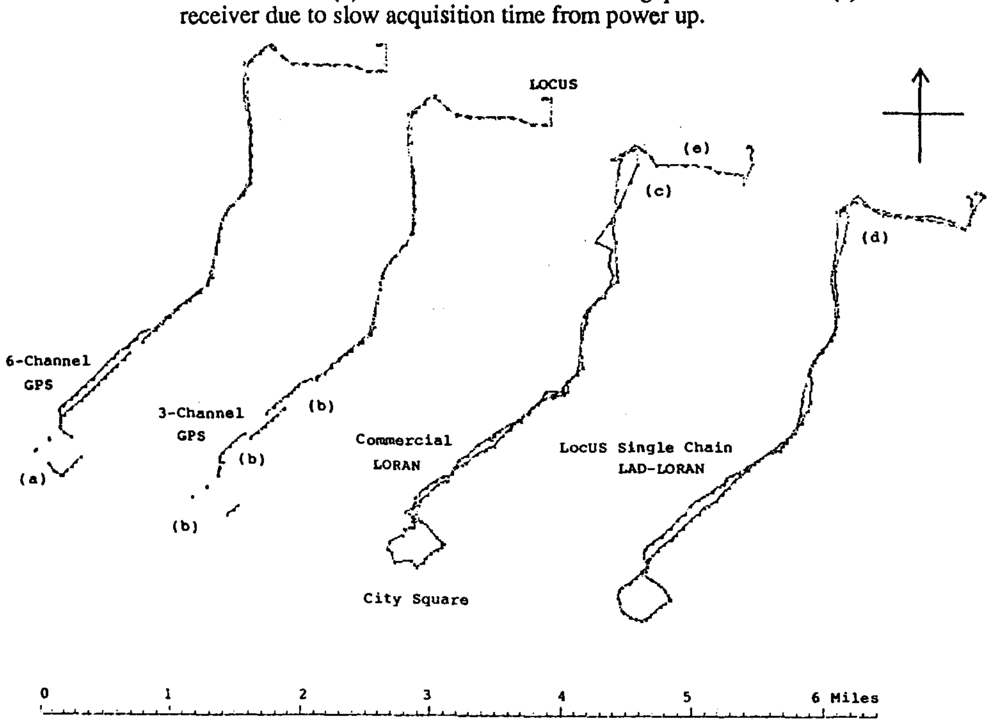


Figure 7. Third test run. Note gaps in GPS data for 6-channel (a) and 3-channel (b) receivers. Note power line grid distortion for multichain (c) LORAN and LAD-LORAN (d) receivers. Note initial data gap for multichain (e) LORAN receiver due to slow acquisition time from power up.

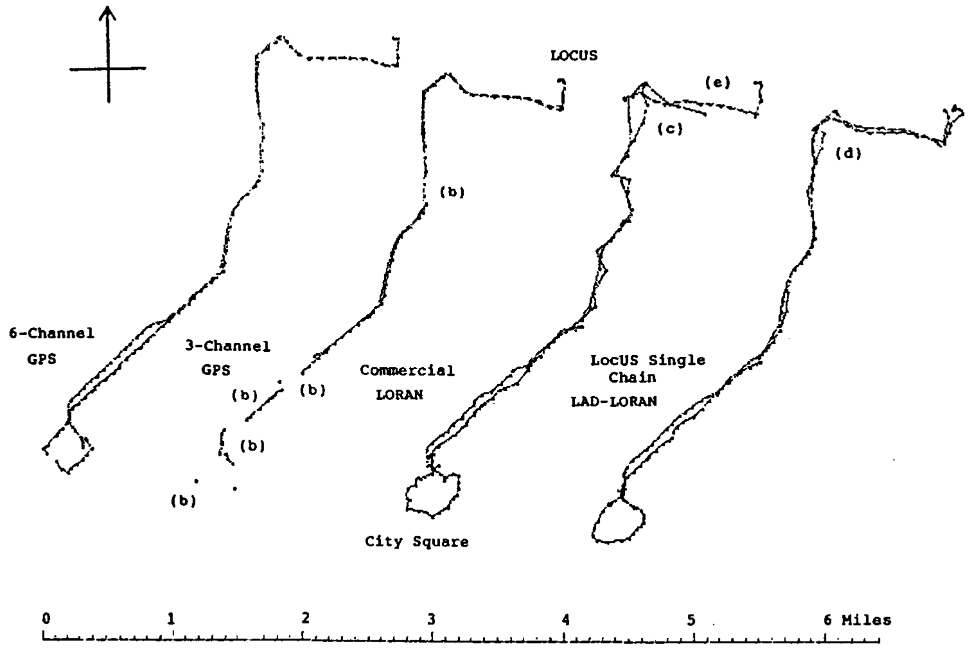
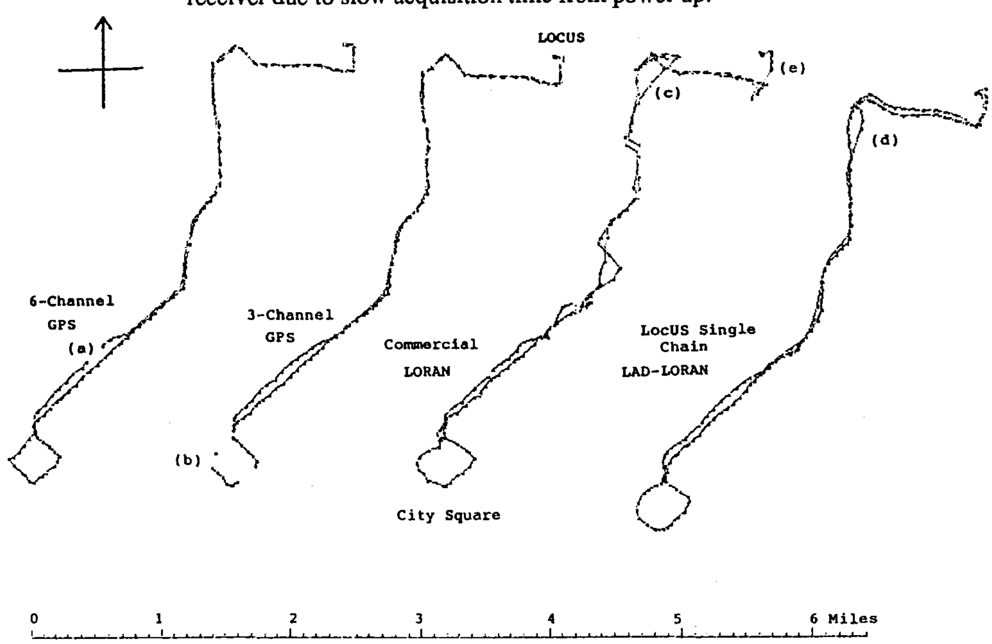


Figure 8. Fourth test run. Note gaps in GPS data for 6-channel (a) and 3-channel (b) receivers. Note power line grid distortion for multichain (c) LORAN and LAD-LORAN (d) receivers. Note initial data gap for multichain (e) LORAN receiver due to slow acquisition time from power up.



For the August 27 run (Figure 6), six satellites with elevation angles of 6-49° were visible at the start, and five satellites with elevation angles of 11-41° were visible at the end. For the September 3 run (Figure 7), six satellites with elevation angles of 4-44° were visible at the start, and six satellites with elevation angles of 11-60° were visible at the end. For the September 6 run (Figure 8), six satellites with elevation angles of 13-87° were visible at the start, and six satellites with elevation angles of 9-72° were visible at the end.

For these data, several general trends are evident: (1) GPS receivers appear to generate a more accurate representation of the route than LORAN receivers; (2) GPS receivers show some gaps in the data, and the 3-channel receiver has more data gaps than the 6-channel receiver; (3) LORAN receivers appear to offer continuous coverage throughout the route and show some grid distortion near power lines; and (4) the commercial LORAN receiver appears to be more susceptible to power line grid distortion than LAD-LORAN, and is much slower to lock-on from power-up.

Repeatability: In order to assess the repeatability offered by various receivers, data generated by each receiver over the four runs were superimposed and then plotted separately, as shown in Figures 9 to 12.

These figures expand the more "downtown" segment of the route, where there are more buildings, trees, etc. that block line-of-site satellite signal penetration. The 6-channel GPS receiver (Figure 9) produced highly repeatable data over the four trial runs, and some data gaps around the city square. The only consistent data gap was on the southwest segment of the square, where 6-12 story buildings border both sides of the street.

Figure 9. Data from 6-channel GPS receiver on an expanded scale. For superimposed data, each point from separate trials are represented as a single pixel. For individual trials on indicated dates, individual data points are connected by a line.

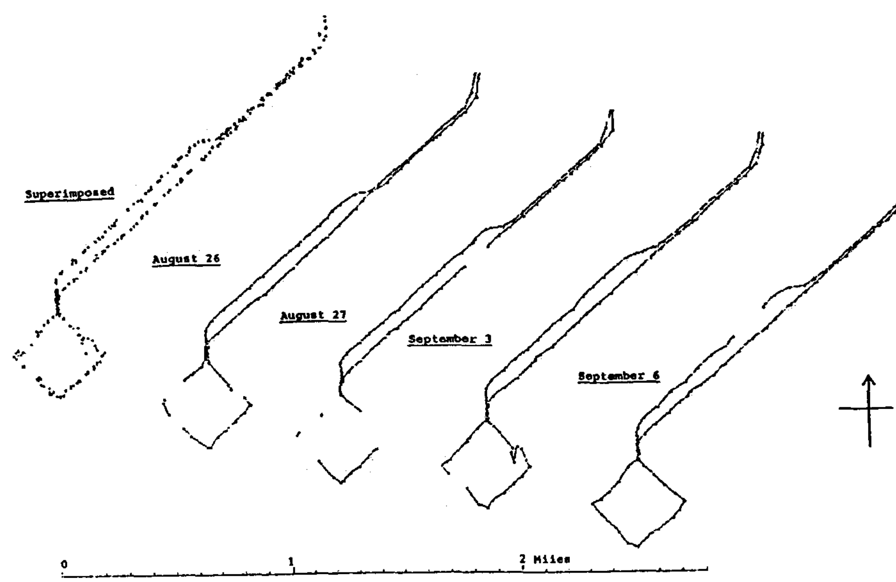


Figure 10. Data from 3-channel GPS receiver on an expanded scale. For superimposed data, each point from separate trials are represented as a single pixel. For individual trials on indicated dates, individual data points are connected by a line.

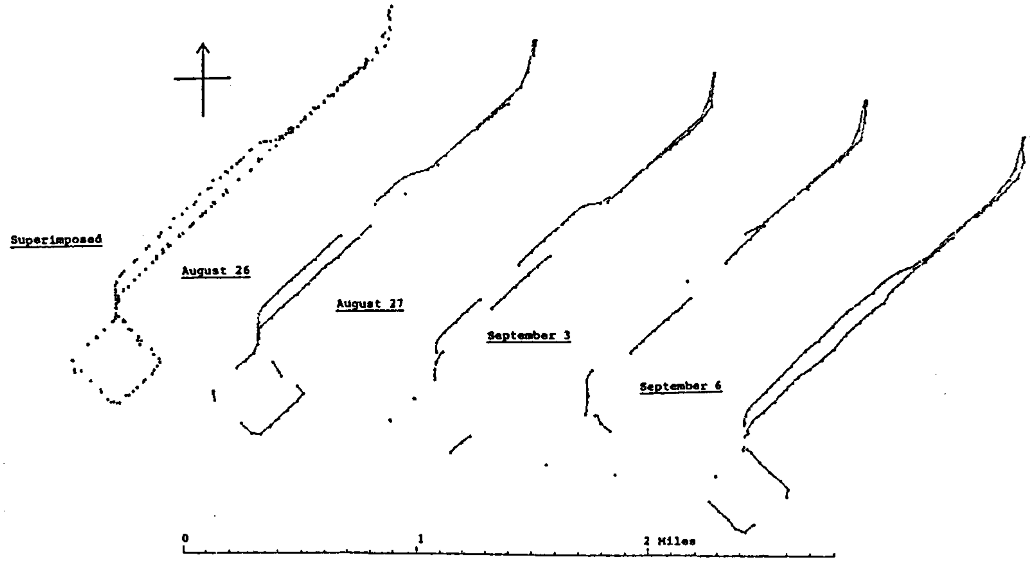


Figure 11. Data from commercial LORAN receiver on an expanded scale. For superimposed data, each point from separate trials are represented as a single pixel. For individual trials on indicated dates, individual data points are connected by a line.

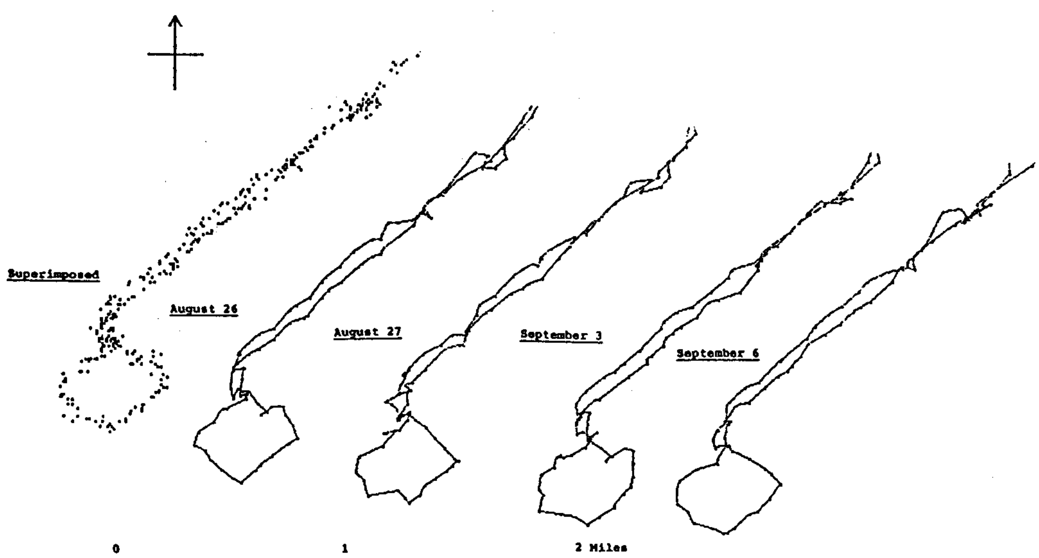
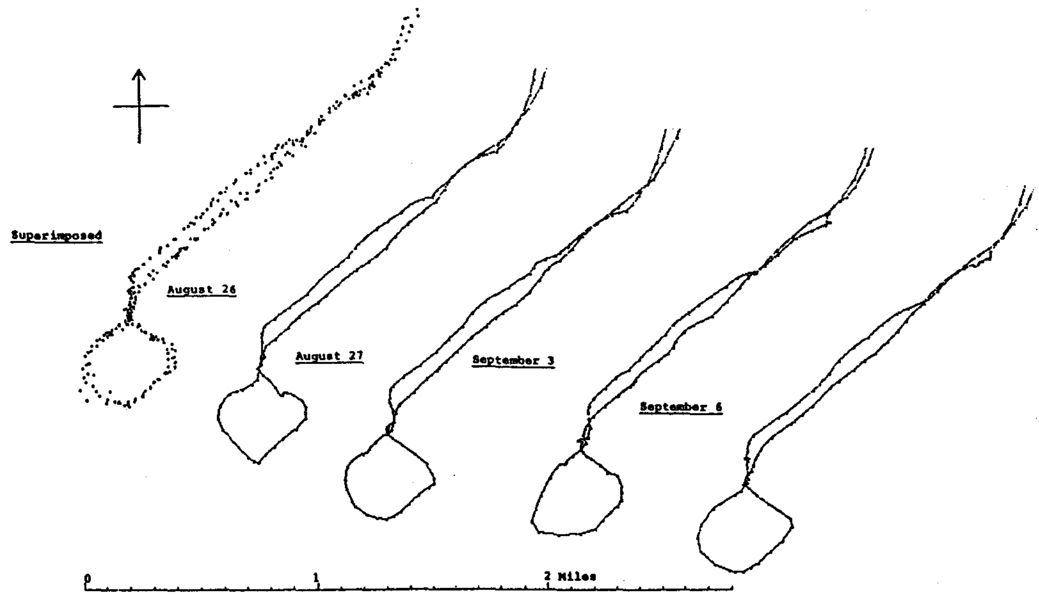


Figure 12. Data from LAD-LORAN receiver on an expanded scale. For superimposed data, each point from separate trials are represented as a single pixel. For individual trials on indicated dates, individual data points are connected by a line.



For the 3-channel GPS receiver (Figure 10), data issued along the same route over four days also appeared very repeatable. However, many more data gaps were present than with the 6-channel GPS receiver, and with the exception of the most densely built-up area around the square, these gaps did not appear in consistent locations.

In regard to actual positions reported, the commercial LORAN receiver appeared to have the greatest variability (Figure 11) of all receivers tested over the four trials.

The LAD-LORAN receiver (Figure 12) appeared to provide better repeatability than the commercial LORAN. Finally, these data also show both LORAN receivers continued to generate positions throughout each trial, even in areas where the GPS units did not issue points.

"Quasi"-Differential Operation

In order to roughly estimate how a differential LORAN system might perform over the example route, we performed a mathematical operation on LORAN data. Because we had no means to calibrate receivers or to determine true geodetic positions, we simply assumed the 6-channel GPS receiver had the best absolute accuracy, and used its data set as our standard reference. By "sliding" an entire LORAN data set over the 6-channel GPS data set until the two were most highly correlated, we obtained a rudimentary idea of how differential LORAN might perform. This data manipulation was performed on the results from the September 6 run, because it was the most complete data set generated by the 6-channel GPS receiver.

We wish to stress this is a rough estimate only. Because this operation moves an entire data set as a block, and corrections could be applied to individual data points in real differential operations, we believe true differential LORAN would yield even better results than illustrated.

Figure 13 shows this operation. On the left, LAD-LORAN and 6-channel GPS plots are superimposed. On the right are the same data, but the entire LAD-LORAN data set has been shifted over the GPS reference data set.

Figure 14 shows the downtown section of these same data in more detail, with the "quasi" differential data on the right.

Figure 13. LAD-LORAN and 6-channel GPS data from September 6 test run. Actual data shown superimposed on the left, and "quasi" differential LAD-LORAN and GPS data on the right. GPS data shown using heavier pixels.

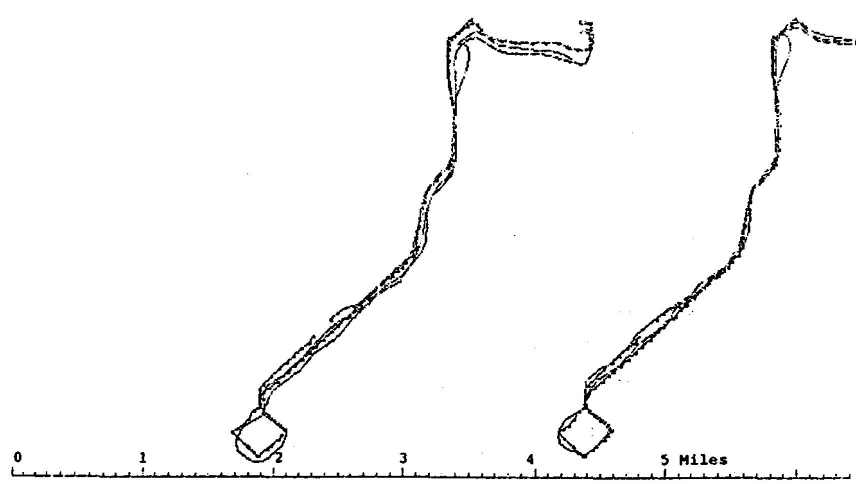


Figure 14. Downtown area from Figure 13 shown on expanded scale.

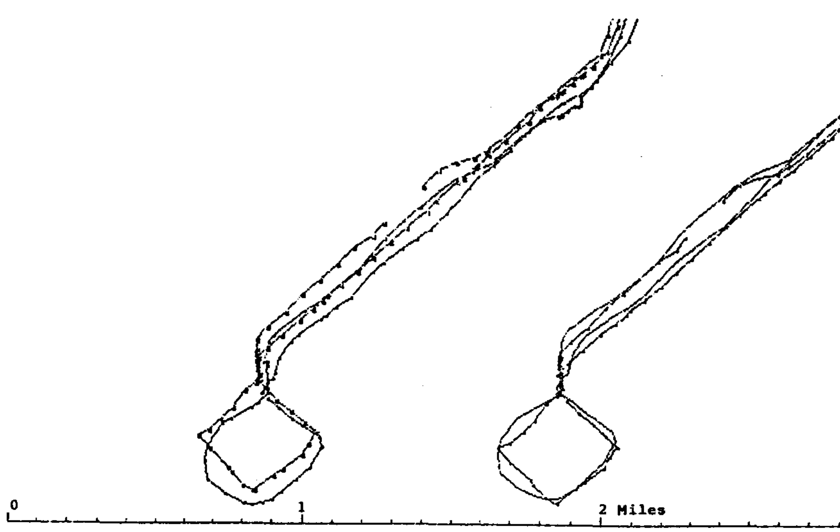


Figure 15. Superimposed 6-channel GPS data and "quasi" differential LAD-LORAN (left) and commercial LORAN data (right) on an expanded scale. Power line grid warps (a) are indicated on LAD-LORAN and commercial LORAN data. On left, 6-channel GPS data illustrated with larger pixels; on right, 6-channel GPS data indicated with smaller pixels.

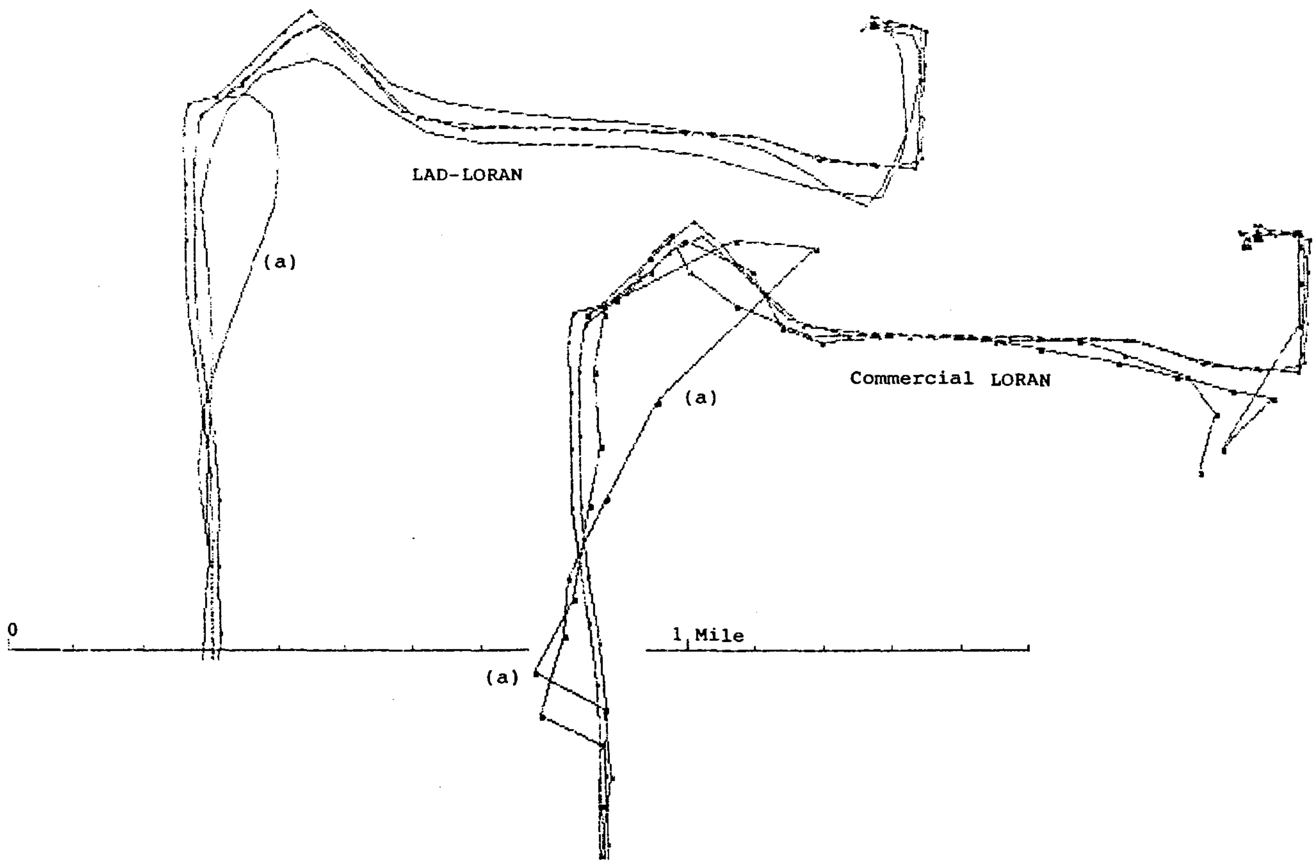


Figure 15 shows the beginning/end of this same run after "quasi" differential operations on LAD-LORAN and commercial LORAN data sets. With the exception of the initial/final south/north segment and exit/entrance to LocUS' parking lot, power lines parallel most of this portion of the route. Although power line grid warps (labeled "a") are evident on both LAD-LORAN and commercial LORAN plots, data from other sections of the route suggest differential LORAN operations would produce excellent results for vehicle location applications.

Static Tests: Finally, a continuous 55 hour static test was performed in order to compare the stability of positions generated by GPS and LAD-LORAN receivers.

There are two important conditions to note regarding these data: (1) they include two complete nights of LORAN data; and (2) Selective Availability (S/A) was on during these tests. We have no means to define the level or variability of S/A during these tests. Results from this test are shown in Figures 16 to 20, where each pixel represents one or more data points. Only data points (i.e. positions) the receivers considered "valid" or "good" are shown.

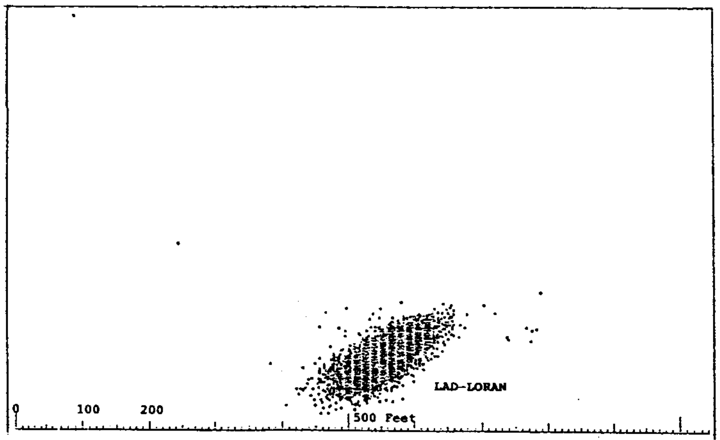


Figure 16. Data issued by LAD-LORAN receiver during 55 hour static test.

In order to clarify data presentation, provide a relative reference, and facilitate direct comparisons in the following figures, only data from the LAD-LORAN receiver are shown in Figure 16. Over the 55 hour period, the error ellipse defined by these data has a radius of approximately 100 feet on the major axis. The receiver considered every point it issued during this test to be valid.

Figure 17 shows data the 6-channel GPS receiver and LAD-LORAN receiver issued during the 55 hours. In relative terms, most LAD-LORAN and GPS positions were about 300 feet apart.

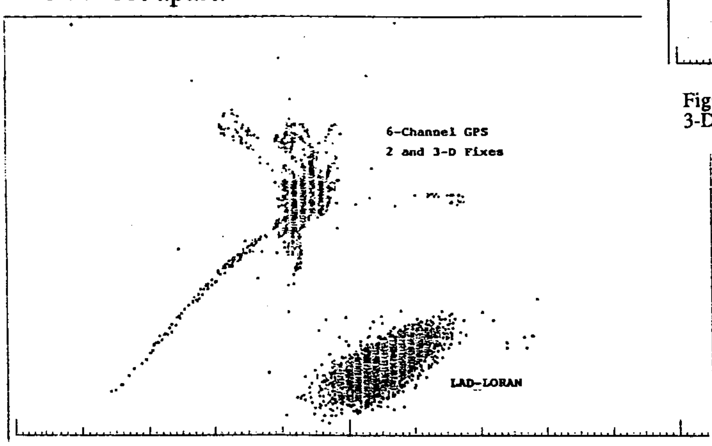


Figure 17. All valid data issued by 6-channel GPS receiver (i.e. from 2 and 3-D fixes) and by LAD-LORAN receiver during 55 hour static test.

Figure 18 shows points the 3-channel GPS receiver and LAD-LORAN receiver issued during the 55 hours. These GPS data clearly differ from those produced by the 6-channel unit, but the majority of points are similarly positioned relative to the LAD-LORAN system.

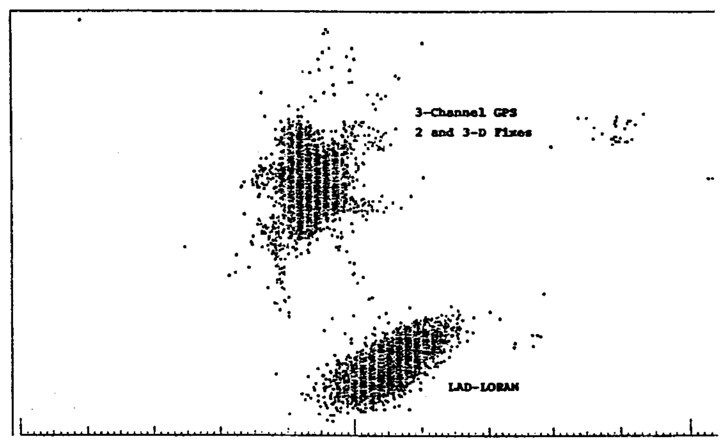


Figure 18. All valid data issued by 3-channel GPS receiver (i.e. from 2 and 3-D fixes) and by LAD-LORAN receiver during 55 hour static test.

Figure 19 displays GPS data generated by 3-D fixes only (i.e. fixes obtained from four or more satellites), along with the LAD-LORAN "reference" data set. For this 55 hour test period, 87% of the 6-channel GPS data were from four or more satellites, and 67% of the 3-channel GPS data were 3-D. 3-D fixes from the 6-channel GPS receiver produced the tightest data cluster during this test.

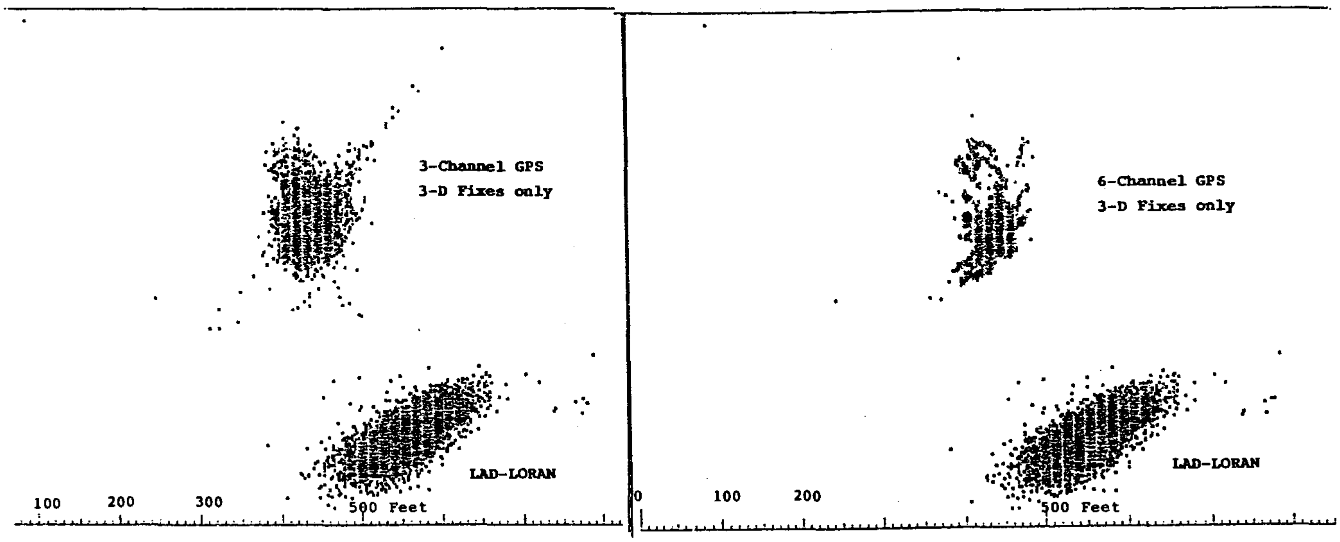


Figure 19. 3-D (i.e. four or more satellite) fixes from 3-channel (left) and 6-channel (right) GPS receivers and LAD-LORAN receiver during 55 hour static test.

Figure 20 displays the 2-D fixes (i.e. fixes obtained from three satellites) from these units, plus the reference data set. During this 55 hours, 13% of the 6-channel data were from three satellite fixes, and only 10 points (not shown) were considered invalid. For the 3-channel GPS unit, 32% of the fixes were 2-D, and 109 points (not shown) were considered invalid.

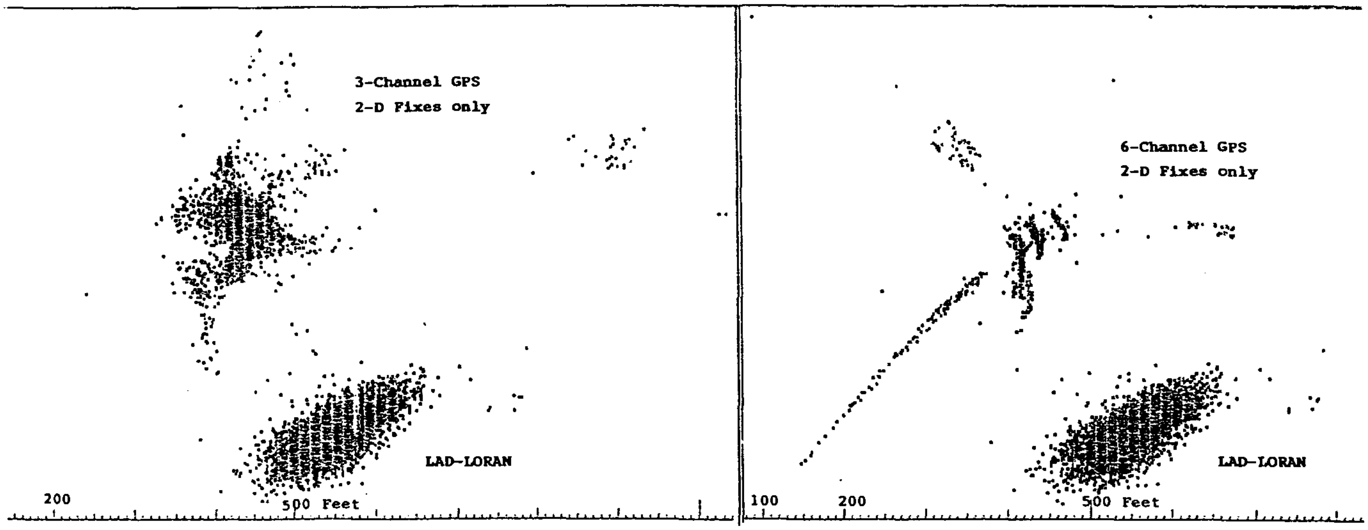


Figure 20. 2-D (i.e. three satellite) fixes from 3-channel (left) and 6-channel (right) GPS receivers and LAD-LORAN receiver during 55 hour static test.

From Figures 17 to 20, it is clear GPS receivers from different manufacturers generate different positions, even under identical static conditions. These differences appear to be most pronounced when satellite coverage is poor (i.e. 2-D fixes in Figure 20), a condition often encountered in AVL applications from line-of-site satellite signal blockage from buildings, trees, etc.

Since these static data were obtained during "low" S/A levels, it appears LORAN would offer better repeatable accuracy than GPS at the 100M standard SPS accuracy. It would be of interest to perform similar dynamic GPS/LORAN comparisons in AVL applications under full S/A conditions.

DISCUSSION

The data presented above compared the relative performance of different LORAN and GPS receivers under identical static and dynamic conditions, with particular emphasis on AVL applications. Results from these real-life comparisons suggest several observations about the performance and use of GPS and LORAN receivers in AVL systems.

(1) For AVL applications, 6-channel GPS receivers provide more continuous coverage than 3-channel GPS receivers. Because of line-of-site blockage problems, it appears GPS receivers with many channels will provide better performance than GPS receivers with fewer channels.

(2) Under identical AVL conditions, different GPS receivers generate different results; different LORAN receivers generate different results; and LORAN and GPS receivers generate different results.

(3) Under the "low" S/A levels implemented during these tests, it appears GPS receivers defined vehicle routes in "light urban" conditions more accurately, but LORAN receivers provided more continuous coverage.

(4) For some applications requiring highly accurate tracking, it may be desirable to use differential GPS or differential LORAN systems. Differential operations would eliminate S/A errors in a GPS system, but line-of-site blockage would still occur. Differential LORAN would correct tracking errors due to systematic ASF errors.

(5) Finally, in order to optimize accuracy and coverage continuity in an AVL system -- and in other dynamic navigation applications requiring very reliable, accurate coverage -- a combined LORAN/GPS system would appear to offer complementary performance characteristics.

Biography

G. Linn Roth, Ph.D.
Linn Roth is President of *LocUS, Inc.* He is a graduate of the University of California - Berkeley and holds a Ph.D. in Neurophysiology from the University of California Medical Center - San Francisco. Linn subsequently was awarded an NIH Post-doctoral Fellowship to perform research and teach at the University of Wisconsin Medical School. He then joined Nicolet Instrument Corporation, where he was a Business Unit Manager and Director of Marketing. Linn has been with *LocUS* for 3 years.

Kendall E. Post
Ken Post is Vice President of Engineering at *LocUS, Inc.* He was an electrical engineering major at the University of Wisconsin - Madison, where he emphasized digital and analog design. Ken worked as an electrical engineer at the University's Space Astronomy Laboratory and Instrumentation Systems Center, where he provided instrumentation for a wide variety of research programs. He joined Amtel Communications, Inc., where he became Director of Engineering and supervised the development of microprocessor based telecommunications equipment. Ken is a co-founder of *LocUS*.

NMEA 0183 — Version 2.0
Standard for Interfacing Marine Electronic Navigational Devices

Frank Cassidy
Chairman, NMEA Standards Committee
DATAMARINE INTERNATIONAL
Pocasset, Masssachusetts

Abstract

The NMEA 0183 Standard is used to interconnect Loran-C, OMEGA, and GPS receivers to autopilots, position plotters and RADAR displays; compasses, depthsounders, and meteorological instruments from various manufacturers make their data accessible using NMEA 0183. The standard has evolved to become the accepted international interface standard for marine equipment.

Proposed Version 2.0 of NMEA 0183 maintains compatibility with previous versions but greatly improves the readability and reduces ambiguities. In addition, sentences for Loran-C, GPS and RADAR have been added and numerous sentences have been recommended for phase out. Version 2.0 has formed the basis for an IEC standard that will meet the IMO requirement for SOLAS regulated vessels.

This paper describes the history of NMEA standards, discusses some of the common usage errors and describes the changes and clarifications present in Version 2.0.

NMEA

The National Marine Electronics Association is an organization of retail dealers, distributors, manufacturers and individuals that are involved in the sale, manufacture, installation and use of marine electronic equipment.

Founded in the late 1950s, the NMEA was organized for the primary purposes of keeping members more informed on products and technology, providing feedback on proposed regulations to government agencies, training technicians and developing technical standards. While it is a United States national organization, about 10% of its 350 members are from other countries; manufacturers make up about 25% of its membership. The NMEA has a full time Executive Director and a slate of volunteer officers and ten Regional Directors. The directors are elected locally and represent ten regions of the United States.

Along with an annual meeting there are a number of regional meetings each year throughout the country. As part of its education program the NMEA sponsors technical workshops and papers at these meetings. The Certified Marine Electronics Technician (CMET) program offers three levels of certification, Certified, Advanced Certification and Senior Grade, and functions to insure the dealer and customer of the qualifications of servicing technicians. The voice of the NMEA is the bimonthly journal Marine Electronics, The Official Journal of The NMEA, published in Winter Park, Florida. Marine Electronics provides technical articles, industry news, new product announcements and updates on NMEA Standards.

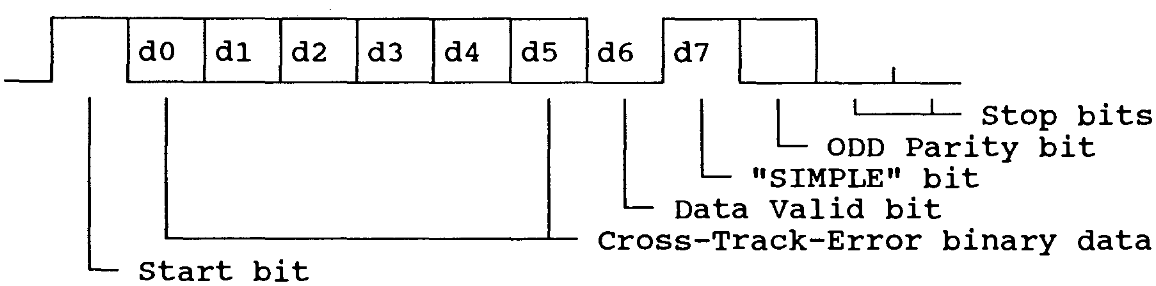
The NMEA Interface Standards committee drafts and maintains standards for interfacing marine electronic devices. At present three standards are in place: NMEA 0180, NMEA 0182 and NMEA 0183.

NMEA Standards

NMEA standards activities were initiated by autopilot manufacturers who were anxious to make use of realtime navigation data available when "navigation computers" were added to Loran-C receivers. Realizing that the overall performance of the pilot could be improved by automatically correcting for wind and current effects, manufacturers in the NMEA suggested a standard format for providing cross-track-error (XTE) data. "NMEA 0180 - Standard Interface Format Between a Loran-C Receiver and an Autopilot" was approved in February, 1980.

This interface, and those to follow, were meant to have a single talker (sender, transmitter, driver) but could have multiple listeners (receivers). The physical interface consists of a two-wire plus shield interconnect between an RS-232 or TTL driver and an opto-isolated receiver. NMEA 0180 data is a single asynchronous serial character at 1200 Baud representing cross-track-error left or right of the course line. Binary data with a maximum range of ±0.31 is transmitted in units of 0.1 microseconds or 0.01 nautical miles, with no distinction between the two sets of units. A single bit is used to indicate data valid and an additional bit was reserved for future use to distinguish this "simple" data from "complex" data messages that might follow. The bit assignments for the NMEA 0180 character are shown below.

Work was hardly finished on NMEA 0180 when in 1981 manufacturers were using more sophisticated autopilot algorithms and proposed additional "complex" characters that would provide XTE with units indication, bearing angle to the waypoint, latitude/longitude and a full description of receiver status and waypoint arrival status. In March of 1982 "NMEA 0182 - Complex Format For Communication Between a Loran-C and an Autopilot" was approved. This standard calls for an asynchronous serial interface using the same hardware and Baud rate as NMEA 0180 (in fact both data types can be mixed on a single interface cable) with 37 characters in printable ASCII form.



NMEA 0180 SIMPLE CHARACTER (1200 BAUD)

```
$MPN0.03LM28942D36.85'N070D24.32'WA<ETX>
    Sentence terminator
    Status, manual cycle lock
    070°24.32' West longitude
    42°36.85' North latitude
    289° Magnetic, bearing to waypoint
    0.03 nautical miles cross-track-error, Left
    MP, sentence identifier (fixed)
    $, start of sentence
```

TYPICAL NMEA 0182 DATA STRING (1200 BAUD)

A typical NMEA 0182 sentence as it would show on a terminal or serial printer is shown above. The NMEA 0182 sentence is now frozen as one very specifically defined sequence of characters, however it was originally structured with a two character address and a number of data fields that could be varied in order to provide a number of formats.

A revision of the NMEA 0182 structure resulted in a more universal interface specification, with greater flexibility, for devices serving varied navigation and safety needs and made by different manufacturers. This new standard "NMEA 0183 - Standard For Interfacing Marine Electronic Navigational Devices" uses the same hardware specification but at a 4800 Baud rate. Various data field types are identified and fields are separated by "," delimiters to allow for variable length fields. A large number of interface sentences are defined in detail, each having two characters to identify the sender and three characters to identify the data format of the fields that follow. In addition non-standard "proprietary" sentences are allowed and each manufacturer has a unique 3-character code for use in constructing their own proprietary sentences. NMEA 0183 was first approved in February of 1983, updates and corrections were made periodically resulting in NMEA 0183 Version 1.5 which was approved in December of 1987. A typical NMEA 0183 sentence is illustrated below.

```
Sentence terminator, carriage-return/line-feed
Name of waypoint
Distance to waypoint, nautical miles
Bearing to waypoint, Magnetic
Bearing to waypoint, True
$LCBWC,142348,4232.83,N,07038.23,W,039,T,055,M,39.2,N,LOC4<CR><LF>
    Waypoint longitude
    Waypoint latitude
    UTC time of observation
    BWC, sentence identifier, Bearing to Waypoint Great Circle
    LC, Talker identifier, Loran-C
    $, start of sentence
```

TYPICAL NMEA 0183 DATA STRING (4800 BAUD)

Experiences with NMEA 0183

NMEA 0183 has proven to be a tremendous asset to the marine electronics community - manufacturers, dealers and customers alike. Interconnecting of various types of equipment from many different manufacturers is taking place today in numbers never thought possible in 1983. It is the de facto international standard for interfacing marine equipment, and in the vast majority of cases the interface is smooth, clean and trouble-free.

However there have been, and continue to be, problems in getting some equipment with "NMEA 0183" interfaces to work properly. When this happens the customer is dissatisfied, the manufacturers are frustrated and the dealer is caught in the middle. Often the offended is very vocal!

The problems generally fall into three categories:

1) Cases where manufacturers fail to correct gross mistakes, or intentionally use a modification of the standard to meet their special requirements but still refer to their output as NMEA 0183.

2) Cases where the standard is misinterpreted. This was even more of a problem in the early days until the designers "learned" the standard, but is still a daily headache.

3) Cases where talkers and listeners are not programmed for the same set of sentences.

Examples of errors that have been reported on equipment that is advertised as meeting "NMEA 0183" include:

- Listening devices "counting" characters rather than determining field locations by "," delimiters
- Baud rates different than 4800
- Incorrect voltage levels and inverted outputs levels
- Receiver DATA"-" not isolated
- Multiple sentences following eachother without "$" at the start of each new sentence
- ASCII "null" character used instead of an empty null field
- Manufacturers making up and using their own sentences in an "approved" sentence format instead of using a "proprietary" format.

Often manufacturers are reluctant to change, even after the problem is pointed out, due to the number of units of their own design, or that of other manufacturers that acquiesce, that are in the field that depend on the <u>incorrect</u> interface.

Version 2.0

Version 2.0, to replace Version 1.5, has been designed to help in minimizing the above problems by being clear and explicit in order to avoid misinterpretation. In some cases the new version has taken a "pragmatic" approach and includes modifications that will bring the standard into conformance with that which is encountered in practice.

The entire document has been rewritten, reformatted and reorganized for clarity and ease of understanding. A very large part of the effort involved developing consistent symbols and terminology, careful attention to sentence presentation and the addition of many definitions and descriptions that were missing from the original document. Each sentence and field has its usage defined so as to remove ambiguity and the need for interpretation.

Except where explicitly pointed out below, it has not been the intention to change the standard and compatibility between existing and new equipment has been a requirement in the revision process. A number of suggestions have been received calling for the new revision to be labeled NMEA 0191, these suggestions have been strongly resisted on the basis that Version 2.0 is not a new standard but rather a clarified and strengthened NMEA 0183, compatible in a practical way with earlier versions.

The following is a summary of the important proposed changes:

- Specific information is required in operator's manuals including a list of sentences and fields used and an interface schematic

- Talker drive circuit is changed from NMEA special [$\leq$+0.5 to $\geq$4.0, $\pm$15 volt max, source 15mA, sink 0mA] to EIA-422 [differential, inverted outputs, positive voltage, nominal +0.5/3.5 volts]

  Receiver circuit is changed from an optoisolated load of 500 ohm minimum to low current optoisolated load required to operate at 2.0 volts minimum and limited to drawing 2.0 mA at that voltage.

  This change was driven by the need for a more standard hardware interface and the need to support more than one or two listeners on a system.

  Although technically almost all existing equipment would be in "non-conformance" with the new version, everything should con tinue to work pretty much as it does today, and improve as lis teners adopt the low-current optodiodes . Some manufacturers have been using EIA-422 drivers for years. An optodiode circuit designed to meet the existing 500 Ohm requirement would use a 325 Ohm series resistor, while the low-current/low-voltage receiver would now use a 300 Ohm resistor.

- Existing approved sentences can be officially changed in the future by the Standards Committee simply by appending new fields on to the end of the sentence.

  This change is necessary to eliminate the need to create new sentence to make up for the shortcomings of existing sentences as needs and technology change. For a listener that is correctly decoding an earlier approved sentence there should be no problem, it should stop decoding before the new information and not even know it is there.

- A number of new Talker Identifiers have been added for RADAR/ARPA, communications equipment, etc.

- Most field definitions are unchanged but they have been more fully defined and their symbols standardized.

  In variable numeric fields the transmission of the decimal point has been made optional depending on the need for precision. This matches the mixed practice observed with existing equipment.

  Time fields which have been fixed fields in the past have been changed to semi-fixed fields to allow for decimal seconds to be transmitted.

Waypoint Identifier fields, 4 or less number/upper-case alpha characters, have been changed to a variable alphanumeric field.

- Sentence changes and additions include the following

a) APB - Autopilot, changed to allow "Bearing, origin to destination" to be True/Mag instead of only Mag

b) ASD - Autopilot System Data, new sentence at the request of IEC

c) DPT - Depth, new sentence to replace multiple existing sentences

d) GGA - GPS related, added field at end for differential GPS

e) GSS - GPS related, new sentence listing satellites, DOPs

f) GSV - GPS related, new sentence - azimuth and elevation

g) GLC - Loran related, new sentence replacing multiple existing sentences

h) GLL - Lat/Lon, added fields at end for time and status

i) HDG - Heading, new sentence replacing multiple existing sentences

j) LCD - Loran related, new sentence replacing multiple existing sentences

k) OSD - RADAR/ARPA own ship data, new sentence at the request of IEC

l) RMA - Loran Minimum, added fields at end for GRI indication

m) ROT, RPM - Rate of turn and RPM, new sentences at the request of IEC

n) RSD - RADAR system data, new sentence at the request of IEC

o) TTM - RADAR target data, new sentence at the request of IEC

Much of the misinterpretation of NMEA 0183 is a thing of the past as designers gain experience, and this new version should minimize any future confusion.

A continuing problem however is where the talker and listener are not using the same set of sentences (autopilot listens for APA while Loran talks APB, etc.). Enormous amounts of time, money and frustration are involved when talker and listener don't match up. This is an ongoing problem even today and is moderated slightly as the more sophisticated equipment is designed with a larger list of sentences, and some with programmable choices - both a tremendous burden on the equipment design! Designs from newer companies can immediately fall into the trap of picking the wrong sentences to include in the design and face instant incompatibility in the marketplace.

The solution to this problem is not easy or quick. If a clean sheet a paper were in front of us we would wisely dictate a specified list of data sentences that would be required for transmission by various equipment types. But the multitude of sentences available at this time make this impractical.

The first step in the solution has been taken over a period of time by the manufacturers. By trial and error they have learned which sentences to use and have expanded this list within their equipment and ignored the others.

The second step is provided by Version 2.0. This version creates two listings of official sentences: current sentences and those not recommended for new designs. Approximately 60% of the existing NMEA sentences have been placed in a separate Appendix labeled "Not Recommended For New Designs", in almost all cases a current sentence is recommended as a substitute. The 40% of sentences that remain in the main body of the standard have been supplemented by new sentences (about 10%) that combine functions and serve new applications that were not considered in the original NMEA 0183.

Initially some manufacturers will transmit both sentences, not a lot different than what they have to do now, but eventually the older sentence will disappear from use. One of the big advantages in this move is that poorly conceived, under utilized sentences that are now present can be eliminated before their use becomes popular.

By consolidating and reducing the number of sentences available the NMEA is setting the stage for the third part of the solution were it will be possible to require the transmission of a minimum complement of sentences in order to be considered in compliance with the Standard.

Version 2.0 and IEC TC80/WG6

IEC Technical Committee 80 established Working Group 6 to develop a technical standard for Digital Interfaces for equipment that is specified by IMO to meet the SOLAS regulations. At the same time NMEA was in the process of revising and updating NMEA 0183 Version 1.5.

In the interest of avoiding the emergence of a second digital data interface standard for marine equipment, the NMEA offered the use of NMEA 0183 as the basis for a standard that would satisfy IEC requirements for IMO/SOLAS applications. Further the NMEA offered to consider IEC requirements during the revision process that was to lead to NMEA 0183 Version 2.0, with the goal in mind of producing a common international standard that would satisfy IEC needs while maintaining compatibility with the current version of NMEA 0183. The NMEA established itself as the U.S. Representative to IEC TC80/WG6 and worked with the IEC towards this goal.

The result is that both organizations intend to adopt the same document. All protocol, definitions, wording, paragraphs, paragraph numbering, and appendices will be the same. The two standards are exactly the same with regard to software protocol and sentences, they differ unfortunately at the hardware interface.

The IEC at this time is firm in its intent to adopt an existing hardware standard (EIA-422) which consists of a balanced driver and a differential-amplifier receiver. For improved common-mode noise rejection and for compatibility with existing NMEA 0183 equipment, NMEA 0183 requires an optoisolation device for a receiver but could adopt EIA-422 for the driver. The EIA-422 driver is compatible with both differential-amplifier and optoisolation receivers. The EIA-422 differential receiver is not compatible with the existing unbalanced (0 to 4 volt) NMEA driver.

There will two separate documents, IEC has specific page layout rules and will print in English, French and Russian. Each document will reference the other. The IEC requires only a subset of the NMEA sentences but will list the others for reference. The IEC has identified Talker IDs and sentences for their use and have requested that NMEA include these additional Talker IDs and sentences. NMEA 0183 Version 2.0 flags the Talker IDs and sentences in use by IEC.

The NMEA and the IEC will maintain separate documents and control changes so as to not impact the other. The NMEA will remain a member of IEC TC80/WG6 or any follow-on committee and an IEC representative will continue as a member of the NMEA Standards Committee in order to track progress and changes. Clearly it would be undesirable for either to make changes that would impact the other after the two standards are released.

Status

As of October 1991 both the IEC document and NMEA 0183 Version 2.0 are in the final review stages by their respective committees. IEC TC80/WG6 will meet in Berlin, Germany in conjunction with the IEC TC80 Plenary Session in mid-October. The NMEA Standards Committee will hold a panel discussion for the general membership and a Standards Committee meeting as part of the NMEA Annual Meeting in early November at St. Petersburg, Florida. It is anticipated that NMEA 0183 Version 2.0 will be released prior to the end of 1991.

References

For copies of the NMEA Standards contact:

Robert Sassaman
NMEA Executive Director
P.O. Box 50040
Mobile, AL 36605

For technical information on NMEA Standards contact:

Frank Cassidy
Chairman, Standards Committee
Datamarine International
53 Portside Drive
Pocasset, MA 02559

For information on IEC Standards contact:

Mike Fox
Secretary General, IEC TC80
C.I.R.M.
South Bank House
Black Prince Road
London SE1 7SJ, England

Biography

A member of the WGA since 1972, Frank Cassidy has been active in LORAN-C design and development from 1969 to the present. He received his B.S.E.E. from Northeastern University and the S.M. in Engineering and Applied Physics from Harvard University. At Datamarine Frank is involved in the design and development of Loran-C and GPS receivers and Electronic Chart Systems.

Frank served as Technical Co-chairman of the 1989 WGA Symposium and was chairman for one year of the WGA Audit Committee. Besides membership in the WGA he is active in the RTCM, the NMEA and is Chairman of the NMEA 0183 Standards Committee.

The Recreational Boater and Loran-C

P/C Anne S. Peskin N
Stamford Power Squadron

How does the recreational boater use Loran in general and his loran in particular? This paper will consider the opportunities and depth for learning to use Loran. It will then consider how knowledge and use of Loran make a difference in races approach to short day or evening races around the buoys on Long Island Sound. Finally it will explore the boaters use of Loran in planning the longer (two or three week)cruise down Long Island Sound and East. This last portion will be presented in journal format. The journal excerpts will contain preplanning before the day's excursion (30-60 miles) and the debriefing after the day's run. The paper is based on interviews with a number of recreational boaters.

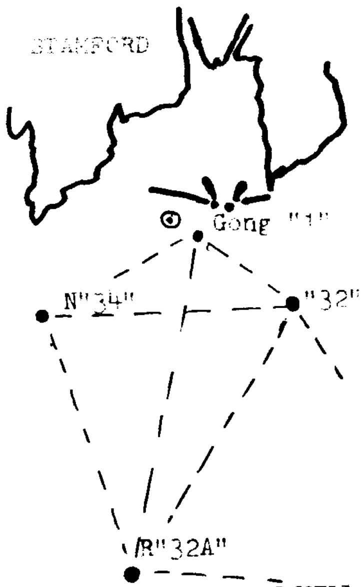
How is the recreational boater prepared for the use he can make of a Loran unit be he sailor, power boater whose boat ranges from 20' to 50'? First let us consider where he learns what to buy. It may be a friend who raves, a salesman who has four or five different sets ranging in price from 200 to 1200, or a blurb in one of the boating catalogues giving the various functions. Basically each source says"you will know where you are." Is this really preparation? Let us assume some machine has been purchased and installed. What is the next step? Yes, we can read the manual, buy a how to video,ask a friend, learn in a course.

The course literature I use talks of the history, the chains of transmitting stations TD's and lines of position. The LOP's are discussed in units of tens e.g. 14880.0 and then I quote "by examining the adjacent lines you should be able to interpolate easily." It further mentions that in addition to TD's and Lat/Lon some units give SOG,COG and course to steer. In the course itself one portion of one session is devoted to finding and placing TD's and Lat/Lon of points on a representative chart. Yes it is a beginning of hands on but only a few hundreds take this course.

How do the tens of thousands of users learn? a friend? or directions? There is only one problem - each machine is different. I know for this year I used one on the boat I raced, another navigating a larger boat back from Bermuda and still another that I bought this year for my boat. Each machine has distinctly different directions for entering waypoints, converting, finding courses. You start from scratch.

In a survey this summer, I found that it was the captain that knew how to use his loran and the mate or crew knew little. In our Skipper Saver Course, we taught and demonstrated just how to turn on the loran and what to press on my machine in order to read out present position. I must admit it is embarassing to hear "that's all there is to it?" We did tell them to with their captain try their loran. In teaching my crew to put in waypoints there was great hesitancy in pressing the keys for function numbers and "enter" and "clear." After several starts andthe realization that nothing will break or get lost forever it became a useful tool. Here I suggest that a simulator or actual unit be available to help those who fear to practice or at least try it out.

Well the Loran is in the boat - how do sailors of short 5-10 mile around the buoy races in Long Island Sound use loran. In my survey of racing boaters, there are 3 sets: one says I see and know the buoys and only use them in bad or a night for courses to the mark; the other says I use it for range and bearing, to establish tacking position, course over ground COG and to help ascertain current and wind effect; the third set uses all the above and includes cross track error, range and



RACES AROUND THE BOUYS

Figure 1

bearing to the mark. All the racers have found that it is better for repeatability to take actual readings of each buoy that is used. I recall one race boat in my division following me in a race because he know I had a Loran and therefore knew where the mark was located. Yes, loran has changed racing in that positions are known and the boats actions in relation to the marks are available.

Let us now turn to still another group of recreational boaters. These are ones that travel together for a one or two week vacation. Below are excerpts of this year's trip which is a prototype of howwloran is used in planning the trip and what can happen on a voyage

Journal: 6/10/91
All twelve captains settled on our trip. Reservations are made. We are staying at least two nights at each stop except Marion. We are to meet at Stonington on 7/27 then to Block Island,Marion, Plymouth, Wellfleet, Quisset... Figures 2 and 3. We (3 boats) will leave at 6 from Stamford and make the 70 mile run. The other boats are stopping at Branford a 35 mile run on the way. Marty used his loran to check distances. The long run is from Block Island to Marion a 52 mile run. The power boats are hosting dinner there for us slow sail boats. I checked the currents, they are with us since we planned our leaving times.

Journal: 7/25/91
I studied the route, made some choices and found the TD's. I have written them in my blue work book for each day's trip. Paul and Sam said they have put all their choices into their Lorans. Tomorrow I'll put in the first leg, and some major ones I know I'll need. I'm starting at #35 so that my racing bouy numbers won't be touched.

Log: 7/26/91 Left Stamford 1130
arrived Branford 1620 (rained)

Journal: 7/26/91
As we passed New Havenwe decided to stop at Branford since it was too late to make the run to Stonington. I had to quickly find the numbers to put in my loran for the entrance - some were in TD's others I had to find in Lat/Lon. It's a tricky entrance between the rocks so I found the courses from buoy to buoy using the range and bearing from __to __ function to obtain compass courses. I used the arrival alert set at .25 as an additional aid. So much for advanced planning.

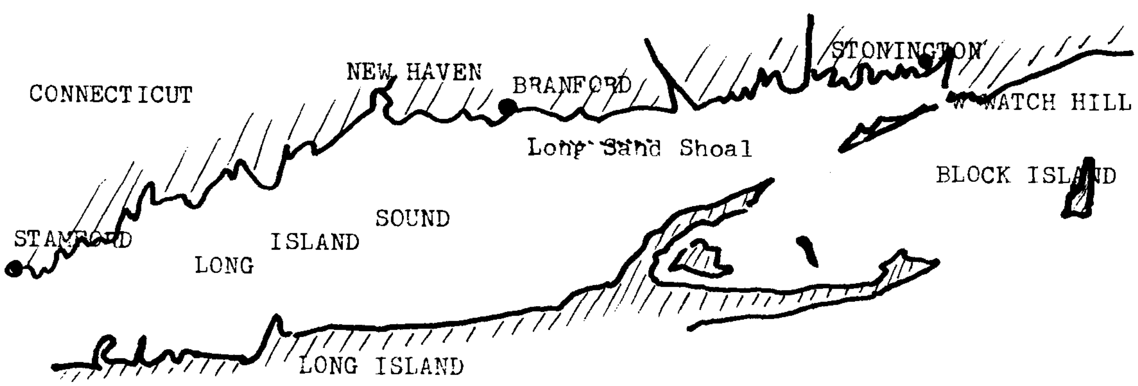


Figure 2

Journal 7/27/91
What again! because we left late after my Captain cut the prpylene line off the propeller, I had to redo my loran positions We went outside the Long Sand Shoal to catch the greater current. We rafted with Larry and now the cruise begins.

Journal 7/28/91
Today we left Stonington, I too the actual TD's on Gong "1" off Watchhill which we will use when we return. There was a difference. I enjoyed the sail and the arrival alarm gave us time to take in the sails - I am enjoying that function.

Journal: 7/30/91
Janet and Lillian (my two pupils from this year's Advanced Piloting class) came on board to discuss how they had planned the trip so far and how they planned the trip to Marion. Janet is excited because she is doing the navigating and brought her boat into Branford using her loran plots.

She has chosen a different route than I up Buzzard's Bay. I am keeping both sets handy...mine is down the middle, hers on the North side. She has the chart book that lists the Lat/Lon at each position - she is not determining them herself. Since Lillian still is hesitant we helped her think through the route and ask her captain if he agreed. I went over finding values and interpolating with them.

Journal: 7/31/91
Today I spent time interviewing the sport fishermen at the dock. They are here for the Bill Fishing Tournament. They use loran basically for point to point and they use it to mark the position of the catch. They like the loran to be user friendly.

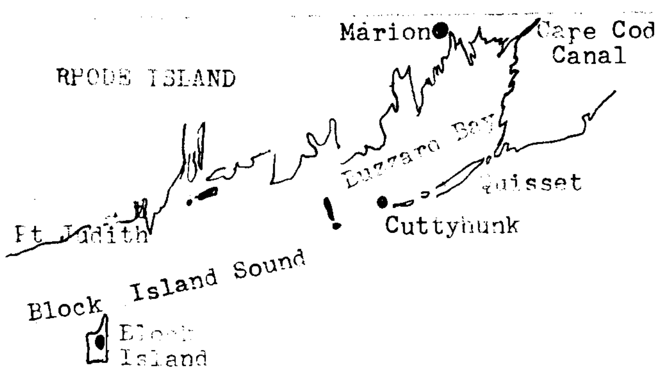


Figure 3

Journal: 8/2/91
Well am I glad I didn't put in all the waypoints in advance and had alternates ready. The weather - the seas were bad 6-8 foot waves. Sailing even powering was difficult. We used the north shore route which I had taken from Janet to be on the lee shore. It was good to pick up the mooring at Marion. (Figure 3)

Journal:
Whow did we travel quickly through the Cape Cod Canal. The COG/SOG function showed we were travelijg over the ground at 11.0 knowts I had only the first and last of the canal buoys positions in the loran. The trip to Plymouth was smooth but the entrance circuitous - the loran came in handy I used it to check compass course , range and bearing. (Figures 4,5)

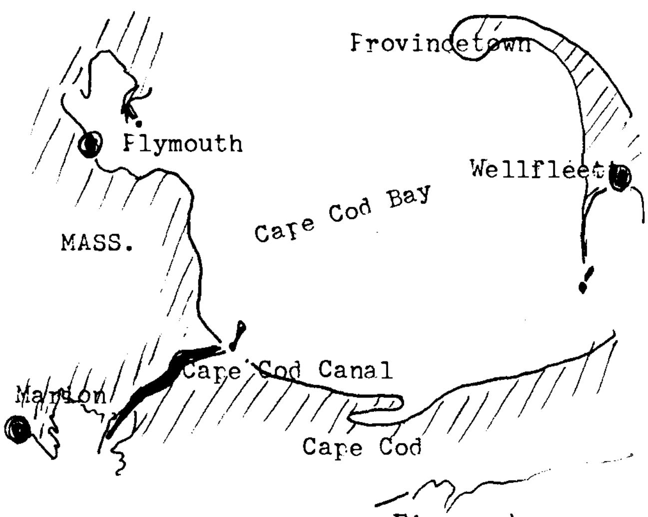


Figure 4

Journal: 8/4/91
I spent the morning interviewing fellow travellers on their use of loran. The power boaters use it for point to point travel - Sam puts his loran route number on is chart in indelible ink highlighted in yellow so that he can follow easily. He uses his cross track function to stay close to the rhumb line. Murray keeps track of his course by taking loran fixes every hour. Marvin keepstrack of "actual readings in a separte book to replace the calculated ones. All of us check values put in and courses given - so that the boar is really going were it is planned. Finger errors occur often when under tension. Each one speaks of his loran as "great".

Journal: 8/5/91 (fig.5,6)
I went over to Lillian's boat and with her captain had her choose and put in Lat/Lon values for several positions. At last she touched"the machine". We studied the Wellfleet approach. It makes Plymouth look like child's play. I have laid out the courses and buoys in loran in great detail. The run into the harbor from gong"1" is over 12 nm.

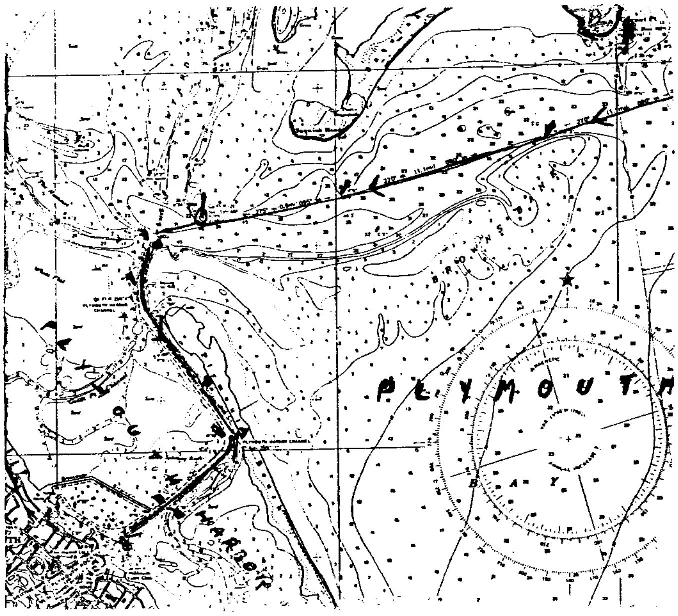


figure 5

Log: 8/7/91 Leave Cuttyhunk 0600
Log: 8/8/91 Arrive Stamford 0350

Journal: 8/8/91 (fig.3,4)
Although we have been crew on voyages as far as the Abacoas to Southwest Harbor, Maine; navigated back from bermuda, this trip from Cuttyhunk was the first over night with just the two of us. It all started at 1630 outside of Saybrook when we agreed to ...go for it ... I chose the lighted buoys , put them in the loran and set the alarm arrival alert for 1.0. The reading of the TD fixes first every hour (this is normal procedure on our boat)then TD fixes every half hour as it got dark gave us comfort as we plotted our course. Outside New Haven all the lights and electronics went off. It was then as we traveled by flashlight over the compass that I appreciated Loran and the security it gave us. Thank goodness the captain figured out the problem and the lights and electronics went on. We felt exhilarated and enervated.

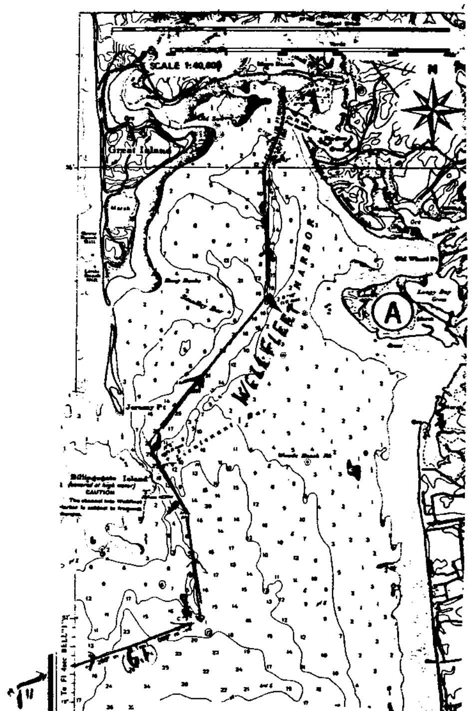


Figure 6

In summary I found that the recreational boater uses the Loran C mainly for way-points and courses and crosstrack error. Most prefer the Lat/Long entry of positions and reading. There is a more sophisicated group that use the other functions. All have confidence in their Loran and are not even aware that each one has a different set of instructions. It has become for those traveling the coastal waters an integral part of the boating experience. I believe I have shared with you the more adventurous boaters use for there are still many that use it to go out for the day and return.

Dr. Anne S. Peskin is Professor Emeritus of City College of CUNY where she teaches Mathematics and Mathematics Education. She is a member of the Coast Guard Auxiliary and the first woman Commander of the Stamford Power Squadron. She is a liscensed Coast Guard Captain, and a distinguished navigator with several ocean voyages and racing trophies to her credit.

LORAN-C On Florida's Southwest Coast

Francis W. Mooney
The MITRE Corporation
2907 Bay-to-Bay Boulevard, Suite 303
Tampa, Florida 33629

The Southwest Florida Coast has four sets of Loran-C lines available for use, but the novice navigator really isn't sure which pair is the right one to use for navigation. This paper addresses Loran-C coverage from Tampa Bay to Marathon, FL. Recommendations for which lines to use from the Coast Guard, fishing guides, cruising guides and private charts are discussed, then compared with personal observations obtained from different Loran-C sets. A pair of satisfactory lines are recommended for general use; the choice differs from the Coast Guard recommendations.

BACKGROUND

Loran coverage for Southwest Florida is provided by the South East U.S. (SEUS) chain, GRI 7980. The chain was formed from existing stations at Carolina Beach, NC (SEUS Z) and Jupiter, FL (SEUS Y), supplemented by new stations at Malone, FL (SEUS-M), Grangeville, LA (SEUS-W) and Raymondville, TX (SEUS-X). A coverage diagram, including recommended station pairs for navigation, is shown in Figure 1. The diagram is extracted from the G-NRN Radionavigation Systems publication printed in 1984. While the MZY triad is well defined for navigation off eastern Florida, the locations of W and X combine to cause unusual coverage patterns off Southwest Florida. It is not clear which lines of position (LOPs) should be used for navigation. This paper will first examine the coverage and circumstances for Tampa Bay and Marathon, then discuss published navigation recommendations identified in commercial sources, examine receiver observations and provide navigation observations. Conclusions about the "best" LOPs to use for navigation in Southwest Florida and recommendations addressing improvement in user information are also provided.

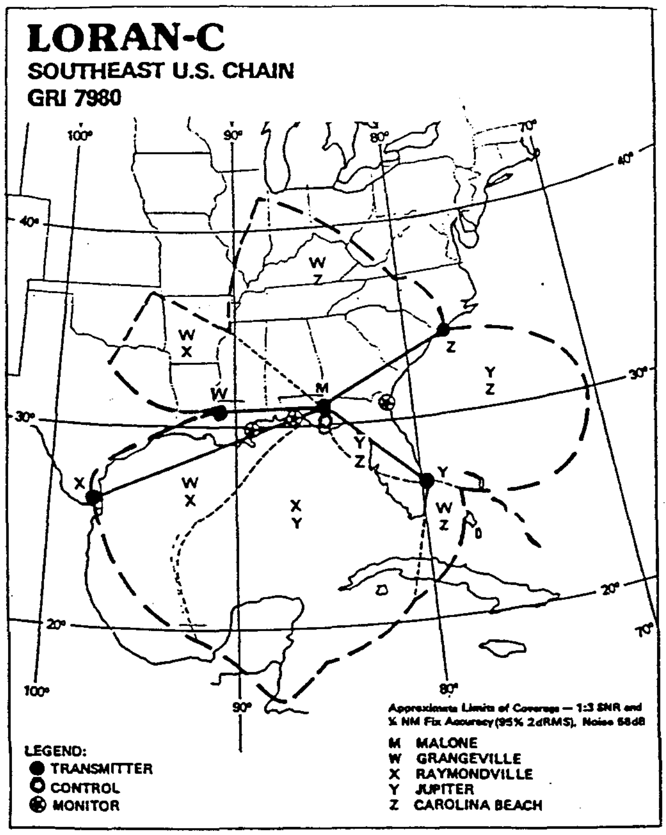


Figure 1. Coverage Diagram for SEUS (7980) Chain

COVERAGE

Tampa Bay

The principal Loran-C chart used in the Tampa Bay area is National Oceanic and Atmospheric Administration (NOAA) chart 11412, titled Tampa Bay and South Joseph Sound. The title is a misnomer because no LOPs are printed in Tampa Bay, only for the approaches. LOPs are displayed for W, X, Y and Z. Typical of NOAA charts, no information is provided to the navigator about which lines to use. Table 1 provides calculated distances of the stations from Tampa Bay, and gradients and LOP crossing angles derived from the chart.

	Approximate Distance in nm*	Gradient in yards/ 0.1 US*	LOP Pair	Crossing Angles in Degrees
M	232	N/A		
W	465	56.8	WX	16
			WY	85
			WZ	49
X	818	32.8	XY	81
			XZ	50
Y	141	17.4	YZ	37
Z	444	30.0		

Table 1. Loran-C Information for Tampa Bay

* nm - nautical miles; US - microseconds

Two sets of LOPs have large crossing angles,WY and XY. These would often be chosen for use since navigation courses traditionally recommend use of bearings with the greatest crossing angles. If the navigator considered the distance from X and realized that groundwaves at that distance are suspect, use of XY would be avoided.

Marathon (Vacca Key)

Loran-C coverage for Marathon is provided from NOAA chart 11449. Fewer choices are provided for the navigator because only LOPs for W, Y and Z are printed. Table 2 provides information for the Marathon area.

	Approximate Distance in nm	Gradient in yards/ 0.1 US	LOP Pair	Crossing Angles in Degrees
M	434	N/A		
W	630	76.5	WY	35-38
			WZ	34-35
X	912	None		
Y	149	38.2	YZ	0-3
Z	444	43.6		

Table 2. Loran-C Information for Marathon

There is little to differentiate between the use of WY or WZ. If the navigator realizes that Y is 300 miles closer than Z, Y will be chosen because the signal is much stronger.

PUBLISHED NAVIGATION RECOMMENDATIONS

Tampa Bay

The only known Government recommendation for LOPs to use in Tampa Bay is that shown in Figure 1. The diagram has been reproduced in a number of receiver technical manuals. The Loran-C User Handbook[1], the most widely read government source on Loran-C, does not provide suggestions on what LOPs should be used. As previously mentioned, NOAA charts do not provide information on recommended choices for LOPs. A Tampa Bay sailor can get some idea by talking with a fellow sailor. Also, a number of "local" fishing points listings have been published. One of the best known, "Coastal Loran Coordinates[2]" was produced by Captain Rod Stebbins, a local mariner. Rod recommends use of WY. A Loran-C "purist" might get concerned by Rod's statement that "input with latitude/longitude, or TD's will produce the same result[3]", but this is true in Tampa Bay for these LOPs. Use of WY is also recommended in "The Loran WayPoint Guide[4]", a plasticized listing of waypoints for the cruising sailor.

Marathon

At Marathon, many mariners use Waterproof Chart "6F[5]", a plasticized copy of NOAA chart 11449 that includes 88 waypoints expressed in WY; Rod Stebbins agrees. However, the Southern 1991 Waterway Guide[6], an almost indispensable reference for cruising sailors, recommends use of WZ (14/61) and provides a listing of waypoints that uses that pair of LOPs from Miami, past Key West to the Dry Tortugas. The Coast Guard recommendation is XY, not even carried on the charts.

RECEIVER OBSERVATIONS

Prior to noting results, three types of receiver acquisition characteristics are noted. Most people think of acquisition as either manual or automatic. For this paper, I have added a second category to automatic. The acquisition types are as follows:

Fully Automatic (FA) - receivers that detect presence of signals, identify the general geographic area and lock to an LOP pair based on the best current solution of gradient, crossing angle and signal to noise ratio.

Programmed Automatic (PA) - receivers that detect presence of signal, determine the geographic area and lock to a pre-programmed set of available LOPs.

Manual - receivers that lock on and track an operator designated pair of LOPs.

Tampa Bay

Since relocating to Tampa Bay, I've had the opportunity to use a number of receivers, and have talked with several hundred owners during Loran-C seminars, boat shows and at harbors during cruises. I've also had the opportunity to talk with a number of local dealers. Table 3 provides a summary of what LOPs are automatically acquired by a representative group of receivers in Tampa Bay.

LOPs Tracked	Receiver Types
XY	Raytheon (PA)*, Apelco (PA)*
WY	Micrologic 8000 (PA), Explorer (PA) and Voyager (PA), E&B Sea Ranger (PA)
YZ	NorthStar 800 (FA), Micrologic Commodore (FA)

Table 3. LOPs Acquired in Tampa Bay

* - Reported by dealers and owners

The receivers that acquire and try to track XY have problems. The weak signal from Raymondville (Y) is marginal for ground wave tracking and it is not unusual for receivers to select the wrong cycle. This results in a fix error of over 1.5 nm. I have seen enough cycle slips on Micrologic 8000 and NorthStar 800 units, two high performance sets, to convince me that use of X should be avoided. Automatic acquisition sets that want to track XY have been manually programmed to track WY by owners and/or dealers.

The other combinations produce excellent navigation results. As a general guide to accuracy, Micrologic receivers display that WY produces repeatable fix accuracy of 192 feet, and YZ provides 169 feet. After 3 years of navigating to the same channel entrance, I'm happy to report that use of WY produces better than 100 foot repeatable fix accuracy throughout the year. These results confirm those obtained by the Coast Guard Research and Development Center during the harbor monitor studies conducted in 1983[7]. Scatter plots for WZ,WY and YZ are shown in Figure 2.

NAVIGATION OBSERVATIONS

The mariner navigating with Loran-C has not been provided with consistent information on what LOPs to use in Southwest Florida. In the case of Tampa Bay, word spread years ago that WY was the pair to use. Why? Because the WY LOPs require no additional secondary phase factor (ASF) correction. This lets an inexpensive manual acquisition receiver with no ASF correction perform comparably with a top-of-the line, automatic acquisition set with ASF. As a general rule, all sets perform equally well in Tampa Bay when WY signals are used.

REPRESENTATIVE 90-DAY TIME DIFFERENCE PLOTS FOR ST. PETERSBURG

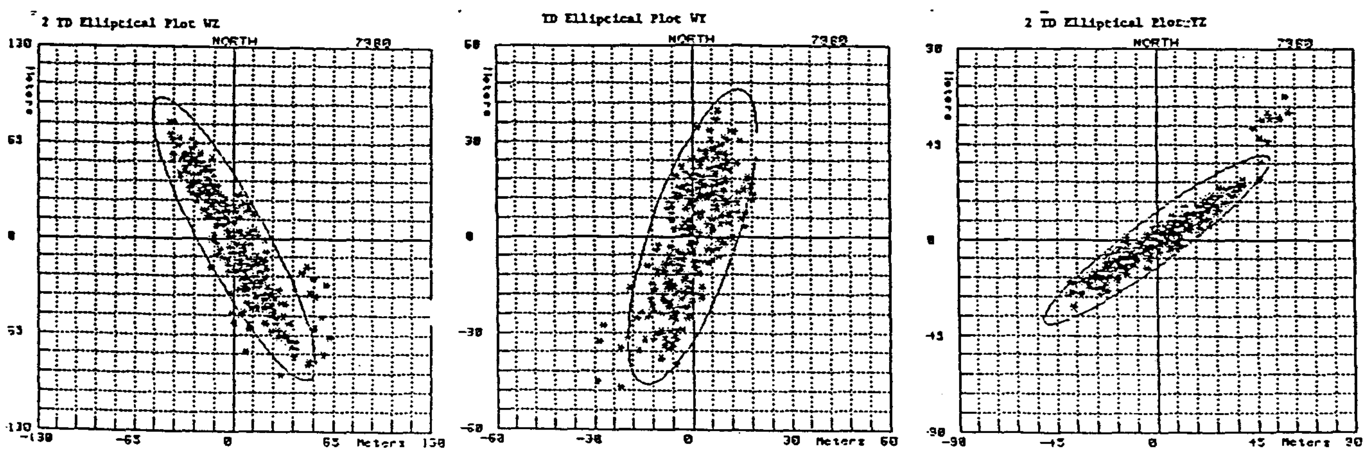


Figure 2. Loran-C Scatter Plots for Tampa Bay

Marathon to Tampa

Last year I conducted a series of measurements in the waters at Marathon and at selected locations from Marathon to Tampa. A portable version of the Micrologic 8000 was used. The portable version includes a coupler, antenna, battery pack and receiver in one assembly. At Marathon, the 8000 selected WY for positioning, but tracked all stations. Use of the receiver with Waterway chart "6F" showed the lines to have a small, fixed offset. The receiver indicated repeatable fix accuracy of 448 feet at Marathon, 377 feet at Key West, and 304 feet at Everglades City (about half way from Key West to Tampa). Signal to noise ratios were excellent at all locations, with the weakest at Marathon; M(99), W(88), Y(99) on a scale of 0 to 100 with 22 representing a 1/3 signal to noise ratio. Receivers from the Marathon Coast Guard Station also tracked these signals. Observed latitude and longitude readings were well within 1/4 nm of the charted positions, and typically within 300 feet.

Personal conversations with sailors who cruise from Tampa South to Key West have disclosed that there is confusion on what signals to use. Some manuals include the coverage diagram shown in Figure 1. Unfortunately, the Y signal never gets any stronger for a boat that transits south and cycle slips have been reported.

For a mariner transiting the Keys from Miami to Key West, the conflicting information between the fishing guides and the cruising guides can cause confusion. If the Coast Guard recommendation is used, the navigator will be surprised when X LOPs are not even shown on the charts. It is also unusual to have two sets of LOPs that are almost parallel and have almost the same gradient. This is the case with Y and Z in the area around Marathon.

CONCLUSIONS

Best Set of LOPs

After using Loran throughout the Florida Keys and making measurements between Key West and Tampa, it is clear to me that LOPs WY are best for navigation. It is possible to use the same set of LOPs for hundreds of miles of coastline. If Y is not present, WZ are an acceptable alternative. Use of X is suspect, and the LOP could be left off coastal chart 11412 without causing any navigational problem to the mariner.

Passing the Word

The best source for providing LOP selection recommendations are the charts because they are the only common reference used by all mariners. Information on distance to stations, gradients and expected repeatable fix accuracy for LOP pairs could be included in the space currently provided for Loran information. The information would help the mariner who must select what LOPs to use for navigation. An alternate source for this data could be the Loran-C User Handbook. The current edition is over 10 years old and the manual needs update because of the introduction of the mid-continent chains.

RECOMMENDATIONS

Revision of the current coverage diagram to show use of WY instead of XY is recommended. Inclusion of additional Loran navigation information on charts is also recommended.

DISCLAIMER

The investigation and information reported in this paper represent individual research on the part of the author. The comments and recommendations are those of the author, and do not represent the corporate position of MITRE.

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BIOGRAPHY

Mr. Mooney has been working in, and around, the Loran-C field since the mid-1960's. His experience includes Loran timing equipment design, transmitter performance measurements, and 5-years supervision of Loran-C operations in the North Atlantic and Atlantic coast areas.

Mr. Mooney is a Lead Engineer at The MITRE Corporation where his principal efforts involve communications systems. For the past 5 years, his off-duty Loran-C efforts have been divided between giving Loran-C Seminars, evaluating Loran Receivers for Motor Boat and Sailing Magazine and using Loran on his boat in Florida waters year round. Through these boating trips, Mr. Mooney sees more Loran information than most people working in the field full time.

Session 4
TECHNOLOGY AND SPECIAL APPLICATIONS

Chairman: David H. Amos, *Synetics*

Dave has been actively engaged in the engineering, operations, policy and administrative aspects of Loran-C for over 16 years, both as a U.S. Coast Guard officer and as an engineer and Director for Synetics Corporation. Dave's Coast Guard assignments included a tour in U.S. Coast Guard Activities Europe as a field engineer and as Loran-C operations officer, and a four-year tour with the U.S. Air Force as the Systems Program Director of the Tactical Loran-C/D Special Program Office at Hanscom Air Force Base. His loran experience includes system planning, engineering, operations and installations.

At Synetics, Dave heads up the Communication, Navigation, and Intelligence Systems Business Unit. The group is engaged in command and control systems engineering, focusing on analysis, modeling, simulation, rapid prototyping, and application development. Dave has been an active member of the Wild Goose Association since 1975.

Papers

M I A S

3-D Approach Guidance based on Hybridizing Loran-C with DME-less MLS or ILS

dr. Durk van Willigen
Delft University of Technology

&

Elso P.M. Vlietstra
Dutch Railways

Abstract

The MLS-Integrated Approach System (MIAS) is a hybridization of Differential Loran-C with the Microwave Landing System (MLS). MIAS yields full 3-dimensional guidance during the non-precision approach phase of the flight and also gives improved Loran-C integrity.

VOR/DME will be phased out as en-route navigation aid in the coming decades. This implies that the airborne DME equipment has to be carried around for use during the landing phase only. Use of MIAS for non-precision approaches makes the MLS precision DME (DME/P) on-board equipment obsolete. The already available Loran-C en-route 'navigator' can smoothly take over this DME/P task during non-precision approaches, thereby reducing cost and weight.

The as yet unassigned MLS auxiliary data words transfer DLoran-C and integrity information to the aircraft. With ILS, a separate VHF channel must be used.

At the decision height of 200 ft (CAT 1), the altitude, X-track and along-track errors are less than 5, 2 and 90 meters (95%), respectively.

1 - INTRODUCTION

The two main categories of civil aviation are airlines and general aviation. The latter group is a recognized user of Loran-C and, therefore, we will focus our attention primarily on general aviation.

It is expected that in the foreseeable future just three radio navigation systems for general aviation remain: Navstar/GPS, Loran-C and MLS. GPS and Loran-C are powerful tools for integrated en-route navigation, while all three systems may be used as approach aids. GPS and Loran-C are limited to non-precision approach systems only, while MLS is fully qualified as precision approach aid up to Category III.

The expansion of Loran-C in the National Airspace of the USA and the improved synchronization of the Loran-C time standard to that of GPS, form the two keys to success of using Loran-C and GPS as an integrated-, or even better, as a hybridized system for sole means navigation [1,2].

Non-precision approaches carried out with Loran-C will possibly become common practice in the coming years. Although GPS gives three-dimensional position information, it is to be seen whether (D)GPS accuracy and integrity are sufficient for vertical guidance in the approach phase of the flight. Much research is going on in the USA and in Europe to analyze DGPS capabilities as three-dimensional approach aid.

The new Microwave Landing System will eventually replace ILS worldwide. The accurate three-dimensional approach guidance of MLS is based on measuring the elevation and the azimuth bearing angles of the airplane relative to the center line of the runway. The third dimension, the distance to the runway, is obtained from the precision Distance Measuring Equipment (DME/P). Reference [3] gives a good overview of the ILS and MLS systems, while detailed information about these systems can be found in references [4,5,6].

Some airports in the USA and in Europe now have MLS installed on an experimental base. MLS CAT-III approach tests have shown impressive results of this powerful landing aid [7,8]. However, it will take many years before all major airports are fully MLS-equipped [9].

As the DME/P on-board unit is only used during the approach phase of the flight, it is economically interesting to see whether it is possible to omit the DME. As will be shown in the following paragraphs, Loran-C is a good candidate to take over the role of DME/P in vertical guided non-precision approaches.

2 - MIAS

MIAS, the acronym for MLS Integrated Approach System, is based on integration of MLS with GPS and/or Loran-C [10]. In this paper we will exclusively concentrate on the combination MLS/Loran-C.

The normal three-dimensional positioning with MLS is based on the measurement of the azimuth and the elevation angles relative to the runway center line, and on the range measurement to a DME/P station positioned closely to the azimuth antenna. In the proposed MIAS concept, the DME/P range-measurement function is replaced by the positioning function of Loran-C. The ideal situation is pictured in fig. 1. The intersection of the MLS azimuth and elevation planes yields a bearing line. This line connects the position of the aircraft to the intersection point of the azimuth plane and a line through the reference datum and the elevation antenna. The found bearing line now intersects the Loran-C vertical position line (full Loran-C solution) or the vertical TD-plane in the case of just two usable Loran-C transmitters. In this way we have determined the three-dimensional position of the aircraft. Due to errors in the MLS angles and in the Loran-C position, a three-dimensional error volume is obtained. This error volume has the approximate form of an ellipsoid with its long axis along the MLS bearing line.

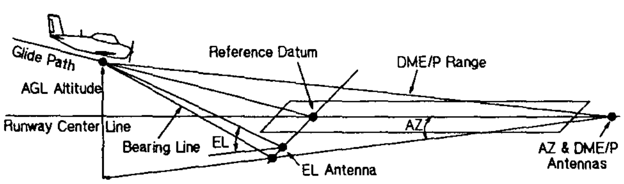

Fig. 1 *General geometry setup of the Microwave Landing System. The bearing line is the intersection of the azimuth and the elevation planes.*

The accuracy of the aircraft position is quite different in the three axes. We define the origin of the three axes in aircraft position. The X-axis is in the azimuth plane (pointing from the AZ-antenna) and horizontally oriented. The Y-axis is in the horizontal plane (counter-clockwise from the x-axis) and perpendicular to the azimuth plane, while the z-axis points vertically upward.

The probability density function (PDF) of the vertical MIAS position depends on the mean and standard deviation of the elevation angle, and further on the PDF of the lateral position in the direction towards the elevation antenna. See figure 2. The mean altitude above ground level Z equals:

$$Z = R \cdot \tan(EL)$$

and the altitude error - ε_Z - is given by:

$$\varepsilon_Z = \sqrt{\left\{\varepsilon_R \cdot \tan(EL)\right\}^2 + \left\{\varepsilon_{EL} \cdot \sqrt{R^2+Z^2} \cdot \cos(EL)\right\}^2}$$

where

- Z = altitude above ground level in meters
- R = lateral distance to the EL-antenna in meters
- EL = MLS elevation angle in radians
- ε_Z = 2σ altitude error in meters
- ε_R = 2σ lateral DLoran-C position error (m) towards the EL-antenna
- ε_{EL} = 2σ MLS elevation error in radians.

The FRP states that the 95% error limit of differential Loran-C will not exceed 90 meters [11]. The 95% elevation error amounts to 0.08 degrees [3]. Further, for conventional take-off and landing procedures (CTOL), a standard glide path of 3 degrees is assumed. At a decision height of 200 ft (CAT I) the lateral distance to the MLS elevation antenna then equals 1145 meters. At that distance, we find a 2σ altitude error ε_{EL} = 5.0 meters. This 2σ-error increases to 51.9 meters at the 20 NM range limit of MLS.

The lateral MIAS position is given by the joint probability function of the DLoran-C error and the MLS-azimuth error (fig. 3). We see now that the error ellipse is rather narrow. The short semi-axis of the ellipse nearly equals the MLS azimuth error, while the long semi-axis is controlled by the DLoran-C error. At the range limits of MLS, the short 2σ-semi-axis ranges from 1.6 m (Z=200ft/EL=3deg) to 51.7 m at the MLS coverage limit, while the long semi-axis will not exceed 90 meters (DLoran-C/95%).

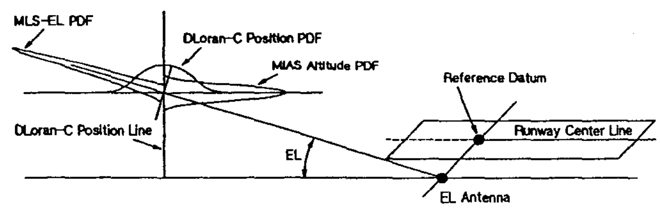

Fig. 2 *MIAS altitude derived from the lateral Loran-C position and the MLS elevation angle. The MLS elevation error here is considered small in relation to the DLoran-C error.*

In the above given MIAS concept, a runway-fixed coordinate system has been selected. Although this is a rather practical choice, it is in contrast with en-route navigation systems where GPS applications make the Earth-Centered-Earth-Fixed (ECEF) approach more appropriate. Due to the curvature of the earth's surface some inconsistencies in the RF and ECEF altitudes in the en-route approach transition region will be found. At 20 NM from the reference datum, the MIAS RF altitude and the GPS ECEF altitude may differ up to 110 meters.

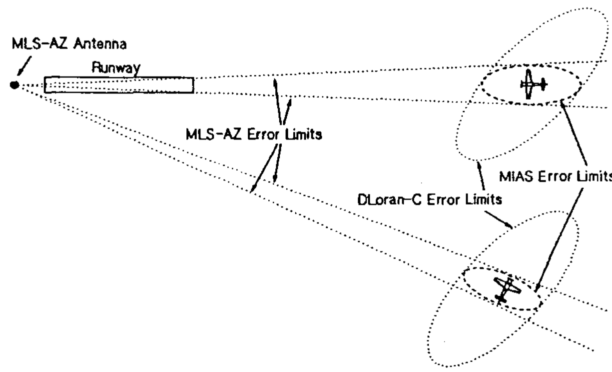

Fig. 3 MIAS error ellipses composed from the MLS and the DLoran-C errors.

The phase centers of the MLS elevation and the azimuth antennas do not coincide. This, together with the slightly curved vertical Loran-C position line due to altitude-dependant ASF, makes the exact 3D-position calculation rather complex [12].

For good absolute position accuracy, differential Loran-C is applied. The reference receiver is installed in the tower or at any other place which is close to the runway. The Federal Radionavigation Plan 1990 [11] states that the 95% Dloran-C error will not exceed 90 meters. If we accept the standard Loran-C accuracy of 0.25 NM, then an increase in the MIAS altitude error becomes apparent, especially at short distances from the threshold. At the decision height of 200 ft, the altitude error grows then from 5.0 to 24.3 meters (2σ). At the 20 NM (EL=3deg) MLS range limit from the reference datum the MIAS altitude error just increases from 51.9 to 57.1 meters. Fortunately, differential Loran-C is needed for integrity reasons anyhow!

3 - INTEGRITY

During the approach phase of the flight, substantial integrity monitoring is required. The main risk with MIAS is a possible cycle error in the airborne Loran-C receiver which in turn will result in an erroneous altitude. However, the high accuracy of the MLS azimuth determination makes detection of such cycle slips under most conditions, straight forward as is depicted in Figure 4. The 2-σ azimuth error, ε_{az}, amounts to approximately 0.08 degrees (1.4 millirad). At the distance, d_{az}, from the azimuth antenna, the tangent error equals:

$$\varepsilon_{tan} = \varepsilon_{az} \cdot d_{az}$$

At d_{az} = 3000 meters (DH=200ft/CAT-I), we find ε_{tan} = 4.2 m, and at the outer range (37 km) of the MLS coverage area ε_{tan} = 51.7 meters. Loran-C cycle errors are, in most cases, detectable by comparing the measured MLS azimuth angle with the computed azimuth angle from the Loran-C position. The Loran-C position moves at least 1500 meters in case of a cycle error. It then depends on the direction of the LOP's and on the distance from the AZ-antenna whether this cycle error is detected or not. If the Loran-C position slips almost in the same direction as that of the MLS azimuth beam, then a cycle error is not detectable by this technique. This is shown in the upper half of figure 4. If, however, the position slip causes an AZ directional error larger than 10.7 degrees, atan((2•51.7+2•90)/1500) at 20 NM, then the cycle error is detectable (see lower part of fig. 4). Assuming uniformly distributed Loran-C LOP-directions over Π radians, the probability of missed detection amounts then to less than 5.9 %.

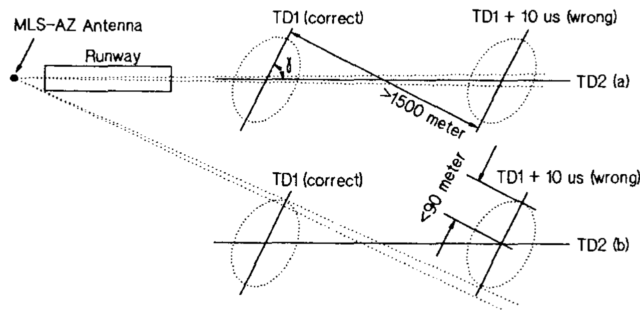

Fig. 4 Loran-C cycle integrity checking based on MLS azimuth angle measurement. The upper part shows the no-integrity situation. The lower part indicates the worst case Loran-cycle integrity.

4 - MLS DATA LINK

Differential and integrity data can be sent to the aircraft through a VHF radio channel. However, due to spectrum crowding, it is worthwhile to investigate the possibilities of using the MLS data link for the differential messages.

MLS uses a time-multiplexed signal format in which a series of specific functions are sequentially radiated. The most important angle functions are azimuth, elevation and back azimuth. In addition, basic data words and auxiliary data words are transmitted. Each function has a random time slot in the signal format and is identified by a unique preamble. To guarantee sufficient tracking bandwidth, each function has a particular minimum repetition rate in the time domain [3]. A full frame cycle takes 615 msec and contains 12 auxiliary data words. Therefore, on the average we get 19.5 auxiliary data words per second. The six basic data words of a frame (see figure 5) and three auxiliary data words per second are reserved for the MLS system itself. This leaves 16.5 auxiliary data words per second free for other purposes. Each auxiliary data word contains 47 data bits, so the 'free' data channel capacity theoretically equals 775 bits per second. This rather high data-link capacity can be used for a large variety of applications. To mention a few:

1 - ATC command for the curved-approach path to be followed by the aircraft
2 - Alert messages
3 - Differential GPS data for precision landings
4 - Differential Loran-C data
5 - Coded weather information

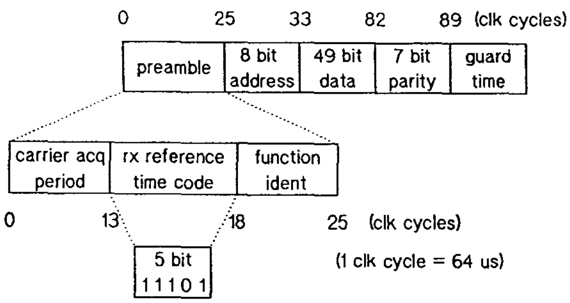

Fig. 5 *Configuration of MLS auxiliary data word function. The clock frequency is 15625 Hz, and the total word takes 89 clock cycles or 5.696 millisec.*

Not all of these messages have the same priority. Item 2 has the highest priority. Somewhat more relaxed are the needs for item 3 and 4. The lowest priorities are probably approach path selection and weather information. Let us first investigate the DLoran-C data capacity requirements. The following data types to be sent to the aircraft are:

a - The Loran-C chains to be used

b - The TD's for which corrections are transmitted

c - TD-corrections for the indicated TD's

d - SNR's of all TX's of which TD-corrections are transmitted

e - Health status of reference station and User Range Error (URE) for all used TD's

f - Altitude-dependent ASF corrections for all used TD's

To keep the load on the data link as low as possible, the on-board DLoran-C receiver also uses ROM-based airport-specific data. Further data reduction is achieved by information coding. For example, at a specific airport the number of useful GRI's is seldom more than 3. Thus, 3 bits are sufficient for the type-1 message to indicate which chain(s) are in use. The same number of bits is adequate for the type-2 message. It will flag up to 3 TD's which can be used for the approach. Type 3 messages use 16 bits for TD corrections per single TD. With a type-3 message, 5 bits express the measured SNR per transmitter in a range from -16 to +15 dB in 1-dB increments. The User Range Error (URE) needs 3 bits, while it is estimated that the AGL-dependant can be coded with 4 bits per TD.

Type	# of bits	Units	Range	Remarks
a	3	n/a	n/a	1..3 GRI's
b	3	n/a	n/a	1..3 TD's
c	48 (3·16)	0.1 m	+/-3276 m	TD correction
d	15 (3·5)	1 dB	-16..+15 dB	SNR
e	9 (3·3)	2^x m	4..256 m	Health and URE
f	12 (3·4)	TBS	TBS	ASF(altitude)

Table 1 *Overview of the MIAS MLS auxiliary data words.*

The above stated message types and the associated number of bits are tabulated in table 1. It shows that a total of 90 bits per message is needed. High quality error detection and error correction may ask for another 20 bits per message. As the TD-corrections and the measured TD's slowly decorrelate in time, a renewal of once per 10 seconds is usually adequate. Therefore, providing the aircraft with precise DLoran-C data makes that just 11 bits per second must be transferred by the data link. In other words, the DLoran-C data link uses just 1.5% of the 775 bps free-space in the MLS data link.

This suggested data transmission frame forms part of a larger system which also complies differential GPS data. An extended Microwave Integrated Approach System offers additional integrity by incorporating the DME/P station. This extended MIAS configuration is primarily designed for airliners. The authors will publish about this concept soon.

5 - ILS

Until now, the integration of DLoran-C and the Instrument Landing System is not mentioned. However, an identical system approach can be performed with ILS instead of MLS. The difficulty with ILS is that the aircraft is not continuously receiving the glideslope or the localizer signals. Hence, the DLoran-C data cannot piggy-back on those signals. However, a single VHF channel can do the job. An elegant solution is to combine the meteo and the differential data in a single modulation pattern on a VHF carrier. As this technique is not new, no further attention is given to that solution.

6 - CONCLUSION

The MIAS hybridization of the MLS angle functions with Loran-C offers good 3-D positioning performance for general aviation during non-precision approaches. It saves costs as the DME/P equipment is no longer needed on board of the aircraft. The lateral Loran-C accuracy is improved by transmitting the differential Loran-C data via the MLS auxiliary data words. This data transfer takes just 3% of the free auxiliary data capacity.
With 3-degree glide slope approaches, MIAS offers altitude accuracies of 5 meters (2σ) at a decision height of 60 meters (200 ft) . MIAS also offers Receiver Autonomous Integrity Monitoring (RAIM) in respect to Loran-C cycle error detection.

Acknowledgements

The authors are very grateful for the valuable support from Prof.Dr. P.J.G. Teunissen.

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Biography

Dr. Durk van Willigen heads as professor at the Delft University of Technology a team of students and staff, working on navigation systems. The main research topics of this group are (integrated/hybridized) system performances, and Loran-C, GPS and MLS receiver structures.
He is the coordinator of the Avionics Engineering Program.
Dr. van Wiligen is active in studies for setting up the new North-west European Loran-C chains. The main concern of these studies is the so generously available European continuous wave interference. The Delft University of Technology and the University of Wales (UK) join their activities in this field.
Dr. van Willigen is also the president of Reelektronika bv, a consultant for radar and radio navigation.
He is member of the Advisory Group of the Netherlands Institute of Navigation, the Wild Goose Association, the Institute of Navigation (USA) and the Royal Institute of Navigation (UK).

Mr. Elso P.M. Vlietstra carried out his thesis research project as part of the master's education program of the Delft University of Technology. In this project he investigated also the possibilities of integrating GPS with MLS. He completed his studies in Electrical Engineering succesfully in June, 1991. Mr. Vlietstra is now with The Dutch Railways.

Author's address:

Prof.dr. Durk van Willigen

Delft University of Technology
Faculty of Electrical Engineering
P.O. Box 5031
2600 GA Delft, The Netherlands
Tel +31 - 15 - 78 61 86
Fax +31 - 15 - 78 17 74

Reelektronika bv
Nieuwenbroeksedijk 6
2811 NJ Reeuwijk, The Netherlands
Tel +31 - 1829 - 3456
Fax +31 - 1829 - 6094

Weighted Spectrum Analysis in Loran-C Receivers

André Nieuwland
Delft University of Technology
The Netherlands

Abstract

It is well known that Loran-C operation in Western Europe experiences serious problems from Continuous Wave Interference (CWI) signals. To suppress CWI signals properly, the more harmful signals have to be detected.
The approach taken in this paper to detect these harmful CWI signals in Loran-C receivers is based on analysis of the received spectrum around the Loran-C band with digital signal processing techniques derived from the Discrete Fourier Transform. Automatic weighting by time domain modulation is applied to improve the effectiveness of digital spectrum analysis.
Also, a receiver structure well suited for making use of real-time spectrum analysis will be presented.

1. Introduction

One of the major problems of Loran-C operation in Western Europe is the number of Continuous Wave Interference (CWI) signals (e.g. Decca Navigator) close to the Loran-C band (fig.1). These CWI signals can be classified in synchronous, nearsynchronous and asynchronous [1, 2]. A

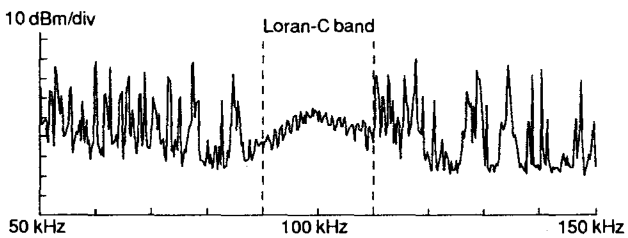
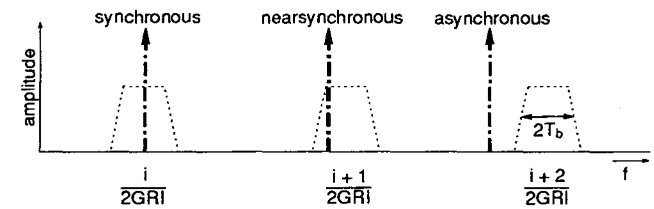


Fig. 1: Loran-C spectrum received in Delft, The Netherlands

signal is called synchronous if its frequency is an integer multiple of a ½ times the Group Repetition Frequency (GRF), nearsynchronous if its frequency lies within the tracking bandwidth of the Loran-C receiver around a multiple of ½GRF and asynchronous otherwise (fig. 2). This repetition interval of ½GRF is caused by the different phasecoding of the Loran-C pulses in two succesive Group Repetition Intervals (GRI) [3].



T_b is the tracking loop bandwidth of the Loran-C receiver

Fig. 2: Interference classes

Especially synchronous CWI signals are very harmful, because they are not rejected by the tracking loop of the receiver. They not only cause an undetectable offset in range measurement, but they can also produce errors in cycle identification which results in range errors of multiples of 3 km [4]! Nearsynchronous interference causes an oscillating range error with a frequency equal to the frequency distance to the adjacent multiple of ½GRF. Asynchronous interference is disturbing, but less harmful because the signal is partly rejected by the receivers phase and envelope tracking loop. Its influence corresponds to an increased noise level [1, 5].
There are only a few strategies to combat this interference problem. On the transmitter side (at the system level) carefully selecting GRI's can reduce the number of (near-) synchronous interferences considerably [6]. In the receiver, a narrow and steep bandpass filter could be used to suppress as many signals as possible around the Loran-C band. However, due to the non-linear phase transfer of such a filter, the rising edge of the Loran-C pulse is delayed and less steep (fig. 3).

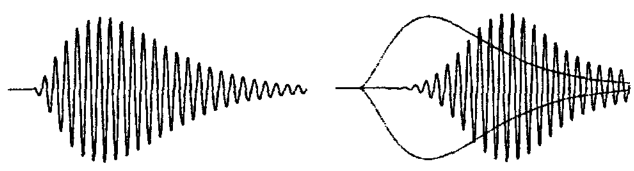


Fig. 3: Loran-C pulse without and with filtering

Ergo, the amplitude ratio of two early successive Loran-C cycles becomes smaller and is more sensitive to disturbances

such as skywaves. This immediately affects cycle identification reliability since the identification is based on this ratio. To decrease this skywave susceptibility, a filter with relatively little phase distortion has to be used. Unfortunately, the consequence of using such a broad and gentle filter is, that the interfering signals close to the Loran-C band are insufficiently suppressed. The only way to suppress these remaining signals is to use notch filters. These notch filters have to be tuned on the more harmful interfering frequencies present in the operational area. Tuning on the synchronous, nearsynchronous and strong asynchronous signals can be done manually. A disadvantage is that the operational area of the Loran-C receiver is severely limited for in another area there are usually other interfering frequencies, and the notch filters are only suppressing noise and not the more harmful signals in that area. Another method is to use automatic tuning level sensitive notches. Although this method is more flexible, it still does not guarantee reliable operation of Loran-C receivers. Level sensitive notches are not able to distinguish between synchronous and asynchronous interference signals. If an asynchronous signal is just a little stronger than a synchronous signal, the notch will be adjusted on the asynchronous signal instead of on the more detrimental synchronous signal.
A more flexible and reliable tuning of the notch filters is obtained by analyzing the frequency spectrum with high resolution during operation of the receiver. The resolution must be high enough to distinguish the different interference classes to make a sensible selection of the frequencies to be suppressed. This selection can be made by applying a weighting function with a high amplitude for synchronous signals and a low amplitude for the less harmful asynchronous signals. In other words, the weighting function corresponds with the sensitivity of the receiver for different frequencies (fig. 4). Then after weighting, the highest value corresponds to the most harmful interfering signal.

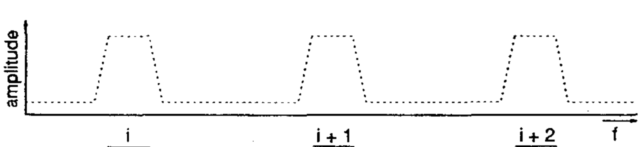


Fig. 4: Example of a simplified weighting function

Spectrum analysis can be performed by using a tunable analog bandpass filter. However, this method is relatively expensive because very stable tunable filters are needed to obtain the required frequency resolution. Digital signal processing does not have these stability problems and has the possibility of integration with today's VLSI techniques. This results in smaller receivers with lower cost price. Another advantage is that a linear phase filter can be implemented. Therefore, digital spectrum analysis is the appropriate choice. High resolution frequency analysis can be performed by using a standard Discrete Fourier Transform (DFT), or one of its faster derivates [7].

In this paper some fundamental properties of the DFT are explained first. It will be shown that the DFT has some severe disadvantages, which will lead to almost unsurmountable problems if this transform is used in a straightforward way. A method will be presented which turns these disadvantages into useful properties, thus enabling the application of Discrete Fourier Transforms for CWI detection in Loran-C receivers. Next, two methods to minimise processing power and memory requirements will be explained. Finally, results of computer simulations supporting the proposed receiver structure will be presented.

2. Properties of Discrete Fourier Transforms

One of the problems of the DFT is that the frequency resolution is limited by the total sampling time and thus, given a certain sample frequency, by the number of samples. This limited number of samples forms a window in the time domain with a length of NT_{sample}. The Fourier Transform of this window is a sinc function with its zero crossings on nonzero integer multiples of $1/NT_{sample} = f_{sample}/N$ (fig. 5).

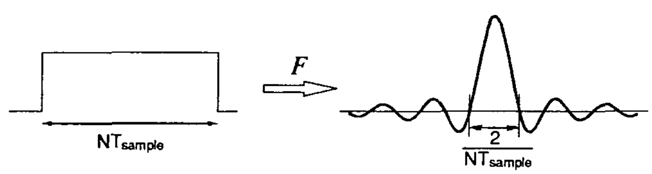


Fig. 5: Time window and its Fourier transform

A signal in the time domain is multiplied with this time window. Since multiplication in time domain corresponds with convolution in the frequency domain, the Fourier transform of the signal is convolved with this sinc function. This means that a Dirac-pulse in the frequency domain (cosine in time domain) is deformed to a sinc function. This sinc function is sampled by the standard DFT on multiples of f_{sample}/N. A Dirac pulse is only preserved if the top of the sinc function lies exactly on a multiple of f_{sample}/N. In this case, all the other frequency samples are located at the zero crossings of the sinc function. As soon as the frequency of the sinc function is not an exact multiple of f_{sample}/N, the input signal contributes to the value of all frequency samples (fig. 6).

The resolution of the DFT is the smallest difference in frequency that can be distinguished. That means that the two sinc functions have to lie far enough apart to be distinguished separately. If the signals lie for example on two succesive frequency samples, than these two samples represent each the

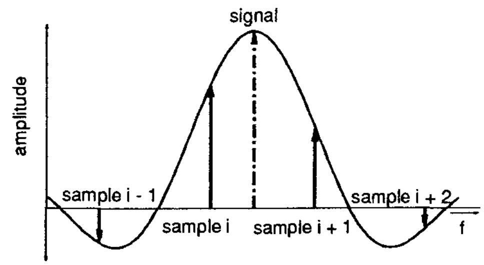


Fig. 6: Sinc function centred at the signal

value of one signal. However, if the frequency difference becomes smaller, e.g. the two signals are shifted towards each other, the sum of the two sinc functions is going to resemble one sinc function with a larger amplitude. In other words, it looks as if there is just one (stronger) signal. The only way to distinguish the two signals is to decrease the sinc width, and thus to increase the number of samples if the sample frequency is not changed.
Essential is that the contribution of one signal to many frequency samples can be regarded as many sinc functions centred at the frequency samples, instead of one sinc function centred at the signal. In this way, each sample represents the amplitude of the signal multiplied by the local amplitude of the sinc function that is centred at this sample. A simple example is given in figure 7. In the following part, this way of thinking will be used.

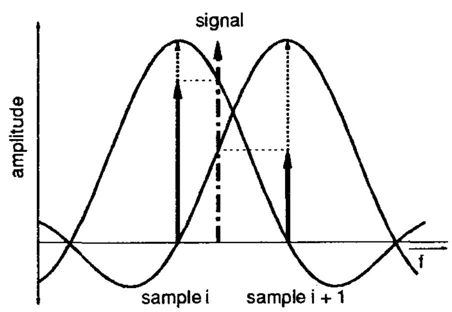


Fig. 7: Sinc functions centred at the samples

A second property of the standard DFT is, that the frequency domain is sampled on a distance of f_{sample}/N from zero to the sample frequency. This results in N frequency samples, as many samples as in the time domain. This symmetry of an equal number of time and frequency samples enables a faster implementation of the standard DFT, well known as the Fast Fourier Transform (FFT). A negative effect of sampling the frequency domain is that signals, not lying on a frequency sample, are rounded in frequency as well as in amplitude towards the frequency samples in its vicinity (fig. 7). Therefore, it is possible that an asynchronous signal lying at a sample is perceived as more powerful than a synchronous signal between two samples (fig. 8).
The only way to solve this problem is to increase the number

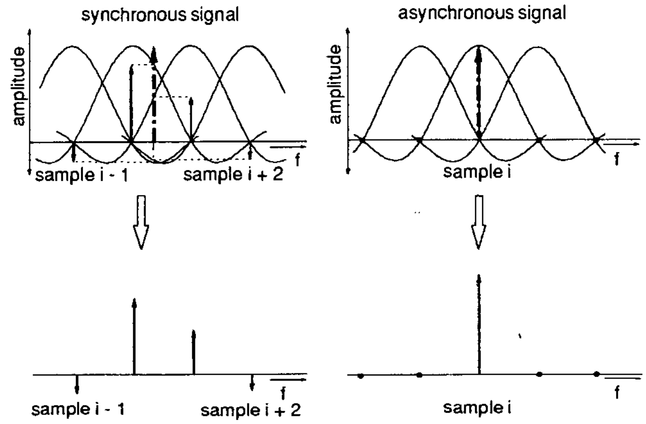


Fig. 8: Influence of signal frequency on the sample value

of samples again, until the frequency resolution is high enough to distinguish the different interference types. Therefore, the spacing of the frequency samples has to be smaller than the tracking loop bandwidth of the Loran-C receiver. If, for example, the tracking loop bandwidth is 0.1 Hz, the distance between the samples should not exceed this value. Because the spacing of the frequency samples of a DFT is $1/NT_{sample}$, the total sampling time NT_{sample} has to be at least 10 seconds. Fortunately, these negative properties can be evaded.

By using the Chirp Z-transform (CZT), a derivate of the DFT, it is possible to control in the frequency domain the place of the first sample, the distance between the samples and the number of samples [8]. With the CZT, the frequency samples can be placed on multiples of ½GRF. This implicates that the 'weighting' sinc function can be centred at multiples of ½GRF! Thus all the synchronous signals are weighted (and detected) with a high amplitude. If a signal is asynchronous, it is weighted with the lower amplitude of the sinc function at the place of the signal. The major advantage of the CZT is that it is no longer necessary to distinguish the different interference classes, since the interference signals are already automatically 'weighted according to their influence'. A high amplitude for nearsynchronous signals can be reached by setting the single sided -3 dB bandwidth of the sinc function equal to the tracking loop bandwidth. If, for example, a Loran-C receiver has a tracking loop bandwidth of 0.1 Hz, the double sided bandwidth of the sinc function should be 0.2 Hz. The double sided -3 dB bandwidth of a sinc function is roughly $1/NT_{sample}$. Thus, to get a bandwidth of 0.2 Hz, only 5 seconds of sampling are required. If the total sampling time is further reduced the sinc function will become broader and more signals will be detected (falsely) as nearsynchronous. The only problem of this automatic 'weighting' function is that between the samples a very low and even zero amplitude is reached. This can inhibit detection of very strong asynchronous signals (fig. 9).

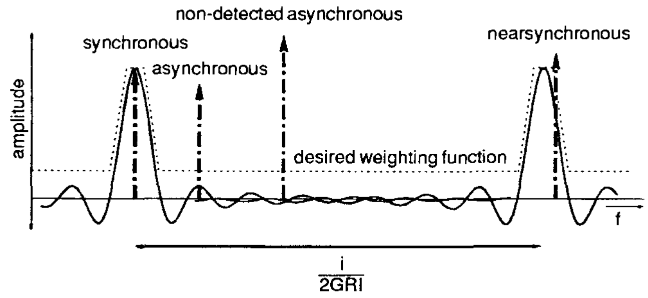


Fig. 9: 'Weighting' with sinc functions

3. Memory usage

To apply digital signal processing, the input signal has to be sampled with at least two times the highest frequency in the input signal. Taking non-ideal filtering into account, the sample frequency has to be at least 300 kHz [2]. For a tracking loop bandwidth of 0.1 Hz, there are at least 10 seconds of sampling needed in the case of an implementation with a straightforward DFT or FFT. This results in a minimum of $3 \cdot 10^6$ samples. To prevent round-off errors, the samples have to be stored in 8 bytes double precision floating point format. The total memory required for a (real) FFT is therefore $8 \cdot 3 \cdot 10^6 = 24$ Mbytes. In case of the CZT, 5 seconds of sampling are sufficient, resulting in $1.5 \cdot 10^6$ samples. An elegant way to implement the CZT is to use two complex FFT's and one inverse FFT [8]. The memory required is the memory needed for two complex FFT's of $1.5 \cdot 10^6$ points. Thus the maximum memory size required for the CZT is $2 \cdot 2 \cdot 8 \cdot 1.5 \cdot 10^6 = 48$ Mbytes. These are both not very practical values, so a different approach is proposed.

Instead of processing all the data at once, the data is split into small segments. After each segment is processed, its result is added to an intermediate result. Because the CZT can be modified to work with segments, it is the algorithm to be used. This modification can not be made to the FFT. The modified CZT is also known as the Segmented Chirp Z-transform (SCZT) [9]. The memory required for the SCZT is the memory required for the CZT of one segment, plus the memory for the complex frequency result. Therefore, roughly $2 \cdot 2 \cdot 8 \cdot (N + M) + 2 \cdot 8 \cdot M = 16 \cdot (2N + 3M)$ bytes, where N is the number of time samples in one segment, and M is the total amount of frequency samples.

To get an indication of the memory size required in this case, the following example is calculated. For a (worst case) GRI of 99990 μs and a spectrum to be analysed of 50 kHz wide, 10^4 frequency samples are needed. If sampling takes place with 300 kHz for GRI seconds, a segment consists of $3 \cdot 10^4$ samples. The memory required is in this case roughly $16 \cdot (2 \cdot 3 \cdot 10^4 + 3 \cdot 10^4) = 1.4$ Mbytes. This is a more sensible value. One could decrease the segmentsize, so less memory is required.

But the price for smaller segments is that the complexity of algorithm shifts from the complexity of the FFT towards the much higher complexity of the DFT. In fact, when the segment size equals 1, the much slower DFT implementation of the CZT is reached. Therefore, a trade-off between processing time and memory size has to be made.

4. Processing Power

Although the memory problems can be solved by segmentation, there is still a lot of processing power required. The only way to reduce the required processing power is to reduce the number of samples, without affecting the resolution. This can be done by applying Quadrature Bandpass Sampling (QBPS) [2]. Quadrature Sampling (QS) is based on orthogonal samples, that are samples taken with a 90° phase shift. Since the frequency band of interest is centred at 100 kHz, it is convenient if the samples are orthogonal at this centre frequency. This can easily be done by taking the quadrature sample 2.5 μs later than the in-phase sample. The phase difference between these two samples is for signals with a frequency below the centre frequency less, and for signals above the centre frequency greater than 90°. The effect in the frequency domain of this non-orthogonal sampling for signals with frequencies other than the centre frequency can be analysed with the DFT formula (1).

$$X(k) = \sum_{n=0}^{N-1} x(n) \exp\left(-j\frac{2\pi nk}{N}\right) \qquad k = 0 \ldots N-1 \qquad (1)$$

where X(k) represents the frequency component on the frequency $k.f_{sample}/N$, and x(n) represent the value of the n^{th} time sample. N is the total number of time samples.

Substitution of a cosine input signal in (1) leads to (2):

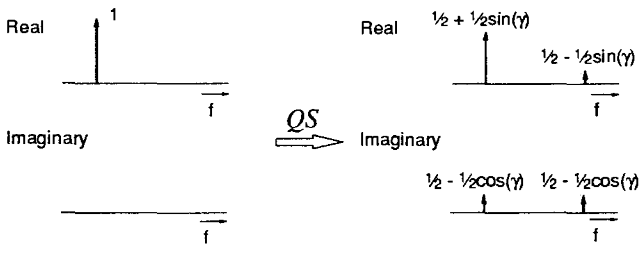
$$X(k) = \sum_{n=0}^{n-1} \left[\cos\left(\frac{2\pi fn}{f_{sample}}\right) + j\cos\left(\frac{2\pi f(n+\delta_t)}{f_{sample}}\right)\right] \exp\left(-j\frac{2\pi nk}{N}\right) \qquad (2)$$

where X(k) indicates the DFT frequency component and k varies from 0 to N-1. 'n' is the number of the time sample and δ_t is the delay between the in-phase and the quadrature-phase sample expressed in wavelengths of the sample frequency.

Expansion of (2) and ignoring terms that do not contribute to the frequency transform gives (3):

$$X(k)=\sum_{n=0}^{N-1}\cos\left(\frac{2\pi fn}{f_{sample}}\right)\cos\left(\frac{2\pi nk}{N}\right)$$
$$-\sin\left(\frac{2\pi f\delta_t}{f_{sample}}\right)\sin\left(\frac{2\pi fn}{f_{sample}}\right)\sin\left(\frac{2\pi nk}{N}\right) \qquad (3)$$
$$+j\cos\left(\frac{2\pi f\delta_t}{f_{sample}}\right)\cos\left(\frac{2\pi fn}{f_{sample}}\right)\cos\left(\frac{2\pi nk}{N}\right)$$

The result of (3) is presented graphically in figure 10.



$$\text{where } \gamma=\frac{2\pi f\,\delta_t}{f_{sample}}$$

Fig. 10: Spectrum before and after quadrature sampling

What can be seen is that, due to the non-orthogonal sampling, the phase relation between a frequency component and its mirror frequency is disturbed. Therefore, the mirror frequencies are not completely cancelled. Another effect is the unwanted creation of frequency components in the imaginary part of the spectrum. This means that if a signal should give only a real frequency spectrum, it gives frequency components in the imaginary part also. The amplitude and sign of these frequency components are frequency dependent and the combination is unique for each frequency (fig. 10). The transform can be applied to a sine input signal too. In this case the result is similar, only now the unwanted frequency components are created in the real part of the spectrum. Although the extra frequency components created in the frequency domain resembles the result of aliasing it is in fact only a rotation in a four dimensional space. So there is a way to restore the clean spectrum. To find this way, the 'rotation' is written as a matrix operation $\bar{y} = A\ .\ \bar{x}$. Where 'A' is the matrix describing the 'rotation' and $\bar{y}$ is a vector of four elements with the obtained frequency results. $\bar{x}$ is a vector of two elements with the frequency components of a signal before 'quadrature' sampling. The first two components in the vectors $\bar{x}$ and $\bar{y}$ represents the real part of frequency component k and the imaginary part of frequency component k respectively. The third and fourth component of the vector $\bar{y}$ represents the real part of frequency component N-k and the imaginary part of the frequency component N-k. In order to restore the original spectrum, the obtained frequency samples only have to be multiplied by the inverse of the 'rotation' matrix.

In a digital receiver, a steep Finite Impulse Response (FIR) filter can be used to reduce the frequency spectrum to be analysed to 50 kHz. Further reduction is possible, but it takes a lot more processing [2]. The filter can be this narrow, because there is no increase in skywave contamination since a FIR filter has a linear phase transfer. Because the spectrum to be sampled is now reduced to 50 kHz, the sampling frequency can be chosen equal to two times this bandwidth. This method is known as Sub Nyquist Sampling or Bandpass Sampling. If 'quadrature' samples are taken also, the sample frequency can be equal to the bandwidth of the spectrum to be analyzed. The combination of these two methods leads to Quadrature Bandpass Sampling (QBPS). Therefore, the QBPS frequency can be chosen as 50 kHz, which is half of the centre frequency. The time delay of 2.5 µs (90° phase shift at 100 kHz) gives with this sample frequency for δ_t the value ⅛. Substitution of $f = 2f_{sample} - f'$ and $f = 2f_{sample} + f''$, for frequencies respectively below and above the centre frequency, gives the opportunity to rewrite the 'alias' matrix to a four by four matrix. Now, vectors $\bar{x}$ and $\bar{y}$ both contain four elements. The first two elements of vector $\bar{x}$ represents respectively the real and imaginary parts of the frequency component on f'. The third and fourth component of $\bar{x}$ represents the real and imaginary parts of the frequency component of f'' respectively. f' and f'' are both expressed in terms of $k.f_{sample}/N$. The first two elements of vector $\bar{y}$ represents the real and imaginary parts of frequency component k respectively. The third and fourth component of vector $\bar{y}$ represents respectively the real and imaginary parts of frequency component N-k. Since the rotation matrix is orthonormal, the inverse is found to be the transposed:

$$A^{-1}=\tfrac{1}{2}\begin{bmatrix}1+\cos(\alpha) & \sin(a) & 1-\cos(\alpha) & \sin(\alpha)\\ -\sin(a) & 1+\cos(a) & \sin(\alpha) & -1+\cos(\alpha)\\ 1-\cos(a) & -\sin(\alpha) & 1+\cos(\alpha) & -\sin(\alpha)\\ -\sin(a) & -1+\cos(\alpha) & \sin(\alpha) & 1+\cos(\alpha)\end{bmatrix}$$

$$\text{where } \alpha=\frac{\pi k}{4N}$$

By using QBPS, the total number of samples to be processed can be reduced from 3.10^6 real samples to 250.10^3 complex samples. Therefore, the required processing power is reduced roughly by a factor 6.

5. Implementation of a weighting function

As mentioned above, the weighting sinc function, automatically generated by the modulation with the time truncation window, has some negative aspects. The amplitude between two successive samples is too low and it even has zero crossings. Therefore, a weighting function has to be found which shows a greater resemblance to the desired weighting function of figure 4. As the example with the weighting sinc function shows, the weighting (modulation) can be performed in the time domain, because the top of the weighting function can be placed on the synchronous frequencies. By transformation to the frequency domain, the signals between the frequency samples are automatically weighted, and rounded towards the samples. If the tracking loop of the Loran-C receiver is approximated by a first order loop, the desired weighting function in the frequency domain resembles the transfer function of a lowpass filter (fig. 11). This weighting function should be transformed to the time domain and multiplied with the time samples. In this way the values of the frequency samples are automatically related to the severeness of the interference. The formula for a first order weighting function in the frequency domain is:

$$H(f) = \frac{a}{j2\pi f + a} \tag{4}$$

The Inverse Fourier Transform of (4) gives:

$$h(t) = a \cdot \exp(-at) \tag{5}$$

The -3 dB bandwidth of this function is determined by the parameter a. Suppose the Loran-C receiver has a tracking loop bandwidth of 0.1 Hz. Then every signal within a distance of 0.1 Hz of a multiple of ½GRF is (near-) synchronous and should be detected with high gain. Therefore, the single sided bandwidth of the weighting function is set to 0.1 Hz. With formula (4) and the required cut-off frequency of 0.1 Hz, the parameter 'a' can be calculated as $\pi/5$. The samples taken most recently have the greatest influence on the final result if the exponential function increases in time (fig. 11). Therefore, the parameter a in the exponent is taken negative. If necessary, the time function can be normalised to 1 at the end of the sample interval, to prevent overflow errors.

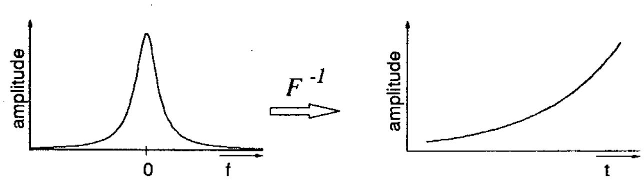


Fig. 11: Weighting function in frequency and time domain

The weighting function repeats itself every ½GRF due to the convolution in the frequency domain, which was the result of the multiplication of the exponential function with the data in the time domain (fig. 12). Figure 12 looks very similar to the stylized weighting function of figure 4. Since the total sample time is limited, the weighting function in the frequency domain is convolved with a sinc function. The ripple on the amplitude transfer of the weighting function, caused by the convolution with the sinc function, is very small and therefore not shown in figure 12.

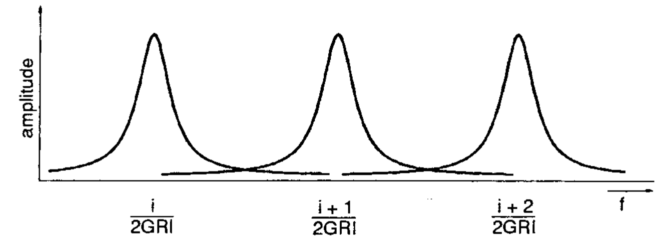


Fig. 12: Weighting function in the frequency domain

To get an impression of the power of this interference detection algorithm, the ratio of the noise bandwidth before and after weighting has to be calculated. To ease computation, the ripple in the weighting function is neglected. Since the FIR bandpass filter is very steep, the noise bandwidth is almost equal to the filter bandwidth of 50 kHz. The noise bandwidth of a first order bandpass filter is $\pi/2$ times the -3 dB bandwidth [10]. This results in a noise bandwidth of 0.3 Hz. The gain in Interference to Noise ratio is therefore $10 \cdot \log_{10}(50000/0.3) = 52$ dB. This means that even interference signals can be detected that are too weak to cause any problem at all. The amplitude of the weighting function in the middle between two frequency samples is -30 dB below the top by a GRI of 99990 µs, and -38 dB below the top by a GRI of 40000 µs.

6. Implementation

The receiver structure proposed (fig. 13) consists of a steep FIR bandpass filter through which only frequencies between 75 kHz and 125 kHz can pass. The quadrature sampling clock of 50 kHz is derived from a master sampling clock of 400 kHz. Quadrature Bandpass Sampling can easily be realized by taking every 8^{th} sample as the in-phase sample, and every $8^{th} + 1$ as the quadrature-sample. Another advantage of a 400

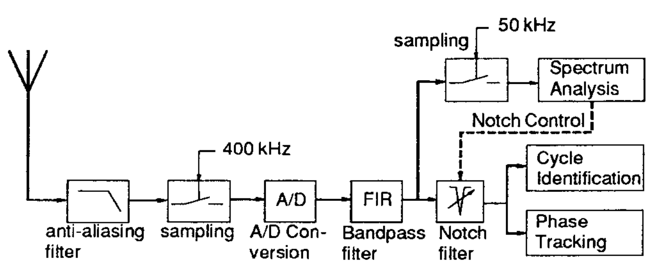


Fig. 13: Basic blok diagram of the proposed Loran-C receiver

kHz sampling clock is that the requirements on the anti-aliasing filter characteristics are less than in the case of a 300 kHz sampling clock. Level sensitive notch filters should be added before the A/D conversion to prevent overload of the electric system. These notch filters are not drawn in figure 13.

7. Simulation Results

The method described above is implemented in the Loran-C Receiver Simulation Program (LOSP) [11]. Figure 14 shows the result of a simulation of the detection algorithm. The total sampling time is 5 seconds, thus $250 \cdot 10^3$ samples of a total of $2 \cdot 10^6$ samples are processed. The input of the program is a Loran-C signal with a GRI of 5000, and a signal to noise ratio of 0 dB. Six CWI signals with an interference to noise ratio of 0 dB are added. The frequencies of the input signals are listed in table 1. The first column contains the frequencies of the CWI signals, the second column contains the distance in Hz to the adjacent multiple of ½GRF. The third column contains the detected power of the CWI signal.

Frequency [Hz]	Distance [Hz]	Detected Power [dB]
76334.9	4.86	-34
79642.6	2.64	-28
85000.0	0.00	0
111556.9	3.15	-30
115000.1	0.09	0
123420.0	0.02	0

Table 1 : Frequencies of input signals (GRI = 5000)

Table 1 and figure 14 show very clear the effect of the weighting function. The synchronous and nearsynchronous CWI signals are detected 50 dB above the noise level. The asynchronous signals with the frequencies 76334.9 Hz and 111556.9 Hz are lying in the middle between two frequency samples. Therefore, they are detected 20 dB above the noise level, that is 30 dB lower than the synchronous signals. The table below the figure lists the 16 strongest signals. What can be seen is that some interference signals are detected more than once, because of the gentle part in the weighting function. E.g, the sample on 76340 Hz is even higher than the sample on 76330 Hz, which is closer to the interference signal. This is caused by the influence of the CWI signal at 79642 Hz. This is not any problem at all, since the notch filters are wider than the distance between two frequency samples.

Figure 15 shows the result of a simulation with the same input. Only now a FIR bandpass filter of 50 kHz width is used. As expected, the noise and the interference signals on the edge of the filter are ±40 dB extra suppressed and thus less harmful. A limited number of notch filters can be used to suppress the remaining interference signals.

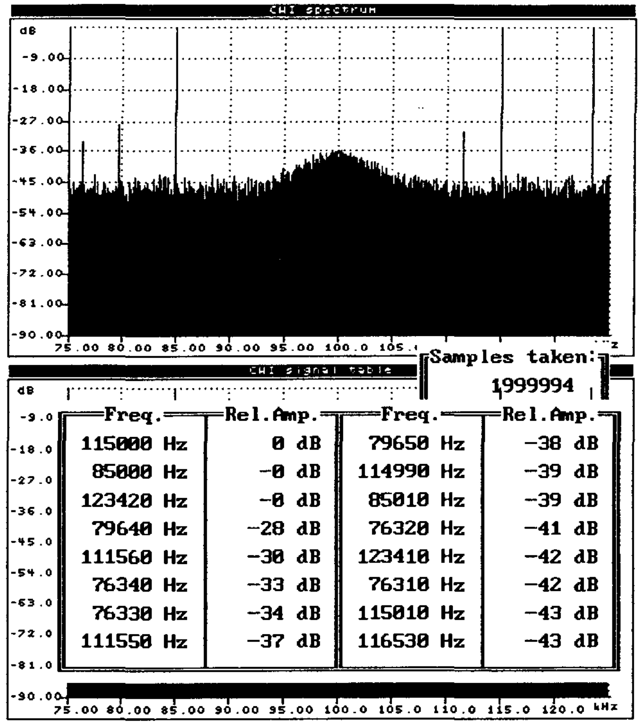


Fig. 14: Result of a LOSP simulation without bandpass filter

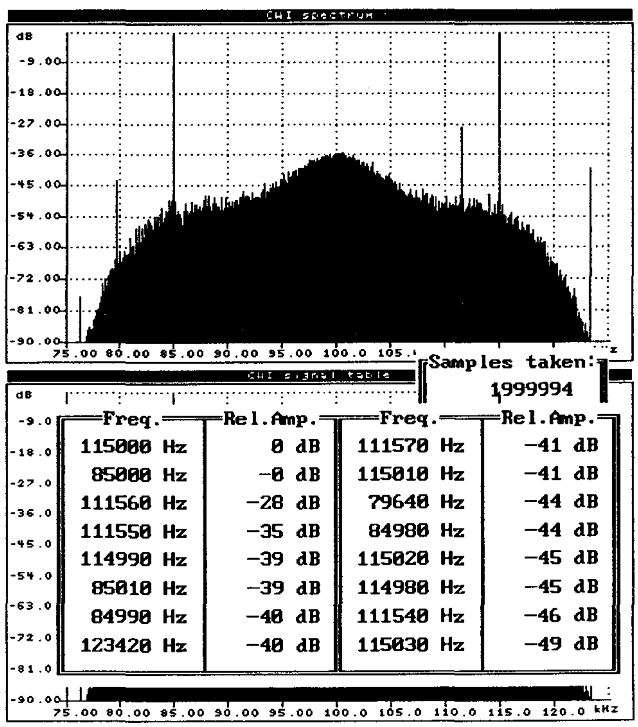


Fig. 15: Result of a LOSP simulation with a FIR bandpass filter

8. Conclusions

An optimal and efficient detection of Continuous Wave Interference signals can be reached by applying weighted spectrum analysis. By using this method, which is based on Discrete Fourier Transforms, all harmful interference signals can be easily located. Since the amplitude of a frequency sample is directly related to the severeness of the interference, an optimal choice of the signals to be suppressed can be made immediately. These interference signals can be defeated by adjusting notch filters accordingly. The enormous memory requirements, normally encountered by high resolution spectrum analysis, can be relieved by applying Quadrature Bandpass Sampling and using the Segmented Chirp Z-transform. Although the segments can have any size, it is advisable that the segmentsize equals a power of two if the CZT is implemented with base-2 FFT's. This leads to the most effective use of the CZT. The smaller the segment, the less memory is required, but the greater the required processing power. In order to find the optimal size of the segments further study has to be made. Another interesting item for further research are weighting functions. In this paper a very simple weighting function has been chosen. To improve the weighting function, one can simply add other functions to it. A more fundamental approach is to include the effects of phasecoding and design the weighting function optimal for a specific type Loran-C receiver. The implementation of notch filters should be studied too. They can be implemented in software in a receiver based on digital signal processing and therefore it is possible to control the shape of the transfer function of the notches. By increasing the notch width, more interference signals are suppressed. However, Loran-C pulse distortion increases as the notch bandwidth increases. A study to the optimal shape and width of the notch filters has to be made.

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About the author

André Nieuwland was born in 1968. He is studying Electrical Engineering at the Delft University of Technology. He completed his masters thesis by developing a method for optimal detection of CWI signals in Loran-C receivers.

VXIbus BASED LORAN-C TRANSMITTER MONITOR AND CONTROL SYSTEM

by

LCDR Doug Taggart and LT Jon Turban

USCG Electronics Engineering Center
Wildwood, New Jersey 08260

1. Abstract

The U.S. Coast Guard's Electronics Engineering Center (EECEN) is pursuing projects aimed at redesign of various portions of the Coast Guard's Loran-C system. One project which has the potential of making a significant impact on the generation, control and monitoring of Loran pulses is the Electrical Pulse Analyzer/Digital Pulse Analyzer (EPA/DPA) Redesign. This project, although it is in the very early conceptual stages, shows significant promise as a mainstay of future replacement for many portions of the equipment suite used at U.S. Coast Guard Loran-C transmitting stations.

Work presently underway is addressing the redesign with the intention of using a recently developed Automatic Test Equipment (ATE) standard referred to as VXIbus (VMEbus Extensions for Instrumentation). This paper will present the development efforts accomplished to date.

2. Introduction

The U.S. Coast Guard Loran-C system is composed of 46 transmitting stations. Of these 46 stations, 31 use older, tube-type transmitters. The remaining 15 stations are equipped with the more modern solid state transmitters (SSX). The Electrical Pulse Analyzer (EPA) is a customized piece of monitoring equipment which is used at each of the Loran-C transmitter stations. Its primary function is to provide real-time monitoring of the radiated Loran-C pulse train as observed on the antenna ground return. The data it provides is a measurement of the pulse shape and the radiated pulse amplitude.

As part of the Coast Guard's modernization initiative, the EPA was targeted as a piece of equipment which could be improved and replaced through redesign. In fiscal year 1990, EECEN was assigned a project to redesign the EPA. The three primary objectives behind the redesign project were: eliminate existing support problems, step ahead with technology, and improve the automation of the Loran-C system.

It can now be stated that the project's initial scope was somewhat short sighted. The project in place today, although significantly more encompassing than initially conceived, still carries the title "Electrical Pulse Analyzer/Digital Pulse Analyzer (EPA/DPA) Redesign". In the early stages of the redesign, it became obvious that a "box for box" replacement effort was not the way to proceed. The requirements analysis showed that the new design should encompass additional functions beyond that of being just a replacement monitor. The inclusion of "control" functions, the "generation" of Transmitter Drive Waveforms (TDW), and the addition of data recording were all desirable features to be considered and implemented.

3. Present Way of Doing Business

Much of this discussion will focus on the EPA/DPA redesign as it will be implemented at a tube transmitter station. For this reason, a brief explanation of tube transmitter operations is necessary.

A tube transmitter station is equipped with two transmitters. One is always on air. The other is in a ready standby status. Normally, the two transmitters are switched between the operate and standby position every two weeks. During these alternating periods, transmitter maintenance is conducted on the standby. Tubes are changed, components tested and replaced if necessary, and variable components are checked and adjusted as required. In essence, every two weeks, the transmitter's amplification characteristics are changed. To account for new transmitter behavior, the transmitter's input must be changed in order to achieve the desired output. The input is called a Transmitter Drive Waveform (TDW). Adjusting this TDW is time consuming and requires the attention of a well trained and experienced technician.

While work is being conducted on the standby, the on air transmitter is monitored and controlled to ensure the transmitted signal is being emitted with the proper format, signal shape and tolerance conditions. If a problem does occur which changes the transmitter's output pulse shape, human intervention is required.

The three functions of the transmitter subsystem are: "monitoring", "generating" and "controlling" of the Loran-C pulse train. The equipment now in use for each of these functions are summarized as follows:

a. **Monitoring**: The monitoring function is accomplished by several pieces of equipment including the Electrical Pulse Analyzer (EPA), the Time Interval Counter (TIC), the Loran-C Data Acquisition (LORDAC) set, and various strip chart recorders.

1) The EPA provides the watchstander with real time status on a variety of selectable transmitted signal conditions. The primary input to this device is a scaled version of the transmitted pulse train as observed with a Pearson transformer connected to the ground current return at the base of the antenna. The outputs of the EPA are a peak voltage of the transmitted signal which is proportional to the antenna current (for a selected pulse), and an average Envelope-to-Cycle Difference (ECD).

2) The TIC provides timing measurements of a number of critical timing signals and various strip chart recorders provide permanent record of selected parameters. Those relevant for this discussion are ECD (actually created by the EPA) and a local timing number called TINO.

3) LORDAC is not a permanent piece of monitoring equipment. It is a piece of special test equipment which is used to verify compliance with the published signal specifications. Only a handful of these devices exist, but it does offer significantly more information about the transmitted pulse train. Mentioning LORDAC here implies that any replacement equipment should measure the signal specification criteria on a continuous basis.

b. **Generating**: The device that generates the drive signals for the tube transmitters is called the Pulse Generator (P-GEN). Figure 1 shows the P-GEN and its associated TDW adjustment capabilities.

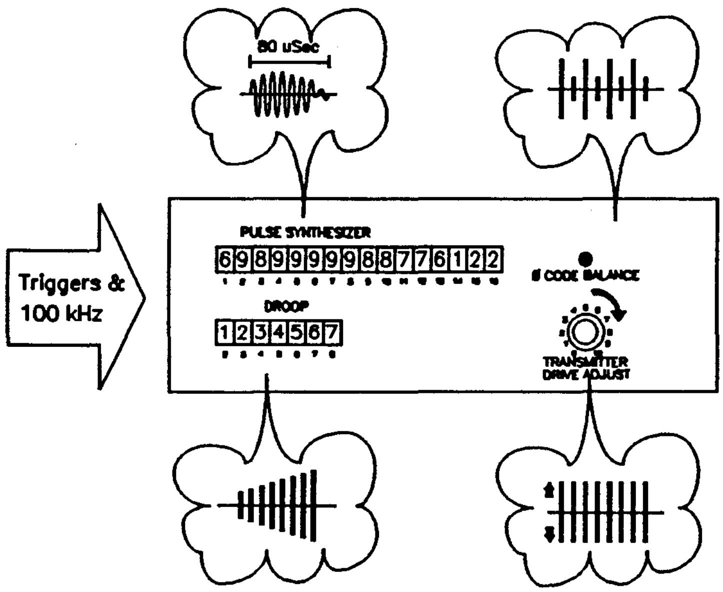

Figure 1
TDW Adjustment Capabilities

The primary inputs to this device are timing signals (triggers) and a 100 kHz sine wave. The output of this device is the Transmitter Drive Waveform (TDW). The user adjustment capabilities in the P-GENs are:

1) Discrete 1/2 cycle amplitude adjustments for the 16 half cycles which result in an 80 microsecond long TDW for each pulse within the pulse train.

2) Discrete amplitude adjustment for the TDW to correct for pulse train "droop". Droop is caused by transmitter high voltage power supply recovery limitations.

3) Amplitude control of the entire TDW pulse train. This is essentially a volume control feature.

4) Balance adjustment of the phase coded pulses. This adjustment corrects for different transmitter amplification characteristics for the positive and negative phase coded pulses.

c. **Controlling**: The control function is accomplished by the watchstander, the human input to the system. In general, the system runs for many hours and even days with no need for human intervention in any area except to compensate for timing drifts. To accomplish this control, the watchstander uses the Remote Site Operating System (RSOS). The timing control action is relatively well automated today and is not the initial concern of this redesign effort. However, this timing control action will become significant as the project develops and will eventually reside within the new subsystem.

With regard to control of the tube transmitter input, the technician's actions are very critical following the switching of transmitters. As stated, following two weeks of standby status and normal preventative maintenance, transmitter characteristics often change. Operating the standby transmitter into a dummy load (a resistive network) provides initial confidence as to power capabilities, but fine tuning the transmitter is not complete until it is switched onto the antenna. Once this is done, the output signal is observed and the input manually adjusted to compensate for any transmitter changes. Figure 2 provides a simple diagram of the system as it now exists.

When the transmitter is on air, adjustments to the TDW signal are made based on a visual comparison of a single full wave rectified RF ground current pulse to an ideal pulse envelope.

These two signals are simultaneously displayed on a dual trace oscilloscope for visual comparison. Once the observed RF signal is matched to the ideal envelope, specifically for the first 65 microseconds, the technician checks the signal shape, degree of error and a calculation of the transmitted ECD value through the aid of a computer program. This program does a root mean square error minimization between the first eight 1/2 cycle peak amplitudes of the selected pulse as compared to an ideal, zero ECD pulse. If the results of this calculation yield a total RMS error exceeding 1%, or the ECD is outside a specified boundary, further adjustments (individual TDW 1/2 cycle drive amplitude changes, phase code balance, pulse train droop, peak power, etc.) are made until the desired conditions are met. Barring any significant changes which would set off alarms, the pulse shape is only checked once daily using the noted program. If and when TDW changes are needed, they must be done by an experienced and well trained technician. Automating this adjustment procedure and closing the control/feedback loop is a very desirable feature of the EPA/DPA redesign.

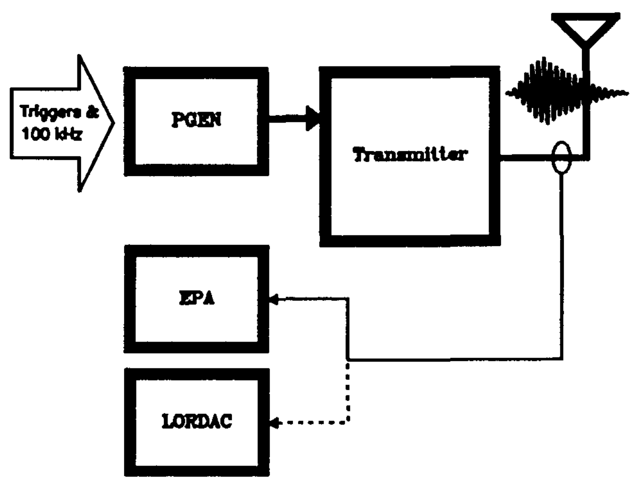

Figure 2
Current Transmitter System

4. Feedback Measurement Criteria

The specifications of the Loran-C pulse are documented in the Department of Transportation publication titled: Specification of the Transmitted Loran-C Signal, COMDTINST M16562.4, dated July 1981. These specifications provide designers, manufacturers, and users with a means of defining, specifying, and classifying the transmitted Loran-C signal. The specifications allow some flexibility to account for various transmitter types and also provide flexibility for those transmitters required to operate dual-rated. The source of the signal for Loran-C measurement, as defined in the specification, is the Loran-C pulse antenna ground return waveform. In brief, the specifications define performance criteria for the following signal parameters:

- o Envelope-to-Cycle Difference (ECD)
- o Half-Cycle-Peak Amplitudes (Ensemble Tolerance)
- o Half-Cycle-Peak Amplitudes (Individual Tolerance)
- o Pulse Trailing Edge
- o Zero-Crossing Times and Tolerance within a Pulse
- o Pulse-to-Pulse Amplitude Tolerances
- o Pulse-to-Pulse ECD Tolerances
- o Pulse-to-Pulse Timing Tolerances

The LORDAC set measures and records the performance of a station relative to these specifications. In the new EPA/DPA, these specifications become the basis for making decisions as to whether or not the transmitted pulse shape needs to be adjusted. The first phase of the EPA/DPA redesign effort must provide the watchstander with a piece of equipment which provides a more detailed, real-time measurement data on the transmitted pulse, i.e., a combination of the present EPA and LORDAC capabilities. This redesigned monitor subsystem must be transparent to the transmitter type, so the equipment can be used at either tube or SSX stations.

5. Discussion of the Prototype Equipment Suite

The redesign of the EPA/DPA was approached as a piece of Automatic Test Equipment (ATE). Automatic Test Equipment is a term used to explain a variety of off-the-shelf electronic instrumentation designed to be controlled by a computer. The computer primarily controls the test equipment through an interface. The GPIB (IEEE-488) interface is the most common.

An ATE system is constructed from a collection of instruments. The system is designed to test a specific piece of equipment. The technician connects the equipment in question to the ATE system, then starts the program on the computer controller. The ATE system uses signal generation equipment to drive the equipment under test and uses signal monitoring equipment to measure the response of that equipment. The controller collects this data and informs the technician of the equipment condition. Once the equipment is attached to the system and the program is running, all tests are automatic, hence the term, Automatic Test Equipment.

The Loran-C Timing and Control Equipment (TCE), as well as the Local Site Operating System (LSOS) used in today's Loran-C transmitter subsystem are both collections of custom built Automatic Test Equipment. Figure 3 is a block diagram of the TCE and LSOS equipment at a typical Loran-C Station.

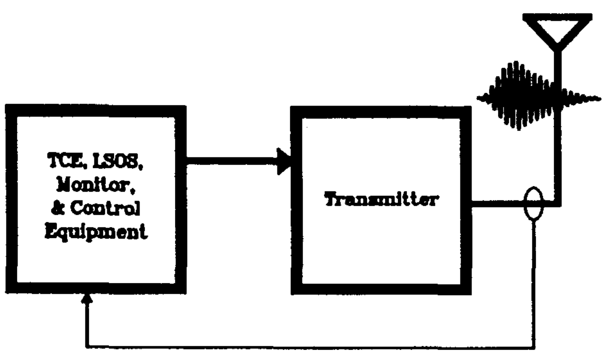

Figure 3
Loran-C as an ATE System

In this customized ATE system, the transmitter is the equipment being tested. The TCE does the testing by generating the signals needed to drive the transmitter. The TCE also monitors the operating condition of the transmitter and modifies the driving signals accordingly to keep the transmitter operating within the parameters of the published signal specification. The LSOS is the controller of the Automatic Test Equipment. The TCE/LSOS equipment has two goals. These are:

- o Control the Time of Emission (TOE) of the Transmitted Signal
- o Control the Pulse Shape of the Transmitted Signal

In the early requirements analysis of the EPA/DPA redesign, it was decided that meeting these two goals would be met by replacing the current custom built TCE/LSOS equipment with a new subsystem composed of off-the-shelf test equipment.

The prototype of this new EPA/DPA redesign has focused on the next generation of ATE called VXIbus. VXIbus is an acronym for VMEbus Extensions for Instrumentation. Providing the development history of the VXIbus standard is beyond the scope of this paper. However, the primary reason for choosing the VXIbus standard can be summarized as:

a. VXIbus is an open, non-proprietary architecture that fully incorporates the VMEbus standard. This has the promise of longer support through multi-vendor products.

b. VXIbus employs embedded controllers which improve data transfer rates.

c. VXIbus offers increased awareness of system software development costs and reduced ATE program development time by supporting a consistent programming environment called "Standard Commands for Programmable Instrumentation" (SCPI).

d. VXIbus offers flexibility by coexisting with existing GPIB equipment.

e. VXIbus supports a wide range of instruments-on-a-card and has the added feature of providing high levels of timing performance, clock frequency and signal synchronization within that customized system.

The VXIbus instruments reside on plug-in modules that fit into a rack mounted mainframe which supplies power, cooling and interference rejection. The plug-in modules can have up to three connectors. The number depends upon the host mainframe for which they are intended. The specification for the entire P1 connector and the center row of the P2 connector are taken directly from the VMEbus standard. The VXIbus standard defines the outer rows of the P2 connector and completely defines a new connector called P3. The P3 connector is available only on D-size VXIbus modules. This P3 connector includes some very desirable performance features which are needed to meet the development plans for the EPA/DPA redesign. For this reason, the VXIbus mainframe and some of the modules being used in the prototype development effort are D-size.

6. New Way of Doing Business

Figure 4 shows a simplified drawing of a vacuum tube transmitter. The shaded area represents some of the existing Timing and Control (TCE) equipment. As previously mentioned, the Timers and P-GEN are used for signal generation. The Time Interval Counter and Electrical Pulse Analyzer are used for signal monitoring.

The New Subsystem. Figure 5 is a simplified version of the new EPA/DPA and how it will fit into the current tube transmitter subsystem. Many of the signals from Figure 4 (Multipulse Triggers, Phase Code Set, etc.) are internal to the current TCE subsystem. These signals are used to interface the various pieces

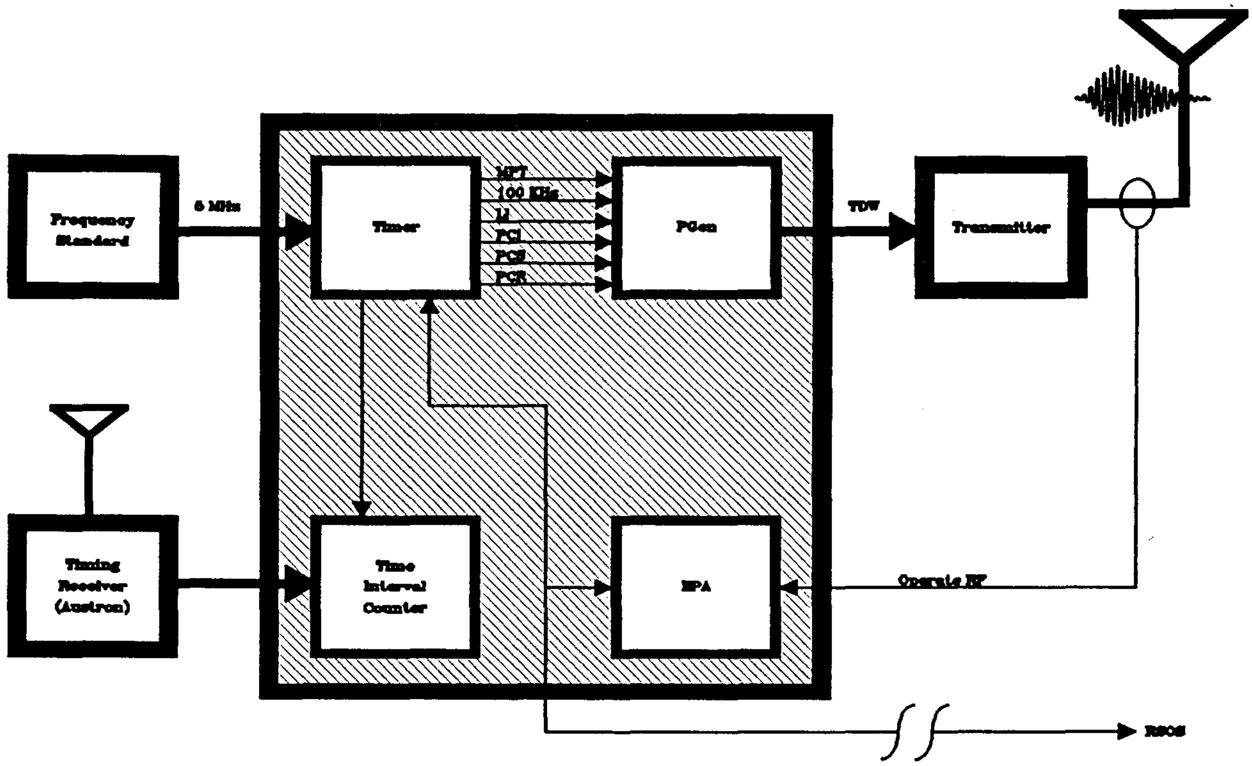

Figure 4
Loran-C Vacuum Tube Transmitter Block Diagram

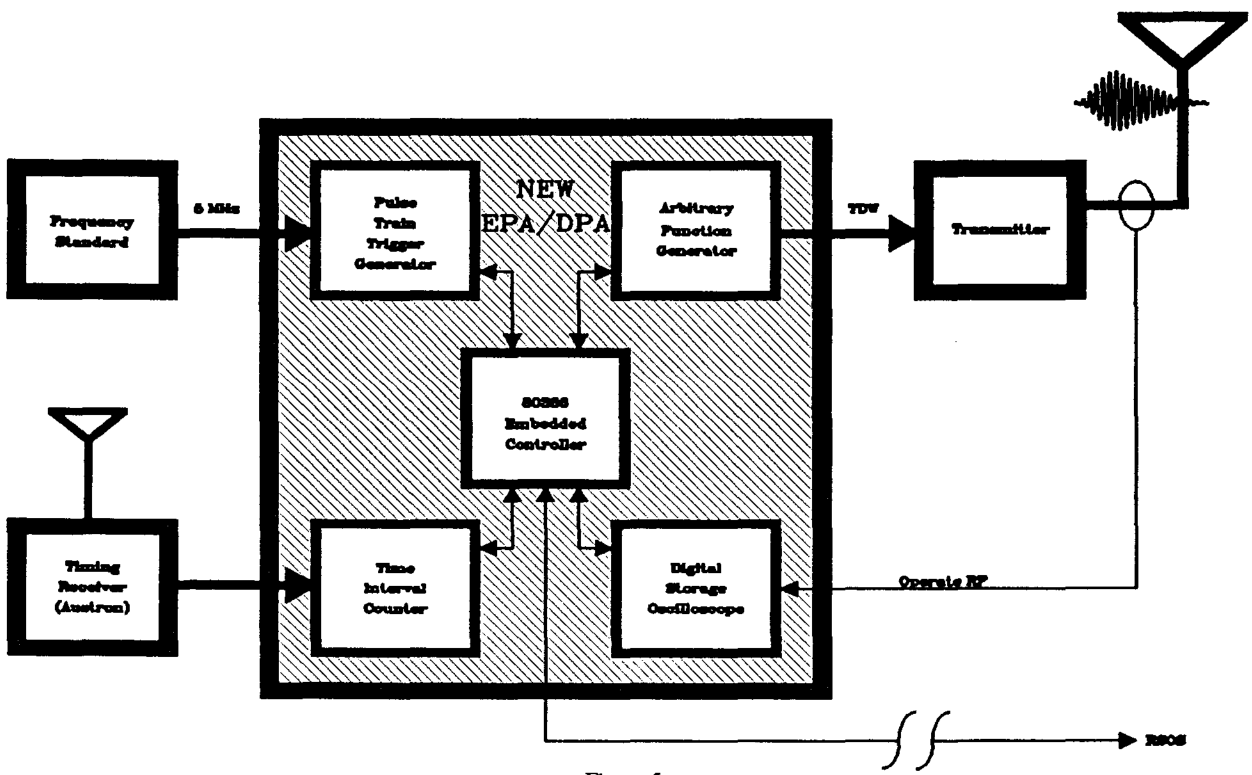

Figure 5
Tube Transmitter with EPA/DPA Subsystem

of the TCE subsystem to each other. Many of them are not actually needed to operate the tube transmitters (although some will be needed later in the project development cycle to provide input to the SSX transmitter).

The simplified version of the resulting ATE system shown in Figure 5 is composed of five hardware components. These are a Digital Storage Oscilloscope, an Arbitrary Function Generator, a Time Interval Counter, a Pulse Train Trigger Generator, and an embedded VXI controller.

a. A **Digital Storage Oscilloscope (DSO)** is similar to an ordinary analog scope. The main difference is the DSO digitizes the voltage levels of the incoming signal and stores them in memory. Since these values are stored in memory, a "snapshot" of the incoming signal is captured. In the EPA/DPA redesign application, the DSO is used to digitize a feedback waveform (the operate RF ground return). That "snapshot" of data will then be transferred to a computer for evaluation and comparison to the ideal Loran-C waveform. The controller can then extract all the desired parameters (i.e. ECD, frequency spectrum, etc.) of the operate signal.

b. An **Arbitrary Function Generator (AFG)** is the opposite of a digital oscilloscope. The AFG uses digital to analog converters to change the numeric values stored in its memory to voltage levels at the output jack. As a result, an AFG generates an analog output signal.

The new EPA/DPA will use the AFG to replace the Pulse Generators (P-GENs) and the phase adjustment/cycle compensation features of the timers. In the new system, the controller will load the desired Transmitter Drive Waveform (TDW) into the AFG. Each time the AFG receives a trigger (the Pulse Train Trigger signal), it will generate a Phase Code Interval (PCI) worth of TDWs. The AFG will initiate all timing adjustments by using its built in trigger delay feature.

c. The **Time Interval Counter (TIC)** measures the time interval between two triggers. The new EPA/DPA will use the TIC in much the same fashion as the current system.

d. The **Pulse Train Trigger Generator (PTTG)** is a simplified timer. It is simplified because it only divides the frequency standard output into a trigger similar to the desired PCI. It will differ from the current PCI signal because no timing adjustments will be made on the PTTG's signal. The PTTG will have no other functions. It will generate no other signals (i.e. Multipulse Triggers) or carry out cycle compensation, Local Phase Adjustments (LPAs), or Maintenance Phase Adjustments (MPAs).

e. The **embedded VXI Controller** is the "brains" of the EPA. It controls all of the ATE equipment, evaluates the data from the ATE equipment, takes any action to keep the transmitter operating in its specified range, and acts as the user interface. It will also act as the transmitter subsystem's link to the outside world by communicating with the Remote Site Operating System (RSOS).

Signal Generation. The Signal Generation process involves controlling two parameters. The first is the shape of the transmitted signal. The second is the time of emission of the transmitted signal.

Pulse Shape Control of Transmitted Signal. Here, pulse shape control does not refer solely to the shape of the transmitted pulse's envelope but rather, it will be more encompassing and will control the characteristics of the transmitted signal including such items as frequency, phase modulation, phase code, envelope shape, amplitude, droop, etc. The transmitted pulse shape and the other characteristics noted here will be changed by adjusting additional parameters of the transmitter drive waveforms (TDW). This added adjustment capability will make it possible to change the TDW in increments that are currently not possible.

In the current TCE subsystem the P-GEN uses a variety of triggers from the timer and many front panel settings to manipulate the TDW used to drive the transmitter. The P-GEN uses internal customized circuitry to construct a TDW from the phase shifted 100 kHz sine wave supplied by the Loran-C Timers. The current P-GEN operates on a TDW by TDW basis. It generates a TDW when it receives a Multipulse Trigger from the Timer. Other signals from the timer tell the P-GEN the expected phase code, the blanking sequence, etc. These signals control the P-GEN circuits which modify the 100 kHz into the desired TDW.

In the new EPA/DPA system the P-GENs will be replaced by an Arbitrary Function Generator. As mentioned, the AFG is essentially the reverse of a Digital Storage Oscilloscope. The AFG has an entirely different scheme of operation than the current P-GEN. It cannot vary the TDW using additional triggers and custom circuitry. It can only convert the values stored in its memory to analog voltages. This apparent limitation can be overcome by noting the repetitive nature of the TDWs. They repeat every PCI. The AFG will generate one PCI of TDWs each time it receives a trigger. The timer now needs to provide the AFG with only one trigger signal, PCI.

The current P-GEN manipulates the envelope's shape by attenuating the amplitude of each 1/2 cycle of the 100 kHz input. This is done by manually adjusting the P-GEN's 16 front panel thumbwheel controls. The AFG will do this by changing the values of the stored TDW data points.

In today's TCE subsystem, control of the transmitted pulse amplitude is obtained by changing the amplitude of the TDW pulse train. The P-GEN does this with an attenuation control on the front panel. The AFG will do this by adjusting the magnitude of the TDW in memory.

The transmitted signal's phase code is controlled in today's TCE subsystem by changing the phase code of the TDW. The P-GEN uses an op-amp circuit to pass the 100 kHz right side up or up side down (+/- 180 degrees) through the PGEN. The Phase Code Set and Phase Code Reset signals from the timer toggle a flip flop in the P-GEN which controls how the op-amp passes the TDW. Again, the AFG is only a digital to analog converter. This means that in the AFG application, phase code is accomplished by storing either positive or negative data sets to produce the prescribed corresponding phase coded TDWs.

The transmitter "droop" is defined as the decrease in peak voltage of each succeeding transmitted pulse in one Group Repetition Interval (GRI). The inability of the transmitter's high voltage power supply to fully recover from a transmitted pulse within each GRI causes this condition. In the current TCE subsystem, the P-GEN adjusts for droop by making each succeeding TDW in a GRI slightly larger than the previous one. The P-GEN uses front panel droop thumb wheel switches to adjust for this condition. The AFG will compensate for droop by storing a larger magnitude TDW in memory for each succeeding pulse.

The vacuum tube transmitters use Push/Pull amplification. This technique results in a situation which causes positive phase coded pulses to have a different amplitude than corresponding negative phase coded pulses. In the current system, this phase code "bounce" is compensated for by adjusting the overall amplitude of the positive TDWs in relation to the amplitude of the negative TDWs. In the new EPA/DPA, the AFG will compensate in the same manner; scaling of the positive and negative phase coded TDWs will be done by scaling them relative to each other within the AFG memory.

The AFG will duplicate pulse shape control in the same manner as the current P-GEN. In addition, the AFG can control other pulse shape parameters not previously possible. The AFG could construct a transmitter drive of any desired shape for any duration. Therefore, it is possible to drive a tube transmitter with a 500 microsecond long TDW which contains frequencies other than 100 kHz. By doing this, it is possible to correct and control phase modulation and the shape of the pulse tail. It appears possible to compensate for phase modulation by slightly changing the frequency of the transmitter drive so the transmitted pulse has zero crossings exactly 5 microseconds apart. In the same sense, it is possible to clean up the tail of the transmitted pulse by driving the transmitter for 500 microseconds instead of 80 microseconds. If the amplitude of a specific half cycle in the tail is too large, we can drive the transmitter with a small amount of 100 kHz that is 180 degrees out of phase with the transmitted pulse. This would act like a vacuum tube version of the solid state transmitter's "tail biters". These actions could improve the power spectrum of the transmitted signal. Unfortunately, the trade off comes from the limitations of the tube transmitter. Any additional drive waveforms, specifically the TDW length beyond 80 microseconds, must be weighed against the additional currents developed within that transmitter.

The Solid State Transmitter has variable tuning in its coupling network. It tries to hold the frequency of transmitted signal to 100 kHz by compensating for ambient conditions at the transmitter. The AFG can do the same by slightly changing the frequency of the TDW.

Within limits, the AFG's complete control of the TDW can be used to counteract minor transmitter problems. Using the TDW to compensate for aging Power Amplifier (PA) tubes is a good example. When the final Power Amplifiers age, it is difficult to increase the steepness on the front of the transmitted pulse. The current P-GENs can only construct 100 kHz TDWs with 10 discrete steps of amplitude. This restricts the steepness of the resulting TDW's leading edge. The AFG has finer control. It can make the front of the TDW much steeper and compensate for these aging PA finals. In practice this may extend the life of the tubes and provide cost savings.

Time of Emission Control of Transmitted Signal. As mentioned, the Arbitrary Function Generator method of generating TDWs requires only one trigger for each PCI. The transmitted signal's Time of Emission (TOE) can be changed by moving this trigger in time. This greatly simplifies timing control because only one trigger needs to be changed, automatically adjusting the phase of the 100 kHz drive signal.

The present way to control the TOE is to use the timers to move the trigger. Another way is to take advantage of the controllable trigger delay feature of the AFG.

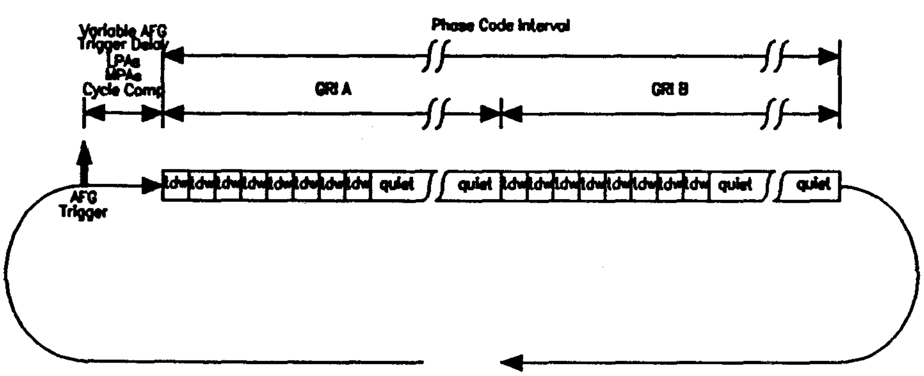

Figure 6
AFG Memory Contents

By treating the AFG's internal trigger delay as a variable, it can be used to adjust for any phase changes within the system. With this approach, the AFG receives a single trigger, waits some variable time period, then generates the TDW pulse train. The advantage of using the AFG's trigger delay is that the PCI trigger can be held stationary in time and the timing adjustments can be accomplished by sending software commands to the AFG. Eventually, this will greatly simplify the timer's circuitry. The AFG also has the potential of allowing timing/phase adjustments in increments smaller than the present minimum timing adjustment increment of 20 nanoseconds.

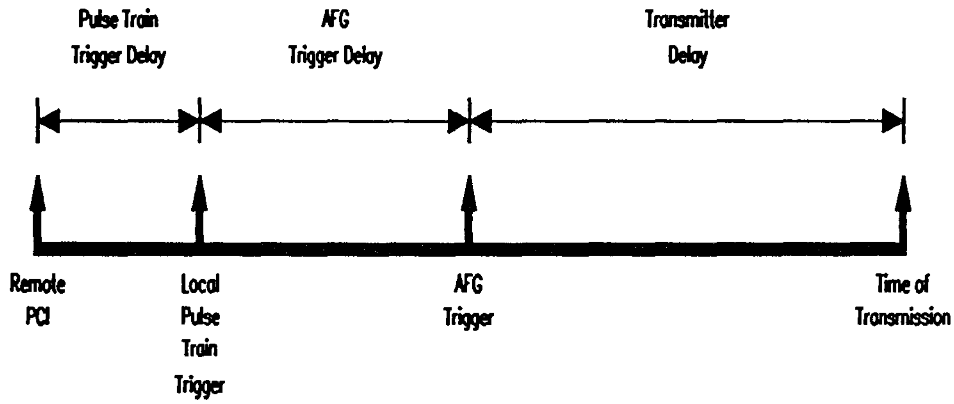

Figure 7
EPA/DPA Timing Sequence

Figure 6 shows the contents of the AFG's memory. The AFG will contain an entire PCI worth of data. The drive waveforms stored in memory will compensate for the shape of the transmitted signal. Each time the AFG receives a Pulse Train Trigger (PTT), it will wait a programmed delay (internal AFG trigger delay), then generate an entire PCI worth of transmitter drive waveforms. Timing adjustments are made by simply changing the internal AFG trigger delay. The controller will automatically make cycle compensation timing adjustments to the AFG trigger delay. The watchstander or the existing Calculator Assisted Loran Controller (CALOC) will tell the embedded VXI controller to make the LPA adjustments to the AFG trigger delay.

New Timing Diagram. Figure 7 shows the new timing diagram. As stated, only the internal AFG trigger delay will be varied to control the Time of Emission. The PTT is the stable local timing reference derived from the oscillators. It is similar to PCI but its movement is fixed in time. To parallel the PTT to the existing system, it can be thought of as a Coding Delay.

Cycle compensation in today's equipment corrects for slight phase variations due to transmitter delay. In the new system the controller will change the AFG trigger delay to counteract these variations. The goal is to keep the sum of the AFG trigger delay and transmitter delay constant. For example:

AFG Trigger Delay + Transmitter Delay = Constant

With regard to system LPAs (phase adjustment to correct for oscillator drift and propagation path changes) the transmitter's TOE must be shifted. In the new system, the controller will insert an LPA by moving the Internal AFG Trigger Delay. In this case, the constant will change. For example:

AFG Trigger Delay + Transmitter Delay =
New Constant = Old Constant +/- LPA

Again, drawing a parallel to today's system, in the case of cycle compensation, the SYNC value (TINO + transmitter delay) will remain the same. In the case of LPAs the SYNC value will change. In both cases, the timing adjustments will be stored on the controller's hard disk. This data logging feature eliminates the need for the cycle compensation and phase (TINO) strip chart recorders.

Signal Monitoring. Like the signal generating process, the signal monitoring process involves measuring two parameters. The first is the shape of the transmitted signal. The second is the TOE of the transmitted signal. This process will contain a user interface to present these parameters to the watchstander in an easy to interpret manner.

Pulse Shape Monitoring. Pulse shape implies ECD measurement. However, it is any parameter that defines the characeristics of of the transmitted pulse. The present TCE system measures transmitted ECD by calculating an average ECD as determined by two opposite phase coded pulses from GRI A and GRI B. The new system will monitor ECD on the entire pulse train. In addition to ECD, the new system will continuously monitor individual pulse amplitude, phase code, phase code balance, droop, and power spectrum.

The new system will monitor the above pulse train parameters using the Digital Storage Oscilloscope. The DSO will digitize the return RF and the controller will store the data. Software subroutines will use this data to calculate the pulse train statistics as specified in the published signal specification.

Time of Emission (TOE) Monitoring. The TOE measurements are composed of the three time measurements shown in Figure 7. Transmitter delay measurements are extracted from the same data used to calculate pulse shape statistics. The controller will calculate transmitter delay by adjusting the volts per division of the DSO to the minimum level, creating a hard limited RF signal. The controller will scan the data and find the 30 microsecond zero crossing. Once this point is found, the controller will have a measure of the delay between AFG's trigger event and the 30 microsecond point. This is the transmitter delay. The AFG trigger delay is the current trigger delay value held in memory by the controller. The PTT delay is the time interval between the Remote PCI (from the Austron receiver) and the local PTT. The PTT delay will be measured with the embedded TIC in the VXIbus mainframe.

7. Present Status

The EPA/DPA redesign effort has been underway for nearly two fiscal years. Primary efforts during the first year and a half focused on requirements analysis and system design. It was in this phase of the project that it became clear that the initial project scope was quite limited and that a "box for box" replacement of the existing Loran-C equipment suite was not the best approach. It was evident early on that adding new equipment, specifically developed and customized to meet the Loran-C system needs, would not result in a system with a long term, supportable life cycle. An equipment suite comprised of commercially procurable equipment with minimal customization required to adapt the equipment for Loran-C purposes was deemed necessary. In pursuit of this goal, it was decided that the VXIbus standard showed the most promise in meeting the project objectives, namely: new technology, a supportable system comprised of off-the-shelf hardware, and the flexibility required to meet the demands of future system expansion.

As the VXIbus approach to the prototype system was being researched, significant work was being done on an "engineering model". Work in this area was well underway in the middle of fiscal year 1991. The engineering model was broken up into pieces and each piece was approached using existing equipment to demonstrate concepts that would later be designed into the VXIbus prototype. Figure 8 shows a simple feedback system and highlights the pieces that were individually addressed by members of the project team.

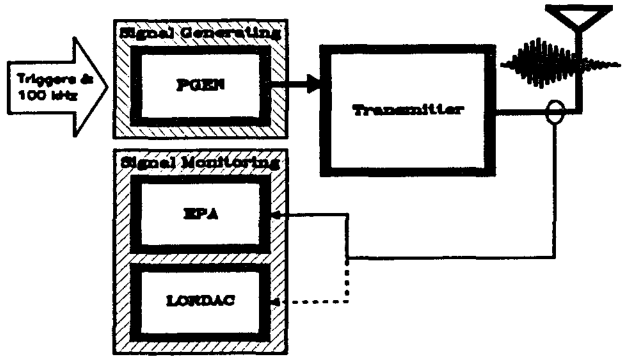

Figure 8
Loran-C Tube Transmitter System

The feedback portion of Figure 8, which "monitors" signal performance, was tested using a Digital Storage Oscilloscope (DSO) card embedded in a MS-DOS PC. Software was developed to capture antenna ground current waveforms, calculate, then display, ECD and pulse half-cycle amplitude values. This effort demonstrates the ability to emulate the monitoring features of the present EPA using a DSO, provides a measure of the software's complexity, and provides information as to the types of input triggers and input signal amplitudes which must be considered for follow up work in the prototype. In addition to writing the software to emulate the EPA, the LORDAC signal specification software was transferred to the MS-DOS PC and successfully demonstrated. This effort alone, independent of any work to follow, has resulted in a next generation LORDAC.

The TDW "generation" portion of Figure 8 was conceptually tested on EECEN's AN/FPN-42 transmitter using a commercially available Arbitrary Function Generator (AFG) controlled by a MS-DOS PC. In this demonstration, the AFG output was fed into an actual Loran-C transmitter and the output was captured using a Digital Storage Oscilloscope. With the aid of "canned" software, these two signals were used to create an inverse digital filter representation of the transmitter and antenna. This inverse digital filter was excited with an ideal pulse waveform; the output became a new TDW. This new TDW was loaded into the AFG. The iterative process was executed manually three to four times to minimize the error between the actual output pulse and an ideal pulse. Here again, this effort demonstrates that the AFG approach is feasible, provides direction as to what inputs are necessary for prototype work, provides a measure of the software complexity, and places some constraints on the input function's duration. This constraint, as previously mentioned, is based on the need to keep the transmitter currents reasonable; trying to make a "perfect/ideal pulse" from a transfer function mathematically results in a TDW significantly longer than the presently used 80 microsecond TDW signal. In practice, the pulse could be improved, but the output power has to be lowered to avoid excessive cathode currents.

Figure 9 is a representation of the "engineering model" system that has been tested in the EECEN laboratory environment. The transmitter used is the AN/FPN-42 tube transmitter. This transmitter was chosen for a number of reasons, but primarily, the only TCE input required is a TDW pulse train. Since no other triggers or timing signals needed to be generated, the AFG concept of TDW generation was easier to develop at the engineering model level.

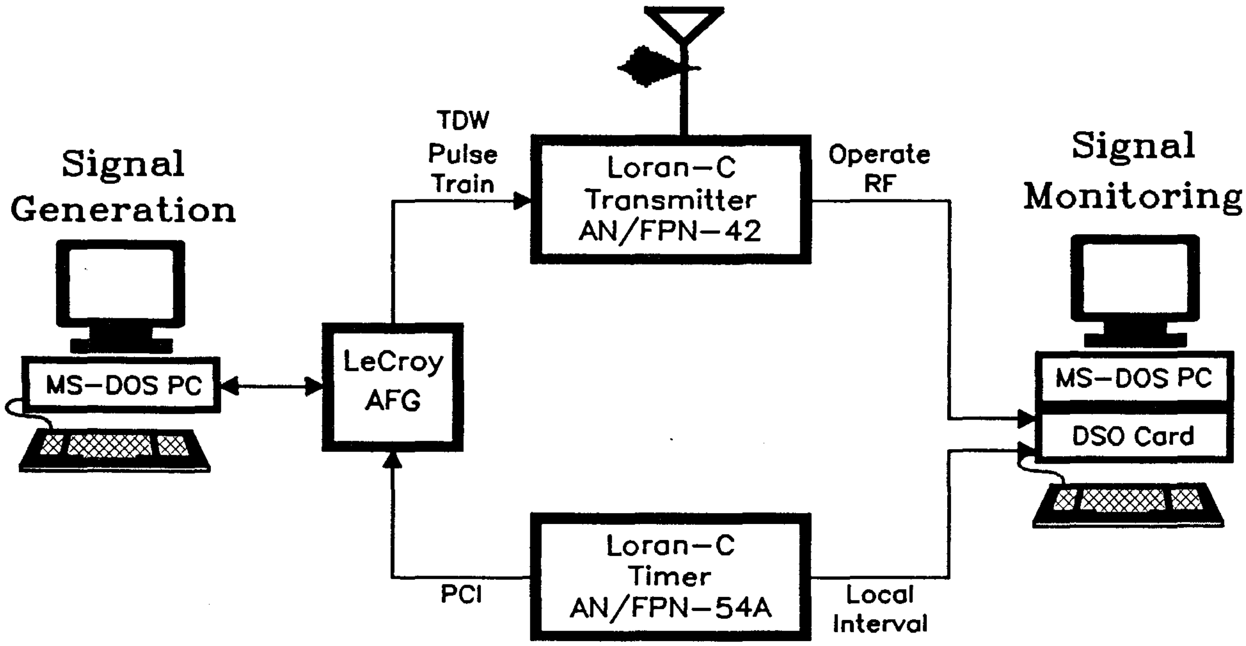

Figure 9
EPA/DPA Engineering Model

8. **Phased Approach**

Due to the very broad nature of this redesign, a phased implementation approach is preferred. At present, four phases are planned. The VXIbus based automatic test equipment approach to implementation allows this to be done quite easily. As the project progresses through the various phases, the hardware can be expanded upon by adding new modules to the VXIbus and implementing the additional software required to run these new modules. The four phases of the implementation cycle are:

a. **Phase 1.** Development of a prototype monitor consisting of a VXI mainframe, an embedded VXI controller, and a digital storage oscilloscope module. It replaces the current EPA and LORDAC. This phase will provide additional monitoring capability by adding the VXIbus system in parallel to the existing system. This phase can be accomplished at both tube and SSX equipped Loran-C transmitting stations.

b. **Phase 2.** Addition of Arbitrary Function Generators (AFGs) to the VXI mainframe. This will be a large step forward and will be aimed at the replacement of the P-GEN. This phase will only apply to transmitting stations with tube transmitters. Implementation of the VXIbus equipment during this phase will still use the existing Loran-C timers for the "generation" of the necessary timing signals. Timing adjustments and the cycle compensation activity will therefore remain part of the existing timers. During this phase, the present EPA (paralleled in phase 1) will be removed altogether from the system.

c. **Phase 3.** Addition of a Time Interval Counter to the VXI mainframe. Implementation of this phase will have its greatest impact on the existing TCE equipment suite. Once this phase has been achieved, the existing TCE equipment will be altogether different. This phase will apply to both tube and SSX equipped Loran stations. The equipment eliminated will include the Strip Charts, the Time Interval Counter, the Status Alarm Unit, the Timers, and the new Automatic Blink System (ABS - a short term solution for ABS is presently under development).

d. **Phase 4.** Intended software addition to the system. Executing this phase will eliminate the Local System Operating Set. In all likelihood, replacement of the LSOS system will occur in part as each of the phases are implemented.

9. **Conclusions**

The new EPA/DPA will be more than just a direct replacement for the present EPA. It will also perform tasks currently done by other pieces of equipment and will be a replacement for a large portion of the present Timing and Control Equipment (TCE) suite. This redesign is necessary to reduce the complexity of the Loran transmitter station, to improve automation, and to provide a next generation Loran-C equipment suite which can be supported into the next century.

The new EPA/DPA will use a microcomputer based VXI controller interfaced to state-of-the-art VXIbus Automatic Test Equipment. The controller will communicate with these instruments (i.e. Digital Storage Oscilloscope, Time Interval Counter, etc.) via a computer bus.

Approaching the redesign in this manner will benefit the transmitting stations by:

- Simplifying the overall system design;
- Allowing easier inclusion of new and developing system requirements such as the Automatic Blink System and Inter-chain timing;
- Providing a base for other Electronic Equipment Replacement Project (EERP) improvement projects;
- Automating chain operations data collection;
- Providing a more accurate and detailed picture of the transmitter's condition.

This approach will also mesh well with the Loran requirements for the future. It will facilitate the inclusion of functions currently handled by other pieces of equipment. The result will greatly reduce the complexity of Loran-C transmitter stations. This will ultimately decrease costs, decrease maintenance, enhance system performance, and finally increase overall system reliability.

10. Acknowledgments

The authors would like to acknowledge a number of people who have contributed to the material contained in this paper. Without their assistance, patience, dedication and commitment to a "quality product", the project and this paper could not have been realized. They are:

LCDR Charles Teaney (EECEN Loran-C Branch Chief)
LCDR Greg Kmiecik (EECEN Loran-C Transmitter Section)
LT John Macaluso (COCO MEDSEA Chain)
CWO4 W. George Hamilton (EECEN Loran-C Transmitter Section)
CWO4 A. Alborano (EECEN Loran-C Transmitter Section)
ETC John Hartzell (EECEN Loran-C Transmitter Section)
Mr. Edward J. Campbell (UNYSIS Systems Analyst)
Mr. David Freese (EECEN Computer Systems Branch Chief)
Mr. George K. Hunter III (Drexel University Co-op Student)
Mr. Anthony Genovese (Drexel University Co-op Student)
Mr. Bradford Doklan (Drexel University Co-op Student)

11. Biography

LCDR Doug Taggart graduated from the U.S. Coast Guard Academy in 1976 with a B.S. degree in Electrical Engineering and received his MSEE degree from Purdue University in 1980. During his Coast Guard career, assignments not directly related to Loran-C included a tour as the Communications Officer on the U.S. Coast Guard Cutter Hamilton, and a brief tour at the Department of Transportation's Transportation Systems Center in Cambridge, Massachusetts. Loran-C related tours prior to his present assignment included a tour at the Coast Guard's Research and Development Center in Groton, Connecticut, and as the Coordinator of Chain Operations for the Mediterranean Sea Chain. During his tour at R&DC, he was project manager of a number of R&D Loran-C projects directly related to the use of Loran-C. They were the Harbor/Harbor Entrance Survey, Loran-C Stability Study and the Loran-C Guidance Equipment projects. In 1987, he was transferred to his present assignment at the Coast Guard's Electronics Engineering Center in Wildwood, New Jersey as the Transmitter Section Chief. He is the project manager on a number of Loran-C improvement projects. They include the Electronic Equipment Replacement Project (EERP), the development and installation of the Automatic Blink System (ABS), and the replacement of the AN/FPN-42 transmitters in the Northern Pacific Chain.

LT Jon Turban received his B.S. degree in Electrical Engineering from the U.S. Coast Guard Academy in 1983 and his MSEE from Yale University in 1989. He is also a licensed professional engineer in the State of Connecticut. Upon graduation from Yale University in the fall of 1989 and until September 1991, LT Turban was part of the Loran-C Transmitter Section at the Coast Guard's Electronics Engineering Center in Wildwood, New Jersey. He was the Project Manager of the Electrical Pulse Analyzer/Digital Pulse Analyzer redesign project, which includes the VXIbus based Loran-C Transmitter Monitor and Control System. Mr. Turban is currently part of the Navigation Systems Branch at the U.S. Coast Guard's Research and Development Center in Groton, Connecticut. He is a member of the project team tasked to implement a Differential Global Positioning System. Mr. Turban's professional interests include: digital signal processing, computer architecture, system engineering, and electronic navigation systems.

A Thousand Signals - Carrier-Wave Interference in Europe

Richard Farnworth, David Last, Mark Searle

Radio-Navigation Group, University of Wales,
Bangor, Gwynedd, United Kingdom

Abstract

In Europe, carrier-wave interference, from the many stations with which Loran-C is obliged to share its frequency band, is the principle factor which limits its coverage. Although this fact has been known for many years, the lack of a quantitative model has made it difficult to estimate the performance of proposed chains. The situation has been complicated by large number of potential interferers and by the complex dependence of their effects upon their frequencies and the characteristics of the receivers. This paper moves our understanding forward from the present analyses which describe the effects of single carrier-wave interferers on specific aspects of the operation of receivers. It considers the real-world, multiple interferer situation. The results are embodied in a performance model which is used to predict the coverage of current and proposed Loran-C chains. It demonstrates the crucial importance of the choice of GRI and the correct use of receiver filters.

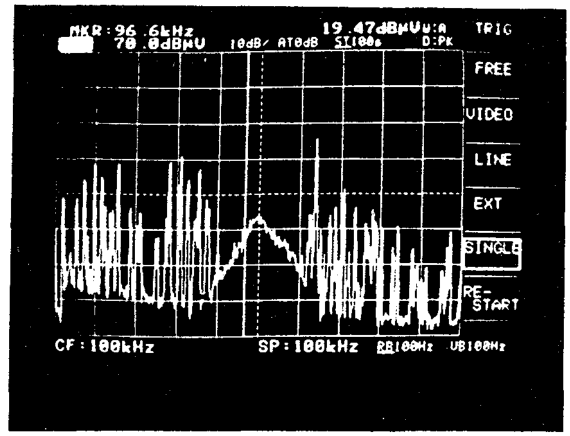

Fig.1 Typical frequency spectrum from 50 kHz to 150 kHz received in the Europe. Note the large number of interferers surrounding the Loran-C signal.

1 Introduction

One of the principal factors that must be considered when implementing Loran-C coverage prediction in Europe is carrier-wave interference. It has therefore been necessary to modify traditional coverage prediction techniques which assume coverage to be limited by atmospheric noise.

The problem of modelling carrier-wave interference (CWI) is a daunting one. Fig.1 shows the frequency spectrum between 50 and 150kHz measured in the United Kingdom. There are almost 1000 transmissions in this frequency band which are potential sources of interference to Loran-C in different regions of Europe. The field strength of each of these transmissions, and consequently the effect it has on Loran-C receivers, varies throughout the geographical area.

The problem has been tackled in several stages. The first stage was to adopt an increased value of atmospheric noise to account for the high levels of interference. The actual levels of atmospheric noise in Europe vary between 40 and 53 dBμV/m, but a higher level of 61 dBμV/m was adopted for use in the coverage prediction process. This value was recommended by the North-West European Loran-C Technical Working Group [1] on the grounds that the resulting coverage areas corresponded with Loran-C users' experience.

More recently a method has been developed for modelling CWI independently of atmospheric noise. This paper describes that method. The effects of the large numbers of transmitters which lie within 50 kHz of the centre of the Loran-C frequency band have been considered. The results have been used in a coverage prediction model to demonstrate the importance of the choice of GRI and the advantage which can be gained from the use of receiver notch filters.

To describe how this has been done we must first look at the effects of interfering signals on Loran-C receivers.

2 Effects of CWI on Receiver Operation

The basic structure of all types of Loran-C receiver is shown in Fig.2. The bandpass filter will considerably attenuate many interfering signals but some of the stronger signals will still pose a threat to the receiver. A few remaining interferers may be rejected using notch filters. The performance of a receiver largely depends on the interference which remains after the signal has passed through these filters.

The way in which the phase and envelope shape of the Loran-C signal are altered by interference is complex. It depends on the frequency and field strength of the interference relative to those of the Loran-C signal.

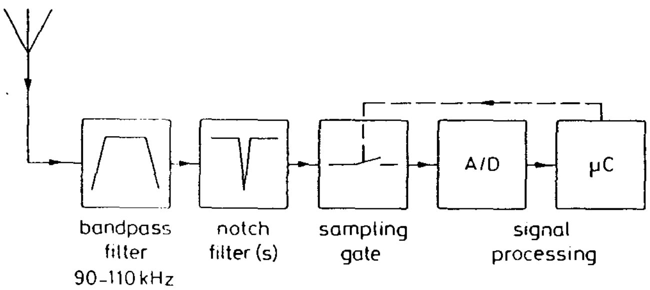

Fig.2 Simple block diagram of a typical Loran-C receiver architecture (After Beckmann [4]).

2.1 Classes of Interference

The frequency spectrum of the Loran-C signal consists of many individual spectral lines separated by the minimum repetition frequency of 1/(2GRI). The effect of an interferer on the receiver is highly dependent on how close its frequency is to a Loran-C spectral line. The Minimum Performance Standards (MPS) for Loran-C receivers [2] specifies three categories of interference:

Synchronous - where an interferer has precisely the same frequency as a Loran-C spectral line. Synchronous interference causes a fixed offset in a range measurement.

Near-Synchronous - where the interference frequency is close to a Loran-C spectral line (within the tracking loop bandwidth of the receiver). This type of interference causes an oscillating offset in a range measurement.

Asynchronous - This class encompasses all other interferers. Asynchronous interference causes an apparent increase in the background noise level experienced by the receiver.

Fig.3 illustrates these three types of interference.

These different types of interference cause different problems for Loran-C receivers but it is the synchronous and near-synchronous interference which poses the greatest danger. Research at the University of Delft [3,4] has demonstrated how to evaluate the navigation errors introduced by each type of interference. These effects are heavily dependent on the filters used in the receiver and on the GRI of the chain.

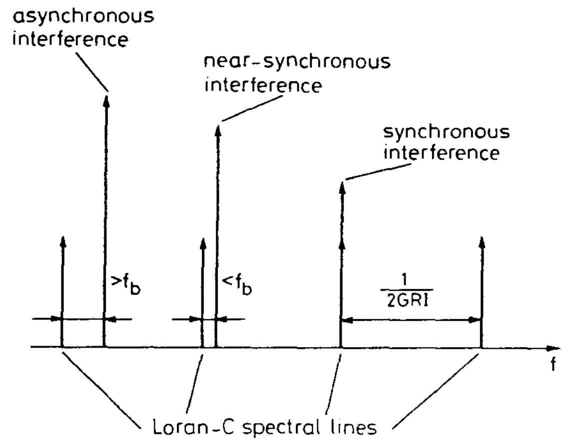

Fig.3 The three classes of interference specified by the MPS (After Beckmann [4]).

There are two separate mechanisms in a Loran-C receiver which are affected by CWI: phase tracking and cycle identification. Much research has been carried out into the effects of CWI on phase tracking but the errors introduced into the cycle identification process have not been poorly understood until very recently. Research at Bangor [5] indicates that the errors introduced to the phase-tracking mechanism will be the most serious. The receiver tracking loops used in the cycle identification process have much narrower bandwidths than those used for phase tracking. An interferer must therefore be much closer to a Loran-C spectral line to be near-synchronous. Consequently, very few interferers will cause problems to the receivers' cycle identification mechanism.

This analysis therefore only considers the phase-tracking errors introduced by carrier-wave interference.

It has been shown [6] that the phase tracking error due to CWI is related to the signal-to-interference ratio (SIR) by the following equation:

$$E = \frac{T_L}{2\pi} \arcsin \left[\frac{1}{SIR} \right] \tag{1}$$

Where T_L =Loran-C carrier period of 10μs.

E = Phase tracking error in μs.

A database of interferers between 50kHz and 150kHz assembled by Beckmann [6] from International Frequency Registration Board (IFRB) sources is employed in this analysis. This lists all interfering transmitters by name, frequency, power and position. The analysis was limited to Europe so only stations which lie between longitudes 70°W and 60°E and latitudes 30°N to 90°N were included. This area stretches from the east coast of Canada, through all of Europe and well into the Soviet Union and from North Africa up to the Svalbard islands north of Norway.

To predict the effect that all these signals will have on a Loran-C receiver each one must be considered individually. The attenuation introduced by the propagation path and by receiver filtering must be evaluated.

2.2 Weighting of Interferers due to receiver filters

In the model it is necessary to predict the resulting signal strength after the attenuation due to both the propagation path and the receivers filters. In reality, of course the attenuation caused by the receiver filters is experienced by the signals after the attenuation due to the propagation path. It makes no difference to the result if these are applied in the reverse order. It was found more convenient to apply the attenuation due to receiver filters to the listed transmitter powers before predicting the attenuation caused by the propagation path.

A bandpass filter judged to be typical of those found in Loran-C receivers was chosen for the analysis. The amplitude transfer function of the chosen filter is shown in Fig.4. This response was measured on a commercially available Loran-C receiver. The amplitude of each of the interferers is weighted according to this filter response. The bandpass filter response can be altered to observe the effects on coverage of using different filters.

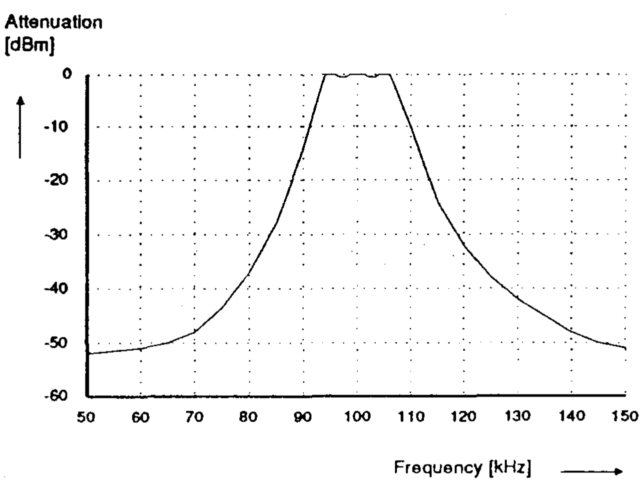

Fig.4 Amplitude Transfer function of the standard bandpass filter. Measured from a commercial Loran-C receiver (After Beckmann [6]).

To simulate the effect of the receiver phase tracking process the amplitude of each interferer is multiplied by another weighting function which is also a function of frequency. Fig.5 shows a graphical representation of the weighting function which gives the attenuation to be applied to all types of interference. The interferers are weighted according to their proximity to Loran-C spectral lines of the GRI specified. Synchronous interferers are not attenuated but other interferers are attenuated by an amount which depends on how close they are in frequency to a Loran-C spectral line. Near-synchronous interferers will not be attenuated significantly as they lie close to the spectral lines. Asynchronous interferers will be significantly attenuated. The roll-off of the weighting function is -6dB/octave which simulates a type I tracking loop. The bandwidth chosen is 0.1 Hz which is wider than that found in most marine Loran-C receivers but typical of a receiver designed for higher-dynamic applications. Different weighting functions can be substituted to simulate different types of receiver.

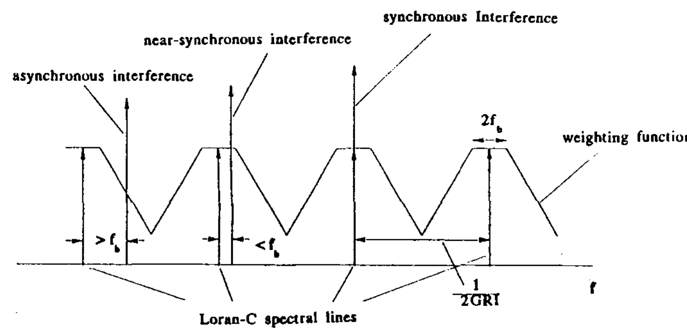

Fig.5 Weighting function applied to the spectrum of interferers to simulate receiver tracking filters. Roll-off = -6dB/octave.

3 Field Strength Prediction

To calculate how the interference will affect the receiver it is necessary to know the signal-to-interference ratio (SIR). The Bangor coverage prediction model is already equipped to calculate the Loran-C groundwave and skywave field strengths over large areas [7]. The same techniques have been applied to predict the field strength of each of the 1000 interferers by both groundwave and skywave modes of propagation. The groundwave field strength prediction process makes use of the same ground conductivity data-base which is used for predicting Loran-C field strengths. The amplitude of the skywave reflected signals will vary both annually and diurnally, but the statistics of this variation are known [8]. To be consistent with the USCG practice of taking the atmospheric noise level exceeded only 5% of the time throughout the year we have chosen to use the skywave field strengths not exceeded for more than 5% of the time over the year.

An array of field strength values for all the interferers is calculated at 12,000 sample points within the coverage prediction window which lies between longitudes 70°W and 50°E and latitudes 30°N to 80°N. The points which constitute these arrays are spaced at points of 1° of longitude by 0.5° of latitude. These are the same points at which the Loran-C field strengths are computed [5].

The groundwave and skywave components of each interfering signal are combined and then the contribution from all of the signals is combined by root-of-sum-of-squares addition to establish a total value of interference signal strength at each point in the array. Fig.6 illustrates a section of this array which shows the levels of interference throughout North-West Europe.

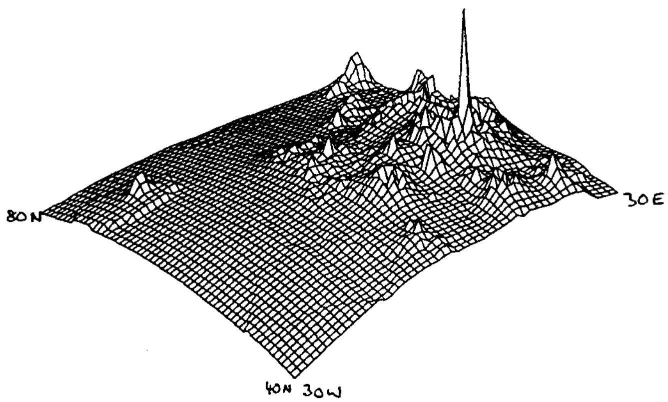

Fig.6 European carrier-wave interference signal levels. Calculated from IFRB list [6].

4 Coverage Limits due to CWI

Existing coverage prediction techniques assume that the limit of coverage occurs when the signal-to-atmospheric noise ratio is -10dB. It is assumed that receivers provided with signals with this level of SNR or better will be able to measure time-differences with standard deviations of less than 100ns. Given this accuracy in time-difference measurement, the geometrical factors must then limit the resulting position uncertainties to less than 1/4 n.mile (2drms).

The the present analysis retains this coverage limiting criterion but adds an additional limit due to CWI. If the tracking error due to CWI at any location exceeds 100ns then that point is deemed to lie outside the coverage area of the chain. Thus the coverage boundary due to CWI is defined as the point where the SIR results in an rms tracking error of 100ns. Equation (1) shows that a tracking error of 100ns results when the SIR is 24dB. This is however the worst-case tracking error and what is required is the rms error. Assuming a sinusoidal variation in the tracking error this gives a 3dB reduction in the limiting SIR.

4.1 Interference Rejection due to Phase-Coding

The previous analysis ignores the additional interference rejection provided by the phase-coding of the Loran-C signals. It can be shown that phase-coding provides an improvement of between 10dB and 18dB [9] depending on the frequency of the interference. The interference array calculated in the model is a made up of a number of frequencies between 50 and 150kHZ so a nominal value of 12dB was incorporated as the additional interference rejection due to phase-coding. Thus the limiting SIR, which gives an rms tracking-error of 100ns, becomes 9dB.

5 The effect of interference on coverage

A single chain has been chosen to illustrate the effect of CWI on coverage. One proposal for the North-West European Loran-C system contained a central chain with five secondaries.

5.1 GRI selection

Beckmann [4] has warned in a previous paper to the WGA that the choice of GRI is very important, particularly when large numbers of interfering signals are present. An investigation was carried out into which GRIs would lead to there being the smallest number of synchronous or near-synchronous interferers. The best GRI found was 4013 which resulted in only seven synchronous or near-synchronous interferers from the entire list. This low GRI would not be feasible for use with the chain chosen since it has five secondaries and would require a minimum GRI of 7686. The best GRI above this minimum is 7777. There are only 29 near-synchronous and synchronous interferers for this GRI. In contrast the worst possible GRI of 8000 results in 497 interferers being near-synchronous or synchronous.

Fig.7 shows the coverage of the proposed chain calculated using atmospheric noise alone and the reduced coverage calculated using 61dBμV/m as the noise level for the entire region. Introducing CWI limits using the worst GRI of 8000 gives the coverage area shown in Fig.8. This is very poor indeed but can be dramatically improved by changing the GRI to 7777. This results in the improved coverage indicated by the bold line in Fig.9. This is without any notch filters! The coverage out in the Atlantic is much better than that predicted using the 61dB approximation; in fact it almost reaches the limit set by atmospheric noise. This makes sense since no interfering transmissions emanate from that region; most interfering transmissions come from Central and Eastern Europe and the Figure shows that the coverage in these areas is reduced. There is a hole in the coverage area due to a transmitter in the west of France. This is a 10 kW station on a frequency of 111.6 kHz which is not significantly attenuated by

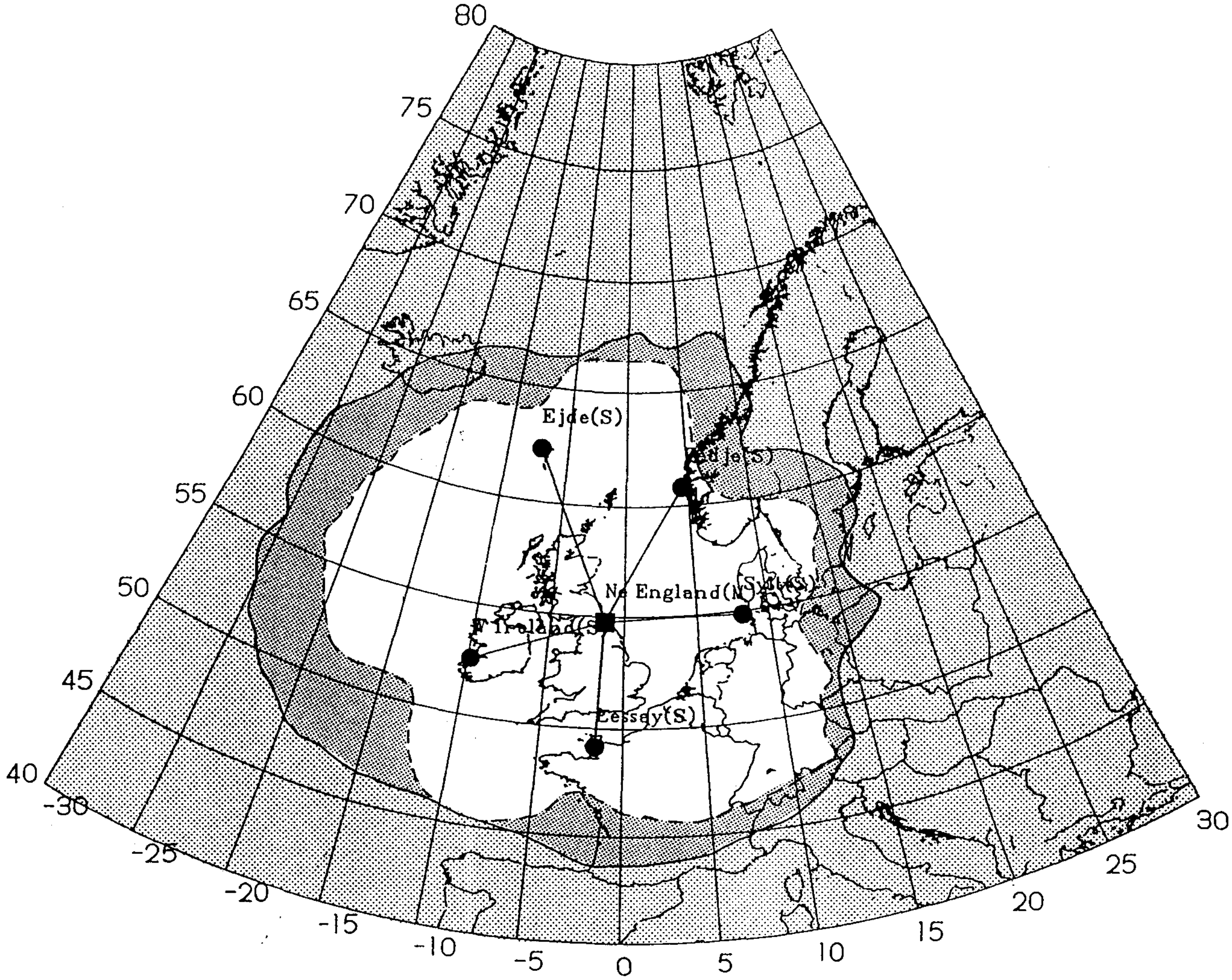

Fig.7 Coverage of a proposed European Loran-C chain. The solid line shown the coverage limits which arise when the noise experienced by receivers is assumed to be purely atmospheric. The dotted line shows the coverage calculated using 61 dBμV/m as the noise level.

the bandpass filter. A receiver operating in this area will definitely need a notch filter tuned to this frequency.

5.2 Notch Filters

The introduction of just three notch filters improves the coverage of the chain with the worst GRI from that shown in Fig.8 to that shown in Fig 10. This improvement does however require ideal notch filters. ie. The notches are tuned to the most harmful interferers at any location.

The coverage area when a good GRI is chosen, shown in Fig 8, is already quite good without any notch filters in the receiver. It is further improved by equipping the receiver with three automatic level sensitive notch filters which tune to the strongest interferers at any location. The increased coverage area is indicated by the dotted line in Fig.9. The coverage area over the land mass of central Europe has now increased and we have also gained a little near to Iceland. This coverage area, even the part close to the strongest interferers, is almost the same as that calculated using atmospheric noise alone.

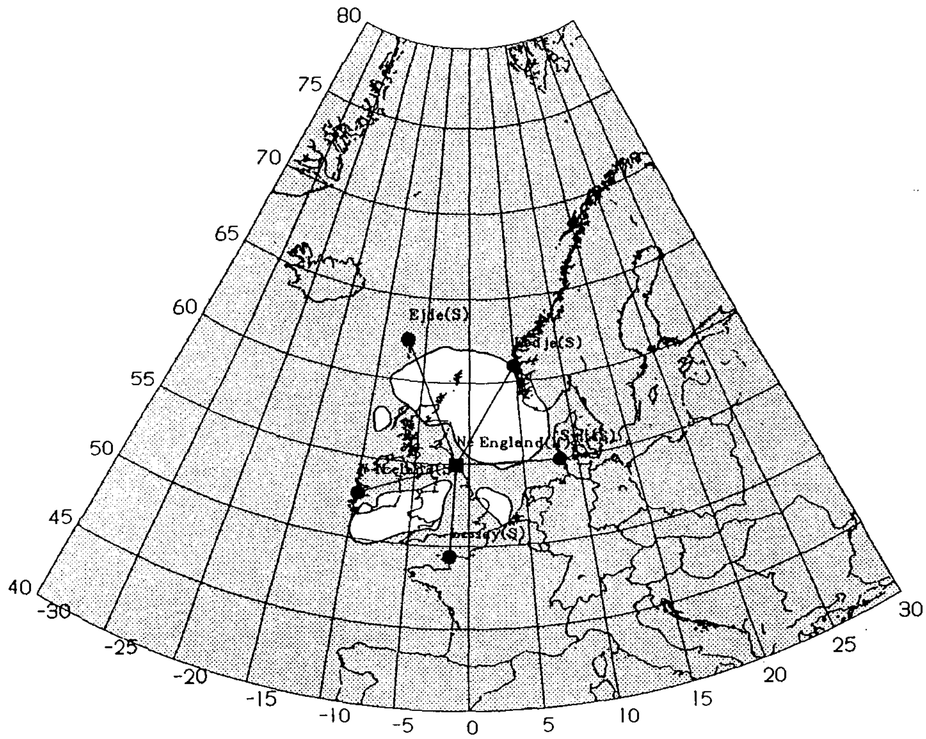

Fig.8 Coverage of proposed European Loran-C chain in the presence of CWI. GRI = 8000 and no notch filters are assumed.

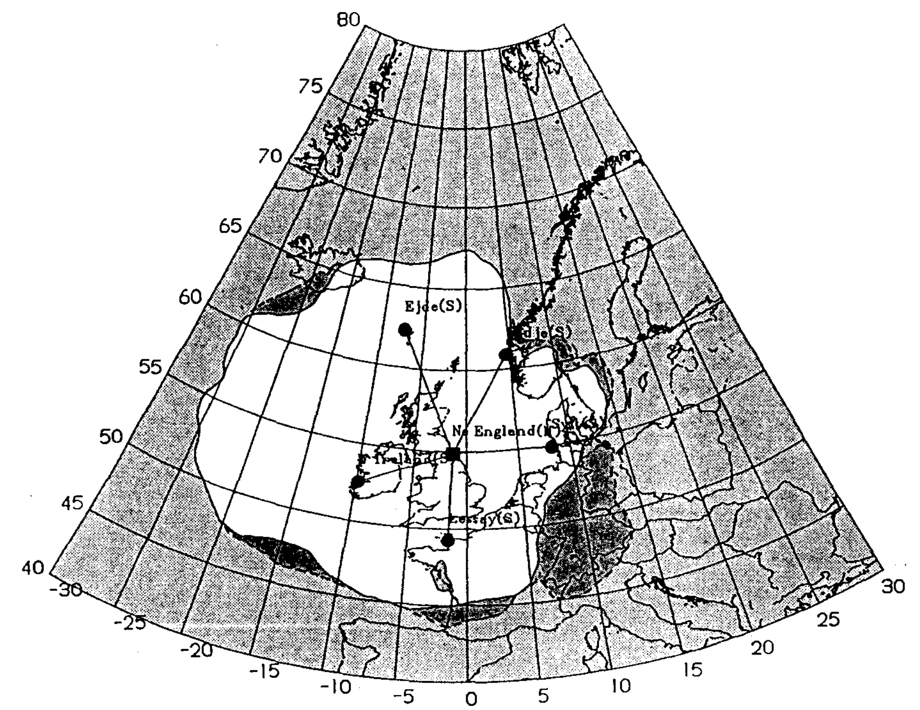

Fig.9 Coverage of proposed European Loran-C chain in the presence of CWI. GRI = 7777. The solid line shows the coverage without notch filters. The dotted line encloses the increased coverage area achieved when three automatic level sensitive notches are assumed.

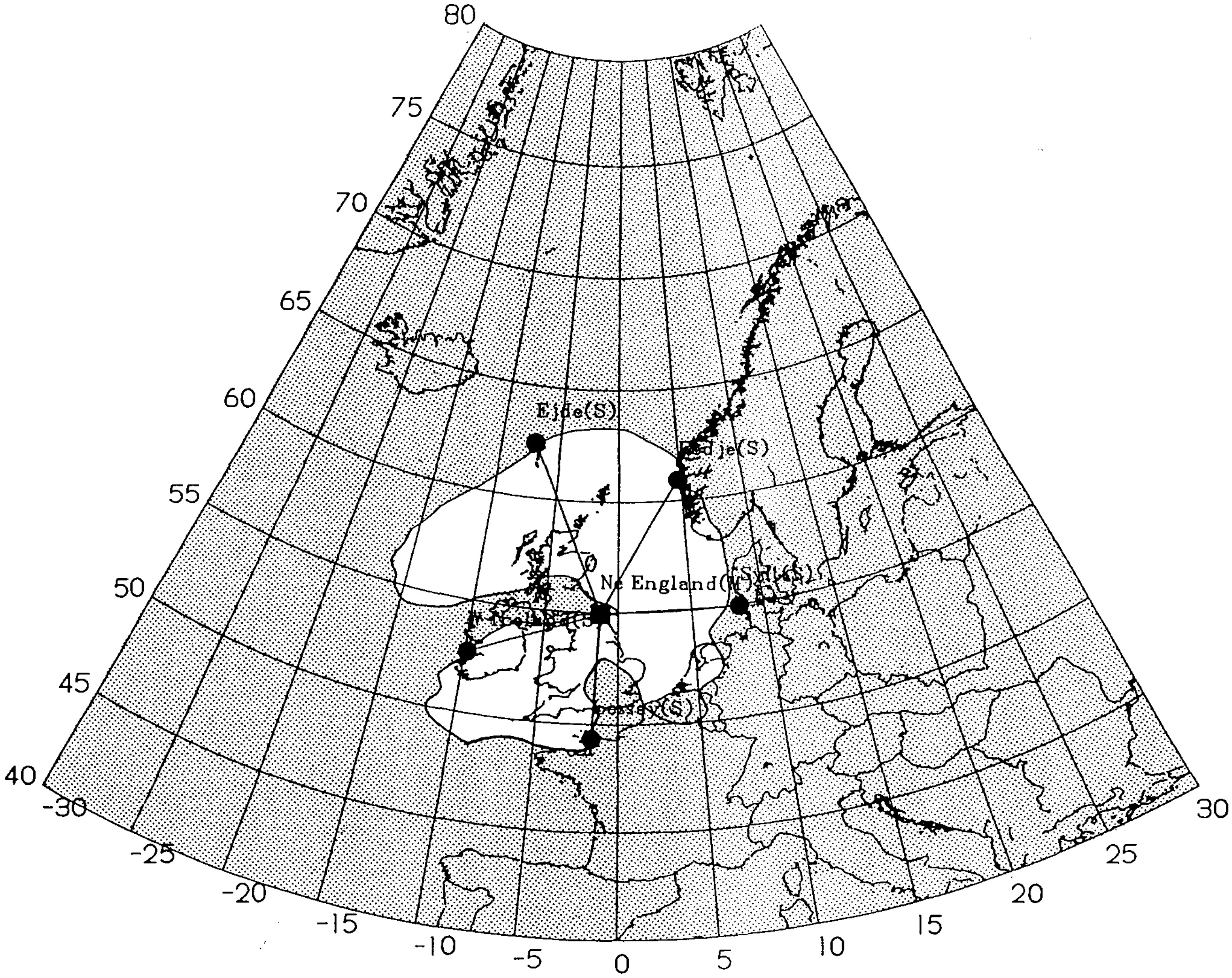

Fig.10 Coverage of proposed European Loran-C chain in the presence of CWI. GRI = 8000 and three ideally set notch filters are assumed.

6 Conclusions

The introduction of carrier-wave interference into coverage prediction is essential for use in Europe. Increasing the levels of atmospheric noise to 61dBμV/m has resulted in approximately correct coverage boundaries in the areas where the interference level is very high, but underestimates the coverage in regions such as the Atlantic, where no interferers exist.

The results shown here clearly illustrate the importance of intelligent GRI selection when Loran-C chains are to be used in the presence of interference. The coverage area gained by the introduction of notch filters has also been illustrated for the first time.

It has been demonstrated that by intelligent GRI selection and the use of a small number of notch filters the coverage limits can almost be increased to those introduced by atmospheric noise alone.

7 Acknowledgements

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Richard Farnworth graduated from the University of Wales, Bangor in 1988. He is currently working towards a Ph.D. on Loran-C coverage prediction techniques.

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

Dr. Mark Searle was awarded the degrees of B.Sc., M.Sc. and Ph.D. by the University of Manchester, England in 1985, 1986 and 1989, respectively. He is employed as a Post-doctoral Research fellow working on Loran-C studies, including coverage prediction and additional secondary factor mapping techniques, at the University of Wales, Bangor.

GETTING THE BEST OUT OF LORAN C

N. Ward

Trinity House Lighthouse Service, England

Loran C receivers can be designed to operate using a pair of stations from one chain and either one or two stations from another. The technique is well known, but has only recently become available to the ordinary user. It can considerably extend Loran C coverage, increase accuracy by improving geometry and provide redundancy in the event of system malfunction. This paper describes the method of fixing and gives the results of trials carried out. Predictable accuracies of a few tens of metres have been obtained in areas well outside the coverage available to conventional receivers.

Introduction

Conventional Loran C receivers use the Master and two Secondary stations from a single transmitter chain, that is three stations with a common Group Repetition Interval (GRI). More sophisticated receivers can operate in cross-chain mode, using a Master-Secondary pair from each of two chains. This can provide increased coverage in areas between two chains and improved accuracy in areas where the geometry of the single chain configuration is poor. There is a third mode of operation, known as semi-circular or pseudo-secondary which can provide further increases in coverage and accuracy by using a Master-Secondary pair from one chain and a single Master or Secondary from another. This technique has been used in some specialised receivers in the past, but is now available in low-cost equipment for the general user.

Theory

The conventional hyperbolic mode of Loran C uses three transmitters, the Master and two Secondaries with a common GRI, producing intersecting hyperbolic lines of constant time difference. This solution is self-contained, the timing of each Secondary is measured relative to the Master, the differences in emission times are recorded in the receiver's memory for that particular GRI. Coverage of a particular chain is limited either by signal strength or by the geometry of the stations. The need to receive the Master transmissions and to include the Master in any triad of stations restricts the usable area of the chain.

The cross-chain solution requires the receiver to deal with two GRIs at once, but the time differences are still between the Master and Secondary of each chain. This mode of operation can improve coverage in an area between two chains.

The semi-circular mode derives its name from its superficial similarity to true circular, or range-range mode, however it is actually a hyperbolic solution, using one Master-Secondary pair and one station from another chain in a pseudo-Secondary role. This is possible because all Loran C Masters are synchronised to Universal Coordinated Time (UTC) to within 2.5 us. A phase difference measurement can therefore be made between two chains to within +/- 5us. The drift rate of this artificial synchronisation is approximately 10m per 24 hours. A mobile in a position known to within 15 nautical miles can establish this synchronisation and maintain accuracy within 70m for a period of up to 10 days. Since most users will return to a known point within such a period this drift rate is not a problem. An example of an area where this mode of operation provides a large increase in coverage is the Southern U.K., as shown in Fig 1.

Practical Example

A Loran C receiver with the pseudo-secondary capability was fitted to a fishing vessel in Cowes, Isle of Wight, England. The receiver was interfaced to a track plotter. The M-W pair of the 7970 Norwegian Sea chain and the Master transmitter of the 8940 French chain were selected. The receiver was initialised for its known position alongside the wharf, then the vessel was taken round a number of buoys, returning to the same position alongside. Fig 2 is a reproduction of the track plotter display, showing the buoys and the track followed according to the receiver. Table 1 shows the assigned positions of the buoys, the positions given by the receiver and the differences, which were generally less than .03 n. miles (50m). Considering that the scope of movement of buoys in the prevailing depth of water (10-20m) could be as much as 50m, it can be seen that the receiver gave absolute accuracies better than 100m.

Conclusions

It has been demonstrated that pseudo-secondary operation can provide very good performance in areas well outside the conventional coverage limits. This enhancement can be provided by relatively low-cost receivers, suitable for fitting to small boats or light aircraft.

Author's Biography

Dr Nick Ward is Principal Development Engineer at Trinity House, the Lighthouse Service for England and Wales. He is also responsible for managing R & D on behalf of the Northern Lighthouse Board in Scotland and the Commissioners of Irish Lights in Ireland. He is Secretary of the International Association of Lighthouse Authorities Committee on Radionavigation Systems and has worked closely with the N.W. European Loran C project.

Table 1

	Assigned Position	Loran C Position	Difference (n.miles)
East Cowes (start)	50,45.47N 01,17.34W	50,45.47N 01,17.47W	<0.01 (corrected)
East Lepe Buoy	50,46.08N 01,20.82W	50,46.08N 01,20.75W	0.03
West Lepe Buoy	50,45.20N 01,24.00W	50,46.20N 01,24.01W	<0.01
Hampstead Ledge Buoy	50,43.83N 01,26.10W	50,43.83N 01,26.20W	0.06
East Lepe Buoy	50,46.08N 01,20.82W	50,46.09N 50,46.09W	0.02
Gurnard Buoy	50,46.18N 01,18.75W	50,46.20N 01,18.78W	0.02
East Cowes (finish)	50,45.47N 01,17.34W	50,45.48N 01,17.33W	0.01

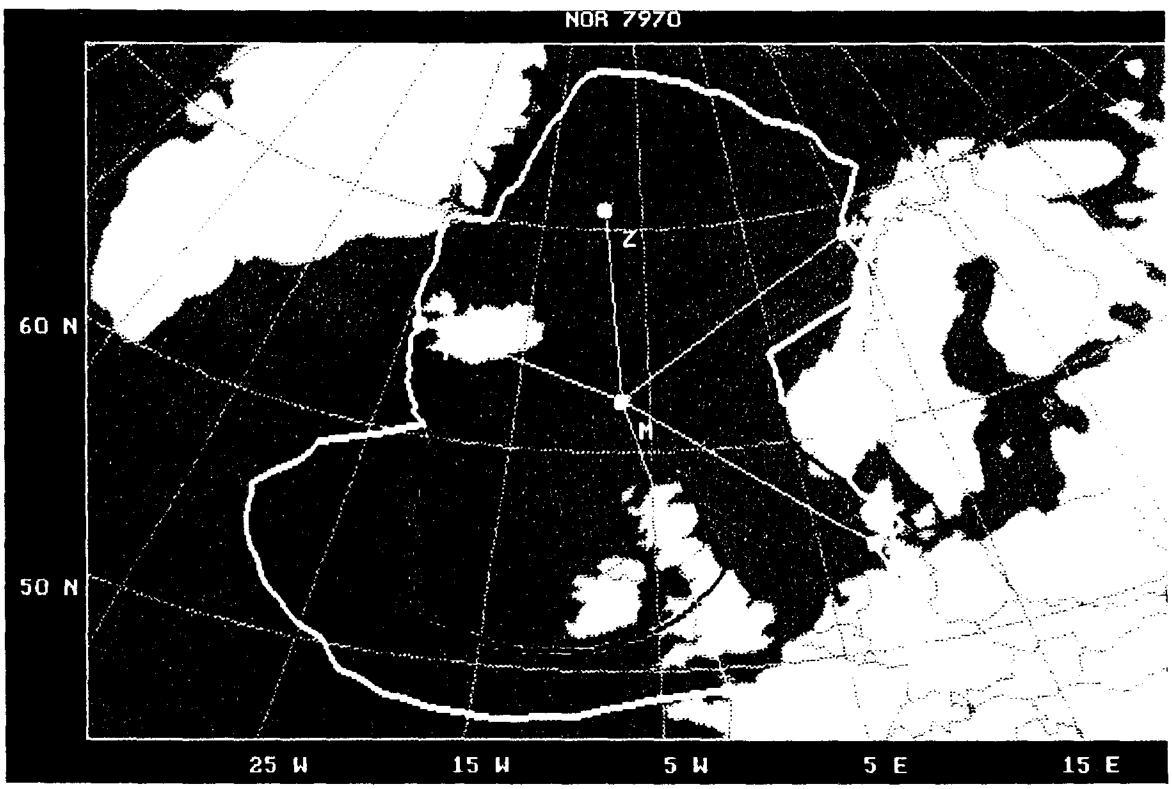

Figure 1 Single chain and pseudo-secondary coverage in UK waters

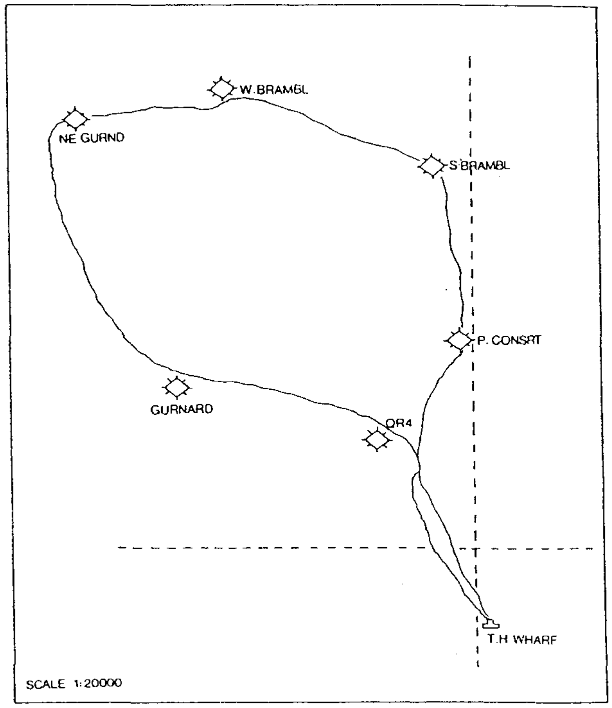

Figure 2 Track plot from Loran C receiver operating in pseudo-secondary mode

Notes on the Computation and Use of Atmospheric Signal-to-Noise Ratio in Loran Receivers

J. V. Carroll

Center for Navigation
John A. Volpe National Transportation Systems Center
Cambridge, Massachusetts

Abstract

This paper addresses the effect atmospheric noise and signal-to-noise ratio (SNR) on the performance of Loran receivers. An estimate of SNR is computed by the receivers as part of the process of assessing the adequacy of the Loran navigation solution. A fuller understanding of how atmospheric noise affects receiver performance is becoming more critical, as many Federal transportation agencies have committed to the use of Loran, and must set safe yet realistic operational procedures. A Loran noise laboratory with unique analysis capabilities has been established at VNTSC which can simulate Loran signals and atmospheric noise models, including the FAA benchmark model used in the certification of airborne Loran receivers. These signals are input in real time to the receivers, thereby providing a controlled signal and noise environment.

1. Introduction.

The Volpe National Transportation Systems Center is currently analyzing receiver performance by digital and real-time simulation, and by studying actual Loran signal-to-noise ratio (SNR) data measured by a suite of three unique receivers at several airports. This paper is intended in part to be a response to some operational issues which have recently arisen among the airnav community regarding the interpretation of SNR measurements.

Atmospheric noise is computed in the Loran receivers using one of several possible techniques. In addition, noise sensitivity of the receivers is established by calibration with respect to a standard specified by the FAA. In view of results from recent flight tests of Loran equipment, it is also necessary to examine the relationship of the FAA atmospheric noise model to actual atmospheric noise in a standard, controlled environment, so that actual receiver performance is optimized. VNTSC is currently establishing a simulation and test facility to assess Loran receiver performance under controlled conditions.

2. Atmospheric Noise - Background

The Loran signal-to-noise ratio is defined as the ratio of the rms (root mean square) value of the Loran signal at the third cycle crossing of the Loran pulse, to the rms value of the atmospheric noise. Computing and/or estimating the SNR is not straightforward. Manufacturers develop their own methods for computing SNR independently, and art is nearly as much a part of the design process as science. Since atmospheric noise is a major factor in the ability of a Loran receiver to navigate, it is very important to understand its effect on receiver performance.

The amount of noise (undesirable signals which "corrupt" the signal of interest) directly affects Loran receiver acquisition and tracking performance, as well as receiver integrity. Regarding integrity, unacceptably high noise levels add to the time it takes a receiver to determine if the Loran signals are suitable for navigating. The FAA has set an integrity limit of 10 seconds for nonprecision approaches (NPA), that is, an IFR approach in which the navigation aid does not supply glide slope (altitude) information. There is a related requirement that approved airborne receivers must "flag" an alarm whenever the SNR level becomes worse (falls below) -6 dB. Because there should be a direct correlation between SNR and integrity, and because the receivers are known to compute different SNR readings for the same conditions, it therefore follows that a fixed value such as -6 dB is not an appropriate threshold for all receivers, in all conditions. One of the goals of our work at VNTSC is to resolve this issue.

While there are several contributors to

receiver noise, atmospheric noise dominates other noise sources, and typically is difficult to predict or measure. This is especially true in certain weather conditions such as thunderstorms.

As stated above, the FAA has developed standards and performance requirements to which a certified Loran receiver must conform. As work continues in incorporating Loran into the National Airspace System (NAS), it is becoming clear that portions of the requirements and standards need to be clarified, augmented, modified, eliminated, and/or replaced.

The central issue being addressed by the VNTSC SNR project is:

> Are the navigation capabilities of today's commercial Loran receivers being fully exploited, or should more realistic requirements be developed which would result in more optimal performance?

An illustration of the importance of resolving this issue occurred recently, when a Bendix-King KLN-88 was being flight-tested for nonprecision approaches in Louisiana. Low SNR warnings were being flagged to the point of pilot distraction, and yet the receiver seemed to be navigating adequately. Because of such incidents the following questions must be addressed:

> Are SNR values being generated accurately?
>
> Do "accurate" SNR values correlate to receiver performance at or near current operational thresholds?
>
> What guarantee is there that a receiver which meets FAA standards on noise will perform better than a receiver tuned to some other standard?
>
> How should Loran procedures be developed or changed to reflect properly the Loran receiver's capabilities in different weather and atmospheric noise conditions?

Part of the approval process for a Loran receiver is that it must be certified to FAA standard TSO-C60b. If receivers are designed to perform optimally in the atmospheric noise environment modeled according the TSO-C60b, they may or may not work well in real atmospheric conditions. Feldman (1972) and others (e.g., Spaulding and Washburn, 1985) show rather convincingly that atmospheric noise is a more complex phenomenon than is evident in TSO-C60b. It is necessary to keep in mind, however, that despite its relative simplicity, TSO-C60b may be adequate in establishing performance thresholds.

The TSO-C60b standard includes an atmospheric noise model (hereinafter called the "FAA model"). Like most models, certain assumptions are made in order to simplify analysis and/or representation of the process being modeled. It is therefore necessary to validate the model somehow against real atmospheric noise. We are not aware of any comprehensive study which does this for atmospheric noise near the Loran frequency.

There is a need to construct a noise database as comprehensive as the CCIR model[1], but centered around the Loran frequency. Enge (1991) has done an overview analysis of the properties of the FAA model. In Enge's study, some basic limitations of the model were identified and analyzed, as well as some of its strengths. Although it is a reasonable engineering model, it is constricted by many fixed parameters, and cannot therefore simulate the wide variety of noise environments experienced in the field.

It is now necessary to conduct controlled, repeatable experiments on the adequacy of the FAA model, using commercially available Loran receivers. This paper will report on the progress of these efforts at VNTSC.

Historically TSO-C60b noise has been very difficult to simulate in the laboratory in real time. As a consequence, many manufacturers of airborne Loran receivers calibrate them to a gaussian noise standard, and not directly to the FAA model. Technology is now at hand, however, to simulate the FAA noise model rather straightforwardly with commercial equipment. Of significance is the fact that other noise models can just as easily be simulated using the new facility, so that better performing alternatives to the FAA model - if they exist - may be developed.

The next section presents certain technical issues related to noise thresholds in Loran receivers, and Section 4 summarizes the results of this paper.

3. Atmospheric Noise and Loran Receivers.

The following features regarding atmospheric noise will be addressed:

[1]Established by the International Radio Consultative Committee (1964).

Significance of the 8 dB shift which relates the FAA noise model to gaussian noise

Use of the statistical variance of measured SNR data, including: (i) Deterministic component of "random" SNR variance; (ii) Significance of the 95% confidence band; (iii) Should a "persistence factor" be defined?

Policies and Procedures Issues

3.1. Significance of the 8 dB Shift. The 8 dB shift is a fixed adjustment to measured noise or SNR whose purpose is to account for the difference between gaussian and atmospheric noise. In a sense, it is the critical number in defining the TSO-C60b atmospheric noise model, as will be shown below. It also appears to be widely used in industry as a corrective factor for computing SNR in those receivers which have been calibrated to gaussian noise.

The actual value of this adjustment varies greatly with both atmospheric conditions and noise power level (Feldman, 1972). Depending on these factors, a more realistic shift may be other than 8 dB - and any value selected may change significantly within hours[2].

For obscure historical reasons, then, 8 dB was selected to represent in a gross manner the difference between atmospheric noise (modeled by TSO-C60b) and its gaussian component. If the quantity A stands for the rms value of the total noise and X is the rms value of its gaussian component, we have

$$X_{dB} = A_{dB} - 8$$

Since noise is primarily measured in units of power, the above is equivalent to:

$$20\log_{10}(X) = 20\log_{10}(A) - 8$$

The inverse log is:

$$X = \frac{A}{2.5118864} = 0.3981072A$$

which squares up to

$$A^2 = 6.309X^2$$

This equation gives the ratio of total (atmospheric) noise power, A^2 , to the power of its gaussian component, X^2 .

The non-gaussian component of atmospheric noise in TSO-C60b models the lightning bursts. From the above equation, we can see that this component is 5.3096 times the gaussian power:

$$A^2 = X^2 + 5.309X^2$$

The ratio 5.309 was derived in TSO-C60b from another perspective. It is clear from the above development that the value for this ratio is valid only under the assumption of a fixed 8 dB difference between the gaussian and total noise components. This shift is therefore inherent in the FAA model, as was claimed above.

The FAA model for the non-gaussian, impulsive component of the noise is a series of 30 μsec wide pulses of 100 kHz, with an rms value per pulse of $A_{imp}X$, where A_{imp} is the (fixed) relative amplitude of the 100 kHz pulse, and X is as defined above, the rms value of gaussian noise. As stated in TSO-C60b, this definition and the ratio 5.309 mean that 84.15% of the atmospheric noise power in the FAA model is due to the impulsive component, since

$$\frac{5.309}{1+5.309} = 0.8415$$

Similar development, as done in TSO-C60b, shows that the value for A_{imp} , the amplitude of the 100 kHz pulse relative to the rms gaussian, is about 60.

It should be noted that many researchers feel that fixing the impulsive amplitude is overly restrictive, since it is a very unrealistic representation of multiple

[2] Feldman (1972) defines three basic weather/noise conditions: "quiet", "tropical" and "frontal". Quiet is closest to gaussian (it thus has the smallest shift), and frontal conditions produce the severest noise (squalls, thunderstorms).

lightning bursts[3]. We have just seen, however, that relaxing the fixed amplitude assumption of the impulsive noise component would render the (fixed) 8 dB shift totally meaningless.

The 8 dB shift is called a "noise scalar" in the RTCA MOPS. The MOPS then states that hard-limited receivers will perform in the laboratory at -2 dB gaussian noise the same as it would in the "real world" -10 dB environment. In the context of the above, this statement has the following interpretation: a hard-limited receiver essentially eliminates from the actual noise the non-gaussian, or impulsive component, leaving gaussian noise. Since the total noise is -10 dB, it is assumed that its gaussian component is -2 dB; so that when the non-gaussian part is filtered out, there is only the -2 dB of noise left which actually affects the receiver's navigating performance. The MOPS statement, therefore, is accurate only to the extent that TSO-C60b models "real" atmospheric noise.

To summarize: under the assumption that calibrating to TSO-C60b is appropriate, the designer need merely calibrate his hard-limited receiver to gaussian noise. To find the gaussian component in the field, it is only necessary to subtract out 8 dB from the dB noise reading. Conversely, since noise is in the denominator of the SNR parameter, the 8 dB is added to the actual SNR reading to get the gaussian SNR component of the dB noise. The 8 dB shift is therefore a way to determine the gaussian component of a noise or SNR reading under the assumption that the measured noise conforms in critical aspects to the TSO-C60b model.

Digital simulations which vary the ratio of the impulsive component of the FAA model to the gaussian component, from 0 (gaussian) to 5.309 (FAA model) confirm these results. The simulation uses 2000 trials, which is equivalent to the processing capability of Loran receivers over about 20 seconds of real time. Also, fewer trials result in overly noisy test statistics and errors in the SNR estimation. Figure 1 shows the progression to the left as the impulsive component - and total noise - increases. The full shift is about 8 dB to the left of the gaussian curve.

3.2. Use of the Variance of the Data. Current FAA policy is now consistent with standards accepted by other navigation organizations in that the ensemble mean is the primary statistical quantity used in the performance requirements which relate to Loran operation. As procedure development evolves to a more complicated level, there is a move by some FAA organizations to add "confidence bands" and other variance-related parameters to these requirements. Before doing this, it is very important to understand more completely some underlying principles - and also to use the statistics appropriately.

Deterministic Component of Variance. The Loran signal is affected by predictable (hence, deterministic) diurnal influences (cf., 24-hour SNR plot, Figure 2). If 2σ or similar confidence bands are to be established, the statistical variance, σ^2, should not include the diurnal component. If the latter is assumed to be a sinusoid (period of 24 hours) of amplitude A, then

$$\sigma^2 = A^2/2$$

should be excluded from any confidence band.

The diurnal effect on the ensemble mean is zero if the data are processed modulo 24 hours. If other time intervals are used, the improper variance would in general produce misleading results.

Significance of the 95% Confidence Band. The variance is a measure of how often a particular data point will fall within a certain distance of the ensemble mean. For gaussian statistics, a popular confidence interval is the $2\text{-}\sigma$ band, which means a band whose border is twice the standard deviation from the mean. Using the gaussian probability distribution, it turns out that about 95% of the gaussian random variables sampled will fall within 2σ of the ensemble mean (Figure 3). It follows

[3] The other major difficulty with the FAA model is its basic assumption that the "arrival" times of the lightning bursts are sequenced in a Poisson distribution. It is well known, however (Feldman, 1972; Spaulding and Washburn, 1985), that actual lightning bursts are time-dependent events which cluster, whereas the Poisson sequence is a series of statistically independent events.

naturally that a sample will fall outside of this band about 5% of the time.

It is incorrect to state (as has been done) that establishing a minimum operational threshold for SNR at -6 dB less 2σ is equivalent to having SNR values above the -6 dB threshold 95% of the time. There are two problems with this reasoning:

(i) It assumes gaussian statistics, which is not necessarily true of the atmospheric noise phenomena; and,

(ii) As Figure 3 clearly shows, random variables falling outside the confidence band do so symmetrically above and below the band. For gaussian statistics, 95% of the SNR samples can be expected to be above the lower band threshold if a 90%, and not a 2σ (95%) confidence band is used.

Item (ii) says that for a 2σ band, half of the points which fall outside the band (that is, is 2.5% of the total) will be more than 2σ above the mean, due to the symmetry of the gaussian density function. These SNR points are naturally of lesser concern. Using a 90% confidence band means that 10% of the samples will be outside it, and under gaussian statistics, we expect that 5% will fall below the mean, and the other half above the mean. Therefore, under gaussian statistics a 90% confidence band will statistically ensure that 95% of the sampled data will fall above the lower threshold of the band. The significance of this is that a larger variance than allowed under the proposed FAA rule would actually meet the intended performance requirement - or, stated differently, a 5% requirement on allowed "bad" points" also allows a lower ensemble mean under gaussian statistics (Figure 4). Operational considerations may result in requiring a 95% confidence band in any event, for an added safety margin.

Should a "Persistence Factor" be Defined? Another aspect of using a 95% or similar threshold requirement on SNR data relates to "persistence" - i.e., How should the allowable 5% "bad" data be distributed among the good data? For example, if noise bursts or similar impulsive noise phenomena are relatively isolated, would a Loran receiver even "see" it? This issue must be examined under controlled conditions, but it seems unlikely that data structured like this example would interrupt Loran tracking, even if the bad points were somewhat below the threshold. There seems therefore to be a need to quantify a persistence factor as part of the performance requirements.

3.3. Policies and Procedures Issues.

1.) The introduction of automatic aviation blink should alleviate the need for tightening current Loran NPA performance requirements. Since this should occur within a year, should any of the basic operational or performance requirements be changed prior to automatic blink?

2.) Analysis of Loran data gathered at several airports so far is that the actual measured SNR value can vary greatly from one receiver to the next (Figure 2). { delete this Figure reference if Fig 2 doesn't show 3 receivers } There is therefore a need to establish a common aviation performance evaluation process, so that these receivers can be calibrated against a uniform and consistent standard. VNTSC has begun to develop a calibration laboratory at its Cambridge facility.

3.) There is obvious merit to the desire within some FAA branches to tighten requirements. The motivation seems to be to accommodate some effects which aren't directly related to atmospheric noise, but which Loran receivers may not distinguish. An example is p-static electricity, which builds up on the skin of an aircraft flying through the atmosphere.

4.) VNTSC recommends that current standards be held, or at least not made more restrictive, until aviation blink is operational and until a more comprehensive look at the effects of atmospheric noise on Loran performance can be completed.

4. Summary

VNTSC has initiated a project to determine the effect of controllable atmospheric noise environments on the performance of Loran receivers. This effort was undertaken because of concerns within the air navigation community that more standardization of performance metrics and criteria is needed. This paper discusses some of the issues related to consistent use of the SNR parameter, and issues cautionary advice to those who may be too eager to use or interpret certain statistics on Loran data.

The overwhelming acceptance of Loran by general aviation pilots strongly supports making Loran approved as a secondary navigation aid for NPA as soon as possible. Taking such a course right now, with no changes or delays, is safer than delaying, and thereby denying Loran to several facilities where there is no other instrumented coverage. Details of the operating procedures can be resolved as more analysis is done.

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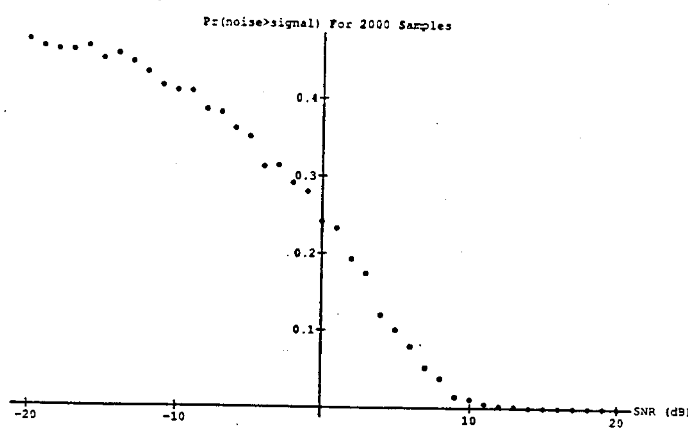
Biography

James Carroll has been a Senior Project Engineer at the DOT Center for Navigation at VNTSC in Cambridge, Mass. for the past year and a half. 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.



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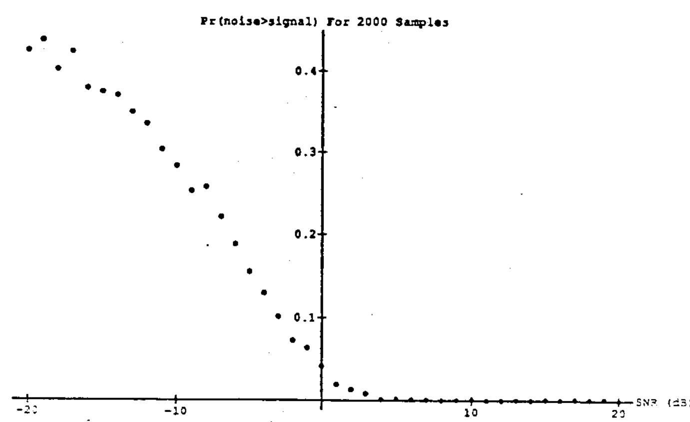

(B) Power Ratio = 5.3

FIGURE 1. SIMULATED RATE AT WHICH NOISE EXCEEDS SIGNAL

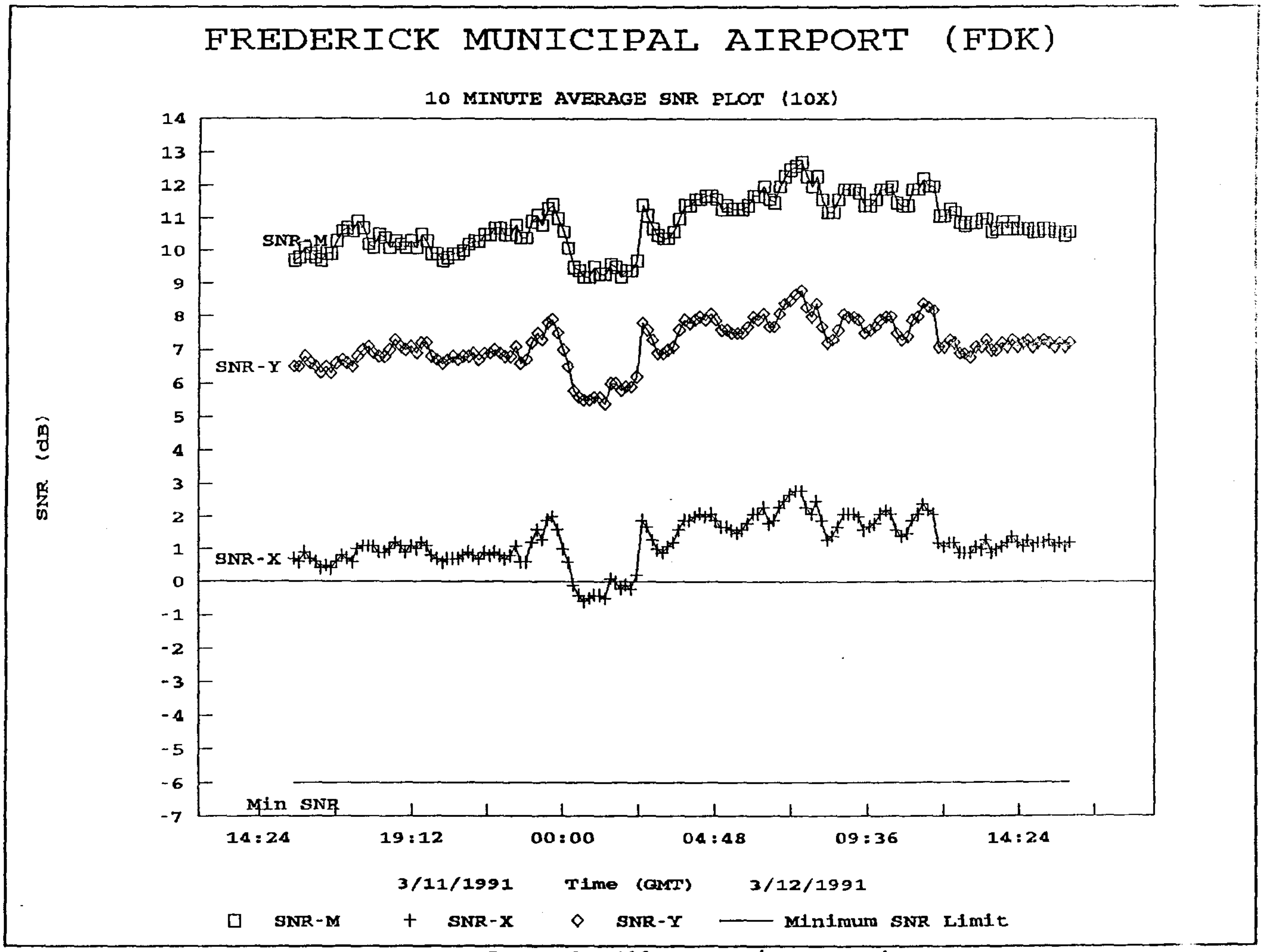

Figure 2. **SNR PLOT (10X LORAN/GPS receiver)**

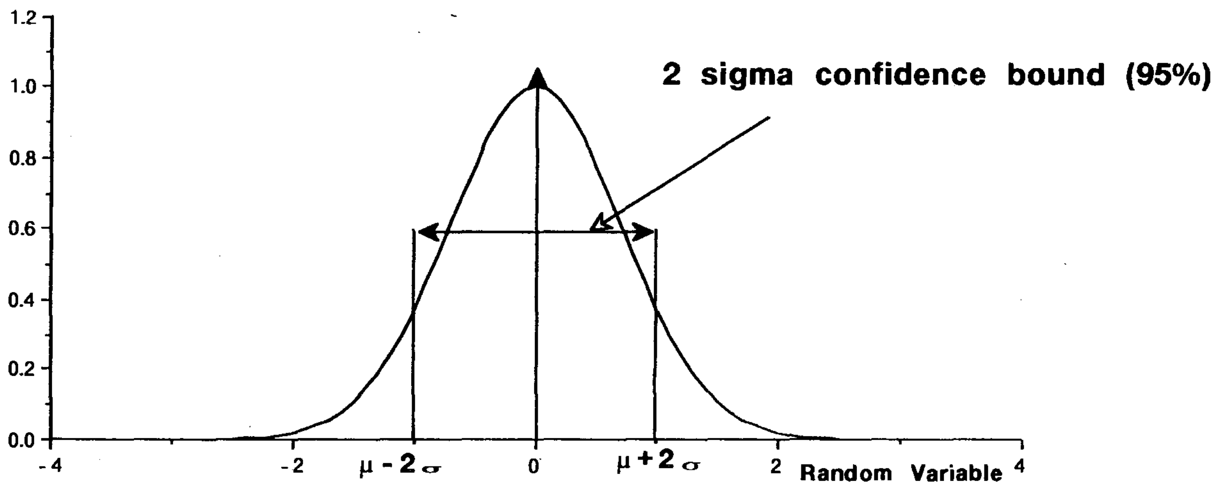

Figure #3

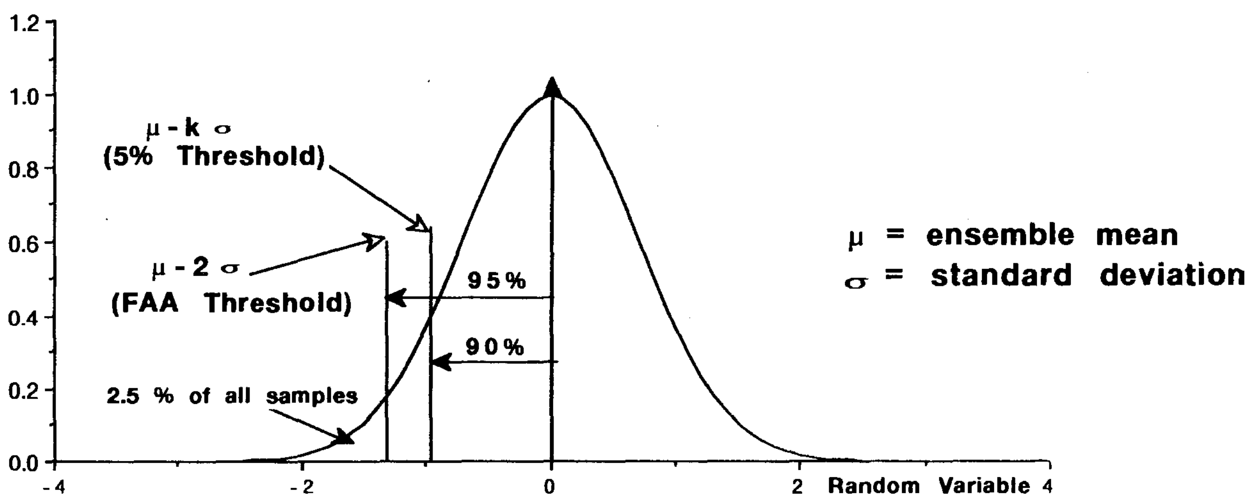

Figure #4

Session 5
PROPAGATION AND SIGNAL ANALYSIS

Chairman: Dr. Robert H. Miller, *II Morrow, Inc.*

Bob got his B.S. from West Point in 1958 and attended Penn State from 1964 to 1968 where he earned his M.S. and Ph.D. degrees. He served in the U.S. Army until his retirement in 1979 when he joined Kaman Tempo, a division of Kaman Sciences Corporation. It was at Kaman Tempo where Bob began his involvement with loran and other navigation systems. In the loran area, Bob directed a Coast Guard sponsored effort to calibrate the Gulf Coast and Southeast U.S. chains from aboard the Coast Guard Cutter *Ingram*. He also directed a loran program involving the autonomous flight of an unmanned vehicle using loran for navigation. In 1987 he left Kaman Tempo to become Research and Development Manager at II Morrow in Salem, Oregon. Still with II Morrow, now a subsidiary of United Parcel Service, Bob is the Chief Systems analyst in the Planning and Support Division and is still heavily involved in loran matters.

Bob revitalized the Goose Gazette in 1986 and published quarterly editions through 1988 when the editorship was handed over to Bob Lilley. He has been the Technical Chairman for two previous WGA Annual Technical Symposia.

Papers

LORAN-C SIGNAL ANALYSIS IN THE LOWER ST. LAWRENCE USING A MOBILE GPS SYSTEM

B. Townsend
G. Lachapelle
Department of Surveying Engineering, The University of Calgary
2500 University Dr. N.W., Calgary,Alberta, T2N 1N4

D. Hains
Canadian Hydrographic Service (Québec Region), Institut Maurice-Lamontagne
Fisheries and Oceans Canada, 850, Route de la Mer, P.O. Box 1000, Mont-Joli, Québec, G5H 3Z4

ABSTRACT

Loran-C signal performance along the Lower St. Lawrence, between Québec City and Gaspé on the south shore and Havre Saint-Pierre on the North Shore, were analysed using LORCAL[2], a mobile Loran-C coverage validation and calibration system consisting of analog and digital Loran-C equipment and a GPS system. The first series of road measurements conducted during March 1991 are presented herein. Signals were received from the following three chains: Canadian East Coast Chain (5930), Northeastern U.S. Chain (9660), and Labrador Chain (7930). The Loran-C Time Differences (TDs) were calibrated along some 1800 km of roads using GPS. A preliminary analysis of the following measurements is presented: TDs and T D distortions, Signal-to-Noise Ratio (SNR), Field Strength (FS), and Envelope-to-Cycle Differences (ECD). Preliminary conclusions pertaining to Loran-C coverage and performance in the area are presented. Plans for future work are outlined.

INTRODUCTION

This paper constitutes a progress report of Loran-C investigations being sponsored by the Canadian Hydrographic Service (Québec Region) in the Lower St. Lawrence area as shown in Figure 1. The overall objective of the project is the performance analysis and calibration of Loran-C in the above area under a wide range of climatic conditions and atmospheric noise present in Winter and Summer and mixed land-sea path conductivity variations typical of Loran-C in the above area. This performance analysis and calibration procedure will hopefully result in a greater understanding of Loran-C propagation effects under the above conditions in the Lower St. Lawrence area and in more reliable and more accurate Loran-C navigation for marine users in that part of the river.

The three Loran-C chains available over all or parts of the above area are listed and shown in Figure 1. All transmitters belonging to these three chains were available at least in parts of the area surveyed, except for Angissoq (Labrador Sea Chain) located on the southern tip of Greenland.

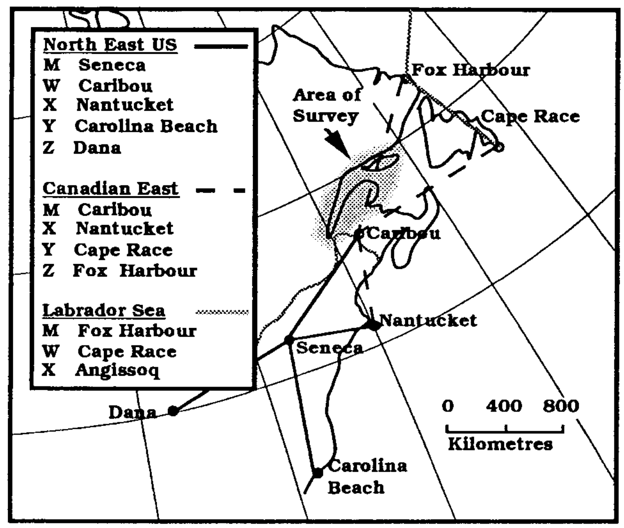

Figure 1: Loran-C Chains available in the Lower St. Lawrence Area

METHODOLOGY

Two field measurement campaigns were conducted during the winter and summer 1991, respectively. The winter campaign, which is reported in this paper, was conducted in early March along the land roads shown in Figure 2. In this figure, the roads surveyed are subdivided into segments of up to about 200 km for analysis purposes. The North Shore part consists of some 900 km of road, including some 200 km up and down the Saguenay River. The South Shore part also consists of some 900 km along the St. Lawrence and around the Gaspesia Peninsula to Restigouche. Each of the above routes were observed twice to provide an adequate quality control of the results. The observations were taken during two periods each day when the GPS satellite coverage was sufficient to have an Horizontal Dilution Of Precision (HDOP) ≤ 7. These two periods were approximately between 800 and 1200 and 1600 and 2100, respectively.

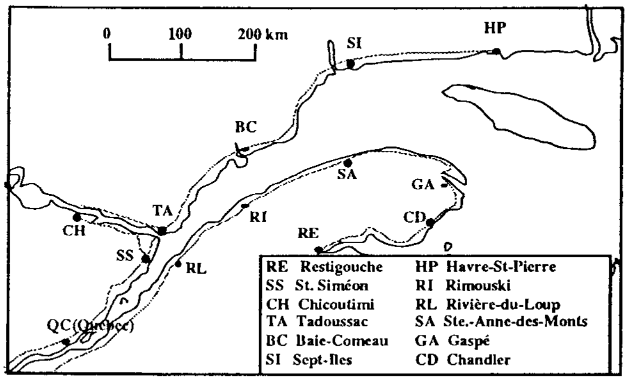

Figure 2: Land Roads Observed During the Winter '91 Campaign

The following measurements were made with the LORCAL[2] system [Lachapelle & Townsend 1991] of The University of Calgary at intervals of 30 seconds to provide the continuous profiles required for a thorough analysis of Loran-C signals:

- Loran-C Field Signal Strength
- Signal-to-Noise Ratio (SNR) of the incoming Loran-C signals
- Loran-C Time Differences (TD's)
- Envelope-to-Cycle Differences (ECD)
- Single Point and Differential GPS positions

The LORCAL[2] system configuration used during the winter campaign is shown in Figure 3. Each one of the three single-chain receivers used was dedicated to one of the three chains available in the area as shown in Table 1, 2 and 3, respectively. The error budget of the system is estimated as follows: (1) internal Loran-C receiver noise, ≤ 10 m, (2) dynamic effects, ≤ 50 m, (3) effect of GPS time synchronization error, ≤ 5 m, (4) single point GPS, 20 - 40 m, 2 drms, HDOP ≤ 7, with Selective Availability off during winter 91, and (5) differential GPS, 5 - 10 m. The system was tested in a mountainous area north of Vancouver, B.C., in early winter 91. TD distortions were relatively large, namely several hundred metres over distances of less than a few km. Such an area was well suited to evaluate the repeatability of the system. Comparisons of forward and backward runs resulted in an agreement of about 50 m in DGPS mode [Lachapelle et al. 1991]; this accuracy level is consistent with the above estimates.

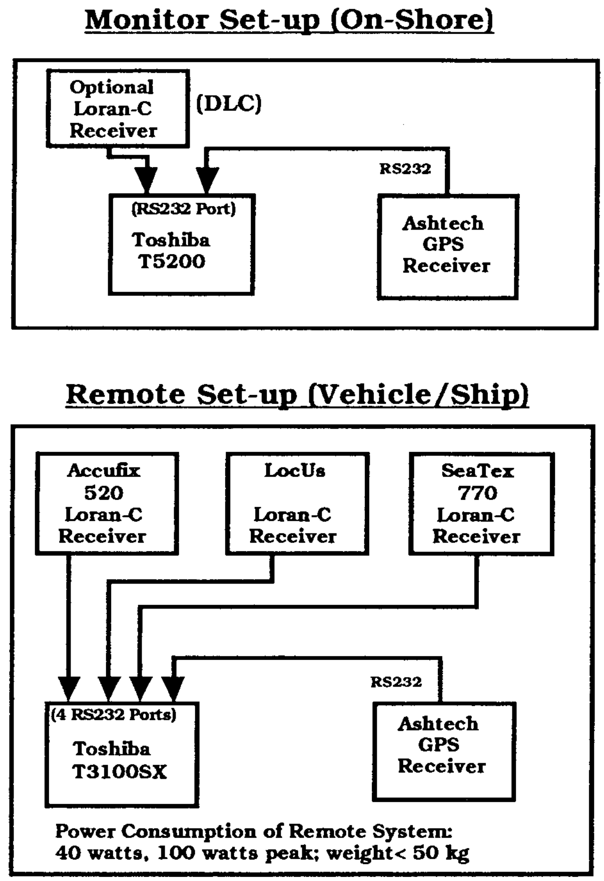

Figure 3: LORCAL[2] System Configuration

RESULTS AND PRELIMINARY ANALYSIS

The parameters examined during the preliminary analysis conducted up to now include SNR and SNR variation along the routes selected, the field strength (FS), the Envelope-to-Cycle Differences (ECD) and the Normalized Time Differences (NTD). The latter value is define herein as

$$NTD = TD_{Loran\text{-}C} - TD_{GPS}$$

where TD_{GPS} is the time difference calculated using the single point GPS fixes and the RF wave propagation velocity in vacuum, and $TD_{Loran\text{-}C}$ is the time difference observed by the Loran-C receiver. The primary, secondary and additional secondary phase lags due to tropospheric refractivity, sea conductivity and mixed land/sea conductivity were not removed from the $TD_{Loran\text{-}C}$s used to calculate the NTDs listed in the tables. Since single point GPS fixes were used to calculate the TD_{GPS}s , these are accurate to about 30 - 50 m (2drms, HDOP ≤ 7)

The ranges of the above parameters are given in Table 1, 2 and 3 for the Canadian East Coast Chain, the North East U.S. Chain and the Labrador Chain for each of the road sections previously identified in Figure 2, respectively. Preliminary findings which can be deduced from these tables are as follows:

Canadian East Coast Chain (5930):

- The SNR was generally $\geq$ -10 dB for M (Caribou), X (Nantucket) and Y (Cape Race). Reception of Z (Fox Harbour) was marginal except around the Gaspesia Peninsula. In the latter, reception likely benefitted from the recovery effect of the sea between Anticosti Island and the Peninsula. In the other areas, poor signal reception of Z was likely due to the relatively low conductivity along the continental propagation path, namely about 0.001 siemens m^{-1} [e.g., Hamilton 1987].
- The ECD variations within a 200 km road segment reached 5 μs. These observations are to be interpreted with caution as they were varying widely over relatively short distances and are considered unreliable at this time. Such variations are however within the ranges expected in view of the overland paths and rugged topography prevailing along some of the road segments, e.g., Saguenay area and Gaspesia Peninsula.
- The NTDs, which are due to the combined effect of the primary, secondary and additional secondary phase lags, reach 5 μs in some cases. The variations with a 200 km road segment reach 3 μs in the Gaspesia Peninsula. These are likely the result of a rapidly varying ASF which, in turn, is affected by the local topography.

Table 1: Summary of Loran-C Measurements - Canadian East Coast Chain (5930) [1]

Section of Road	5930 - M		5930 - X		5930 - Y		5930 - Z	
	SNR	FS	SNR	FS	SNR	FS	SNR	FS
QC - RL	> 10	> 75	2 ↔ 4	65 ↔ 70	-10 ↔ -5	45 ↔ 55	< -10	< 50
RL - RI	> 10	> 75	-7 ↔ 3	55 ↔ 65	-15 ↔ -5	50	< -10	40
RI - SA	> 10	> 75	-5 ↔ 3	50 ↔ 55	-5 ↔ 0	50	< -10	< 40
SA - GA	> 10	> 70	-5 ↔ 0	50 ↔ 60	-5 ↔ 0	50 ↔ 60	-10 ↔ -5	50
GA - RE	> 10	> 70	-5 ↔ 5	50 ↔ 60	0 ↔ 10	55 ↔ 65	< -5	< 50
QC - TA	> 10	> 70	-5 ↔ 10	50 ↔ 65	-15 ↔ -5	40 ↔ 50	< -10	< 40
SS - CH	> 10	60 ↔ 75	-10 ↔ 5	45 ↔ 55	< -10	< 40	< -15	< 35
CH - TA	> 10	> 70	-10 ↔ 5	45 ↔ 55	< -10	< 40	< -15	< 35
TA - BC	> 10	> 70	-5 ↔ 5	50 ↔ 60	-10 ↔ 0	40 ↔ 50	< -15	< 35
BC - SI	> 10	> 70	-10 ↔ 0	45 ↔ 55	-10 ↔ 0	45 ↔ 55	< -10	< 40
SI - HP	> 10	> 70	-10 ↔ -5	50 ↔ 55	-10 ↔ 0	50 ↔ 60	< -10	< 50
	ECD	NTD	ECD	NTD	ECD	NTD	ECD	NTD
QC - RL	-1 ↔ 1	--	-1 ↔ 1	1 ↔ 3	-1 ↔ 3	4 ↔ 5	--	--
RL - RI	-1 ↔ 1	--	-2 ↔ 1	2 ↔ 3	-1 ↔ 2	4 ↔ 5	--	--
RI - SA	1 ↔ 2	--	0 ↔ 2	2 ↔ 3	-1 ↔ 0	4 ↔ 5	--	--
SA - GA	1 ↔ 2	--	-1 ↔ 1	2 ↔ 3	-1 ↔ 0	3 ↔ 4	-4 ↔ 0	0 ↔ 2
GA - RE	-1 ↔ 1	--	-2 ↔ 2	1 ↔ 3	0 ↔ 2	0 ↔ 3	-4 ↔ 1	2 ↔ 1
QC - TA	-1 ↔ 1	--	-2 ↔ 1	2 ↔ 3	-2 ↔ 2	4 ↔ 5	--	--
SS - CH	-3 ↔ 3	--	-4 ↔ 0	2 ↔ 3	--	--	--	--
CH - TA	-4 ↔ -1	--	-4 ↔ -1	2 ↔ 3	-3 ↔ -1	4 ↔ 5	--	--
TA - BC	-3 ↔ -1	--	-4 ↔ -1	2 ↔ 3	-4 ↔ 0	4 ↔ 5	-3 ↔ -1	4 ↔ 5
BC - SI	-3 ↔ 0	--	-3 ↔ 1	2 ↔ 3	-3 ↔ 0	4 ↔ 5	-3 ↔ 1	3 ↔ 4
SI - HP	-2 ↔ 0	--	-3 ↔ 1	2 ↔ 3	-2 ↔ 2	3 ↔ 5	-3 ↔ 0	3 ↔ 4

SNR & FS (Field Strength) in dB
ECD & NTD (Normalized Time Difference) in μs
1 Using a LocUS Pathfinder Loran-C Receiver

North East U.S. Chain (9960):

- The SNR was generally ≥ -10 dB for M (Seneca), W (Caribou) and X (Nantucket). Reception of Y (Carolina Beach) and Z (Dana) was marginal due to the relatively large distances from these transmitters over overland propagation paths.

- ECD variations - same comments as for the Canadian East Coast Chain.

- Again, the NTD variations with a 200 km road segment reached 3 μs in the Gaspesia Peninsula. The reasons are likely the same as for the corresponding variations observed on the Canadian East Coast Chain.

Labrador Chain (7930):

- Only M (Fox harbour) and W(Cape Race) could be observed around the Gaspesia Peninsula. No direct measure of the SNR is available on the SeaTex receiver used. A cursory analysis of the NTDs indicate hovever that the quality of the data was acceptable. Obviously, a multi-chain Loran-C receiver would have to be used in the Gaspesia Peninsula for the single TD value observable to be useful for positioning.

Table 3: Summary of Loran-C Measurements - Labrador Sea Chain (7930)[3]

Section of Road	7930 - M		7930 - W		
	SNR	FS	SNR	FS	NTD
QC - RL	--	--	--	--	--
RL - RI	--	--	--	--	--
RI - SA	OK most of the time.				--
SA - GA	OK	OK	OK	OK	0 <> 1
GA - CD	OK	OK	OK	OK	-1 <> 0
CD - RE	--	--	--	--	--
QC - TA	--	--	--	--	--
SS - CH	--	--	--	--	--
CH - TA	--	--	--	--	--
TA - BC	--	--	--	--	--
BC - SI	--	--	--	--	--
SI - HP	OK most of the time.				--

SNR & FS (Field Strength) in dB
ECD & NTD (Normalized Time Difference) in μs
3 Using a SeaTex Loran-C Receiver

Table 2: Summary of Loran-C Measurements - Northeast U.S. Chain (9960) [2]

Section of Road	9960 - M		9960 - W		9960 - X		9960 - Y		9960 - Z	
	SNR	FS	SNR	FS	SNR	FS	SNR	FS	SNR	FS
QC - RL	0 ↔ 5	60 ↔ 70	5 ↔ 10	> 75	0 ↔ 5	> 75	< -10	< 50	< -10	< 50
RL - RI	-5 ↔ 5	55 ↔ 65	5 ↔ 10	> 75	-10 ↔ 0	> 75	--	--	--	--
RI - SA	-10 ↔ 5	50 ↔ 60	> 10	> 75	-10 ↔ 0	> 75	< -10	< 40	< -10	< 50
SA - GA	< -10	< 40	5 ↔ 10	70 ↔ 75	-5 ↔ 5	70 ↔ 75	--	--	--	--
GA - RE	< -5	< 50	> 5	> 75	-5 ↔ 5	> 75	< -10	< 50	< -10	< 40
QC - TA	-5 ↔ 5	45 ↔ 65	5 ↔ 10	> 70	-5 ↔ 5	> 70	--	--	< -10	< 40
SS - CH	< 0	30 ↔ 50	0 ↔ 10	50 ↔ 75	< 0	50 ↔ 75	--	--	-20 ↔ -5	< 50
CH - TA	-10 ↔ 0	30 ↔ 50	0 ↔ 10	60 ↔ 75	< 0	60 ↔ 75	--	--	--	--
TA - BC	-10 ↔ 0	40 ↔ 50	> 5	> 70	-5 ↔ 5	> 70	--	--	--	--
BC - SI	< -10	< 40	-5 ↔ 5	50 ↔ 70	< 0	50 ↔ 70	--	--	--	--
SI - HP	-10 ↔ 0	40 ↔ 50	5 ↔ 10	65 ↔ 75	-10 ↔ 0	65 ↔ 75	--	--	--	--
	ECD	NTD	ECD	NTD	ECD	NTD	ECD	NTD	ECD	NTD
QC - RL	0 ↔ 2	--	1 ↔ 2	-3 ↔ -2	0 ↔ 2	0 ↔ 1	0 ↔ 4	4 ↔ 6	1 ↔ 4	4 ↔ 5
RL - RI	-1 ↔ 1	--	0 ↔ 2	-5 ↔ -4	1 ↔ 2	-2 ↔ 0	--	--	--	--
RI - SA	-1 ↔ 1	--	-1 ↔ 0	-5 ↔ -4	-2 ↔ 2	-2 ↔ 0	--	--	--	--
SA - GA	0 ↔ 3	--	-1 ↔ 1	--	-1 ↔ 1	--	--	--	--	--
GA - RE	-1 ↔ 0	--	0 ↔ 2	-6 ↔ -5	0 ↔ 1	-3 ↔ -4	--	--	--	--
QC - TA	-2 ↔ 1	--	1 ↔ 3	-5 ↔ -4	1 ↔ 3	-3 ↔ -2	--	--	1 ↔ 2	4 ↔ 5
SS - CH	0 ↔ 5	--	-3 ↔ 3	-5 ↔ -4	2 ↔ 4	-3 ↔ -2	--	--	-2 ↔ 1	--
CH - TA	-2 ↔ 4	--	0 ↔ 3	-5 ↔ -4	0 ↔ 3	-2 ↔ 0	--	--	--	--
TA - BC	-2 ↔ 0	--	0 ↔ 2	-5 ↔ -4	0 ↔ 2	-3 ↔ -2	--	--	--	--
BC - SI	-2 ↔ 0	--	0 ↔ 3	-5 ↔ -4	0 ↔ 2	-3 ↔ -1	--	--	--	--
SI - HP	-1 ↔ 1	--	-1 ↔ 1	-5 ↔ -4	-1 ↔ 1	-3 ↔ -1	--	--	--	--

SNR & FS (Field Strength) in dB
ECD & NTD (Normalized Time Difference) in μs
2 Using a Megapulse Accufix 520 Loran-C Receiver

CONCLUSIONS

The method presented herein is effective to collect the data required for the analysis and calibration of Loran-C signals over large areas. A preliminary analysis of the results collected over some 1800 km of land road in the lower St. Lawrence region during March 1991 reveals a fairly constant signal availability along the roads measured and significant TD distortions in many areas, presumably due to ASF and topographic variations.

Further analysis of this data is being pursued to assess the effect of local atmospheric noise and conductivity using the SNR and field strength (FS) data collected during the field observations and predicted conductivity values [e.g., Hamilton 1987] and seasonally and diurnally adjusted atmospheric radio noise [e.g., CCIR 1988].

A second observation campaign was conducted in late July - early August 1991 along the same land roads and in the St. Lawrence River in shipborne mode. These data are being reduced and will compared against these reported herein to detect potential seasonal variations in coverage and TD distortions. The latter will be modelled across the St. Lawrence River to analyse the overall Loran-C coverage characteristics in the area.

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CCIR [1988] Characteristics and Applications of Atmospheric Radio Noise Data. CCIR Report 322-3, International Telecommunication Union, Geneva.

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WHAT ARE WE MEASURING?

ROBERT ERIKSON
FAA TECHNICAL CENTER
ATLANTIC CITY, NJ

ABSTRACT

As Loran becomes an approved navigation system by the Federal Aviation Administration (FAA), the need to test receiver performance and measure signals-in-space is becoming very important, especially for non-precision approaches. This need is based on a requirement for the FAA to insure that a navigation system has a certain accuracy, reliability, and integrity. The FAA Technical Center has been tasked with establishing calibration methods for Loran simulators and receivers. This paper addresses the effort to review existing standards and methodologies.

INTRODUCTION

The Federal Aviation Administration (FAA) must insure that any navigation system that it approves or certifies has a certain accuracy, reliability, and integrity. As Loran becomes an approved navigation system the need to test receiver performance and measure signals-in-space is becoming very important, especially for non-precision approaches. Basic Loran system accuracy meets the appropriate requirements when using area calibration values. Concern over testing the receiver and measurement of signals-in-space is to insure the receiver will not present incorrect information to the pilot. Wrong information can be presented to the pilot if the receiver has acquired on the wrong cycle or is unable to detect certain conditions in a reasonable time. The conditions are station off-air and blink.

Low signal-to-noise ratio (SNR) conditions, poor pulse shapes, and poor receiver design are the major reasons for a receiver reporting wrong information. Testing of the receivers will insure that the receivers will be able to perform correctly within some range of SNR and envelope-to-cycle difference (ECD) values. Protection of receiver integrity will only be maintained if the signal conditions at an airport are within the conditions established for receiver testing. The FAA has published procedures which must be followed when approving a receiver. Procedures are also in place for establishing approaches using Loran.

Before an approach will be certified for use, it must pass many steps. The first step uses a Loran screening model to determine if the proposed approach has merit for further work. The program calculates the GDOP, SNR, and ECD for various Loran chains and triads. If these parameters are within acceptable limits the establishment of the approach may proceed.

Step two in the process will be to look at data from the Loran Aviation Monitor (LAM). Signal conditions reported by the LAM must be within acceptable limits. The Loran Aviation Monitor is a fixed site monitor. Tests have shown that Loran conditions within a 90 nautical mile (nmi) radius are homogenous. Based on this information, locations for the LAM's were chosen so that most airports in the United States would be within 90 nmi of a LAM. The LAM measures the Loran signals and archives the information. The archive information is then read remotely by the National Field Office Loran Data Systems (NFOLDS) and used to calculate time difference (TD) correction values. In order to establish an approach, a LAM must be located within 90 nmi of the approach.

To insure that the LAM observes the same signals as the airport of interest, a temporary fixed site monitor will be installed at the airport. The temporary fixed site monitor is known as the Loran Site Evaluation System (LSES). If signals-in-space are within acceptable limits and the approach meets all the requirements for procedure development, the approach will be flight inspected. Flight Inspection flies the approach checking the procedures, obstructions, flyability, and signals-in-space.

Anyone who has had any contact with Loran knows that terms like SNR and ECD as very common. While these terms seem to be well defined, the actual measurement techniques can vary depending on who is measuring them and the specific application. The term "signal quality" is becoming a common term in the 90's. This term is a recognition by some people that a new parameter may be needed to define the Loran signals-in-space.

The FAA Technical Center has been tasked with establishing calibration methods for flight inspection receivers. Since a Loran simulator must be used to perform the calibration, a method to calibrate the Loran simulator must also be established. To aid in testing Loran receivers, the program office is establishing two test facilities. The test facilities will be used as a standard to calibrate and test flight inspection receivers, the Loran Aviation Monitors, the Loran Site Evaluation System, and help in the certification of Loran receivers. The facilities will be established at the Volpe National Transportation Systems Center (VNTSC) and the FAA Technical Center.

This paper addresses the first part of the project. The first part of the project is to develop methodologies which can relate transmitter, simulator, and signal-in-space measurements. The methodologies must be independent of specific Loran receivers.

THE STANDARDS

In order to discuss the measurement of a Loran pulse it is necessary to establish some reference. In the case of aviation, the FAA has published Advisory Circular 20-121A[1] which describes the approval process for airborne Loran C receivers. The Advisory Circular references an FAA Technical Standard Order (TSO) C-60b[2]. The TSO in turn references a Radio Technical Commission for Aeronautics (RTCA) Minimum Operational Performance Standard (MOPS)[3]. Finally, the MOPS references a United States Coast Guard (USCG) transmitter specification[4]. It is the combination of these documents which form the beginning standard for any measurements.

When discussing the measurement of certain Loran parameters it is necessary to understand some basic terms. The standard zero crossing, standard sampling point, and pulse shape are three terms which are frequently used. The USCG maintains timing control relative to the standard zero crossing (SZC). It is assumed that receiver manufacturers will use this point to obtain time difference measurements and ultimately present position. References to field strength are related to the standard sampling point (SSP) and pulse shape is used to find the SZC and SSP.

As defined in the USCG transmitter specification the standard zero crossing is "the positive zero crossing at 30 microseconds of a positively phase coded pulse on the antenna-current waveform". The pulse is measured on the transmitter antenna current return. Once the signals leave the antenna and reach the far field, the SZC is generally defined as the third positive zero crossing for a pulse with positive phase code. It is commonly referred to as the 30 microsecond point.

When determining the strength of a Loran pulse it is necessary to measure the pulse at some non-zero point on the pulse. If the amplitude is measured at the peak of the pulse (typically 65 microseconds into the pulse) the pulse will be the strongest but the potential for skywave interference exists. If instead the amplitude were measured early in the pulse the amplitude would be low resulting in more noise at the measurement point. The actual measurement is a compromise. Per the USCG transmitter specification, "the standard sampling point (SSP) is the point on the Loran-C pulse envelope 25 microseconds after the beginning of the pulse. The point is to be used in the calculation or measurement of Loran-C far field strength or Loran-C signal strength from a simulator". When measuring signal strength at the transmitter, the USCG uses the amplitude at the peak of the pulse. Figure 1 shows where the SZC and SSP would appear on an ideal antenna current pulse. The pulse has a positive phase code and ECD of 0 microseconds. Note that a zero crossing is present at 25 and 30 microseconds into the pulse. The SSP really occurs 27.5 microseconds into the pulse. If the far field equations were used the pulse would be shifted in time by 2.5 microseconds. The time would make the SSP occur at 25 microseconds but the SZC would be shifted to 27.5 microseconds.

It is the shape of the pulse which allows a receiver to determine time into the pulse. As long as the ECD is between plus and minus 5 microseconds a receiver can determine the SZC. <u>This only occurs under very ideal conditions.</u> From a practical point of view, a receiver can only determine the SZC correctly when the ECD is between -2.5 and +3.5 microseconds. Per the USCG transmitter specification, "ECD is the time relationship between the phase of the RF carrier and the time origin of the envelope waveform". Figure 2 shows graphically the concept of ECD. The same specification states: "ECD is determined by first computing the deviation between the actual waveform, sampled at the first eight half cycle peaks, and the standard leading edge. This deviation is minimized in a root-sum-square sense over ECD and pulse peak. The ECD of the pulse is that value which minimizes this deviation." Once an ECD is determined for the pulse, an ensemble of the first 8 half-cycles and individual half-cycles for the first 13 are compared to an ideal pulse.

SNR is a metric which relates the relative strength of the signal to the relative strength of the noise. Per the USCG transmitter specification, "Loran-C Transmitted Signal Level: The level of a Loran-C signal is the RMS level of a CW signal having the same peak-to-peak amplitude as the Loran-C pulse envelope at the peak of the pulse". When dealing with far field measurements or simulator field strength measurements the TSO states: "For purposes of defining signal power levels, the level of a Loran-C signal (a group of pulses from a single transmitting station) is the RMS level of a CW signal having the same peak-to-peak amplitude as the LORAN-C pulse envelope 25 microseconds after the beginning of the pulse." The TSO defines the noise level as the RMS level after filtering by a single resonator L-C filter having a center frequency of 100 kHz and a 3 decibel (dB) bandwidth of 30 kHz. SNR is the difference formed by subtracting the noise level

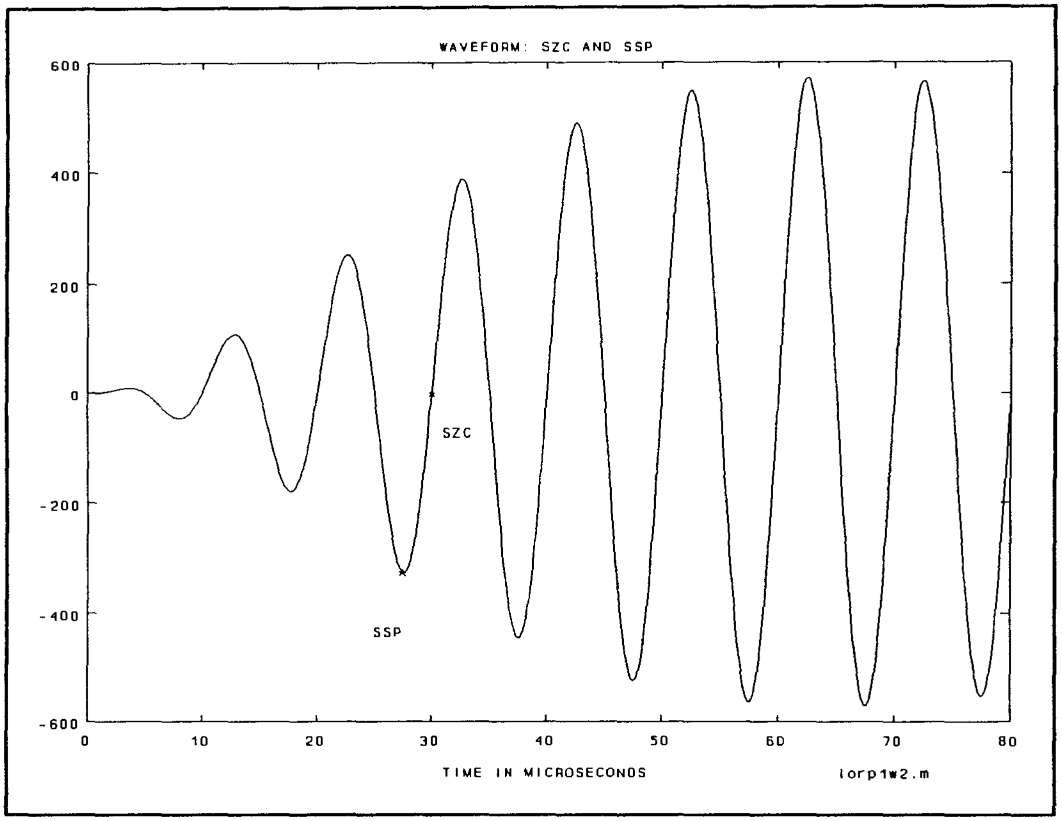

Figure 1 Standard Zero Crossing And Sampling Point

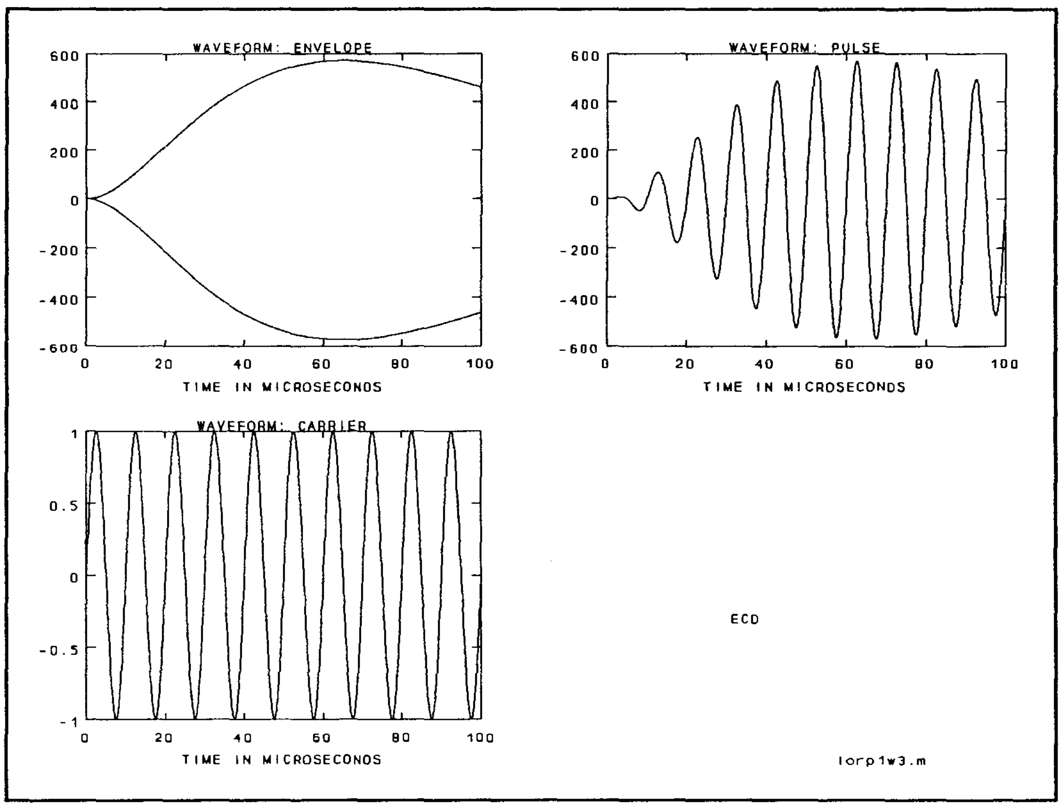

Figure 2 Example Of ECD

from the field strength of the Loran pulse. The levels are generally expressed in decibels.

Noise is not measured at the transmitter therefore it does not appear in the USCG transmitter specification. The FAA standards define two models of noise for receiver testing. The first is gaussian and the second atmospheric. Gaussian noise is defined to have a uniform power spectrum with a gaussian amplitude distribution. The level of noise is to be measured as an RMS level through a filter. The filter is equivalent to that defined in the above paragraph. The specifications do not define insertion loss or loading. Atmospheric noise is to be generated by mixing gaussian noise with bursts of 100 kHz energy. The bursts should have a poisson distribution in time and be 30 microseconds wide. A formula can be found in the TSO which combines the burst amplitude, burst width, and gaussian noise level to get the atmospheric noise level.

POINT OF VIEW

The way one looks at the Loran system is in part due to the observer's point of view. Someone who works with the Loran transmitter sees a large well defined signal without much noise. A user of Loran receivers does not see the details of the Loran system. The user only knows if the receiver is easy to use and can provide guidance to some point or tell the present position. Manufacturers may review published reports on how the system is supposed to work, but the manufacturer must produce a product that works in the "real world" and can satisfy the customer. Then there is the regulatory people! They want everything to be neatly packaged. This means all parameters must be measurable, repeatable, and correlated with every measurement device.

Anyone who has every observed "real world" Loran signals know they do not look like the ideal pulse published in the transmitter specification. Certification of Loran receivers must however be referenced to existing standards. Those standards are the Advisory Circular, Technical Standard Order, and Minimum Operational Performance Standard identified earlier in this paper. All the standards point back to the MOPS. The MOPS was written by representatives of the user community, manufacturers, and FAA. This set of documents is the current reference.

The rest of the paper will concentrate on implementing the requirements of these documents. Over the years there have been many talented individuals who have discovered the more subtle points of implementing the procedures in the transmitter specification. Their accomplishments have been lost or overlooked. Lost because the point is now part of a standardized measurement or computer program and is transparent to the user. The box or technique has been lost due to personnel changes. The same is true for many contractors. Manufacturers develop special techniques to make their products work in the "real world". The special techniques are not generally published because it provides an advantage for them in the market place. The following are observations of known concepts which are often overlooked or not thought about except by a few individuals.

THE ANALYSIS

WHICH EQUATION, ANTENNA CURRENT OR FAR FIELD?

The definitions refer to an ideal Loran pulse in terms of both the antenna current equation and far field equation. The two equations are identical except that the antenna current equation uses a sine multiplier (A exp() * sin()) term while the far field equation uses a cosine multiplier (B exp() * cos()) term. The USCG transmitter specification provides equations for both types of pulses. Figure 3 shows both pulses plotted on the same time axis. The far field equation is the pulse which starts closest to time zero. The transformation of the signal from the antenna current waveform to far field waveform is the reason for two equations and is a source of confusion.

If the ECD using the far field equation is set 2.5 microseconds less than the value used for the antenna current equation and the entire pulse delayed by 2.5 microseconds both equations will produce identical pulses. The USCG generally transmits a 0 microsecond ECD pulse (referenced to antenna current). This means the pulse in the far field (just outside the near field) could have an ECD of 0 or 2.5 microseconds depending on the equation used. Both equations will have zero crossings every 5 microseconds but the start point of each cycle will be different. Since the antenna current equation uses a sine function, zero crossings will start 5 (could also be 0 depending on point of view) microseconds into the pulse. Far field equations use a cosine function which means the first zero crossing will start 2.5 microseconds into the pulse. For the purposes of this paper all references to the ideal pulse will assume the equation for antenna current unless otherwise noted.

WHAT TIME IS IT?

Absolute time into the pulse only exists for the ideal pulse based on the equation. With the ideal pulse, the envelope is shifted in time based on ECD value while the sinusoidal term (carrier) remains constant with time. Since the sinusoidal term remains constant in time the zero crossings also remain constant in time. When the ECD is negative a half-cycle will actually occur in negative time. A note in the transmitter specification

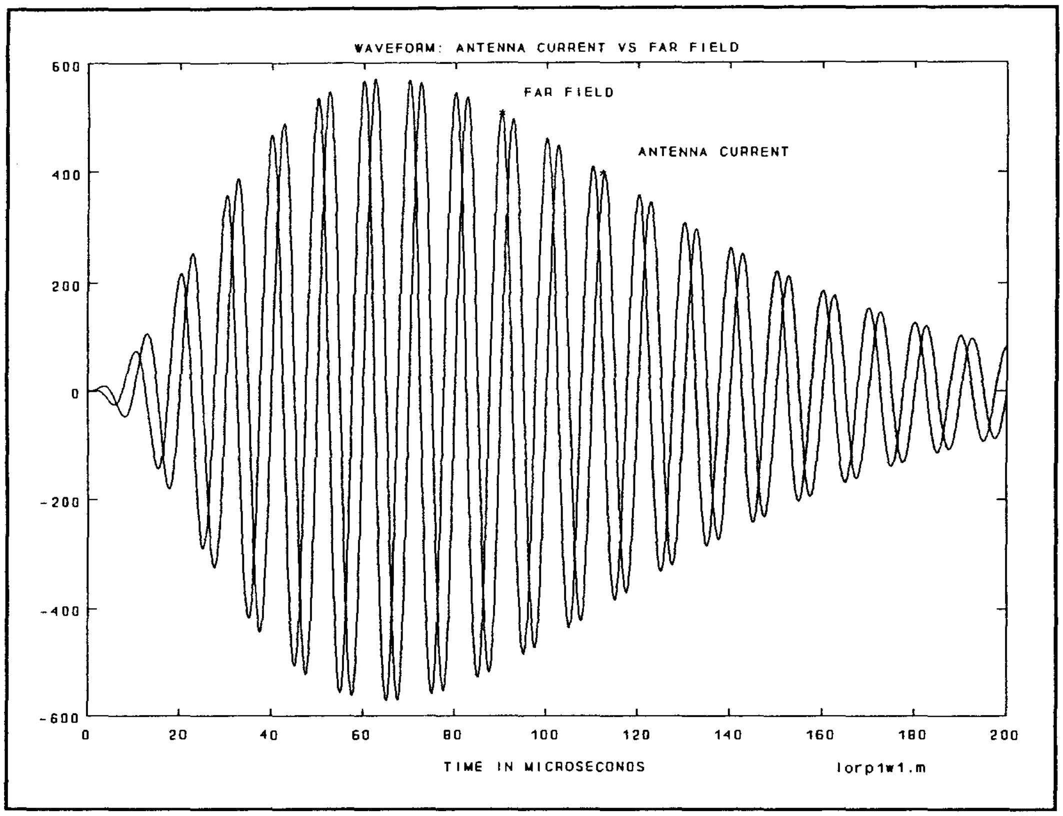

Figure 3 Ideal Loran Pulse

states this is difficult to achieve in practice. When the ECD is positive, the start of the first half-cycle of the pulse will be delayed from time zero by an amount equal to the ECD.

In practice absolute time into a pulse can only be estimated. Time references for an observed pulse must be estimated by finding the best fit between the observed and ideal pulse. The simplest method to find the SZC is by using the ratio method. With this method, the operator measures half-cycle amplitude points using an oscilloscope, computes the ratio between two half-cycle points, and compares the ratio to an ideal pulse. The oscilloscope and ratio method work for well defined pulses. Loran receivers use various methods to find the proper tracking point in the pulse, they include: delay and add, linear, and digital signal processing. The number of points measured on the pulse and the number of samples processed vary by manufacturer.

WHEN DOES THE PEAK OF EACH HALF-CYCLE OCCUR?

When calculating the ECD of an ideal pulse it is necessary to make sure the measurement technique and analysis are in agreement. At first glance it might seem that the peak of a half-cycle of the Loran pulse should occur mid-way through the half-cycle. This is not true! Figure 4 shows the relationship of half-cycle peak to half-cycle midpoint for various values of ECD. It can be shown that for any ECD, the largest time between the mid-point and peak will occur for the first half-cycle and decrease as the number of the half-cycle increases. As the ECD becomes more positive the time between the mid-point of the half-cycle and the half-cycle peak increases. For an ECD of +4 microseconds the difference is 2.2 microseconds.

When the differences in time between the mid-point and the peak of the half-cycle are related to differences in amplitude more dramatic changes are found. Figure 5 shows the relationship between the amplitude of the half-cycle peak and the amplitude at the mid-point of the half-cycle for various ECD values. The difference is expressed as a percentage of the half-cycle peak. The largest differences in amplitude for a constant ECD occur for the first half-cycle and decreases as the number of the half-cycle increases. The amplitude difference increases as the ECD is increased. In fact, when the ECD is + 4 microseconds, the amplitude at the mid-point of the first half-cycle is almost zero. This means that measurements of half-cycle amplitudes taken every 5 microseconds would miss the half-cycle amplitude for the first few half-cycles.

The effect maybe overlooked by or transparent to many people but is well known. For example, the USCG has established a method to determine pulse shape at

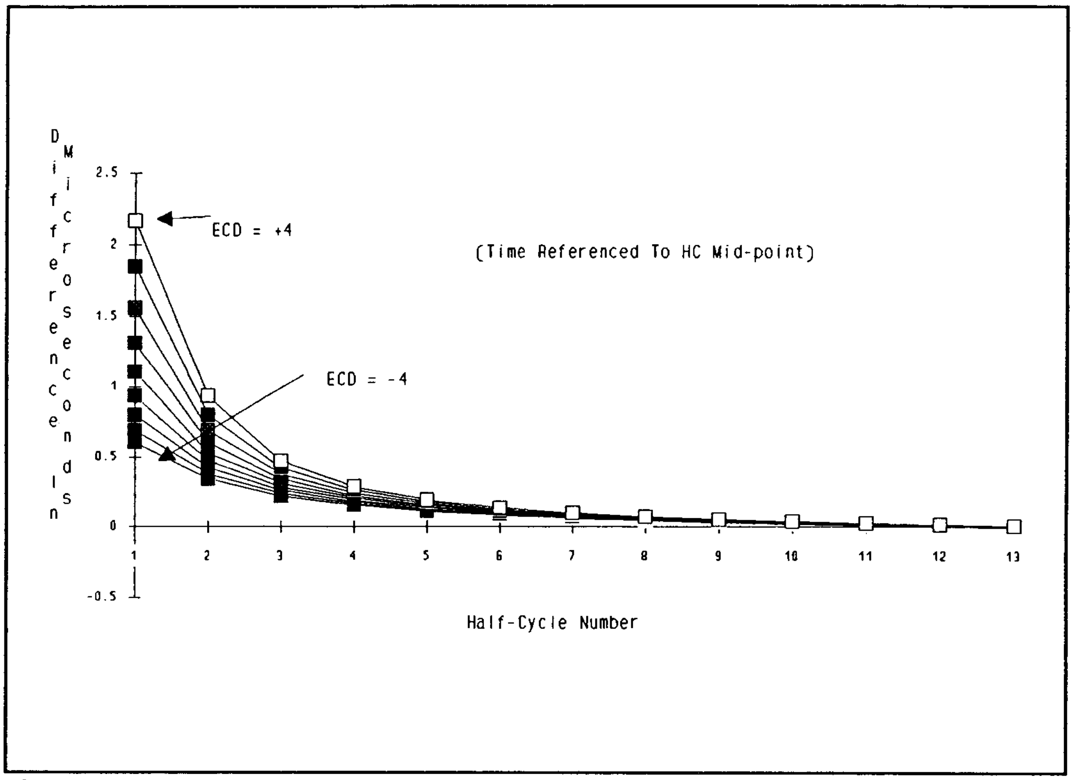

Figure 4 Difference In Time Between Half-Cycle Mid-Point And Half-Cycle Peak

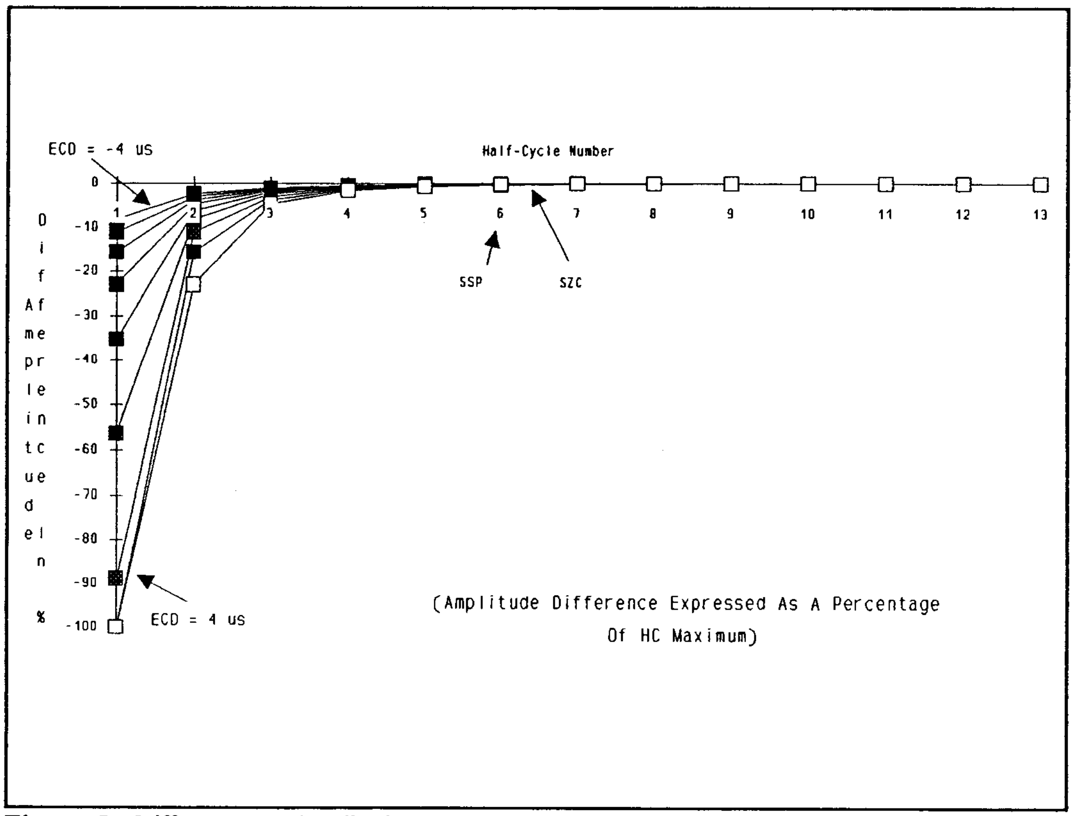

Figure 5 Difference In Amplitude Between Half-Cycle Mid-Point And Half-Cycle Peak

the transmitter. The method requires the measurement of half-cycle amplitudes using an oscilloscope and then running the results through a USCG program known as LOIS. This program uses the "Freeze" equations which implements the analysis using half-cycle peak times and not the mid-point time of the half-cycle.

THE ENVIRONMENT

ABSOLUTE SIGNAL LEVELS

A major difference when measuring the pulse shape or field strength of a Loran pulse is the absolute levels of the signals involved. The USCG uses a current transformer on the ground return of the antenna to sample the transmitted Loran pulses. The Loran pulse at this point will have a zero to peak voltage of between 50 and 200 volts. The voltage is dependent on the actual antenna current of the transmitter. Field strength measurements at a transmitter are made at the peak of the pulse. The signal will include only the desired pulse and perhaps a cross-rate signal if the transmitter is dual-rated. Very little other noise or interference would be expected.

Typical signal levels from the output of a Loran simulator would range from 45 to 110 dB above a microvolt. At 45 dB the RMS amplitude at the SSP would be 177 microvolts (251 microvolts peak). The Loran field strength measured in the far field could go to zero but from a practical point of view is limited by geometry and SNR considerations. Typically only field strengths down to about 45 dB above one microvolt per meter are of any interest. Airborne Loran antennas are generally less than one meter in length. If the effective height of the antenna is assumed to be 0.2 meters then the signal received at the base of the antenna would be reduced by 14 dB. The RMS signal level received at the antenna coupler would then be only 36 microvolts. The differences in amplitude will affect the methods used to make the measurements.

PULSE SHAPE

Determination of ECD at a Loran transmitter or Loran simulator is relatively easy. Measurement of pulse shape in the far field is a much more difficult task. Far field signals have lower field strengths and are contaminated by atmospheric noise, other Loran rates, interfering signals, carrier wave interference (CWI), skywave signals, and filtering in the receiver. A receiver operating in the far field sees the combination of the various components. At a Loran simulator each component can be set individually and then summed together.

Use of half-cycle peaks after the 30 microsecond point could result in the measurements being contaminated by skywave and use of earlier half-cycles would result is very low amplitude signals. Measurement of pulse shape in the far field is only necessary to make sure a Loran receiver can properly acquire the correct cycle. It is the pulse shape which allows a receiver to determine the correct point on the Loran point to track. Receiver manufacturers use different techniques to determine the track point. The basic methods are 1) delay and add, and 2) linear.

The delay and add method delays the received pulse, changes the gain of the pulse, and adds it back with the original pulse. This new mixed signal is amplified and then clipped. The proper track point is determined by finding the point in the pulse which has a phase change. The technique is sometimes referred to as a non-linear method. While clipping does take place toward the end of the process, the beginning of the process still relies on linear relationships.

The linear method preserves the shape of the pulse and then samples the pulse at predetermined points. The points are compared to a reference pulse to determine the correct tracking point. The number and location of samples are determined by the manufacturer. An emerging technology is the use digital signal processing techniques.

Measurement of pulse shape is therefore more than just determining the ECD, it must include some kind of metric which will address the various points of the pulse used by a Loran receiver.

NOISE

Regardless of the model of noise used to test a Loran receiver, some manufacturers will argue that only testing a receiver in the "real world" is a valid test. Any model is only an estimate of the real thing. The noise model appearing in the TSO is based on a noise model from the marine community. Measurement of "real world" noise is a difficult process. One detailed study was published by Donald Feldman and titled "An Atmospheric Noise Model With Application To Low Frequency Navigation Systems"[5].

By definition the noise level is the RMS level as measured through a filter with a center frequency of 100 kHz and a 3 dB bandwidth of 30 kHz. From a practical point of view it can only be measured when the Loran signal is not present, since the Loran signal cannot interfere with itself. While the level of the noise will affect a Loran receiver the spectral content is also very important. Some recommend a signal-to-noise ratio estimate based on the output of a tracking loop.

SUMMARY

This paper has presented the results of reviewing existing standards. It has also presented some of the more subtle points which need to be considered when implementing the procedures defined in the standards. The next step will be to use the standards to calibrate a Loran simulator and then Loran receivers. Since the "real world" is known to be different than that defined in the various standards some considerations must be made when applying the standards.

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BIOGRAPHY

Robert Erikson graduated from Drexel University in 1973 with a BS in electrical engineering. Since graduation he has worked at the Federal Aviation Administration (FAA) Technical Center in Atlantic City, NJ. While at the Technical Center he has worked on the evaluation of various navigation systems like TACAN, Omega, and Loran. Work on Loran started in the late 1970's and has concentrated on the evaluation of Loran as a landing aid for aviation. The work has included both ground based and aircraft based measurements. He has been the author of many published technical reports. Results of various projects have been presented at several WGA technical symposiums. He is a member of the Institute Of Navigation, Wild Goose Association, and Institute Of Electrical and Electronics Engineers (Senior Member).

SODANO'S ALGORITHM IS CORRECT

Richard E. Keating

U.S. Naval Observatory
34th Street and Massachusetts Avenue, NW
Washington, DC 20392-5100

ABSTRACT

In 1958, Emanuel M. Sodano published a rapid "rigorous non-iterative procedure" for calculating the geodesic distance between two given points on a spheroid. Sodano's algorithm has been widely implemented in computer programs used to compute propagation times for radio-navigation systems, *i.e.*, Loran. This paper will show that Sodano's solution of the following expression

$$Q_1 + Q_2x + Q_3x^2 = x$$

for x is correct and was obtained by a straightforward application of reversion of series.

INTRODUCTION

In 1958, Emanual Sodano published a mathematical procedure for calculating the length of a long geodesic running on the surface of a spheroid between two points (Ref. 1). This non-iterative algorithm was an updated and improved version of an algorithm originally presented by him in August 1950 in Army Map Service (AMS) Technical Report No. 7 (Ref. 2).

In 1963, Sodano and Robinson published a Revised AMS Technical Report No. 7 (Ref. 3) to replace the original AMS TR No. 7, which was out of print. The Revised AMS TR No. 7 contained more general and accurate formulae than the original 1950 AMS TR No. 7. In 1965, Sodano published a reformulation of his algorithm in terms of the spheroid parameters a,m, and ϕ, use of which gave his power series development a more "concise, orderly pattern." In June 1966, he presented yet a further refinement in which the spheroid parameters were factored out and isolated, thus giving his formulae a yet simpler appearance.

Sodano's papers are presented in a tightly condensed form intended to be read by persons already very familiar with Helmert's solution of the "inverse geodetic" problem. Readers not possessing such a background tend to be mystified rather than enlightened by Sodano's papers. Since the pertinent basic references in this area of geodesic computation are often out of print, not available, not accessible, or not written in English, persons wishing to understand and use Sodano's formulae intelligently eventually realize that they are confronted with a complex problem with a long and convoluted history.

Sodano's formulae have been widely implemented in computer programs, but users should be aware that Sodano's formulae can produce inaccurate results for long antipodal geodesics if proper care is not used.

There is very little doubt that Sodano's formulae give geodesic distances which, to the desired level of accuracy, are correct in most cases, yet the fact is that for very long nearly antipodal geodesics, Sodano's formulae, if not properly iterated, can produce inaccurate results. In 1983, B. R. Bowring drew attention to the fact that a power series expansion of 1/(1-x) is incorrect if x > 1.[1] Because Sodano appeared to have made heavy use of just such expansions, this raises the question: Are Sodano's formulae correct? Is the known problem with Sodano's formulae for very long antipodal geodesics evidence of mathematical error?

Blind use of Sodano's formulae for all cases merely because convenient computer code is available, is, for these rare antipodal cases, inadvisable. Sodano's formulae are not a single magic recipe valid for all geodetic lines. Users must recognize that making powerful procedures like Sodano's available in computer code is like making automated ray tracing available to novice optical workers. Persons using the computerized procedure must understand the limitations if they are to avoid blundering. Used properly, Sodano's formulae are indeed correct, but users of Sodano's formulae should always be aware that when antipodal geodesics are being calculated, computation according to Sodano's formulae will definitely result in slightly inaccurate results unless special tests are used to detect, and then correct for, the unusual mathematical conditions that occur in these rare situations.

Attention is therefore drawn to the fact that, as usually implemented in all computer programs known to the author, Sodano's formulae will give, for long antipodal geodesics, slightly inaccurate results. Avoidance of inaccurate results for these rare cases is, as Sodano himself (Ref. 1, pp.24-25) noted, simple: one merely iterates Sodano's formulae using an updated value z for Sodano's equation $\lambda = L + x = L_n + z$, where λ is the absolute difference in longitude on the *auxiliary sphere* between the auxiliary sphere's reduced points corresponding to the endpoints of the geodesic on the spheroid, and L, the absolute difference between the geodetic longitudes of the geodesic endpoints on the *spheroid*, and L_n is a quantity taken almost equal to the value of λ that resulted from the first use of Sodano's formulae in order that z may be made smaller than x.

BOWRING'S CRITIQUE

Bowring, in 1983, while developing his own formulae for the solution of the "Geodetic Inverse Problem," noted that some of his series expansions were similar to Sodano's. Bowring further noted that his own series expansions involved a term $\sigma/\sin\sigma$ which for long lines would invalidate the use of expansions of such expressions as $1/(1-\theta)$ into $1 + \theta + \theta^2 + \ldots$ since $\theta > 1$.

We will show here that although Sodano stated his solution for x without proof, Sodano's solution is, in spite of Bowring's critique, nevertheless correct to Sodano's intended order of accuracy. If greater accuracy in the solution for x is required for very long antipodal geodesics, one may either numerically evaluate a reversion of series solution for x that does not use the expansions to which Bowring correctly takes exception, or, as Sodano recommended, Sodano's formulae may simply be iterated using a smaller quantity z for x (Ref. 1, pp. 24-25). In effect, Sodano's recommendation of iteration with a quantity z for x amounts to reverting to the Helmert iteration procedure which is stable even for the rare case of nearly antipodal geodesic lines.

Finally, for reference and for checking calculations, a combined table of the standard ACIC test geodesics (Ref. 8 and 9) is presented.

HELMERT'S SOLUTION

Sodano's formulae are based on, and derived from F. R. Helmert's (Refs. 18, 19) iterative solution of the "inverse geodetic problem," *i.e.*, the problem of calculating the length of the geodesic line on a given spheroid between given endpoints. In order to orient those readers who may be unfamiliar with the inverse geodetic problem, we first present a short overview of Helmert's iterative procedure.

Conceptually, the Helmert solution for the geodesic distance is a straightforward integration of a differential line element ds in the surface of the spheroid used for the earth. Integrating a differential line element ds along a geodesic is not simple because on a spheroid a geodesic is a space curve having double curvature. Therefore, one must always remember that a geodesic on a spheroid is not a plane curve.

The integration is carried out by surrounding the spheroid with an auxiliary sphere which is tangent to the spheroid at the spheroid equator. The differential line element ds in the surface of the earth-spheroid is related to a corresponding differential great circle spherical element $d\sigma$ on the surface of the auxiliary sphere; and the integration of ds is carried out using, as independent variable, the spherical $d\sigma$ on the auxiliary sphere and the differential relation $ds/d\sigma$.

The endpoints of the integration are defined by points on the auxiliary sphere whose coordinates are defined in a special way to correspond with the given endpoints on the spheroid. In particular, the latitudes β of the endpoints on the *auxiliary sphere* are defined as "reduced" or "parametric" latitudes, *i.e.*,

(1) $$\beta = \arctan\left((b/a)\tan(\phi) \right)$$

where b and a are the spheroid semiminor and semimajor axes respectively, and ϕ is the geodetic (geographic) latitude on the *spheroid*.

In moving a point from the initial position along the geodesic to the final position on the spheroid, the geodetic latitude of the moving geodesic point will gradually rise to a maximum value and then begin falling. Similarly, the reduced latitude of a point on the *auxiliary sphere* corresponding to the point moving along the geodesic on the spheroid, will rise to a maximum and then decrease. The auxiliary sphere is thus further specified and defined so that corresponding to the point on the geodesic where the geodetic latitude ϕ_o of the geodesic is a maximum, is a point on the auxiliary sphere whose spherical latitude equals the reduced latitude β_o.

The forcing of the integration of ds to pass through the highest point on the *geodesic* path, this highest point corresponding to β_o, is the condition which selects only the geodesic path from among the many possible integration paths.

Once the above mentioned integration is carried out, one has an expression which gives the relation between s, *geodesic* distance on the spheroid, and σ, *spherical* great circle distance on the auxiliary sphere:

(2)

$$s = b(B_0\sigma + B_2 \sin\sigma \cos 2\sigma_m + B_4 \sin 2\sigma \cos 4\sigma_m +$$

$$B_6 \sin 3\sigma \cos 6\sigma_m + B_8 \sin 4\sigma \cos 8\sigma_m \ldots$$

(See Rapp, reference 16, p. 9, eq. 40)

Here σ_m is a mean spherical distance which is calculated from σ, β_1, β_2, and β_o. The B_i's are calculable functions of the reduced latitude β_o and the spheroid second eccentricity.

However, because of the use of an auxiliary sphere with reduced latitudes and the fact that the geodesic is a curve of double curvature, it is also necessary to derive a differential relationship $dL/d\lambda$ between longitude L on the spheroid and longitude λ on the auxiliary sphere. This is done in a manner similar to what has already been described. Once the differential relationship $dL/d\lambda$ is obtained, it is integrated in the same manner as were ds and $d\sigma$. The result is an expression of the form:

(3) $$x = \lambda - L = \Upsilon \cos(\beta_o)$$

where Υ is a calculable expression dependent on σ, the great circle distance on the auxiliary sphere, on the reduced latitudes β_1, and β_2 corresponding to the end points of the geodesic, and on β_o, the auxiliary sphere reduced latitude of the point at which the geodesic attains its maximum latitude on the path between the endpoints. β_o may be calculated using β_1, β_2, λ, and σ.

In the inverse geodetic problem, one is not given the spherical longitudes λ_1, and λ_2 on the auxiliary sphere corresponding to the endpoints of the geodesic. Suppose, however, that these spherical longitudes λ_1, and λ_2 were known. In that case one could obtain the difference in longitude λ on the auxiliary sphere from

(4) $$\lambda = \lambda_2 - \lambda_1$$

Knowing λ one may calculate the great circle distance σ between the points on the auxiliary sphere corresponding to the endpoints of the geodesic on the spheroid using the cosine law of spherical trigonometry:

(5) $$\cos \sigma = \sin \beta_1 \sin \beta_2 + \cos \beta_1 \cos \beta_2 \cos \lambda$$

Knowing σ one may use equation 2 to obtain the geodesic length s.

As already noted, we do not know λ_1, λ_2, or λ. However, we do know that the longitude difference λ on the *auxiliary sphere* is approximately equal to the longitude difference $L = L_2 - L_1$ of the given endpoint longitudes L_1 and L_2 on the *spheroid*. This observation is the beginning of the Helmert iteration procedure.

HELMERT'S ITERATION PROCEDURE

Helmert's iteration procedure consists in initially assuming $\lambda = L$, then using equation 5 above to calculate an approximate σ. Using the approximate σ to calculate the term Υ in equation 3 above, one obtains the correction x, which added to L gives an improved value for λ. One then starts over again with the improved value of λ and continues to iterate until the difference between the current correction x provided by equation 3 and the previous iteration's x correction is sufficiently small (usually < $0\overset{''}{.}0001$).

Once sufficiently accurate values of λ and x have been obtained, σ is again calculated and the geodesic distance obtained from equation 2.

This was the elaborate "Helmert iteration procedure" Sodano started with when he derived his non-iterative formulae.

Persons desiring a good English language introduction to the inverse geodetic problem and Helmert's solution will find that first reading Rapp's chapters 3 and 4 (Ref. 15) and chapter 1 (Ref. 16) before reading Sodano's papers will be helpful.

SODANO'S FORMULAE

Sodano's contribution was to notice that the cosine of the longitude on the auxiliary sphere λ could be developed into a power series in x, and that this power series could be substituted into the Helmert iteration formulae to develop, finally, an expression for the

$$\Upsilon \cos(\beta_o)$$

term in equation 3. When this was done, the $\Upsilon \cos(\beta_o)$ term had the form:

(6) $$\Upsilon \cos(\beta_o) = Q_1 + Q_2 x + Q_3 x^2$$

Sodano then observed that the Helmert iteration process required that $x \equiv \Upsilon \cos(\beta_o)$. Thus Sodano obtained the equation

(7) $$x = Q_1 + Q_2 x + Q_3 x^2$$

which then could be solved for x. Sodano did not give any explanation of how he found his solution for x; he merely asserted that the required solution was

(8) $$x = Q_1 (1 + Q_2 + Q_2^2 + Q_1 Q_3)$$

From this solution for x, Sodano proceeded to derive various non-iterative algebraic developments and expressions for geodesic distance and azimuth. In his papers Sodano presented three or more different non-iterative algebraic developments, and these became known as Sodano's method 1, method 2, and method 3. When Sodano published reference 1, these earlier methods, which are nothing but various ways of structuring the Helmert solution given x, became obsolete.

The Sodano formulae are thus based on Helmert's iterative spherical solution. For that reason M. Dupuy, in his authoritative International Association of Geodesy report "Evaluation of Methods of Calculating Long Lines on the Terrestrial Spheroid" (Ref. 17) classified the non-iterative Sodano formulae as "rigorous spherical solutions".

Casual examination of Sodano's fundamental 1958 paper makes it clear that Sodano made use of series expansions of expressions such as $1/(1-\theta)$; and so, in view of the known problem of slight inaccuracy for long antipodal geodesic lines and Bowring's critique, it is of interest to give explicit verification and proof of Sodano's solution for x if only to determine just where, why, and how the known antipodal problem arises.

In deriving equations 7 and 8, Sodano asserted that x is a small quantity of the order of the square of the eccentricity (Ref. 1, p. 15). Sodano then considers the Helmert iteration for λ, the longitude difference on the auxiliary sphere, and writes

$$(9) \qquad \lambda = L + x$$

where $x = T\cos\beta_0$, L the longitude difference on the spheroid. He then develops $\cos\lambda$ and Helmert's expression for T into a power series (eq. 6) in x out to the sixth power of the eccentricity (to match the accuracy of Helmert's original development), finally arriving at equations 6 and 7.

In equations 6 and 7, the quantities Q_i are functions of the spheroidal parameters and the radian distance σ on the auxiliary sphere. Sodano then asserted without explanation or proof that the required solution to the proper order for x of this expression was equation 8.

In obtaining equation 8, Sodano apparently made use of expansions of $1/(1-\theta)$. The question thus arises, in view of Bowring's observation, whether or not this solution is accurate. Sodano subsequently developed his expressions for the geodesic length and the azimuths from equation 8. Any error here will necessarily also be reflected in any subsequent formulae for geodesic distance and azimuth.

SODANO WAS AWARE OF THE PROBLEM

It is known that Sodano engaged in correspondence with Rainsford (Ref. 3, p. 25) concerning long antipodal geodesics and that as a result Sodano reexamined his series expressions in x and concluded that although the series expressions did in fact diverge for geodesics halfway or completely around the earth "because the radian distance σ was large, and csc σ, cot σ, and P are approaching infinity," nevertheless this "condition of divergence never prevails in the constant terms, and for succeeding coefficients it is to no greater degree than the power of the corresponding x" (Ref. 3, pp. 23-24).

As a practical workaround of this rare difficulty, Sodano suggested using an initial longitude difference value L_n (Ref. 1, pp. 24-25) on the spheroid more nearly equal to λ, the longitude difference on the auxiliary or reduced sphere, thus decreasing the size of x. Sodano suggested that an appropriate value to use for L_n would be the slightly inaccurate λ that results from a straightforward solution using his formulae.

In effect, Sodano thus recommended that, for the rarely occurring special case of antipodal geodesics, his formulae be iterated using, for the second iteration, as the value for L_n the value of λ obtained from the first iteration.

Nevertheless, the mere fact that an inaccuracy could arise in the case of long antipodal geodesics, raises questions as to just how Sodano arrived at his solution, equation 8 above, and what limitations on the size of x or other quantities may exist.

At first, the quadratic nature of equation 7 makes it appear that Sodano might have obtained his solution as the result of some sort of involved, busy expansion of various quadratic terms. But were this so, it would be difficult to understand Sodano's confidence in asserting that equation 8 was "the required solution of x to the required order" (Ref. 1, p. 17). Further, Bowring's remark about divergence would then appear even more pertinent.

REVERSION OF SERIES

It is now suggested that, in obtaining his solution (equation 8), Sodano used a simple application of a mathematical technique known as "reversion of series."

The mathematical technique known as "reversion of series" is not well known or explained in modern references. Reference (10), the CRC Mathematical Handbook, 12th edition, merely gives the desired coefficients on pages 370-371 with no explanation. Rapp (Ref. 15, p. 8) also gives only summary information. No easily available modern reference was found which provides an explanation of the conditions under which reversion of series is valid. So far, all pertinent references to which access was gained were published approximately one hundred years ago (*i.e.* ref. (11) - (14)).

Reversion of series is best understood graphically. If one is given a power series representation of a function $y=f(x)$, Figure 1, then reversion of series is merely a technique for giving x as a function of y, *e.g.*, $x = g(y)$, Figure 2.

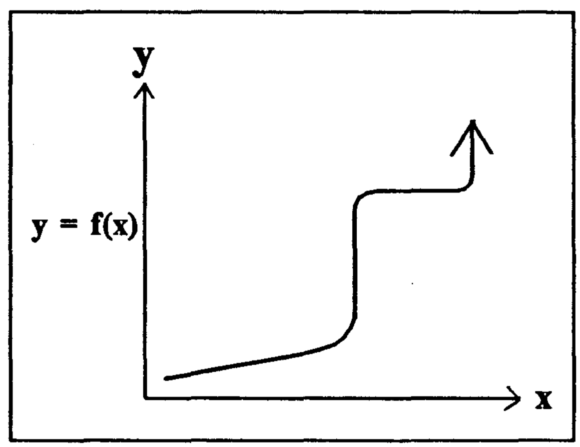

Figure 1

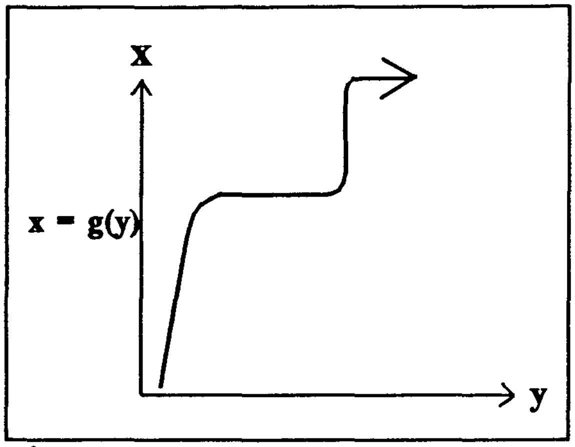

Figure 2

Graphically, reversion of a power series function $y = f(x)$ is equivalent to rotating Figure 1 counterclockwise 90° so that the y-axis points to the left and then flipping the graph over about the now upward directed x-axis so that the y-axis points to the right as in Figure 2.

Thus if $y = f(x)$ is a monotonically increasing one to one mapping of x into y, it is clear that the reverse one to one mapping $x = g(y)$ of y into x also exists.

The advantage of the reversion of series technique is that it does not assume that x is small; the only assumption is that the leading constant coefficient a_0 in the power series in x is not zero. Nevertheless, to obtain Sodano's solution (equation 8) it is still necessary to resort to an expansion of expressions in the form $1/(1-\theta)$.

The method of reversion of series is a technique whereby a given power series for y in terms of x

(10) $$y = a_0\, x + a_1\, x^2 + a_2\, x^3 + \ldots$$

may be reversed to give x as a power series in y:

(11) $$x = A_0\, y + A_1\, y^2 + A_2\, y^3 + \ldots$$

where $$A_0 = 1/a_0$$

$$A_1 = -a_1/(a_0\,)^3$$

$$A_2 = (1/a_0)^5\,(-a_0 a_2 + 4a_1^2/2!)$$

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The general term A_i is given by McMahon. These coefficients A_i are easily derived by assuming equation 11, substituting equation 10 for each y in equation 11, moving all terms to the right hand side, collecting the terms corresponding to each power of x into a single coefficient for that power of x, and then noticing that since the resulting expression is equal to zero, each coefficient of a power of x on the right hand side must also be equal to zero. By this method, the first few expressions for A_i are easily derived, but afterwards the expressions for A_i become very complicated. For our purposes, it should be noted that the only restriction placed upon the use of this method of reversing a power series is that the leading coefficient a_0 be non-zero. No restriction is placed upon the size of x or y, both of which may be greater than unity.

DERIVATION OF SODANO'S SOLUTION

Rewrite Sodano's equation 7 above in the following form:

(12) $$Q_1 = (1-Q_2)\, x \; + (-Q_3)\, x^2.$$

Then, if $y = Q_1$, it is clear that equation 12 can be reversed to give x as a power series in Q_1 with the following coefficients:

$$A_0 = 1/(1-Q_2)$$

$$A_1 = -(-Q_3)/(1-Q_2)^3$$

Thus

(13) $$x = A_0 Q_1 + A_1 Q_1^2 + \ldots$$

or

(14) $$x = (1/(1-Q_2))\, Q_1 \; + (\, Q_3/(1-Q_2)^3\,)\, Q_1^2 \; + \ldots$$

or

(15) $$x = Q_1 \,\{\, 1/(1-Q_2) \; + \; Q_1 Q_3/(1-Q_2)^3 + \ldots\}$$

Next, expanding the $1/(1-Q_2)$ and $1/(1-Q_2)^3$ terms one obtains

(16) $$x = Q_1 \,\{(1 + Q_2 + Q_2^2 + Q_2^3 + \ldots) + Q_1 Q_3\,(1 + 3Q_2 + \ldots\,) + \ldots\,\}$$

or

(17) $$x = Q_1 \,\{1 + Q_2 + Q_2^2 + Q_1 Q_3 \ldots\,\}$$

which is Sodano's solution and where only products of Q_1, Q_2, and Q_3 to third order have been kept. Products of fourth order among the Q's, such as $3Q_1^2 Q_3 Q_2$ and $Q_1 Q_2^3$ have been dropped.

COMMENTS ON SODANO'S SOLUTION (Equation 17)

Because of the use of reversion of series, Bowring's objection does not apply to all terms in Sodano's solution. Further, it is not the size of x, but that of Q_2, which is subject to Bowring's remark that if $\theta > 1$ then expansion is invalid. It appears that this mixing of an expansion of $1/(1-Q_2)$ with the reversion of series technique is the reason that Sodano could say that the "condition of divergence did not affect all terms." The restriction (of $Q_2 < 1$) may therefore be completely removed if one is willing to use a numerical evaluation of a series reversion solution for x which does not also expand $1/(1-Q_2)$ and $1/(1-Q_2)^3$.

Sodano was well aware of the problem caused by antipodal geodesics and in giving his definitive formulae (Ref. 4, p. 72) he omitted presenting an antipodal procedure, and merely referenced his earlier paper (Ref. 1, pp.24-25). Clearly Sodano *never* intended his definitive formulae as given in reference 4 to be used for antipodal geodesics.

In Ref. 1, p. 25, Sodano gives, for antipodal geodesics, an expression for z for which he explicitly says: "the *denominator* of the expression *cannot be algebraically divided* into the numerator" (emphasis mine). The reason is the presence in the denominator of a term containing the quantity P, which is a function of cot σ and csc σ. For nearly antipodal lines, σ is almost 180° and the cotangent and cosecant functions, and therefore P, are growing large. Thus for the antipodal case, Sodano was recommending that, rather than make implicit use of a series expansion of the form $1/(1-\Theta) = 1 + \Theta + \Theta^2 + \ldots$, for large Θ, an unexpanded solution for x, which Sodano here calls z, be *numerically* rather than *algebraically* evaluated.

Thus it appears that, considering the capabilities of modern computers, it may be advantageous to use a direct *numerical* evaluation of x using unexpanded reversion of series terms in Q_1, Q_2, and Q_3. This would result in a Sodano-Helmert solution in which x is evaluated only once even when long antipodal geodesics are in question.

CONCLUSION

It has been shown that Sodano's solution (equation 8) can be easily and directly obtained from equation 7 by means of reversion of series.

Further, Bowring's critique of Sodano's solution for its use of expansions of $1/(1-\theta)$ when $\theta > 1$ does not refer to an expansion of $1/(1-x)$; rather it applies to an expansion of $1/(1-Q_2)$ and powers of it. Bowring's critique therefore only applies to those Sodano formulae which make use of such expansions in addition to the use of reversion of series.

Further, Sodano never intended his definitive formulae as presented in reference 4 to be used in calculating antipodal geodesics. Sodano did, however, give an alternate procedure (Ref. 1, pp. 24-25) by means of which, by use of *numerical* evaluation rather than algebraic expansion, antipodal geodesics could be accurately calculated.

Finally, we conclude that a more extensive numerical use of the reversion of series technique in solving for x would result in a single non-iterative numerical procedure of the Sodano-Helmert type not subject to the presently existing accuracy limitations for Sodano's standard formulae even when dealing with very long antipodal geodesic lines. The only limitations would then be considerations of numeric significance and the limitations inherent in the use of Helmert's integration of a truncated expansion of the kernel of the geodesic differential.

ACKNOWLEDGEMENT

I wish to thank Emanuel Sodano for reviewing this paper after it was written and for suggesting several improvements. The present author nevertheless is, and remains, responsible for any errors.

TABLE 1

Since the Aeronautical Chart and Information Center's (ACIC) references (8) and (9) are out of print and not easy to obtain, we here present a combined table of the ACIC standard test geodesic lines. ACIC carefully computed these lines for the Clarke 1866 ellipsoid, for which:

Semimajor axis a = 6,378,206.4000 meters
Reciprocal of flattening 1/f = 294.978698

The following table contains the initial position in latitude and longitude, followed by the forward azimuth, the length of the geodesic in miles and meters, and finally the latitude, longitude, and backward azimuth of the end position.

INITIAL POSITION			GEODESIC LENGTH OF LINE		POSITION OF GEODESIC ENDPOINT		
Lat.	Long.	Fwd. Az.	Miles	Meters	Latitude	Longitude	Back Azimuth
10°N	18°W	0°	50	80,466.478	10°43'39".078N	18°00'00".000W	180°00'00".000
40°N	18°W	0°	50	80,466.478	40°43'28".790N	18°00'00".000W	180°00'00".000
70°N	18°W	0°	50	80,466.478	70°43'16".379N	18°00'00".000W	180°00'00".000
10°N	18°W	45°	50	80,466.478	10°30'50".497N	17°28'48".777W	225°05'33".200
40°N	18°W	45°	50	80,466.478	40°30'37".757N	17°19'43".280W	225°26'01".695
70°N	18°W	45°	50	80,466.478	70°30'12".925N	16°28'22".844W	226°26'13".935
10°N	18°W	90°	50	80,466.478	9°59'57".087N	17°15'57".926W	270°07'38".786
40°N	18°W	90°	50	80,466.478	39°59'46".211N	17°03'27".942W	270°36'20".315
70°N	18°W	90°	50	80,466.478	69°59'15".149N	15°53'37".449W	271°58'45".079
10°N	18°W	0°	100	160,932.956	11°27'18".032N	18°00'00".000W	180°00'00".000
40°N	18°W	0°	100	160,932.956	41°26'57".248N	18°00'00".000W	180°00'00".000
70°N	18°W	0°	100	160,932.956	71°26'32".550N	18°00'00".000W	180°00'00".000
10°N	18°W	45°	100	160,932.956	11°01'37".857N	16°57'31".358W	225°11'24".056
40°N	18°W	45°	100	160,932.956	41°01'01".097N	16°38'49".777W	225°52'43".715
70°N	18°W	45°	100	160,932.956	70°59'37".295N	14°52'09".888W	227°57'04".162
10°N	18°W	90°	100	160,932.956	9°59'48".349N	16°31'55".877W	270°15'17".480
40°N	18°W	90°	100	160,932.956	39°59'04".850N	16°06'56".642W	271°12'39".796
70°N	18°W	90°	100	160,932.956	69°57'00".764N	13°47'32".949W	273°57'12".072
10°N	18°W	0°	200	321,865.912	12°54'35".538N	18°00'00".000W	180°00'00".000
40°N	18°W	0°	200	321,865.912	42°53'53".164N	18°00'00".000W	180°00'00".000
70°N	18°W	0°	200	321,865.912	72°53'04".295N	18°00'00".000W	180°00'00".000
10°N	18°W	45°	200	321,865.912	12°03'02".498N	15°54'36".649W	225°23'59".176
40°N	18°W	45°	200	321,865.912	42°01'02".610N	15°15'08".672W	226°48'12".147
70°N	18°W	45°	200	321,865.912	71°55'44".745N	11°25'02".986W	231°13'26".981
10°N	18°W	90°	200	321,865.912	9°59'13".405N	15°03'51".963W	270°30'34".337
40°N	18°W	90°	200	321,865.912	39°56'19".507N	14°13'59".336W	272°25'12".925
70°N	18°W	90°	200	321,865.912	69°48'05".702N	9°37'28".707W	277°52'01".046
10°N	18°W	0°	300	482,798.868	14°21'52".456N	18°00'00".000W	180°00'00".000
40°N	18°W	0°	300	482,798.868	44°20'47".740N	18°00'00".000W	180°00'00".000
70°N	18°W	0°	300	482,798.868	74°19'35".289N	18°00'00".000W	180°00'00".000
10°N	18°W	45°	300	482,798.868	13°04'12".564N	14°51'13".283W	225°37'46".346
40°N	18°W	45°	300	482,798.868	43°00'00".556N	13°48'49".111W	227°46'32".222
70°N	18°W	45°	300	482,798.868	72°47'48".242N	7°36'58".487W	234°50'49".050
10°N	18°W	90°	300	482,798.868	9°58'15".192N	13°35'48".467W	270°45'49".945
40°N	18°W	90°	300	482,798.868	39°51'44".295N	12°21'14".090W	273°37'32".768
70°N	18°W	90°	300	482,798.868	69°33'22".562N	5°32'01".822W	281°42'12".088
10°N	18°W	0°	400	643,731.824	15°49'08".725N	18°00'00".000W	180°00'00".000
40°N	18°W	0°	400	643,731.824	45°47'40".974N	18°00'00".000W	180°00'00".000
70°N	18°W	0°	400	643,731.824	75°46'05".589N	18°00'00".000W	180°00'00".000
10°N	18°W	45°	400	643,731.824	14°05'06".663N	13°47'18".635W	225°52'46".641
40°N	18°W	45°	400	643,731.824	43°57'50".690N	12°19'43".420W	228°47'59".982
70°N	18°W	45°	400	643,731.824	73°35'09".210N	3°26'35".190W	238°50'31".359
10°N	18°W	90°	400	643,731.824	9°56'53".751N	12°07'45".595W	271°01'03".684
40°N	18°W	90°	400	643,731.824	39°45'19".750N	10°28'46".813W	274°49'32".801
70°N	18°W	90°	400	643,731.824	69°13'03".648N	01°33'11".478W	285°25'45".725

INITIAL POSITION			GEODESIC LENGTH OF LINE		POSITION OF GEODESIC ENDPOINT		
Lat.	Long.	Fwd. Az.	Miles	Meters	Latitude	Longitude	Back Azimuth
10°N	18°W	0°	500	804,664.780	17°16′24″286N	18°00′00″000W	180°00′00″000
40°N	18°W	0°	500	804,664.780	47°14′32″867N	18°00′00″000W	180°00′00″000
70°N	18°W	0°	500	804,664.780	77°12′35″253N	18°00′00″000W	180°00′00″000
10°N	18°W	45°	500	804,664.780	15°05′43″367N	12°42′50″044W	226°09′01″224
40°N	18°W	45°	500	804,664.780	44°54′28″506N	10°47′43″884W	229°52′15″525
70°N	18°W	45°	500	804,664.780	74°17′05″184N	1°06′51″561E	243°13′18″356
10°N	18°W	90°	500	804,664.780	9°55′09″138N	10°39′43″554W	271°16′14″933
40°N	18°W	90°	500	804,664.780	39°37′06″613N	8°36′43″277W	276°01′06″634
70°N	18°W	90°	500	804,664.780	68°47′25″009N	2°17′23″583E	289°01′02″923
10°N	18°W	0°	1000	1,609,329.561	24°32′29″539N	18°00′00″000W	180°00′00″000
40°N	18°W	0°	1000	1,609,329.561	54°28′32″474N	18°00′00″000W	180°00′00″000
70°N	18°W	0°	1000	1,609,329.561	84°24′56″178N	18°00′00″000W	180°00′00″000
10°N	18°W	45°	1000	1,609,329.561	20°03′33″190N	7°10′22″015W	227°49′35″353
40°N	18°W	45°	1000	1,609,329.561	49°16′35″187N	2°19′56″359W	236°04′46″580
70°N	18°W	45°	1000	1,609,329.561	76°00′26″593N	28°42′03″634E	269°55′22″938
10°N	18°W	90°	1000	1,609,329.561	9°40′41″618N	3°19′52″797W	272°31′12″316
40°N	18°W	90°	1000	1,609,329.561	38°29′31″652N	0°34′31″140E	281°48′53″917
70°N	18°W	90°	1000	1,609,329.561	65°30′59″633N	18°55′21″211E	304°22′03″656
10°N	18°W	0°	3000	4,827,988.683	53°32′00″497N	18°00′00″000W	180°00′00″000
40°N	18°W	0°	3000	4,827,988.683	83°20′01″540N	18°00′00″000W	180°00′00″000
70°N	18°W	0°	3000	4,827,988.683	66°45′22″460N	162°00′00″000E	360°00′00″000
10°N	18°W	45°	3000	4,827,988.683	37°18′49″295N	19°34′07″117E	240°59′37″859
40°N	18°W	45°	3000	4,827,988.683	57°06′00″851N	45°08′40″841E	274°57′29″108
70°N	18°W	45°	3000	4,827,988.683	58°13′05″486N	95°02′29″439E	332°38′58″143
10°N	18°W	90°	3000	4,827,988.683	7°14′05″521N	25°48′13″908E	276°53′56″283
40°N	18°W	90°	3000	4,827,988.683	27°49′42″130N	32°54′13″184E	299°54′41″259
70°N	18°W	90°	3000	4,827,988.683	43°07′36″475N	52°01′00″626E	332°00′43″685
10°N	18°W	0°	6000	9,655,977.366	83°11′48″545N	162°00′00″000E	360°00′00″000
40°N	18°W	0°	6000	9,655,977.366	53°23′45″785N	162°00′00″000E	360°00′00″000
70°N	18°W	0°	6000	9,655,977.366	23°18′44″908N	162°00′00″000E	360°00′00″000
10°N	18°W	45°	6000	9,655,977.366	44°54′05″381N	77°25′26″869E	281°01′12″685
40°N	18°W	45°	6000	9,655,977.366	35°18′45″644N	102°02′29″821E	318°23′43″000
70°N	18°W	45°	6000	9,655,977.366	17°08′38″317N	114°18′43″800E	345°17′56″277
10°N	18°W	90°	6000	9,655,977.366	0°30′55″629N	68°47′05″259E	279°57′13″199
40°N	18°W	90°	6000	9,655,977.366	1°56′54″386N	69°27′01″115E	309°51′53″419
70°N	18°W	90°	6000	9,655,977.366	2°55′17″426N	70°50′04″891E	339°54′37″211

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BIOGRAPHY

Richard E. Keating has been an astronomer with the Time Service Department at the U.S. Naval Observatory (USNO) since 1965. Currently he is a staff member of the Time Service Precise Time and Time Interval (PTTI) Special Projects Division. He has been actively involved with the PTTI calibration of Loran-C transmissions for more than twenty-five years and has made PTTI Loran-C timing calibration expeditions to Loran-C transmitters in Cape Fear, North Carolina; Jupiter, Florida; Seneca, New York; Caribou, Maine; Okinawa, Japan; and Sylt, Germany. He also has been involved in the Observatory's portable atomic clock calibration service. As part of this, in 1971 he carried out the first round the world atomic clock timing experiment which detected special and general relativistic timing effects. As for astronomy, he worked with the Photographic Zenith Telescope for over twenty years to determine time and latitude. Since 1970, he has participated in the Observatory's Danjon Astrolabe Program, which from 1980-1987 did extensive contract astrogeodetic position work in support of the Defense Mapping Agency's Gravity Gradiometer Project and the MX missile program in Wyoming, California, New Mexico, and Oklahoma. Currently he is responsible for the technical aspects of, and computer programs used to reduce, Danjon astrolabe sights as part of a high precision (< 2 feet) astrogeodetic position determination project for the Dahlgren Naval Surface Warfare Center.

Ionospheric Propagation & Loran-C Range — The Sky's the Limit

David Last, Richard Farnworth & Mark Searle

Radio-Navigation Group, University of Wales,
Bangor, Gwynedd, United Kingdom

Abstract

Receivers for the Loran-C terrestrial radio-navigation system are designed to distinguish pulses received by groundwave propagation from skywave interference components which arrive later. However, the technique has significant limitations when implemented in receivers of finite bandwidth. The International Electrotechnical Commission, and other authorities, specify minimum standards of receiver performance in this respect. Drawing data from a range of sources, including Decca Navigator records, the paper proposes methods of predicting skywave--to-groundwave ratio and skywave delay, the key elements of these specifications. This information is used to calculate Loran-C range limits due to skywave interference at various times and seasons, considering individual transmitters and both present and proposed chains. The results demonstrate that the use of high transmitter powers is generally not justified. The paper points out ambiguities in the current minimum performance standards for receivers. It demonstrates that they are inadequate to protect users against the effects of skywave interference and identifies areas in which improved specifications are required.

1 Introduction

Loran-C is a terrestrial, low-frequency, hyperbolic radio-navigation system which serves nearly one million users, principally in North America [1-3]. New chains of Loran transmitters are being planned or constructed in various areas of the world including North-West Europe, the United States, China, India and South America [4,5].

This expansion has focused attention on the methods used to predict the coverage of Loran-C chains. Traditional techniques, principally developed by the US Coast Guard (USCG), only consider the minimum acceptable signal-to-atmospheric noise ratio and the maximum geometrical dilution of precision [6,7]. This approach has been shown to be inadequate under European conditions because of its failure to take into account the exceptionally-high European levels of carrier-wave interference [8].

A computer model has been developed and used to predict the coverage and performance of the North-West European Loran-C chains [9]. In determining the boundaries of satisfactory operation, the limiting factors it considers are those of the US Coast Guard and, in addition, carrier-wave interference [8,10,26] and envelope-to-cycle difference [11].

Another potential coverage-limiting factor included in the computer model is the skywave effect: the interference which unwanted ionospherically-propagated components of the signal cause to the wanted groundwave-propagated signal. This paper describes and explains the techniques developed to estimate skywave interference in a systematic way. The model predicts the limits which skywave imposes on the operational coverage of individual Loran-C stations and complete systems.

Section 2 of the paper will show how a Loran-C receiver distinguishes between groundwave and skywave components. It will discuss the practical limitations of this technique and how minimum performance standards for receivers deal with these limitations in terms of the delay and strength of the skywave components relative to the groundwave.

Section 3 will describe the techniques used by the computer model to calculate and map the severity of skywave interference effects. It will show how the field strengths of the skywave and groundwave signals and their relative delay are estimated. Section 4 interprets the results for individual stations and Section 5 for Loran-C chains.

The study of skywave effects has revealed short-comings in the current minimum performance specifications for Loran-C receivers; these will be discussed in Section 6. The concluding section, Section 7, will consider the implications of this study for Loran-C operation and identify the requirement for improved specifications.

2 Skywave rejection by Loran-C receivers

This Section will describe how Loran-C receivers distinguish between groundwave and skywave components. The technique will be shown to have

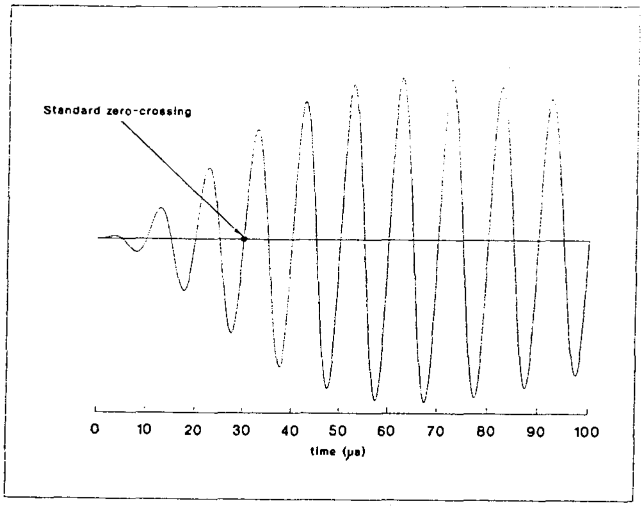


Fig. 1 Pulse shape of Loran-C transmissions. The time reference point is marked "standard zero-crossing".

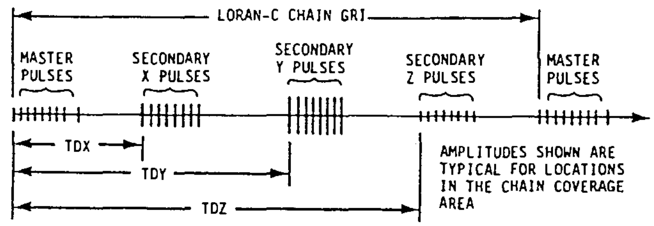


Fig. 2 Sequence of transmissions of pulses by the stations of a Loran-C chain. The master station radiates a pulse group, followed by each secondary. The transmissions are separated by precise time delays (after [25]).

significant limitations when implemented in receivers of finite bandwidth. Minimum receiver performance standards which address these limitations will be examined.

2.1 Loran-C transmission characteristics

Loran-C employs pulsed transmissions (Fig. 1). The pulses are bursts of 100 kHz signal of precisely-defined carrier phase and envelope shape. Each of the stations which constitute a Loran chain radiates a group of such pulses (Fig. 2) in a precise time-sequence. The interval between the groups of pulses from any station is the Group Repetition Interval (GRI), a time between 40 and 100 ms which characterises and identifies that chain.

A Loran-C receiver measures the time differences between the arrivals of corresponding pulses from pairs of stations and uses these measurements to compute its own position. Traditionally the timing point on each pulse is the "standard zero-crossing" (Fig. 1), the third positive-going zero-crossing of the 100 kHz carrier, 30 μs after the start of the pulse. The receiver distinguishes this particular zero-crossing by identifying the corresponding point on the pulse envelope which has the appropriate gradient.

2.2 Principle of rejection of skywave signals

It is assumed that Loran-C signals travel from the transmitters to the receiver as groundwaves. However, signal components also reach the receiver by means of ionospheric propagation. Because these skywave components travel via longer paths, they normally arrive at least 35 μs after the groundwaves. The receiver is presented with the sum of skywave and groundwave (Fig. 3a); however, the standard zero-crossing precedes the earliest skywave component. Thus, the receiver makes its time measurement on the groundwave pulse prior to the arrival of the skywave components.

This protection against skywave interference is a major advantage of Loran-C over continuous-wave navigation aids such as the Decca Navigator System (DNS), which operates in the same radio frequency band. The operational range of Decca is severely limited by the inability of its receivers to distinguish groundwave signals from skywave. Consequently, a single Loran-C chain can serve the same area as many DNS chains.

2.3 Limitations of skywave rejection capability

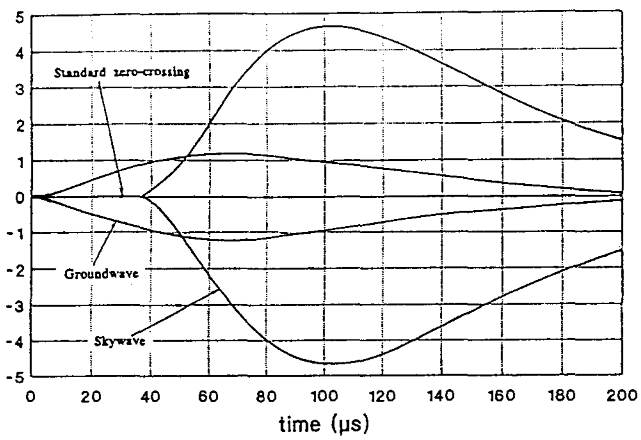
In practice, Loran-C receivers are limited in their ability to identify the standard zero-crossing in the presence of strong skywave signals, especially those of short delay. The finite bandwidth of the filters in a Loran-C receiver increases the rise-time (Fig. 3b). The amplitude of the third cycle is greatly reduced. A later zero-crossing must be selected, after the arrival of the skywave component. The narrower the filter, the greater the rise-time and so the greater the susceptibility of the receiver to skywave interference. In practice, receiver designs are a compromise between filter bandwidth and skywave tolerance.

Fig. 3 shows that both the amplitude and the delay of the skywave signal determine the interference which it causes. These, essentially independent, parameters are cited in published specifications for Loran-C receivers.

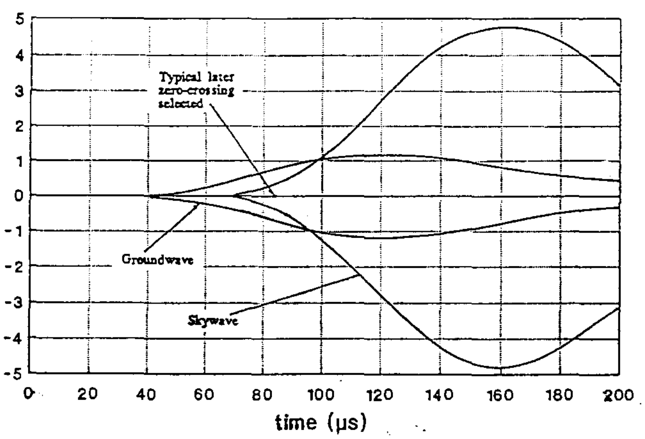
2.4 Minimum performance specifications (MPS)

The International Electrotechnical Commission (IEC) specification for the minimum skywave rejection capability of Marine Loran-C Receiving Equipment [12] states that:

"The receivers shall distinguish between signals received by ground or sky waves in the service area



(a)



(b)

Fig. 3 A Loran-C groundwave pulse followed, 37.5 μs later, by a skywave pulse 12 dB stronger, (a) as received, and (b) after passing through a typical receiver band-pass filter.

and shall adequately suppress contamination by sky wave expected with a 99% confidence while tracking the normal zero-crossing. The combined accuracy shall not be degraded outside the minimum requirements of this standard for combinations of sky wave defined in Appendix B."

Appendix B states, *inter alia:*

"The receiver shall lock on in the presence of sky-wave interference with delays from 37.5 μs to 60 μs with relative sky-wave signal levels from 12 dB to 26 dB respectively."

This range of operating parameters is represented by Region X of Fig. 4.

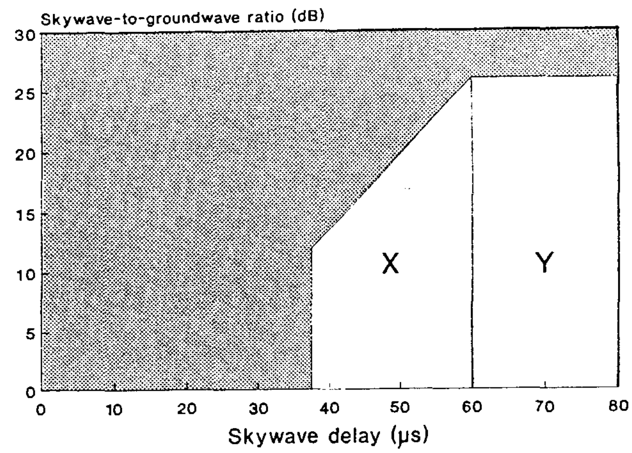


Fig. 4 Minimum performance specifications. The receiver must operate correctly with skywave-to-groundwave ratio and skywave delay in region X. Extended specification, Region Y, is used in the analysis presented.

The Minimum Performance Standards for Marine Loran-C Receiving Equipment of the US Radio Technical Commission for Marine Services (RTCM) [13] are numerically identical to Appendix B alone of the IEC specification, with the following addition:

"Nothing in this MPS implies that skywave levels in excess of 94 dB/1μV/m need be considered."

2.5 Coverage area reduction due to skywave interference

The skywave performance limits of the IEC and RTCM MPS result in a finite operating region around each transmitter. The reason is that, at ranges from the transmitter of between 100 and 2000 km, the rms skywave intensity under given conditions is substantially independent of range, while groundwave intensity falls with distance. Thus the skywave-to-groundwave ratio (SGR) increases with distance until the MPS limit is reached.

The USCG technique for Loran-C chain coverage prediction ignores skywave interference. The inadequacy of the method is clearly illustrated by evidence that skywave interference causes unacceptable errors, within published coverage areas, such as those reported off the south-east coast of Newfoundland when signals from the Angissoq, Greenland station of the Labrador Sea chain are received [14].

This paper will now examine the factors which determine the SGR and the skywave delay. The analysis will then be employed to estimate the range of acceptable operation of Loran-C stations and the coverage of chains at various times of the day and seasons of the year.

3 Estimation of the magnitude of skywave interference parameters

A computer model has been written to calculate and map the severity of skywave interference effects. This section will describe the techniques which the model employs to estimate the field strengths of the groundwave and skywave signals and their relative delay.

3.1 Ground-wave field strength

The techniques for estimating the field strengths of low-frequency radio signals are well established. Bremmer [15] and Norton [16] have published families of curves which show the groundwave attenuation with range over surfaces of various values of conductivity and permittivity. Millington [17,18] has developed a method of dealing with inhomogeneous paths. CCIR Report 717-2 describes these techniques in full [19].

A computer model has been developed for mapping the groundwave field strengths of Loran-C transmitters [9]. It incorporates a database of ground conductivity values, at intervals of 0.1° of latitude and longitude (11 km x 7 km, typically), which covers much of Europe. The CCIR method is used to estimate field strengths point-by-point throughout a large geographical array of locations.

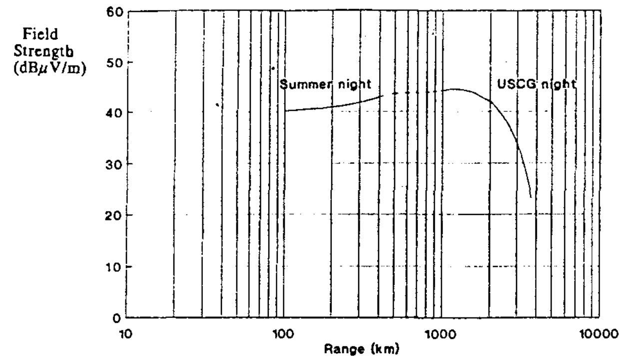
3.2 Skywave propagation

Skywave propagation of Loran-C signals is by ionospheric refraction in the D and E layers. The intensity of ionisation, and hence the effective height of the ionosphere, vary seasonally and diurnally; the average effective height is approximately 73 km by day and 91 km at night. The skywave field strength depends upon the reflection coefficient of the ionosphere; its average values are 0.05 by day and 0.25 at night. Skywave field strength is least during summers' days and greatest on winters' nights.

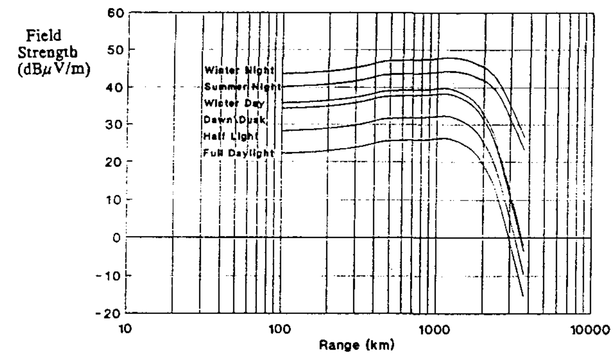
3.3 Skywave field strength

The USCG publish curves of rms skywave intensity at ranges of 1000 to 3700 km for night (Fig. 5a) and for day. Unfortunately, these curves do not distinguish between winter and summer conditions. Further, they ignore ranges of less than 1000 km at which the skywave intensity may be significant. Van Etten [20] has published results which agree well with the USCG curves.

A rich source of additional information on skywave intensities at shorter ranges is the literature on the Decca Navigator System. The frequencies, and hence the propagation characteristics, of Decca signals are similar to those of Loran-C. Skywave interference is the principal limitation to Decca coverage and detailed statistics have been recorded. Sanderson [21] shows theoretical curves of rms skywave intensity at ranges from 100 to 500 km for various ionospheric reflection coefficients. The Decca Navigator Company also publish tables of



(a)



(b)

Fig. 5 Variation of skywave intensity with range (a) Decca "Summer night" and "USCG night" curves combined to form a composite summer night curve, and (b) a set of composite curves for all time periods. A 1 kW transmitter is assumed.

experimentally-derived values [22]. Decca break down their results by time and season (Fig. 6) into the following periods: full daylight, half light, dawn/dusk, summer night and winter night. The Decca time periods were chosen as having the rms skywave intensities, relative to those on summer nights, shown in the "Decca strength" column of Table 1.

When the Decca and USCG results are compared, the "USCG night" curve corresponds well with the Decca "Summer night" curve (Fig. 5a). It is reasonable to produce a composite curve from the two sources by interpolating the 0.4 dB-wide gap between the Decca 500 km level and the USCG 1000 km one. This "Summer night" curve then covers ranges from 100 to 3700 km. Its shape is the "Night" shape, referred to in Table 1. The "Winter night" curve has this same shape but is 3 dB stronger than summer night, as in Decca practice.

A new time period, "Winter day", has been introduced. The 1000-3700 km portion of the winter day curve in Fig. 5b is simply the USCG day curve. At 1000 km range the strength is seen to be 4 dB below the

"Summer night" curve. This difference has been maintained for ranges from 100 to 1000 km. The shape of this curve is the "Day" shape referred to in Table 1. The "Dawn/Dusk", "Half Light" and "Full Daylight" curves have this shape and are spaced in accordance with Decca practice.

The values of skywave intensity used in the computer model are calculated from these curves.

Time period	Decca strength with respect to Summer night (dB)	1000 km strength with respect to Summer night (dB)	Shape
Winter night	+3	+3	Night
Summer night	0	0	Night
Winter day		-4	Day
Dawn/dusk	-6	-6	Day
Half light	-12	-12	Day
Full daylight	-18	-18	Day

Table 1. RMS skywave interference levels and shapes of curves shown in Fig. 5b.

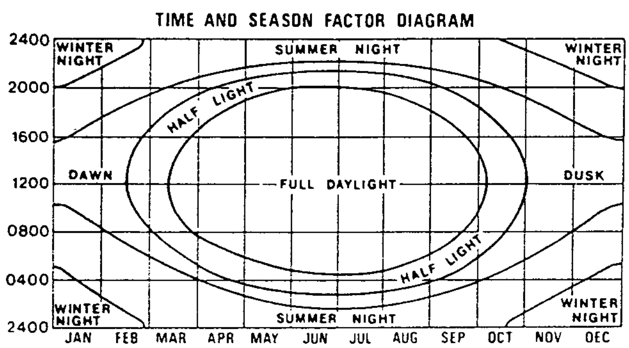


Fig. 6 Decca Navigator time and season factor diagram showing periods of different skywave intensities. Latitude is 52°N, (after [23]).

Short-term variations of skywave intensity are Rayleigh distributed [22]. The levels shown in Fig. 5 are rms values. Unfortunately, both the IEC and the RTCM are silent on the question of whether rms or higher levels of skywave intensity should be used in interpreting their specifications. A decision was made to use in the analyses which follow that value of interference which is reached 1% of the time. This issue will be discussed further in Section 6.1.

3.4 Skywave delay

Skywave delay is the time difference, measured at the receiver, between the arrival of a point on the groundwave pulse from a transmitter and the corresponding point on the first skywave component. At short ranges the delay will be considerable, since the skywave pulse has travelled an additional distance of nearly twice the effective height of the ionosphere. The delay falls as range increases.

From circular geometry it can be shown that the skywave delay:

$$t = \frac{2}{c}\left\{\left[h^2 + 4R(R+h)\sin^2\frac{\beta}{2}\right]^{1/2} - R\beta\right\} \qquad (1)$$

where c is the velocity of EM waves ($3 \times 10^8\ ms^{-1}$),

h is the effective height of the ionosphere,

R is the Earth's radius (6368 km), and

β is the half-angle subtended at the centre of the Earth by the transmitter and receiver; that is,

$$\beta = D/2R$$

where D is the range of receiver from transmitter.

Fig. 7 shows curves of skywave delay with range for typical day-time and night-time effective ionospheric heights, 73 and 91 km, calculated using equation (1). The results correspond closely with Van Etten's curves for heights of 70 and 90 km [20].

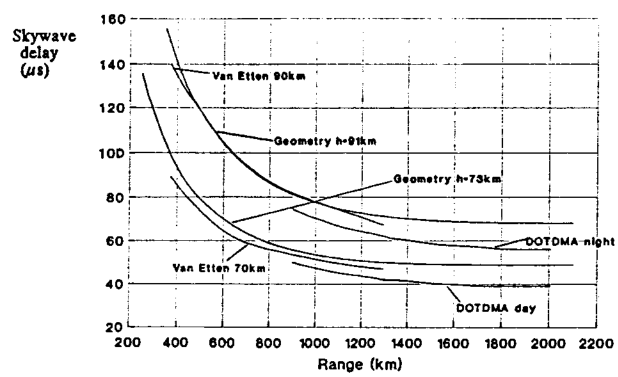


Fig. 7 Variation of skywave delay with range. The "Geometry" curves are calculated. The "DOTDMA" curves are derived from US Department of Transport tables. "Van Etten" curves after [20].

Experimental data on Loran-C skywave delays may be culled from tables published by the US Department of Transport Defense Mapping Agency (DOTDMA). These show time-difference corrections to be applied when navigating by means of a skywave signal from one transmitter and a groundwave signal from another. Thus they represent the additional delay due to the ionospheric path. The "DOTDMA" curves in Fig. 7 have been derived by fitting polynomials to tabulated data for the Norwegian Sea chain.

Fig. 7 shows that the simple geometrical model gives a correct trend of skywave delay. However, the DOTDMA figures are some 6 μs less than the calculated values. These experimental curves, being based upon observation, have been chosen for use in the analysis.

3.5 Skywave effects on receiver operation

The techniques described in sub-section 3.1 are used by the computer model to predict the groundwave field strength at each point in the geographical array. The range of the point from the transmitter is also computed and used to estimate the skywave field strength for the time and season of interest, in accordance with Fig. 5. Thus the skywave-to-groundwave ratio is calculated. The skywave delay is estimated, using the method of sub-section 3.4, from the range and time of day.

The two parameters, SGR and skywave delay, are now compared with the MPS limits (Fig. 4). This determines whether the skywave interference is within the acceptable range. If so, the point is deemed to lie within coverage. Note that the IEC MPS, although stating that skywave delays can vary from 25 to 1500 μs, is unfortunately silent as to what maximum SGR is acceptable for delay values greater than 60 μs (region Y of Fig. 4). In this analysis the SGR has been kept at 26 dB. This question is discussed in Section 6.2.

4 Results for single stations

4.1 Limiting ranges

Skywave interference sets a range limit for each ground conductivity value and each time period. These limits are independent of the power of the transmitter since changes in power level affect groundwave and skywave field strengths equally.

Table 2 shows these range limits, estimated for all times and seasons.

The results shown in Table 2 are surprising: it is widely understood that skywave intensities are greatest during winter nights; certainly Decca ranges are least then. Yet Table 2 shows that, unless the path conductivity is exceptionally low, the shortest Loran-C ranges are achieved on winter days. Figs. 4 and 7 show the reason. The effective height of the ionosphere is less by day than at night and so the skywave delay is less and the reduction of skywave intensity by day is outweighed by this shorter delay.

Conductivity mS/m	Full Daylight	Half Light	Dawn/ dusk	Summer night	Winter day	Winter night
5000	4000	1900	1430	1675	1390	1450
10	3000	1650	1280	1520	1230	1350
5	1650	1380	1150	1280	1080	1150
1	1250	1050	950	930	920	870
0.1	680	585	490	410	460	370

Table 2. Range limits, in km, of single stations, due to skywave interference, over paths of different conductivity types. These limits will be reached 1% of the time.

The range of Decca, in contrast, depends on intensity alone, so its range is least during winter nights.

4.2 Comparison of skywave and SNR limits of coverage

The range of a Loran-C station is conventionally taken to be the distance at which the SNR falls to a limiting value [2]. The USCG assume the noise to be solely atmospheric noise and calculate the level which will not be exceeded more than 5% of the year. They also set a minimum SNR of -10 dB; thus the signal level which determines the station's range limit is 10 dB below this atmospheric noise level for the region.

In North-West Europe, however, it has been shown that it is carrier-wave interference (CWI), not atmospheric noise, which determines the SNR range limit of Loran-C stations. In order to adjust the USCG approach to European conditions, a high value of noise, 61 dBμV/m, has been adopted for use in place of the atmospheric noise. Table 3 compares the range limits set by skywave and by European SNR. The skywave conditions are those of the worst time and season, winter day or winter night, as appropriate. The transmitter power is 1500 kW, the highest value of peak envelope power for Loran-C stations in Europe:

Type of path	Conductivity mS/m	Range limit (km) Skywave	SNR
Sea water	5000	1390	1670
Good soil	10	1230	1520
Cultivated ground	5	1080	1335
Poor soil	1	870	960
Extremely poor	0.1	370	390

Table 3. Range limits of single stations, due to skywave interference (under worst-case conditions) and to signal-to-noise ratio, over paths of various values of conductivity. The transmitter power is 1500 kW (the power of Sandur), the noise level 61 dBμV/m and the minimum SNR -10 dB.

The results are interesting: it is skywave interference, and not SNR, which determines the maximum operating range of this station. Further, had the dominant noise been atmospheric, the SNR-limited range would have been greater and so skywave would have reduced the coverage even more.

4.3 Maximum transmitter power levels

While the skywave range limit is independent of the power of the transmitter, the SNR limit is not. The more powerful the transmitter, the greater the SNR range limit. It follows that, having decided on the noise value to be employed in planning coverage, and knowing the ground conductivity, a maximum transmitter power level can be established. This power (Table 4) will ensure that the SNR limit coincides with the skywave interference limit over the path of poorest conductivity.

Type of path	Conductivity mS/m	Range limit (km)	Power (kW)
Sea water	5000	1390	400
Good soil	10	1250	400
Cultivated ground	5	1080	400
Poor soil	1	870	700
Extremely poor	0.1	370	1250

Table 4. Transmitter power which gives coincident range limits due to skywave interference and SNR over paths of various values of ground conductivity. The noise level is 61 dBμV/m and the minimum SNR -10 dB.

Table 4 shows that the range limits due to winter day skywave and to SNR are both 1390 km over an all-seawater path, when the transmitter power is 400 kW. Paths of poorer conductivity would justify the use of more powerful transmitters; for example, 1 mS/m conductivity would require 700 kW. However, if the noise were less (as in temperate maritime regions outside Europe), even lower-powered transmitters would be required. For example, when the noise level is 51 dBμV/m, the SNR and skywave range limits of a 40 kW transmitter are both 1390 km.

The use of more powerful transmitters than those indicated will not ensure reliable Loran-C coverage at all times of day and seasons of the year.

5 Results for specific Loran-C chains

In predicting the coverage of complete Loran-C chains, the USCG method establishes whether signals of adequate SNR are available [2]. For conventional hyperbolic operation these must originate from a master and two secondaries of the same Loran-C chain. Additionally, the geometry must ensure that the dilution of precision is acceptable.

Introducing the skywave interference factor imposes the further condition that the SGR and skywave delay must lie within the MPS limits. The computer checks this requirement at each array point in the previously-computed coverage. The effect of skywave interference on the coverage of two Loran-C systems will now be demonstrated. The skywave intensity employed will again be that which is reached for 1% of the time.

5.1 Norwegian Sea chain

The Norwegian Sea chain is one of the two Loran-C installations currently operated by the US Coast Guard in Europe. Fig. 8 shows the coverage published by the USCG, as the outer dot-dashed line. When the noise is assumed to be 61 dBμV/m, the coverage is as shown by the solid line. The dashed line shows the boundary set by skywave interference under the worst (winter day) conditions. It defines the region within which a receiver, which just meets the MPS, will experience unacceptable skywave interference for less than 1% of the time.

The lessons regarding transmitter powers are also clearly illustrated in Fig. 8: the reduction in winter coverage over the British Isles is solely due to the diminished range of the exceptionally high-powered, 1500 kW, station at Sandur, Iceland.

5.2 North-West European System

Fig. 9 illustrates the predicted coverage of a proposed Loran-C system of 4 chains for North-West Europe. The noise level is assumed to be 61 dBμV/m. There is no part of this coverage within which a receiver of minimum performance will experience unacceptable skywave interference for more than 1% of the time.

This is in marked contrast to the situation shown in Fig. 8. The reason is that none of the stations of this new configuration has a power level in excess of 400 kW, the limiting value shown in Table 4. Also, in order to minimise carrier-wave interference problems, the stations are rather closer together and the signal levels higher than those of the Norwegian Sea chain. Thus the distances of receivers from transmitters are generally less, which reduces skywave effects.

6 Discussion of Minimum Performance Standards

The results presented in Sections 4 and 5 above call into question the adequacy and clarity of the Minimum Performance Specifications for Loran-C receivers.

6.1 Skywave probabilities

The RTCM MPS requires the receiver simply to "lock-on" to the transmissions under the conditions of skywave interference represented by region X of Fig. 4. The IEC MPS requires it to do so with 99% confidence. The boundary conditions of region X have been used in the analysis above to determine the

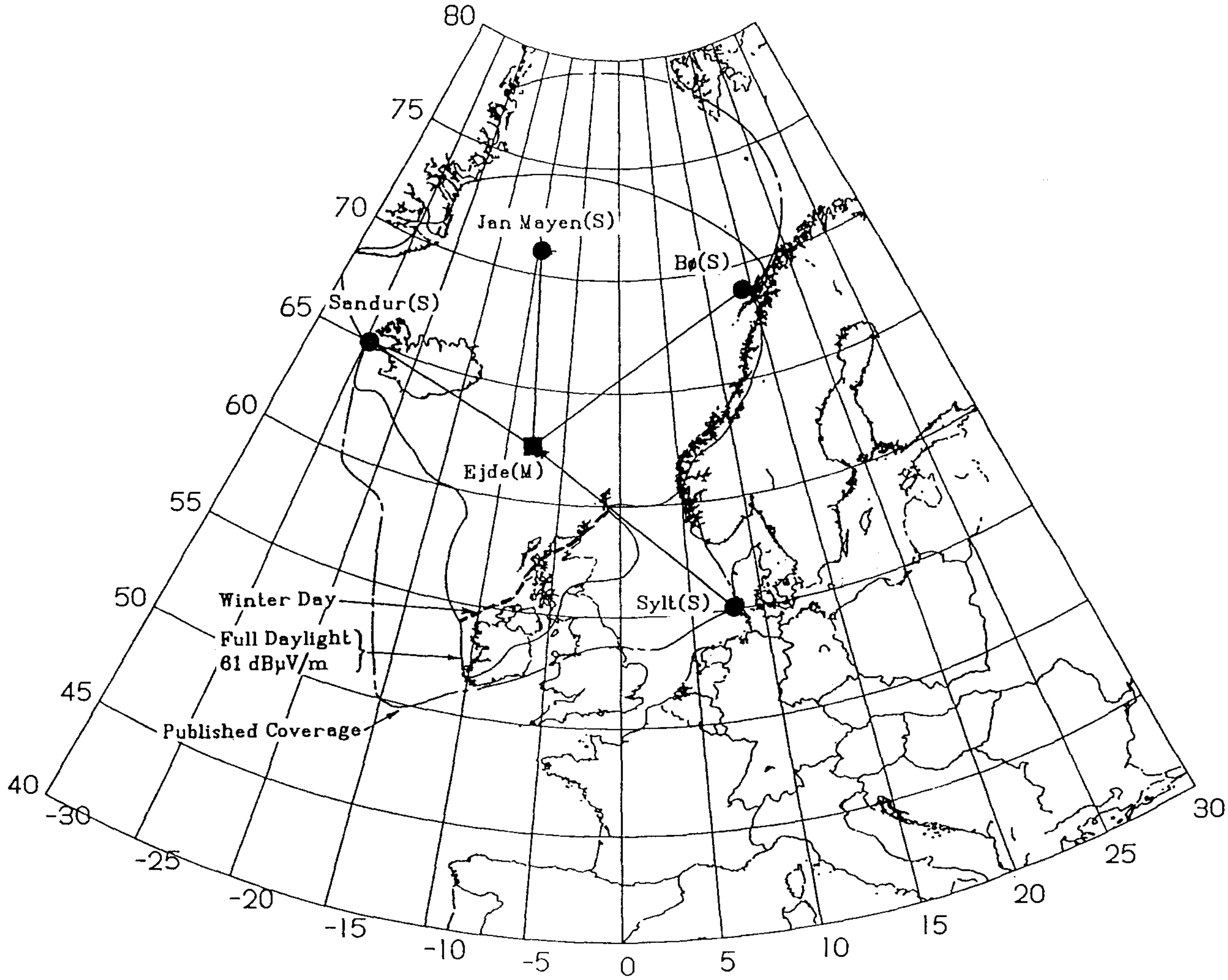


Fig. 8 Coverage of the Norwegian Sea Loran-C chain; (M) and (S) indicate master and secondary stations. The solid line is the boundary set by carrier-wave interference. The boundary due to skywave interference, reached for 1% of the time during winters' days by receivers of minimum performance, is marked as a dashed line. The dot-dashed line is the published coverage.

limits of the service area of each individual transmitter and chain. The positions of the boundaries, however, also depend upon the arbitrary decision (Section 3.3) to use in the analysis that value of skywave field strength which is reached only 1% of the time. The corresponding field strength is 7 dB above the rms value for the period in question.

Thus, at the range limit, the receiver should lock-on to the correct cycle of the transmission 99% of the time according to the RTCM MPS, or approximately 98% of the time (0.99 x 0.99) according to the IEC.

Neither specification offers any guidance regarding receiver operation outside region X of Fig. 4. In practice it is probable that receivers will continue to work under higher levels of skywave interference, but lock less reliably. Further, we cannot determine the probability that a receiver which just meets the IEC specification under limiting conditions will lock correctly under more favorable circumstances. This makes it impossible, on the basis of the two MPS, to predict the probability of correct locking under specific conditions of skywave delay and SGR.

6.2 Skywave delays of more than 60 μs

Both the IEC and the RTCM specifications state conditions under which the receiver shall work (Fig. 4). The maximum value of skywave delay cited is 60 μs. In practice, greater skywave delay values are encountered; neither specification states whether the receiver should withstand this skywave interference and, if so, up to what maximum SGR. Should the upper boundary of region Y of Fig. 4 be infinite, an extrapolation of the slope from 12 to

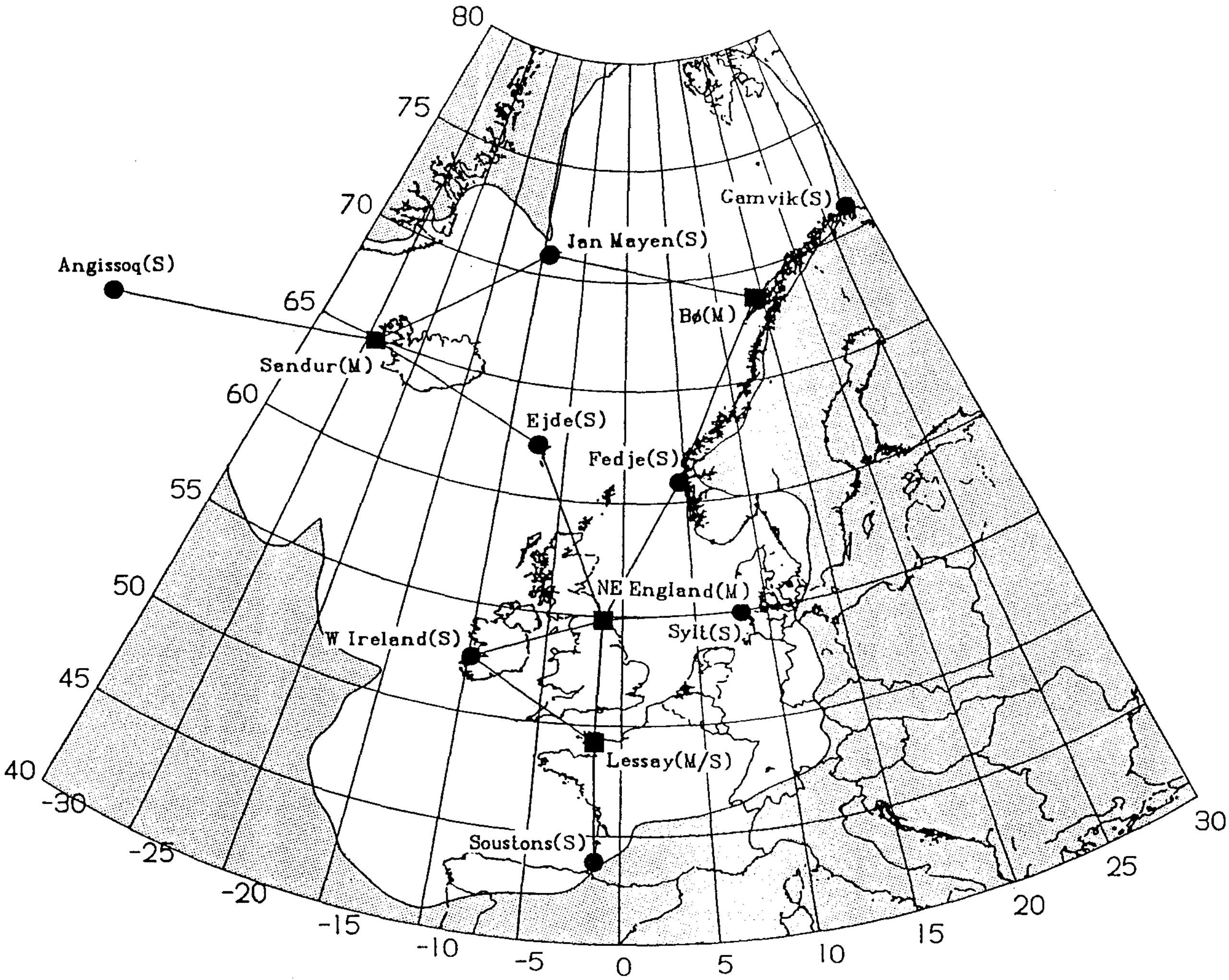


Fig. 9 Coverage of the planned Loran-C system for North-West Europe. There is no part of this coverage within which a receiver of minimum performance will experience unacceptable skywave interference for more than 1% of the time.

26 dB, or level at 26 dB? This important question needs to be addressed. In the analysis (Section 3.5) we chose to set the boundary at 26 dB.

6.3 Adequacy of the Minimum Performance Specifications

Fig. 8 demonstrates that skywave interference limits the coverage of the Norwegian Sea Loran-C chain at certain times of the year, even when receivers which meet the MPS are employed. That is, the MPS is an inadequate specification for guaranteeing satisfactory operation throughout the published coverage of an existing chain. In practice, receivers do fail to lock correctly under winter conditions in regions between the dashed and solid boundaries of the coverage of this chain shown in fig 8. It has been suggested that these failures could be due to synchronous carrier-wave interference, enhanced by skywave propagation. However, the Canadian results (Section 2.5), recorded in an area almost devoid of synchronous CWI, exhibit similar failures due to Loran-C skywave signals.

6.4 Adequacy of conventional coverage prediction models

Given that the MPS is inadequate to ensure reliable operation of Loran-C receivers throughout the coverage of Loran-C chains predicted by current techniques, it is essential to replace those methods by others which take into account the receiver MPS specified by the IEC and RTCM. This has been done in North-West Europe (Section 5.2). The analysis of the proposed system demonstrates that, within the boundaries shown, a correctly-designed set of chains should provide reliable operation even under winter skywave conditions.

7 Conclusions

Although Loran-C is a system designed to allow its receivers to distinguish between skywave and groundwave signal components, their ability to do so is limited. The principal restrictions are due to the finite rise-times of signals which have passed through the receiver bandpass filters. Both the IEC and the RTCM impose minimum performance specifications on the skywave rejection capabilities of receivers. They require them to operate reliably over a range of skywave-to-groundwave ratio and skywave delay values.

Techniques have been described which allow these two parameters to be estimated. The methods are based on USCG, DOTDMA and Decca Navigator sources. The results allow us to predict the limits imposed by skywave interference on the ranges of individual transmitters. These limits have been shown to depend on the conductivity of the ground and the time and season. An unexpected result, that skywave interference is most severe in day-time and not at night during winter, has been found to be due to the high sensitivity of receiver performance to skywave delay. By comparing the range boundaries due to skywave with those determined by SNR, an upper limit may be set to the useful power output of any Loran-C transmitter station. This maximum value is shown to be a function of the ground conductivity and the level of noise in the operating area.

Applying the predicted levels of SGR and skywave delay to the existing Norwegian Sea chain has shown that there is a large area of published coverage within which receivers which meet the MPS will fail to operate reliably under conditions of skywave interference. In contrast, the proposed North-West European system, which uses lower-powered transmitters separated by shorter baselines, has negligible levels of skywave interference.

Examining the implications of the IEC and RTCM standards in this way demonstrates their inadequacy to protect the users of receivers against skywave problems within the coverage of existing chains. It also shows the necessity to take the minimum skywave performance of receivers into account in predicting the coverage of Loran-C chains. This process is not made easier, however, by the incompleteness of the specifications nor by contradictions between the requirements of different authorities.

8 Acknowledgements

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

Richard Farnworth graduated from the University of Wales, Bangor in 1988. He is currently working towards a Ph.D. on Loran-C coverage prediction techniques.

Dr. Mark Searle was awarded the degrees of B.Sc., M.Sc. and Ph.D. by the University of Manchester, England in 1985, 1986 and 1989, respectively. He is employed as a Post-doctoral Research fellow working on Loran-C studies, including coverage prediction and additional secondary factor mapping techniques, at the University of Wales, Bangor.

Modeling and Forecasting Time Difference Variations for Aviation

Frank Coyne, A. Chris Daskalakis, & Ian McWilliams

Department of Transportation
Research and Special Programs Administration
Volpe National Transportation Systems Center
National Field Office for Loran Data Support
Kendall Square, Cambridge, MA, 02142

ABSTRACT

The Federal Aviation Administration (FAA) installed a network of 196 Loran monitors across the continental United States (CONUS) and Alaska. Data from this network is combined with other historical Loran data and information on climate and terrain to make a database for modeling Loran Time Difference (TD) variations. This paper presents the FAA's methodology in forecasting TD corrections across wide-ranging conditions for Loran Standard Instrument Approach Procedures (SIAPs).

1. INTRODUCTION

The FAA is rapidly making SIAPs available to airports and pilots across the contiguous United States and Alaska. The continued success of this effort depends strongly on the FAA's ability to forecast accurate TD corrections, adjustments made necessary due to seasonal meteorological and barometric effects on Loran's low-frequency signals. TD corrections reduce the MOPS error allowance for seasonal variation from .75 μsec (with no updates) to .15 μsec. A lower system error increases the availability of a Loran nonprecision approach. Since the FAA began its first major Loran integration effort with the Early Implementation Project (EIP) in 1984, it has developed and tested several methods of TD correction.

The EIP featured two methods of forecast: linear and non-linear regression. The original linear regression method spanned a 7-day period and related corrected TD values and time; it reduced to near zero the error budget for seasonal variations. The algorithm made use of 168 hourly averages, fitting them to a trend line using least squares criteria to find the slope and intercept. Then the trend line was extrapolated into the middle of the week to be forecast. Pilots thus could accurately adjust their Loran receivers for a given week.

Though this 7-day method successfully provided accurate weekly forecasts for EIP approaches, the FAA and the user community found it impractical to calculate and disseminate forecasts every week. Soon the FAA developed a forecast method coinciding with its approach plate update schedule. Since the seasonal behavior of Loran TDs is sinusoidal, the FAA used a least squares approximation of the trend curve (then with at least six months' data) to find coefficients for the sinusoids. Then they reconstructed the trend curve, extended it into the following 56 days, and drew the forecast from its midpoint. Using these values, the FAA performed successful Loran SIAPs well within error limits specified in the Minimum Operation Performance Standards (MOPS) (see Bibliography).

To expand Loran's use as a SIAP beyond the EIP, the FAA determined the number of operational monitors needed to support SIAPs throughout the contiguous United States. The FAA range of validity study--an examination of data records at five FAA monitors and five U.S. Coast Guard (USCG) Harbor Entrance Project (HHE) sites in the Northeastern U.S.--showed that a 90-mile radius was a monitor's accuracy range of predicting seasonal TD trends. The study also fostered development of a TD correction method using a multiple regression technique and several site-related constants, e.g., latitude, range to secondary, and double range difference. The technique proved accurate, if complex.

The search for a simpler, straightforward alternative uncovered a variation on the Fourier method, based on the assumption that the seasonal variation of all baselines has the same shape. Variations from site to site exhibit differences in amplitudes, or peak-to-peak variations. Data from the Loran monitor at South Bend, Indiana--the EIP site with the widest amplitude variation--was used to create a generic function.

This function, formed using the two largest Fourier coefficients generated from the data, became the seasonal trend model for all other sites. Using six months' normalized data from this function and data from a monitor site, NFOLDS staff performed a linear regression. The slope of the regression line gives the ratio of the TD amplitudes of the site versus the generic function. The intercept gives the yearly average term. The two Fourier coefficients from the function, with the slope and intercept, allow NFOLDS analysts to form the trend curve and forecast a TD for the site at any time of year. This technique has proved very accurate in predicting expected results from adjacent LAMs.

2. DATA SOURCES

This paper examines what NFOLDS calls the "Fast Fourier method" of forecasting TDs using short-term (24 hours) data. NFOLDS employed this method using data taken at various times of the year from three sources:

1. Operation monitors (LAMs, for Loran Area Monitors)
2. Twenty airports nationwide, collected by the VNTSC mobile test facility
3. USCG HHE and FAA EIP monitor sites.

NFOLDS analysts matched three types of average data from the USCG HHE and the FAA EIP according to type: 10-minute, 4-hour, and 6-hour. NFOLDS tested three pairs of sites using the Fast Fourier method: Mansfield OH/Columbus OH, Utica NY/Burlington VT, Rutland VT/Burlington VT. Site criteria included

1. Identical Group Repetition Interval (GRI)
2. Identical baseline data
3. Availability of simultaneous data from both sites
4. Long-term data (offering comparison between predicted forecasts and actual measurements).

NFOLDS sampled data from each season to observe the effect of seasonal variations, and worked with combinations of data files to produce more accurate forecasts.

3. ERROR BUDGET

The TD error budget is created from the expected differences in measurements between airborne and monitor receivers. General error sources include errors in transmitter timing, receiver measurement, propagation model, propagation path calibration, and error caused by seasonal temperature and barometric pressure.

Accuracy limits in forecasting appear in the error budget, defined in the MOPS, for approaches using frequent updates. The root sum squared of ground equipment error (0.1 μsec), airborne equipment error for TD measurement (0.2 μsec) and for the propagation model (0.1 μsec) and TD calibration uncertainty (0.33 μsec) yield a total TD bias of .40 μsec. Adding the amount of error allowable for natural seasonal phenomena (.15 μsec), the calculation gives a total TD error of 0.55 μsec. Multiplying the total TD error by a TD-to-location conversion factor of .49 nmi/μsec (or 3000 ft/μsec) gives the allotted TD location error of .27 nmi. The natural seasonal phenomena ($\pm$ .15 μsec) is the quality factor used in the present study.

4. METHODOLOGY

The "Fast Fourier" method using short-term data emulates the long-term method in measuring the ratio of amplitudes between two sites. The method takes advantage of diurnal temperature effects on TDs over 24 hours. Transmitter events during the 24 hours can skew the measurements of the ratio, and thus yield an inaccurate trend curve. NFOLDS analysts followed this procedure:

1. Produce a trend curve with long-term data from a monitor site.
2. Match a short-term (24 hour) file from the monitor with data from a test site.
3. Normalize monitor data with the long-term average of its TD.
4. Perform non-linear regression using data from both monitor and test site.
5. Scale and shift the monitor's trend curve to produce the test site's trend curve by using the slope (ratio of amplitudes) and intercept (long-term average) of the regression line. The equations are:

$$I = 1 \ldots 52560$$
(i.e., 365 days of 10-minute averages)

$$\text{Slope} = \frac{\text{Seasonal Amplitude of Test Site}}{\text{Seasonal Amplitude of Monitor}}$$

Intercept = Long Term TD Average of Test Site

$$\text{Test Site TD}_I = \text{Slope} * [\text{Monitor TD Trend Curve}_I - \text{Monitor TD Average}] + \text{Intercept}$$

6. Compare the long- and short-term trend curves, with the allotted variation of .15 μsec described above.

Efforts to improve the results by eliminating transmitter effects and isolating diurnal temperature effects included smoothing and averaging the data. Data was smoothed with a low-pass filtering process: Fourier analysis followed by rebuilding the data with only low frequency components. Once NFOLDS had removed the common terms (transmitter shifting in time) from both data sets, they were better able to compare monitor and test sites.

5. RESULTS

Results focus on displaying the effectiveness of the methods employed in predicting long-term seasonal forecasts based on short-term data. The chronological sequence of diagrams is

1. 10-minute files from different seasons
2. 6-hour data files
3. TD averages from different seasons (two sets, combined and processed)
4. Above data, smoothed and reprocessed
5. An unsuccessful test case.

A 24-hour plot of 10-minute averages between the Ohio sites (Figure 1)--collected for the 9960 Z-baseline on 9/1/85--shows particularly good data correlation (a factor of -.903). Linear regression of the baseline data produced an intercept of 56887.268 μsec, which represents the predicted yearly average of Mansfield. This number differed only .012 μsec from the actual long-term average of 56887.280.

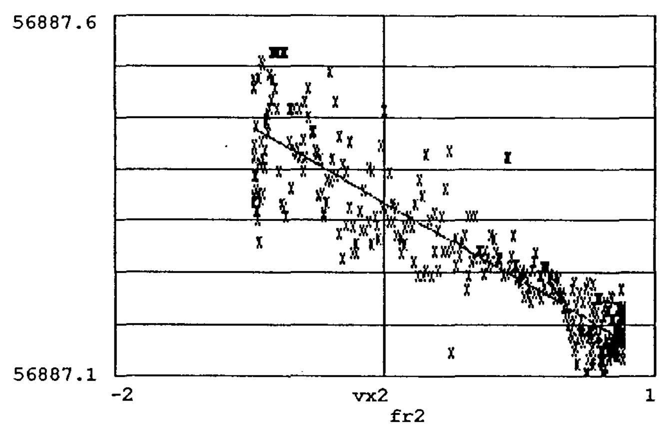
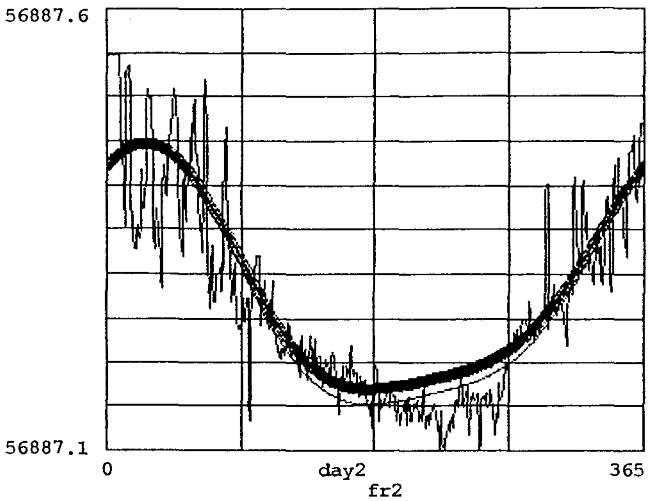


Figure 1.

A plot of one year of TDs at Mansfield's Z baseline of the yearly forecast against a 24-hour predicted forecast (Figure 2) shows close correlation between actual and predicted figures. The difference of .025 μsec falls well within the prescribed limits of the error budget.



The dark band represents a predicted forecast, the thin line an actual forecast, the sinusoidal curve one year's TDs.

Figure 2.

Figure 3 shows the 9960 Y baseline (Mansfield plotted versus Columbus, 5/29/85) in a poorer correlation on the regression analysis, but still an accurate yearly average, with the predicted only .006 μsec higher than the actual.

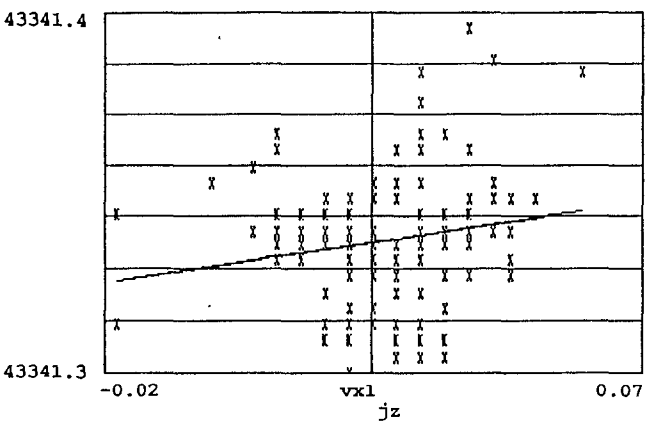


Figure 3.

A plot of predicted and actual values against TDs (Figure 4) finds the predicted within the allowed .01 μsec of the actual.

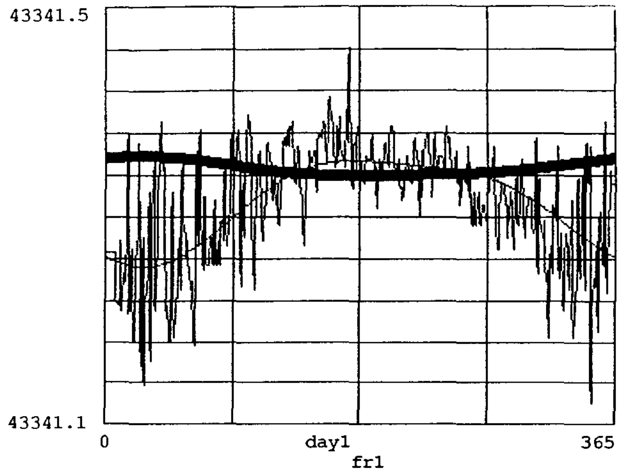


Figure 4.

Figures 5-7 show Rutland's TDs for a year, a yearly forecast, and the predicted forecast using 6-hour average files. Figure 5 (December 1) shows a maximum error of about .08 μsec, Figure 6 (June 1) .10 μsec. Figure 7 (both dates combined) reduces the maximum error to about .06 μsec, yet causes greater variation (thus a more accurate yearly average or intercept.)

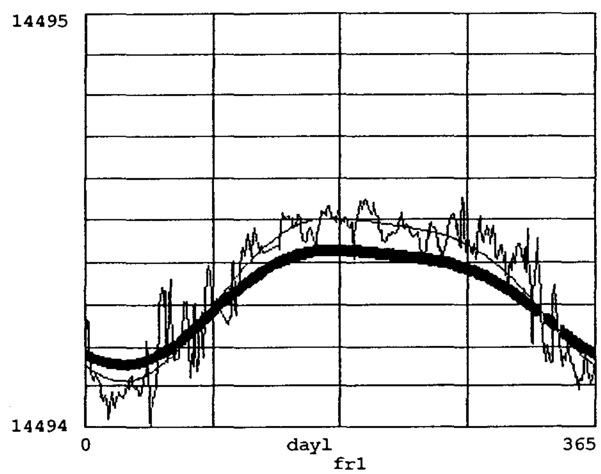


Figure 5.

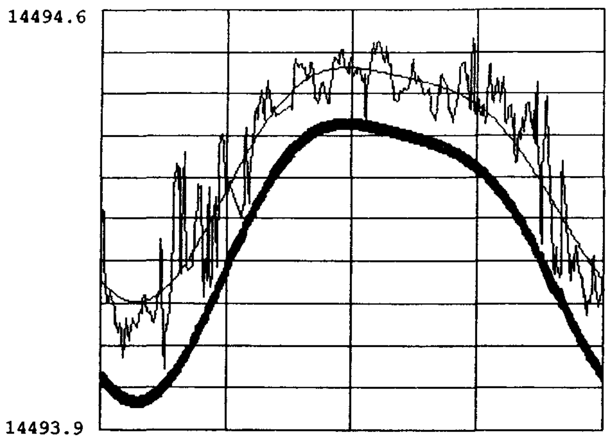


Figure 6.

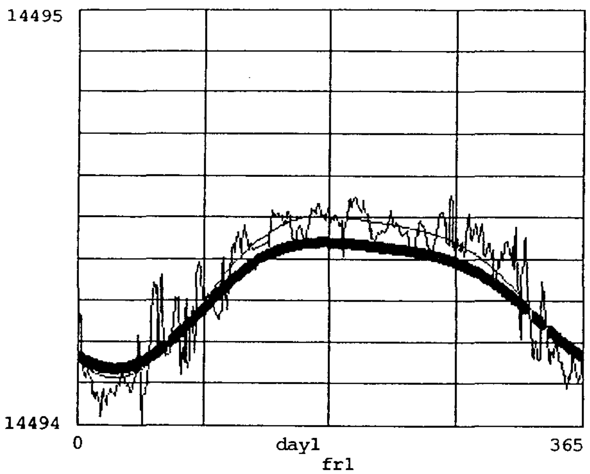


Figure 7.

Unwanted transmitter effects (creating "spikes") distort predicted forecasts, as linear regression analysis performed on such data tends to render the slope and intercept inaccurate. These anomalies are offset by converting average files from 10-minute to 6-hour. Figure 8 shows a predicted forecast for Mansfield (5/29/85) that (compared to Figure 4) shows a proper slope, with an offset of about .08 μsec.

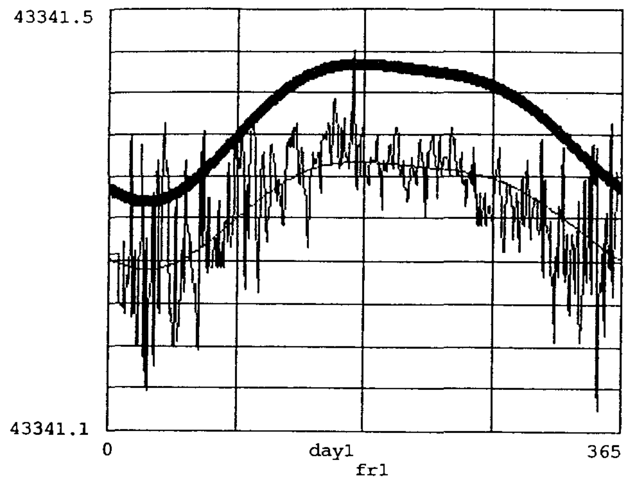


Figure 8.

Since the offset was still large, NFOLDS took another remedial approach. They observed that average files contained large, unwanted TD fluctuations, marked by spikes in the curve. The smoothing alogrithm filtered out unwanted TDs and produced a more accurate forecast. A predicted Mansfield forecast after smoothing (Figure 9) has a maximum error of less than .08 μsec, while error in the forecast (Figure 4) was over .10 μsec.

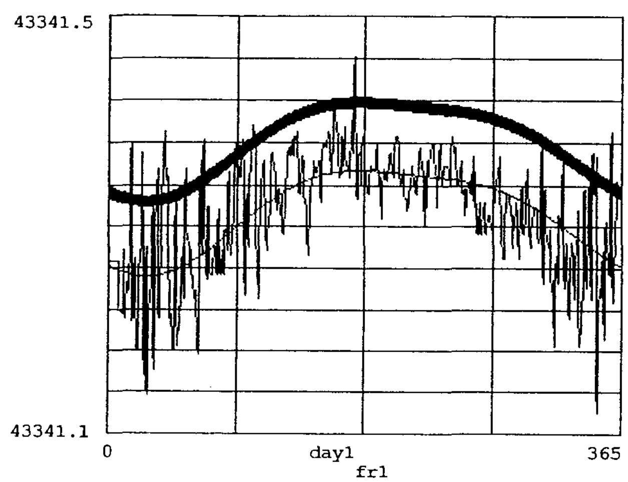


Figure 9.

Though the above figures show positive potential for the Fast Fourier method of forecasting, cases occasionally fall outside the prescribed error budget. A Mansfield prediction for 1/7/86 (Figure 10) using 10-minute average files produced an inverted forecast, with a maximum error of .25 μsec. LR analysis produced an incorrect slope (ratio of amplitudes) that threw off the intercept (yearly average). Examination of the data file showed a large fluctuation of TDs in the last quarter of the day.

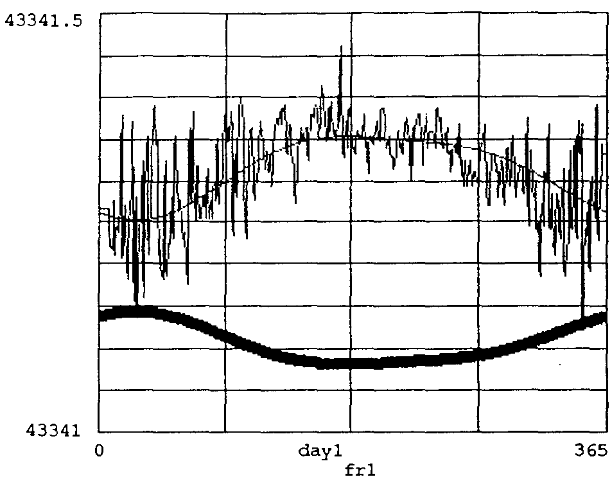


Figure 10.

Current efforts to solve this sort of problem include adding a third monitor site. Using two monitors with known trend curves, NFOLDS first calculates common terms (events caused by the transmitter) which, when removed from the data, also remove the undesirable events; then they calculate an accurate seasonal ratio (slope) between the original monitor and the test site. Developments in perfecting smoothing techniques with use of three monitors are on-going.

6. CONCLUSIONS AND RECOMMENDATIONS

This paper shows the viability of prediction long-term TD forecasts with only 24 hours of data. The Fast Fourier method, can assess short-term variations in diurnal, temperature, and barometric effects while ignoring transmitter effects, can produce forecast trend curves within prescribed error limits.

The study showed that this method worked best using data from sites with relatively large annual TD variations taken during winter months. That combination yielded data dominated by diurnal and temperature events that generally gave accurate trend curves. (Conversely, worst-case results occurred with data taken from sites with small annual TD variations taken during the summer; these cases were dominated by transmitter events.)

Averaging and data smoothing are proving effective means of removing transmitter events in most--but not all--test cases. The use of a neural network to recognize and isolate recurring anomalies in Loran data is also being explored.

The authors recommend that analysis continue in the isolation of seasonal, transmitter and local weather effects on Loran data. Improvements and enhancements of these tools will make for more accurate aviation forecasts.

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Measurement of LORAN-C Envelope to Cycle Difference in the Far Field

Benjamin Peterson, Thomas Thomson and Jonathon Riffe

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

Abstract

With mid continent expansion and increased use of LORAN over extensive land paths by both aviation and terrestrial users, there has been renewed interest in the prediction and measurement of Envelope to Cycle Difference (ECD) in the far field. A number of relevant issues in measurement of ECD are discussed. These include modeling of the far field pulse, analysis and calibration of the receiver front end, the algorithm used for calculation of ECD and the statistics of the measurements as a function of the signal to noise ratio and the noise model. Via network analysis, the magnitude and phase of the frequency response of the receiver is measured and used to create a computer model of the front end. Calibration of this front end is accomplished by supplying an ideal LORAN pulse of varying ECD as the input to the model, measuring the output, and applying a conversion curve in the algorithm. Issues such as receiver bandwidth, order, and the waveform samples used for ECD calculations are discussed. The statistics of the measurement process are examined in detail. Examples of bias due to cross rate interference and procedures for calculating this bias are presented.

Introduction

Recently the Electrical Engineering Section at the Coast Guard Academy was tasked by the Radionavigation Division of Coast Guard Headquarters to study Envelope to Cycle Difference (ECD) in the far field. Nominally ECD varies due to the variation of ground wave phase velocity with frequency. The intent is to shed some light on why and how ECD changes over land paths of varying conductivity. It quickly became obvious that before we could address validation of any theoretical models, we needed a much better understanding of the measurement process. With present technology, how is ECD measured? What are the statistics of the measurement? What sources of bias exist?

In [1], Freese defined ECD as measured in the antenna current and controlled at transmitting stations. His algorithm based on gradient search for the best least squares fit of measured half cycle peak amplitudes to an ideal model essentially serves as the definition of ECD at the transmitter. If as precise a definition for the far field exists, we have not been able to find it. Similar algorithms could be developed for the far field assuming the model was adjusted accordingly for both the inherent differentiation between antenna current and near far field and the receiver front end. In practice, far field ECD's were historically determined via envelope derivers implemented in hardware [2]. More recently one method has been to measure the slope of the envelope via the ratio of quadrature amplitudes. The purpose of this paper is to look in detail at these methods.

Measurement of ECD via Ratio of Quadrature Samples

As ECD for an ideal pulse varies the ratio of two quadrature samples of the waveform varies in a predictable way. Figure 1 shows how the 22.5 and 32.5 μsec samples vary with ECD.

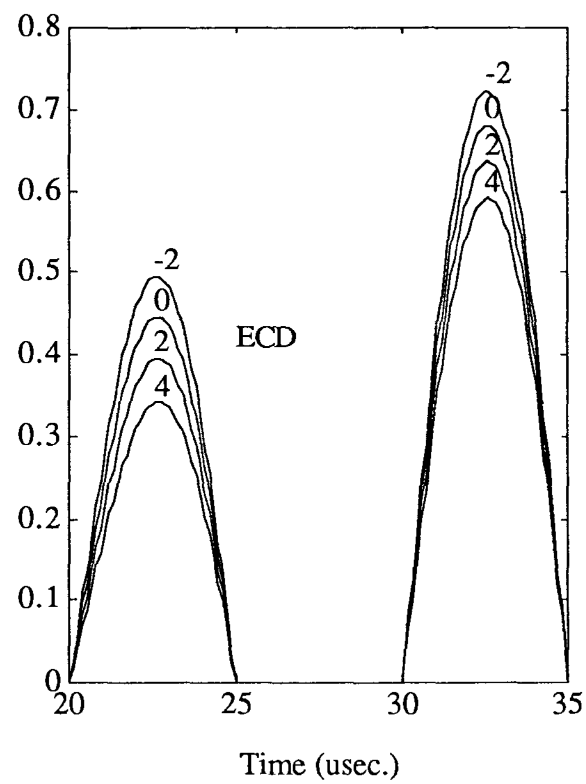

Figure 1. Measurement of LORAN Envelope by Ratio

If the ratio of these voltages is plotted vs ECD, the result is approximately a straight line (Figure 2).

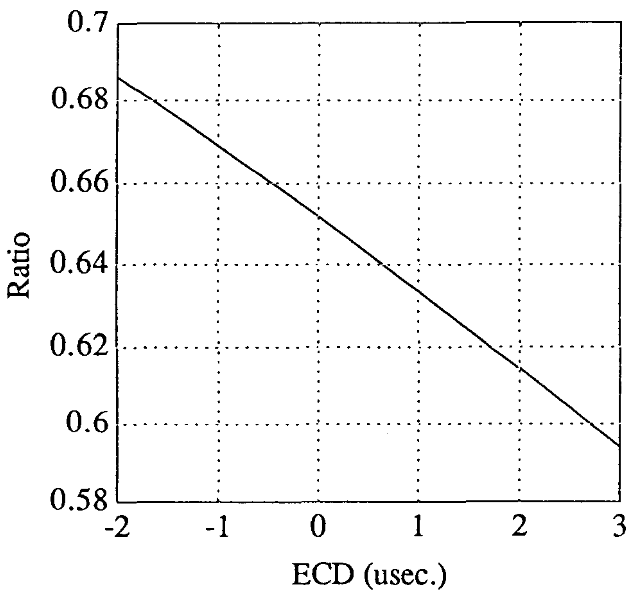

Figure 2. Ratio of 22.5 and 32.5 μsec samples vs ECD for an ideal LORAN pulse.

Some of the relevant issues are:

a. How does noise affect the measurement?
b. Which two samples should be used for the ratio?
c. How the is receiver front end accounted for?

For the ratio of two quadrature samples [$y(t_1) = y_1$ and $y(t_2) = y_2$] given by

$$R = \frac{y_1}{y_2}$$

we will assume for now that (after averaging) the noise in these measurements is very small in comparison quadrature samples, $|\Delta y_1| << y_1$ etc. The change in the ratio is approximately

$$\Delta R \cong \frac{1}{y_2}\Delta y_1 - \frac{y_1}{y_2^2}\Delta y_2$$

and the variance in the ratio is approximately

$$E[\Delta R^2] \cong \frac{1}{y_2^2}E[\Delta y_1^2] + \frac{y_1^2}{y_2^4}E[\Delta y_2^2] - 2\frac{y_1}{y_2^3}E[\Delta y_1 \Delta y_2]$$

If we assume

R_o = nominal ratio (at 0 ECD for example),
$\Delta y_1^2 = \Delta y_2^2 = \sigma_n^2$, and

$$E[\Delta y_1 \Delta y_2] = r\,\sigma_n^2$$

where σ_n^2 is the noise variance, and r is the correlation coefficient of the two noise samples and will be seen later to be primarily related to the autocorrelation function of the receiver front end; it then follows:

$$E[\Delta R^2] \cong \frac{\sigma_n^2}{y_2^2}\left(1 + R_o^2 - 2rR_o\right) \quad (1)$$

The slope of curves such as Figure 2 (at 0 ECD) is given by:

$$\text{Slope} = \frac{\Delta R}{\Delta ECD} \text{ (at } R_o\text{)}$$

$$\cong \frac{1}{\Delta ECD}\left(\frac{y_1}{y_2}\frac{\Delta y_1}{y_1} - \frac{y_1}{y_2}\frac{\Delta y_2}{y_2}\right)$$

$$= \frac{R_o}{\Delta ECD}\left(\frac{\Delta y_1}{y_1} - \frac{\Delta y_2}{y_2}\right)$$

if the envelope is of the form $A\,t^2 e^{-at}$

$$\frac{\Delta y_1}{\Delta ECD\, y_1} = \frac{A\exp(-at_1)\,(at_1^2 - 2t_1)}{A\,t_1^2\exp(-at_1)} = a - \frac{2}{t_1},$$

etc.

Therefore the slope is:

$$\frac{\Delta R}{\Delta ECD} = 2R_o\left(\frac{1}{t_2} - \frac{1}{t_1}\right) \quad (2),$$

and the variance of the ECD estimate is

$$E[\Delta ECD^2] \cong \frac{E[\Delta R^2]}{\frac{\Delta R^2}{\Delta ECD^2}}$$

$$= \frac{\frac{\sigma_n^2}{y_2^2}\left(1 + R_o^2 - 2rR_o\right)}{4R_o^2\left(\frac{1}{t_2} - \frac{1}{t_1}\right)^2} \quad (3)$$

Figure 3 illustrates the results of Equation 3 assuming an ideal pulse and a correlation coefficient of zero. The vertical axis is in μsec of standard deviation times $\sqrt{SNR}$ where signal is defined by rms amplitude of the envelope at 30 μsec. For example, if the SNR is +10 dB, and we average over 1000 pulses the SNR after averaging is +40 dB. If we were to use:

Samples Used	Standard Deviation in μsec
32.5 and 37.5	1.02
22.5 and 32.5	0.42
17.5 and 32.5	0.29

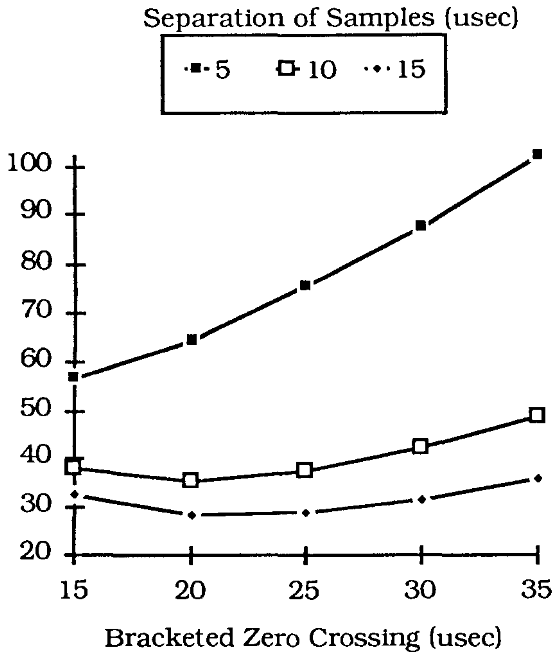

Figure 3. Relative standard deviation of ECD vs. Zero crossing and separation of samples.

The data suggests one can do better by sampling early in the pulse and by using samples farther apart. The minima in the curves above appear to coincide with the maximum of the slope of the envelope (Figure 4.) As we will see later, even if the noise is Gaussian distributed, the ECD samples are not Gaussian distributed and in fact may even have infinite variance. This fact is not of practical significance as long as the SNR after averaging is large, the probability of very large outliers is extremely small.

Equation 1 also suggests that the estimate of ECD can be made much better if the noise samples are highly correlated. Later when we address the receiver front end this is seen to be accomplished by using a narrower or higher order filter and thus a larger autocorrelation function. Intuitively this makes sense as the two samples move together and the variance of the ratio is smaller. This is true to a point, however, as we will see later, the slope in (3) assumed an ideal pulse which is not true for narrowband front ends.

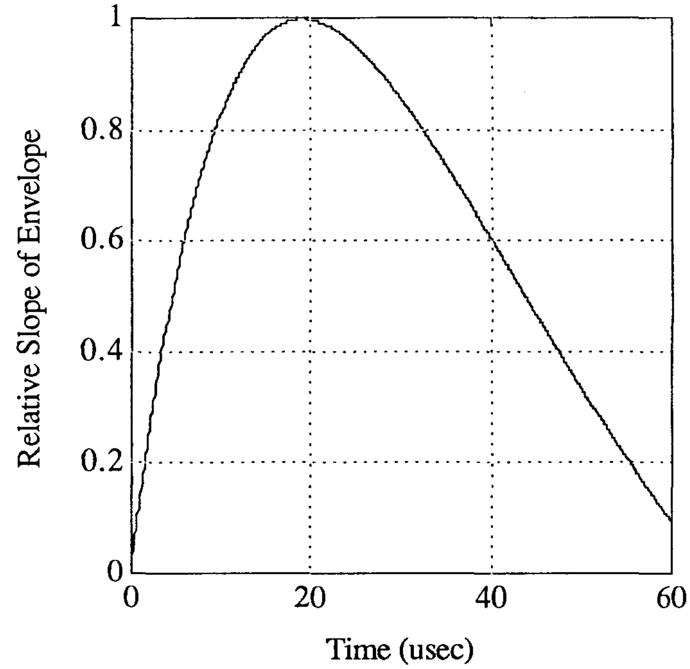

Figure 4. Slope of Ideal LORAN envelope vs time.

Probability Densities of Ratios

As shown in [3], the probability density (pdf) of the ratio (z = x/y) of two random variables is given by:

$$f_Z(z) = \int_{-\infty}^{\infty} |y|\, f(zy,y)\, dy \qquad (4)$$

If the joint density {f(zy,y)} is known then (4) can be numerically integrated to yield the pdf of the ratio. An obvious question is the model to use for the joint density. Figure 5 is a loglog plot of the histogram of voltage measurements in a 40 kHz bandwidth centered at 100 kHz made with a HP35665A Dynamic Signal Analyzer.

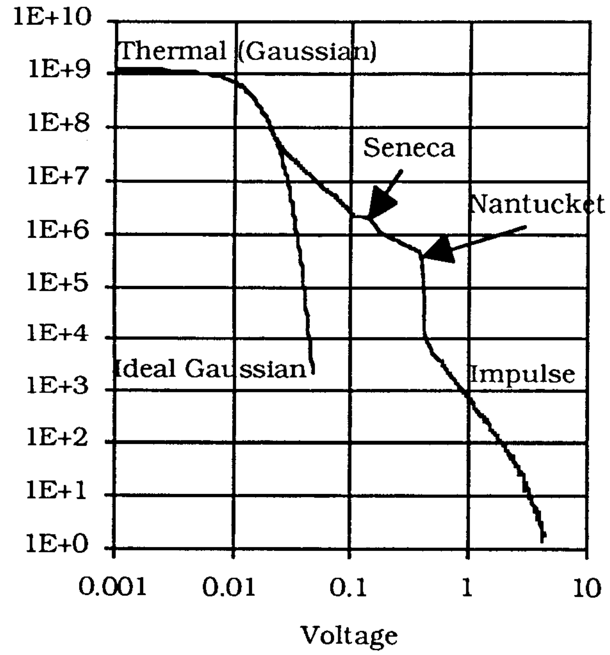

Figure 5. Histogram of voltage measurements at 100 kHz.

At small voltages the distribution is dominated by thermal noise and is Gaussian. At intermediate voltages, LORAN signals dominate and at large voltages, impulses due to lightning dominate. In previous studies, which concentrated on narrower bandwidths in the VLF [4], the distributions have been dominated by impulses, have very closely approximated Cauchy distributions and have been modeled accordingly. Since the Cauchy distribution has infinite variance and does not obey the central limit theorem, with very narrow bandwidths, the ringing due to impulses becomes almost continuous and dominates the distribution. With the wide bandwidths here, impulses are only present an extremely small percentage of the time and they do not dominate the distribution. In our case we will assume some clipping level (beyond the limit of the Gaussian portion) and do all of our analysis assuming Gaussian distributions. The LORAN cross rate interference is deterministic and will be dealt with separately.

Figure 6 shows the results of numerically integrating (2), assuming Gaussian noise, an SNR of +18.6 dB, and for various filter autocorrelation functions.

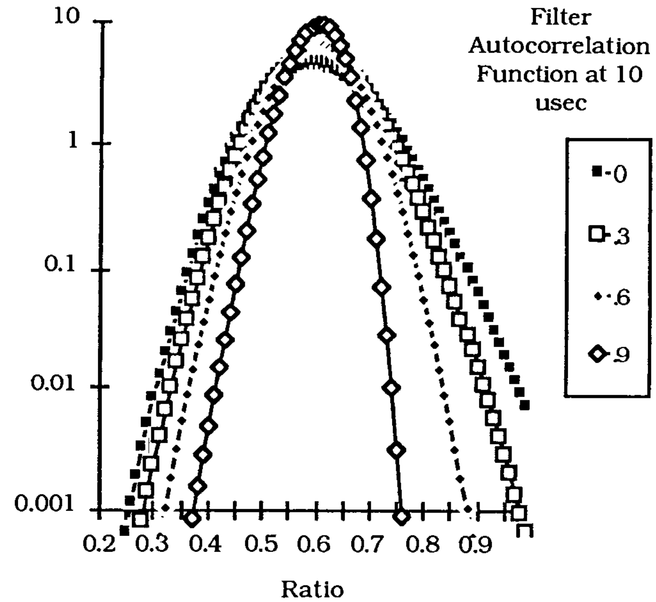

Figure 6. Probability density of ratio measurements for SNR of 18.6 dB.

Figure 6 does confirm equation (1) in that the distribution has smaller variance with more correlation between quadrature samples. It also shows that the distributions are not symmetric about the nominal value and that which side has a greater slope is dependent on the filter autocorrelation function. The consequences of this are shown in Figure 7, in that the measure of ratio is biased. How much this means in terms of ECD bias, is a function of the slope of the curves such as Figure 2 above, but typically when using the 22.5 and 32.5 μsec samples, a ratio bias of 0.02 is approximately 1 μsec of ECD bias. Again, the SNR's in Figure 7, are the SNR's after averaging. For SNR's in excess of 20 dB (or an average of 1000 pulses in -10 dB SNR), the bias is negligible. However, it does point out that one must be careful about averaging ECD's to get better estimates of the true value. The average of the ratio is not the ratio of the averages.

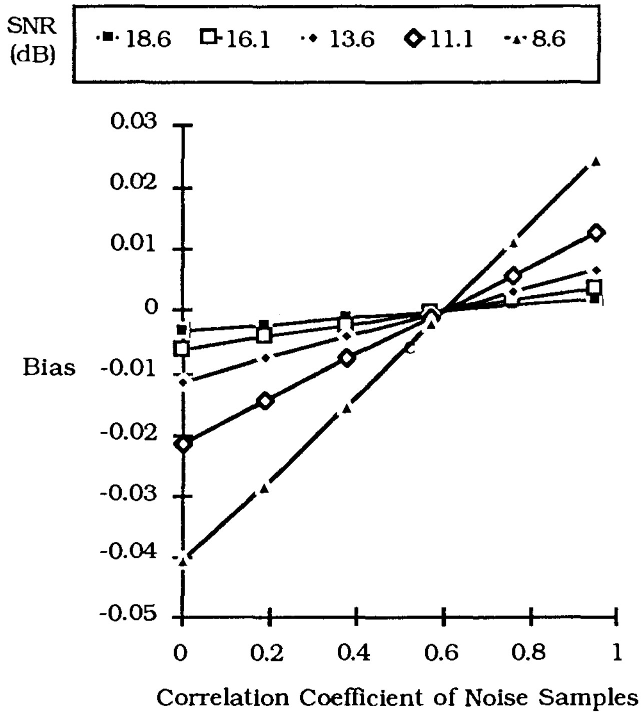

Figure 7. Bias in ratio measurements.

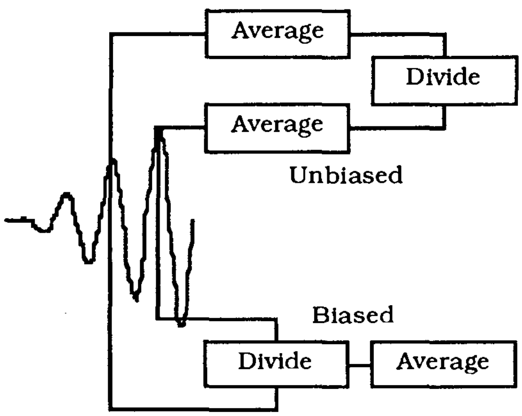

Figure 8. Comparisons of methods of averaging ECD measurements

Figure 9 shows the distribution on a loglog scale illustrating that the tails of the function approach a slope of -2. This implies the distribution has infinite variance. (Note: The distribution of the ratio of two zero mean Gaussian variables is Cauchy.) As long as the SNR after averaging is sufficient, this is primarily of only theoretical interest, as the probability of outliers is extremely small.

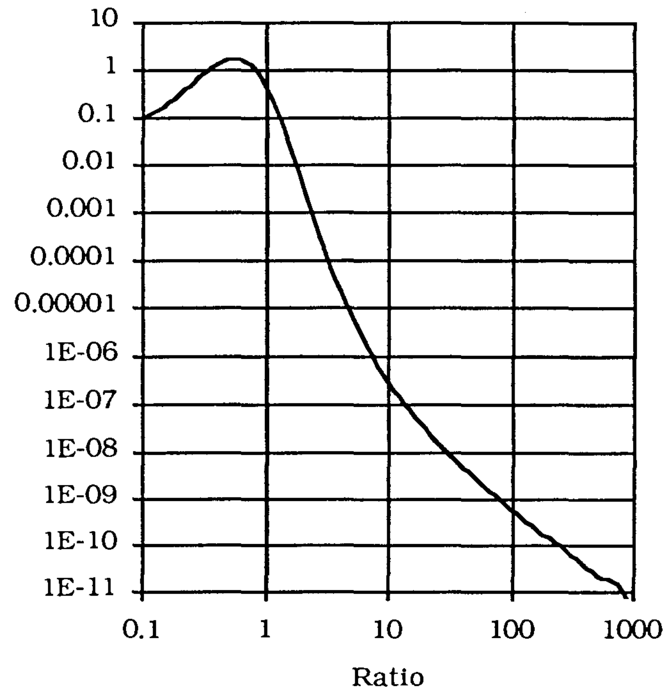

Figure 9. Probability distribution of ratio for SNR of 8 dB.

Receiver Front End

Everything about the measurement of ECD is highly dependent on the transfer function of the receiver front end. In general, to calibrate the front end ideal LORAN pulses of varying (but known) ECD are sent through the receiver and the appropriate ratio measured. This in some cases such as the (Austron 5000A monitor receiver) is done by synthesizing a LORAN pulse in hardware. In other cases, the transfer function is measured with a network analyzer, modeled and analyzed in software. In other cases, particularly when notches adaptively adjust to the interference environment, the entire process may be in software. Once a high order front end is employed, by necessity we will be tracking later in the pulse. Figures 10 and 11 illustrate the group delay for 4^{th} and 8^{th} order Butterworth bandpass filters of various bandwidths and Figure 12 illustrates the 30 μsec delay associated with a 28 kHz wide, 8^{th} order bandpass filter.

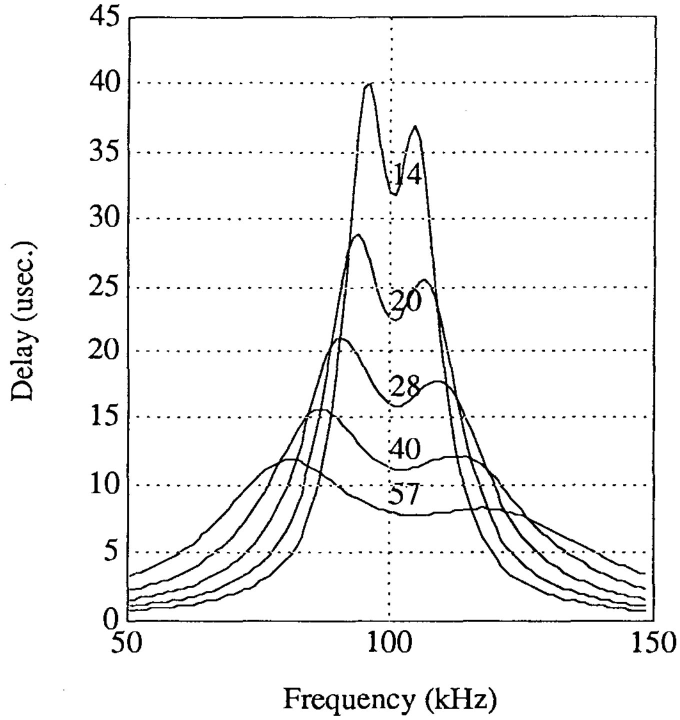

Figure 10. Group delay of 4^{th} order Butterworth bandpass filters.

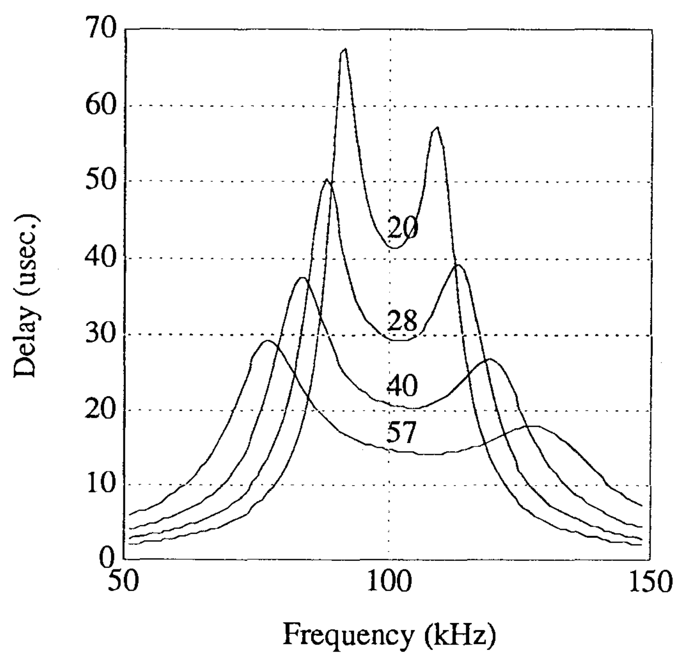

Figure 11. Group delay of 8^{th} order Butterworth bandpass filters.

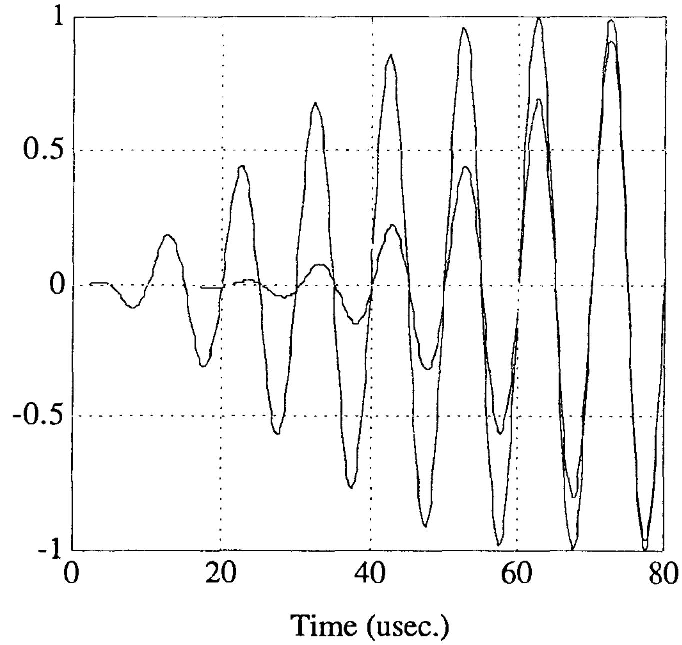

Figure 12. Output of 8^{th} order Butterworth bandpass filter (of 28 kHz bandwidth) compared to ideal LORAN pulse.

If tracked zero crossing and the quadrature samples for ECD measurement are then delayed accordingly (i.e. 30, 20, 15, 10, and 5 µsec for 14, 20, 28, 40, and 57 kHz bandwidths respectively for 4th order,) the resulting calibration curves are shown in Figure 13 and the slopes of these curves in Figure 14.

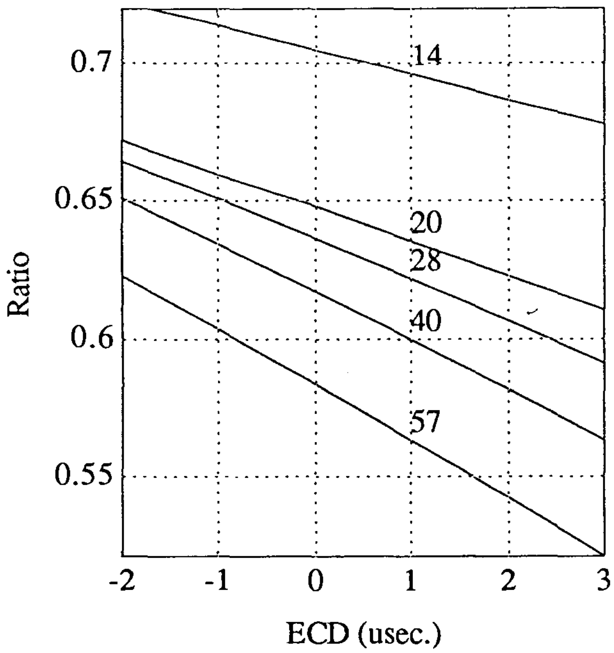

Figure 13. Ratio of quadrature samples 7.5 μsec before and 2.5 μsec after tracking point for 4^{th} order Butterworth filters.

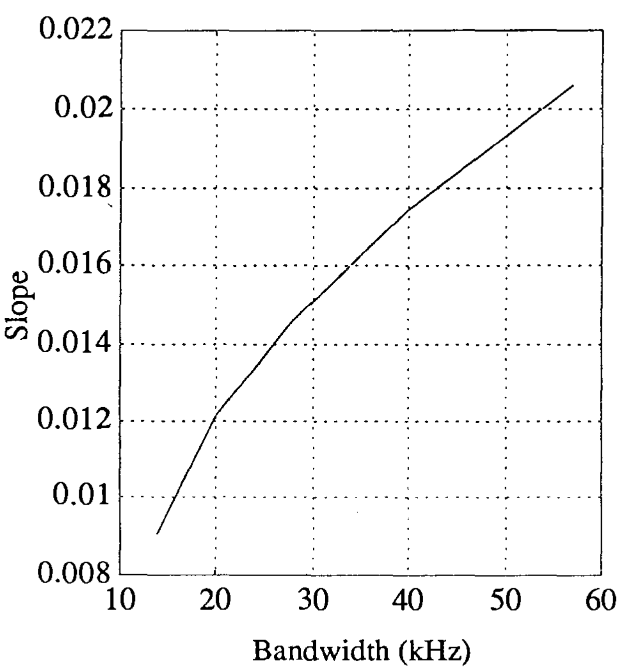

Figure 14. Slope of ratio vs ECD curves for 4^{th} order Butterworth filters.

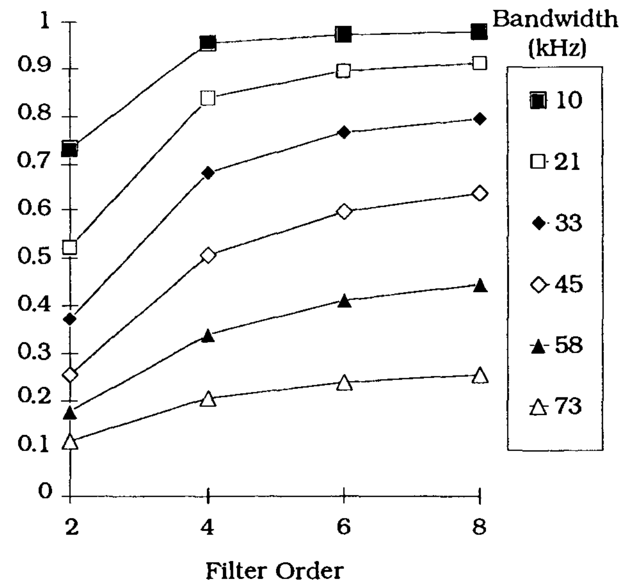

Figure 15. Filter autocorrelation function at 10 μsec for Butterworth bandpass filters.

While Figure 14 appears to confirm what is intuitive, (i.e. because narrow bandwidths spread out the pulse, measurement of envelope is more difficult,) it is interesting to combine the data in Figure 14 with the filter autocorrelation functions (Figure 15) and equation (1) { $E[\Delta R^2] \cong \frac{\sigma_n^2}{y_2^2}\left(1 + R_o^2 - 2rR_o\right)$ }. These results are plotted in Figure 16. What is seen is that the affects of correlation (r) in (1) almost exactly cancels the variation of slope for bandwidths of 20 kHz or more (Figure 14). If one were to assume a flat noise spectrum and that the SNR were inversely proportional to bandwidth, then narrower bandwidths, even to 14 kHz would be better for measuring the envelope.

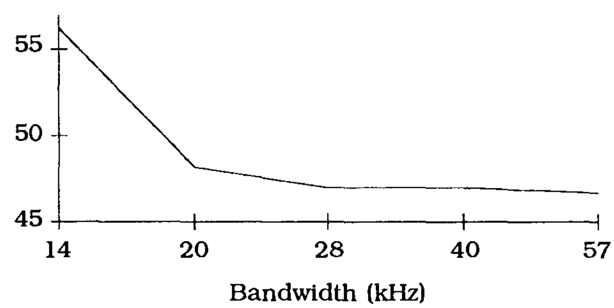

Figure 16. Relative standard deviation of ECD vs. bandwidth for 4^{th} order bandpass filters.

Cross Rate Interference

Figure 17 illustrates the affect of cross rate interference (Nantucket on 5930) when the ECD of the 1st pulse of Seneca on 9960 is measured. Circuitry was fabricated to inhibit the GRI trigger if Nantucket was transmitting on the other rate. A bias of +1.6 µsec exists for positive phase coded pulses and equal and opposite bias for negative pulses. If all 16 pulses in both GRI's were used the net bias is 1/4 of that for a single pulse or +0.4 µsec.

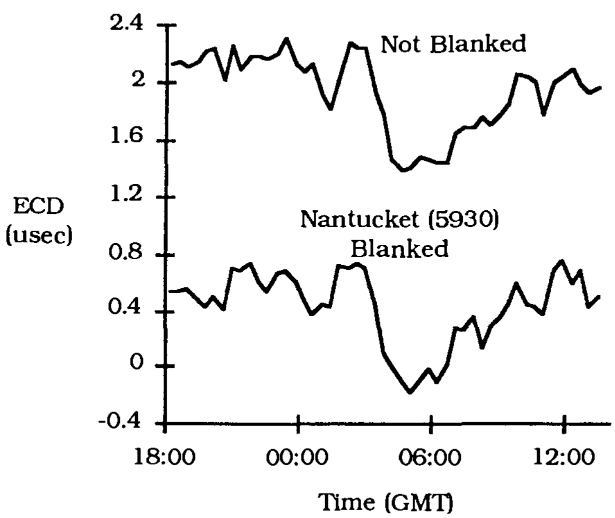

Figure 17. Measured ECD of 1st pulse of Seneca (9960) at New London.

As shown in Figure 18, by using tabulated emission delays for Nantucket on both rates and observed TD on 9960, it is easily determined that during the first GRI after epoch sync, Seneca (9960) is received 12,326 µsec before Nantucket on 5930. The assumption is made that both rates are synchronized to UT.

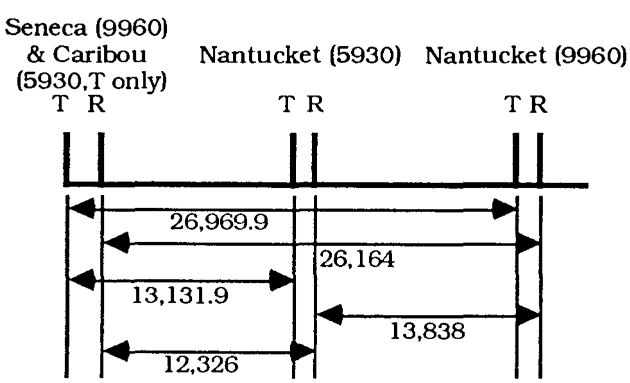

Figure 18. Calculation of cross rate TD.
(T=Transmit, R= Receive.)

Figure 19 shows the results of computer analysis of one cross rate interference epoch of 9960 and 5930. The horizontal axis is cross rate TD. The interpretation of the text is that the 8th pulse in GRI A of the 918th 5930 PCI after epoch sync occurs at the same time relative to a 9960 PCI trigger as the first pulse in the first PCI. It also occurs 100 µsec earlier (relative to a 9960 PCI trigger) than the 4th pulse in GRI B in the 978th PCI. As with all relatively prime rates, there is a net of four positively phase coded pulses at 200 µsec intervals of cross rate TD during each cross rate interference epoch. Since Seneca (9960) is received 12,326 µsec before Nantucket on 5930, there are a net of four positive Nantucket pulses 74 µsec before Seneca averaged over 593 Seneca pulses. Figure 20 shows leading edge of both "+" and "-" Seneca pulses (averaged 2048 times). Since the signal amplitude of Nantucket is approximately five times that of Seneca, the cross rate interference pulse amplitude is $4*5/593 \cong 1/30$ that of the Seneca pulses. 74 µsec earlier is virtually a worst case for ECD bias as close to an integer multiple of 5 µsec and the trailing edge of the Nantucket pulses are on the leading edge of the Seneca pulses. Adding a pulse of this amplitude explains the observed bias. Figure 21 illustrates in general how much bias can be expected as function of the relative times of arrival of the tracked and interfering pulses. The bias is plotted for both stations of equal amplitude and for the GRI of cross rate = 99X0. For the average of all pulses and rates relatively prime, the bias should be divided by 4, for other relatively prime rates, it should be multiplied by 10000/GRI, and for other relative amplitudes, it should be multiplied by the amplitude of the cross rate pulse relative to the tracked pulse. If clipping is employed, the curve would be clipped accordingly.

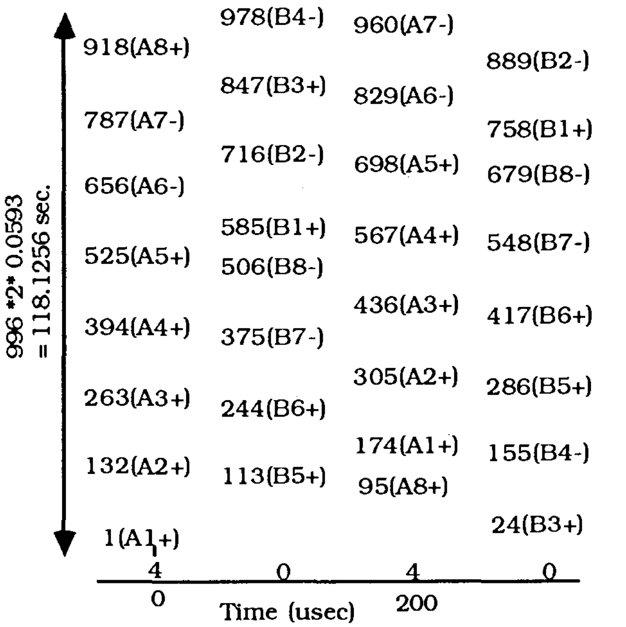

Figure 19. Analysis of cross rate interference (5930 to 9960.)

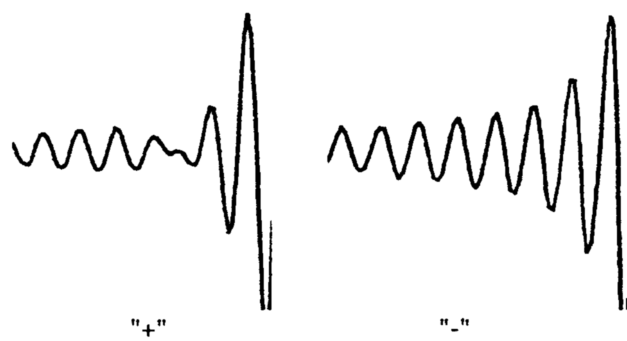

Figure 20. Leading edges of Seneca pulses (9960).

If the two rates are not relatively prime, the ECD bias calculations are much more complicated. Figure 22 shows the equivalent analysis for 8970 (secondary) interference to 9960. In this case the pattern repeats every 600 µsec of cross rate TD. The net positive pulses indicated by the numbers at the bottom of the columns (i.e. 3, -3, 0, -3, 9, 6) together with the cross rate TD MOD 600 and the phase code for each pulse are used to determine the bias for each pulse in the PCI of the received signal and the average determined accordingly.

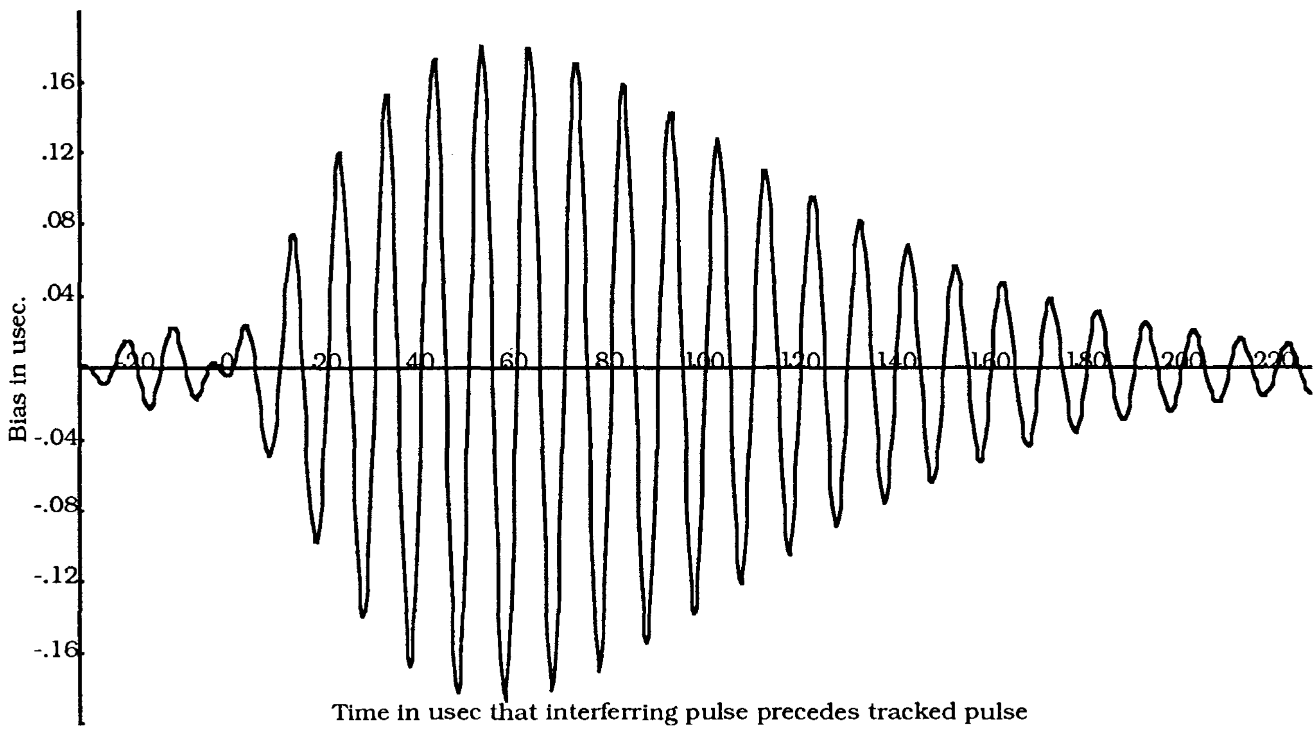

Figure 21. Bias in ECD Estimates of Single Pulse as Function of Cross Rate TD.

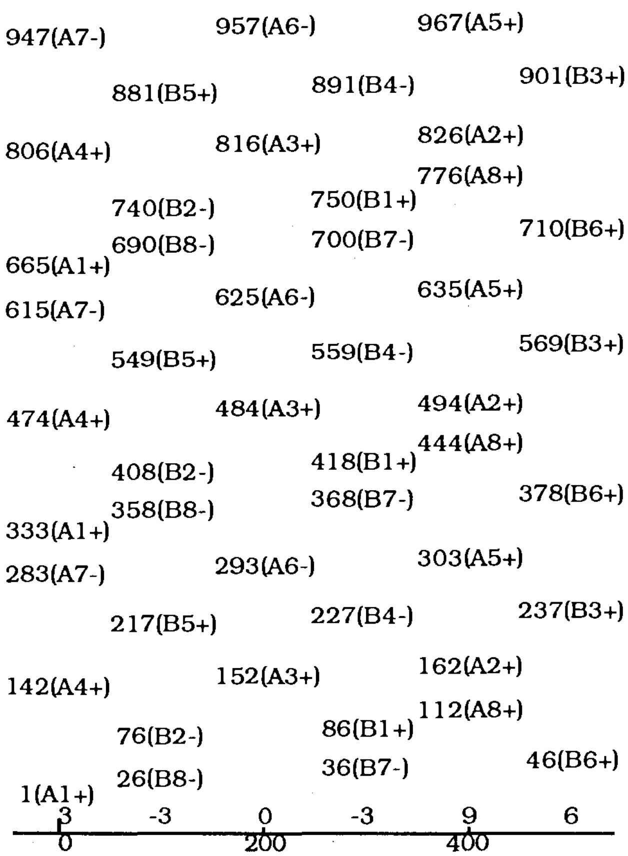

Figure 22. Analysis of cross rate interference (8970 to 9960.)

Summary

Analysis of the measurement of ECD via the ratio of two quadrature samples in general concluded:

a. Taking samples early in the pulse,
b. Using a narrow (within limits) bandwidth front end, and
c. Using samples well separated in time,

would result in less noisy measurements.

The probability density function of the ratio indicated bias in low SNR's which suggests that the quadrature samples should be averaged before calculating the ratio as opposed to the averaging of ratios. The tails of the distribution also suggest the distribution has infinite variance. As long as the SNR after averaging is sufficient this result is not of great practical significance. Strictly speaking, however we cannot calculate the theoretical standard deviation as a function of SNR.

Cross rate interference was shown to produce significant bias and a method to estimate that bias was presented. The necessary entering arguments include emission delays, TD's, and relative amplitudes of the tracked and interfering stations. For relatively prime rates, the analysis is quite simple, and more involved but tractable for other cases.

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4. Peterson, B. B. and Jones, W. H., "The Probability of Cycle Jumps in Omega Receivers and other Phase Locked Loop Applications, **Proceedings of 16th. Annual International Omega Association Annual Meeting**, Vancouver, BC, August 1991.

Biography

Benjamin Peterson is a Coast Guard Captain and is presently Chief of the Electrical Engineering Section within the Department of Engineering at the U.S. Coast Guard Academy. He is also Director of the Academy's Center for Advanced Studies, recently created to promote and coordinate faculty research efforts. He graduated from the Coast Guard Academy in 1969 and earned the MSEE and PhD from Yale University in 1978 and 1983 respectively.

Session 6
AVIATION TECHNOLOGY AND APPLICATIONS

Chairman: Chester "Chic" Longman, *Air Navigation Consulting*

Chick is a Radio Engineering Graduate of Valparaiso Technical Institute with several hours of graduate work in Physics and Math at Oklahoma City University. After graduation he spent 35 years with the CAA/FAA. He was the manager of avionic engineering for the FAA aircraft fleet, including flight inspection aircraft, for 20 of those years. The last six years of his FAA career were spent in the Office of Flight Standards where he worked with all forms of air navigation. He was instrumental in getting the FAA to recognize Loran-C as a radio-navigation system for aviation and for establishing the Loran-C working group for nonprecision approaches. He also worked closely with ICAO on the Microwave Landing System and with DOD on the criteria for civil acceptance of GPS.

Since leaving FAA in 1986, Chick, as the sole proprietor of Air Navigation Consulting, has served as a consultant to several major systems contractors such as TASC, Polhemus Associates, Navcom Systems, and ARINC on navigation related programs. He served on several RTCA special committees. He is a member of ION, WGA, and RTCA.

Papers

A Report on Data Gathering for the FAA Loran Airport Certification Initiative

J.V. Carroll
K.F. Chin
Center for Navigation
John A. Volpe National Transportation Systems Center
Cambridge, Massachusetts

Abstract

This paper presents results from the Loran signal evaluation project being conducted by the Center for Navigation at VNTSC. The objective of this project is to determine the adequacy of Loran signals at selected airports to support IFR nonprecision approaches. The Center for Navigation at VNTSC has designed, tested, and assembled a mobile data gathering facility to meet this objective. Acceptability of LORAN signals at the airports is determined by comparing against their respective standards averages of the receiver signal-to-noise ratio (SNR), and the position difference between the Loran and the GPS reference. Results presented in this paper show that all of the airports visited to date have adequate Loran signals for nonprecision approaches.

1. Introduction.

The Loran airport signal evaluation project has been underway since Fall, 1990. Its primary objective is the detailed gathering of Loran-C data at selected airports located throughout the contiguous states of the US. The data are analyzed to determine the adequacy of Loran signals at the subject airport to support IFR nonprecision approaches (NPA). This activity is one of several steps required to develop a Loran NPA at the airport. The Center for Navigation at the Volpe National Transportation Systems Center has designed, tested, and assembled the mobile data gathering facility used in this project. The primary system elements are three Loran-C receiver models, two Global Positioning System (GPS) receiver models, and IBM-compatible computers used for on-site data gathering and processing. The equipment can run from house current, although field requirements typically result in using one of the two available gasoline-powered generators. The mobile facility (van) has been found able to be adapted to a variety of Loran-related activities.

To date, the mobile facility has gathered extensive data at fifteen airports located primarily in the eastern seaboard and in the northwest. The overall results are that these airports can support Loran NPA's, although the effects of atmospheric noise at certain seasons and times of day may curtail Loran operations at a few of the airports. The mobile facility has performed exceptionally well, logging in excess of 15,000 miles over the past year in its journey to the various facilities, with no significant schedule disruptions or equipment failures.

2. Background

On November 15, 1990, the FAA commissioned the first ten public use Loran NPA's in the National Airspace System. Subsequently, in response to a Loran Program initiative promulgated by the FAA Administrator, Admiral James B. Busey, the FAA, in conjunction with the National Association of State Aviation Officials (NASAO), initially designated an additional twenty airports for Loran approaches. Because of subsequent concerns raised within the FAA, the FAA's Flight Procedures Standards Branch selected an additional ten "towered" runways at five additional airports. The main concern was to provide adequate communication to the pilot executing a Loran NPA at all times during the approach. A list of the airports is shown in Table 1.

The airports selected are typical of those which would benefit most from an approved Loran approach capability, because they typically do not have other operational IFR systems. Exceptions include Burlington International airport in Vermont and Hanscom Field in Bedford, Massachusetts. The Lafayette Regional airport in Louisiana is interesting in that, rather than upgrade their VOR facility there, the FAA Southwest region has approved replacing VOR with Loran-C.

There are nine steps which must be followed in order to obtain an FAA-approved Loran approach at an airport (Table 2). The steps are sequenced in a progressively more exacting order, so that waste of time, energy and money can be avoided if an airport fails at an earlier step. An inconclusive or positive result would lead to subsequent steps being taken, culminating in the approach flight test and procedure publication. The philosophy is to avoid the very expensive flight tests unless there is reasonable certainty that the airport will pass. At the same time, it is necessary to be as certain as possible that an airport has inadequate Loran signals before terminating the approval process.

Step six in the process to develop the Loran-C NPA requires the deployment of a Loran Site Evaluation System (LSES) at a candidate airport to evaluate Loran signal conditions. There is a difficulty, however, because the operational LSES will not be available until the Fall of 1991. In order to proceed with approach development it was therefore decided to develop and employ a mobile test facility at the airports to perform the LSES function.

2.1. Description of Mobile Test Facility. The mobile test facility is housed in a commercially available van, whose interior has been redesigned both to contain the test equipment, and to make it easily accessible to the engineers during data gathering and maintenance. The van is equipped with expanded HVAC capabilities, which have indeed been required during the recent trip. Electric power for the test equipment is normally supplied by one of the two redundant gasoline-powered generators, which are pulled behind the van in their own trailer. The design allows for the generators to provide electricity while the van moves at low speed from site at the airport to another. The van's own battery is not designed to run the primary data gathering equipment (although some of the equipment was run this way after a DC supply failure), but it does power the communication equipment.

The electronic equipment, listed in Table 3, is either rack-mounted or set atop the rack shelf, depending on operational requirements. Not all of the equipment listed is needed for data gathering at airports, because the van performs other activities in the Loran-C program while on the road (see Section 2.2). The equipment and data are protected by a power conditioning system. Figure 1 shows how the equipment is interfaced to perform the data gathering function. As is discussed in more detail in Section 2.4, the software is also robustly designed to accommodate data drop-outs and anomalies, and power failures.

At the heart of the mobile facility are the three Loran-C receivers: a Jet Electronics ANI-7000, a Bendix-King KLN-88, and a Trimble 10X combination Loran and GPS receiver. The ANI and KLN are airborne units, and the 10X is a prototype airborne unit which has been selected for use in the LSES system now being produced for the FAA regions. In addition to the 10X GPS receiver, the facility also uses an Ashtech GPS unit. GPS is used to provide an independent reference position measurement.

2.2. Data Gathering Approach. Extensive planning is required even before the van begins a trip. An itinerary which accounts for road and weather conditions as well as distances and types of roads, the type of activity, and the type and number of personnel, must be developed. A given trip lasts several weeks, so that planning for replacement of personnel is necessary. Planning must also account for the fact that the mobile facility has the opportunity to perform other Loran-related functions while on the road. These include upgrading Early Implementation Program (EIP) monitors, upgrading Loran Operational Monitors (LOM), and measuring in detail the structure and consistency of Loran signals within a mile or so of selected Loran transmitters. Although these activities require less overall effort than airport data gathering, scheduling them properly must be done with care.

Trip planning requires in addition that cognizant FAA and airport personnel be contacted, not only to assist in their activities, but also to provide the necessary coordination needed to get the van safely on and off the taxiways and runways. Finally, before valid data can be gathered, it is necessary to be sure that the EIP monitor designated for the subject airport is operating properly, and that its data can be downloaded remotely.

EIP monitors are stationary Loran receivers usually located so that they can provide Loran information for several airports. An airport covered by an EIP monitor must be within a 90 nmi radius of the monitor. The monitors record Loran signal parameters and store these in a microprocessor for access remotely via a modem. In addition, more basic Loran status data are sent to so-called annunciator boxes located at all approach control facilities servicing the airports designated for Loran NPA's.

If the Loran system is operating normally, the annunciator displays green. If the system is unavailable, due perhaps to electrical storms, or a station being off air, the annunciator displays red. Flashing red is displayed if there is a problem with the monitor. Thus, when the pilot calls in a request for an NPA, the control tower can quickly relay to him/her the status of Loran, and issue the appropriate advisory. As their name implies, the EIP monitors are a "stopgap" system which will be replaced by the automatic aviation blink system now planned for installation at all Loran stations.

2.3. Data Gathering Process. All of the normal data gathering is done while the van is at rest. Data are collected at selected runway thresholds, and at a much quieter "24-hour site". Runway thresholds are typically done first. This is because the airport manager or his designated agent must play a very active role in seeing that the van moves safely to and from the thresholds. Personnel in the van are in voice contact with airport personnel. It is necessary to gather threshold data only for about ten minutes. To keep this time minimal, the generator and key equipment are kept on while the van moves between thresholds. At the smaller airports, data can be gathered at the thresholds usually with less disruption of normal airport operations.

Threshold data helps to provide calibration information. If a U. S. Geodetic Survey reference marker can be found, a reliable position error reference can be made. Since finding the monumentation is often very difficult or time-consuming, GPS receivers are used to provide an alternate reference. The GPS receiver must run until stable (tracking) measurements are generated. As long as the constellation geometry is favorable, only a few minutes are needed. When the geometry is unfavorable, which will happen often until the full GPS constellation is in orbit, it is necessary to wait for the minimum five "visible" satellites. GPS data can be gathered at any time during the Loran-gathering window.

Following runway threshold activity, the van personnel in conjunction with airport personnel select a safe, non-intrusive site for the main 24-hour data gathering task. This site must be as close to one of the runways as possible, and must also have a GPS and/or monumented reference. A little-used taxiway is a desirable site. The engineers also consider the presence of possible Loran obstructions such as power lines, metal buildings, etc. Experience has shown that the best time to begin a 24-hour session is just before local noontime. (All data times are referenced to Greenwich Mean Time.) Two shifts of two personnel each conduct the 24-hour session.

At the 24-hour site, a generator is started, then the power conditioner, power line stabilizer, and finally the receivers and PC's. Once all receivers are tracking, the software is initialized and data storage begins. Data collection can be interrupted without erasing data from any of the files. One PC is dedicated to each of the Loran-C receivers, and the computer processing the ANI data also processes the Ashtech GPS data. The Trimble 10X GPS receiver data are not stored; this receiver is used only on an occasional basis, since it is needed only as a backup for the Ashtech receiver. All valid GPS navigation data are stored, even though it exceeds by far the amount needed for position reference with Loran.

In addition to the automated data gathering of Loran and GPS data, manual entry into log books is made of particular events such as changes in weather, aircraft landing or taxiing nearby, etc.

The most important Loran data collected at each airport are the time differences (TD), signal-to-noise ratio (SNR), and time measurements. These data are processed in the mobile facility using software structured as described below. Other useful quantities, e.g., position in latitude and longitude, are also stored. Receivers in the mobile facility must track the same Loran triad being used by the Loran EIP monitor. This is because the Loran status as measured by the monitor is part of the information relayed by Approach Control to pilots requesting a Loran NPA. The EIP monitor must therefore collect Loran data at the same time data are gathered at an airport, as required by the approval procedure.

2.4. Description of Software; Post-Processing. The Loran airport data collection and processing software overview is shown in Figure 2. The programs are written in Power Basic and C. Standardized Loran and GPS data processing algorithms provide uniformity to the processed data. This results in a requirement to write receiver-specific code to standardize the output of each of the receivers. However, the resultant modularity allows for rapid and efficient replacement, addition or subtraction of receivers according to project requirements. In addition to uniformity of output data, custom code also allows for operational robustness. That is, various receiver status flags can be interrogated so that data taken during periods when the receiver is not tracking can be ignored in the statistical computations[1]. This is done here by adding an asterisk to an appropriate column in any "bad" data record.

PC-compatible computers using a 386 architecture are configured to process key segments of the receivers' data stream in real time. Since upwards of 15 or 20 variables are processed as often as every one or two seconds, a 24-hour session easily generates several Mbytes of raw data. Data processing involves extracting the variables of interest from each receiver's data stream: time, number of data samples, position in latitude and longitude, SNR, and (for the Loran receivers) time differences. Time blocks containing bad data for any of the receivers are identified, and the data ignored, by the process outlined above.

The total number of data samples for a 24-hour session exceeds 32,000 for the ANI-7000 Loran receiver. The other receivers sample at lower rates, the KLN being the smallest at about 17,000 samples over 24 hours. The 10X sample rate can be controlled, and it is now set at its highest possible rate. Each sample represents a record containing the quantities listed above, plus other quantities not selected by the processing program. All of the selected raw data points are stored, and the basic statistics are done on all points. The statistics include ensemble means, variances, standard deviations, minima, and maxima of the SNR, TD's, and position readouts of the three Loran receivers; and of the GPS position data.

Another statistic computed to meet evaluation and data analysis requirements is the "ten-minute average", which is taken of the Loran TD's and SNR's for all three receivers. As the name implies, this is an average of ten minutes of data. Over 24 hours, about 150 of these points are computed, and these are sent to the Lotus graphics package for plotting.

Figure 3 shows a representative 24-hour SNR plot, SNR (in dB) vs time (hours GMT). This plot shows the readings for each triad station at the Frederick, MD municipal airport, as measured by the Trimble 10X receiver. Note that all of the curves are comfortably above the -6 dB threshold. Figure 4 shows one of the baseline TD measurements, also taken over a 24-hour period at Frederick. The 24 hour TD variation in this case is about 200 nanoseconds.

The ten-minute averaging "filters" the raw data, so that maximum and minimum excursions are usually obscured in the plots. The minmax and variance statistics thus provide useful information on how often the data are near the extremes.

Following data processing, a module generates Summary Reports for each runway threshold, and for the 24-hour site. An example is shown in Figure 5. The summary reports display the statistics cited above for all receivers. Minmax values, as well as means, variances, and standard deviations are computed for the position, SNR and TD measurements of the three Loran receivers, for the given triad. Position statistics are also provided for the Ashtech XII GPS receiver.

Note that the Loran receivers output latitude and longitude in WGS-72 coordinates, while the GPS receiver uses WGS-84. In addition, data gathering start and stop times are displayed, along with a plot of Loran positional differences with respect to the GPS reference. This plot plus a final statistic at the bottom of the Summary Report which shows the percentage of all measured SNR values falling below the -6 dB threshold, are primary indicators for determining the adequacy of the airport for Loran approaches:

The criteria for acceptability of Loran signals at candidate airports are:

(i) Loran receiver Signal-to-Noise (SNR) ensemble average over the collection interval must be equal to or greater than ("better than") -6 dB.

(ii) The position error average over the collection interval must be less than one nmi with respect to a reference position established by GPS measurements.

Criterion (ii) leads to the need for a GPS reference position measurement.

The plots described above are part of a comprehensive set of results included in reports sent to the FAA Program Office. One report covers each airport.

As stated above, the mobile facility is configured to allow for other Loran-related activities to be conducted: (i)

[1] A ground rule for accepting and using Loran receiver data is that the receiver has properly acquired and is tracking the correct triad.

Establishing or upgrading EIP monitors. This involves replacing or installing the processor with a 286 system, including a Hayes-compatible modem board and upgraded communications software. The resultant system is then fully accessible remotely for reconfiguring, monitoring status, or data downloading. The EIP monitor for a given airport must be operational before valid data can be gathered. (ii) Loran Operational Monitor upgrading. This is a very similar process to (i), except that these monitors are not needed for airport data gathering. The LOM's are usually located at VOR facilities. They provide a data base for information on the adequacy and availability of Loran signals in their area.

3. Summary

The VNTSC mobile data gathering facility has been assembled and sent to nearly fifty facilities connected with incorporating Loran into the National Airspace System. Logistical details have been developed and executed without serious difficulty. To date, the primary data gathering objectives have been meet at the designated airports, and all of the airports visited meet the criteria for Loran nonprecision approaches.

Detailed reports of the data gathering results for each airport are available at the FAA Loran Program Office, Washington, D.C. The authors are grateful to those at VNTSC who assisted in developing the material for this paper. Special thanks are also due those who spent long hours gathering the data and preparing and maintaining the equipment: A. Caporale, F. Castillo, M. Craven, B-Y Dao, R. Krajci, and T. Papadopoulos. Prof. A. Frost of the University of New Hampshire provided valuable counseling in assembling systems and in interpreting results. This project is sponsored by the FAA Loran Program Office.

Biographies

James Carroll has been a Senior Project Engineer at the DOT Center for Navigation at VNTSC in Cambridge, Mass. for the past year and a half. 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.

Kam Chin is an Electronics Engineer at the DOT Center for Navigation in Cambridge, Mass. He graduated from the Electrical Engineering Department of Northeastern University in 1986, and has been employed at VNTSC ever since. His student coop training was also accomplished at VNTSC. His primary activities at VNTSC involve developing Loran data gathering and analysis systems.

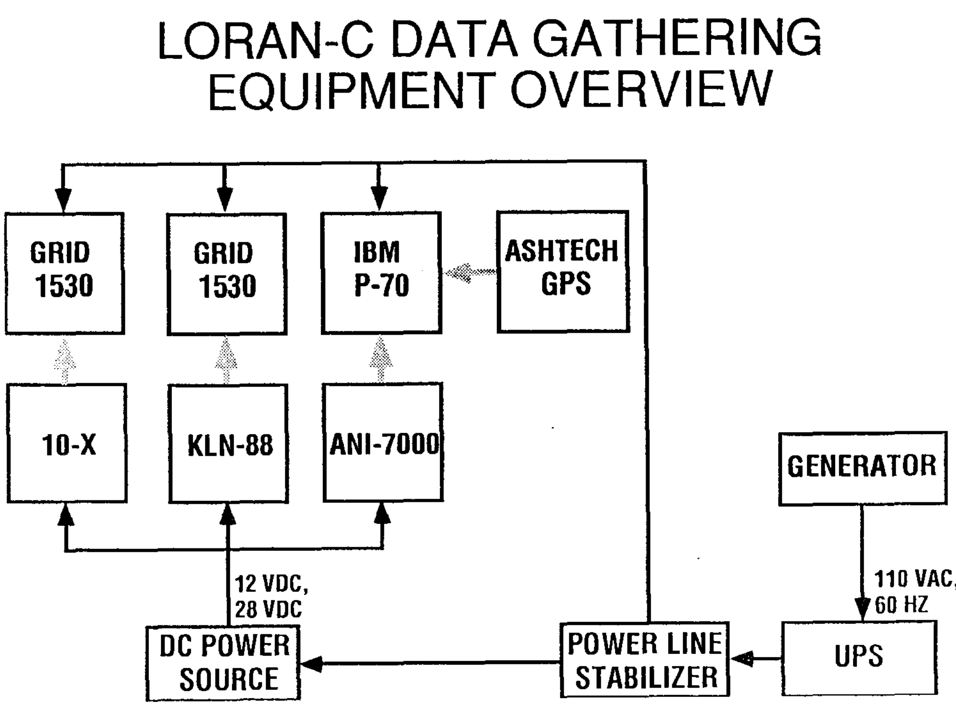


FIGURE 1

TABLE 1 AIRPORTS DESIGNATED FOR LORAN APPROACHES

ID	AIRPORT
2B6	HARRIMAN-AND-WEST, NORTH ADAMS, MA
1B1	COLUMBIA COUNTY, HUDSON, NY
BTV	BURLINGTON INTERNATIONAL, BURLINGTON, VT
RUT	RUTLAND STATE, RUTLAND, VT
C19	TULIP CITY, HOLLAND, MI
3HE	LIVINGSTON COUNTY, HOWELL, MI
I78	UNION COUNTY, MARYSVILLE, OH
JYO	LEESBURG MUNICIPAL/GODFREY FIELD, LEESBURG, VA
W66	WARRENTON-FAUQUIER, WARRENTON, VA
FDK	FREDERICK MUNICIPAL, FREDERICK, MD
W54	CARROLL COUNTY, WESTMINSTER, MD
N67	WINGS FIELD, PHILADELPHIA, PA
7MY	SOUTH JERSEY REGIONAL, MOUNT HOLLY, NJ
39N	PRINCETON AIRPORT, PRINCETON (ROCKY HILL), NJ
3S2	AURORA STATE, AURORA, OR
KLS	KELSO-LONGVIEW, KELSO, WA
TDO	TOLEDO-WINLOCK ED CARLSON MEMORIAL FIELD, TOLEDO , WA
LFT	LAFAYETTE REGIONAL, LAFAYETTE, LA
HUM	HOUMA-TERREBONE, HOUMA, LA
BOW	BARTOW MUNICIPAL, BARTOW, FL
MRB	EASTERN WEST VIRGINIA/SHEPHERD FIELD, MARTINSBURG, WV
TTN	MERCER COUNTY, TRENTON, NJ
ACY	ATLANTIC CITY INTERNATIONAL, ATLANTIC CITY, NJ
BED	LAURENCE G HANSCOM FIELD, BEDFORD, MA
BVY	BEVERLY MUNICIPAL, BEVERLY, MA

TABLE 2 STEPS FOR LORAN NPA DEVELOPMENT

1	USER VFR ASSESSMENT OF AIRPORT COLLECT INITIAL DATA
2	REQUEST FAA REGION FOR LORAN NPA - PRESENT INITIAL DATA
3	COLLECT ADDITIONAL DATA PER DIRECTION OF FAA REGION
4	RUN AIRPORT SCREENING MODEL (ASM) ANALYSIS OF AIRPORT
5	IF ASM RESULTS ARE POSITIVE, COMPARE INITIAL DATA WITH ASM RESULTS
6	DEPLOY THE LORAN SITE EVALUATION SYSTEM (LSES) TO MEASURE LORAN SIGNALS AT THE AIRPORT
7	DEVELOP LORAN APPROACH PROCEDURES
8	CONDUCT FLIGHT INSPECTION OF AIRPORT
9	PROCEDURE PUBLICATION

TABLE 3 EQUIPMENT IN THE VNTSC MOBILE FACILITY

ANI 7000 LORAN RECEIVER AND ANTENNA	HP-3585A SPECTRUM ANALYZER
BENDIX-KING KLN-88 LORAN RECEIVER AND ANTENNA	FLUKE PM3323 DIGITAL OSCILLOSCOPE
TRIMBLE 10X LORAN/GPS RECEIVER AND ANTENNA	TEKTRONIX 5110 OSCILLOSCOPE
ASHTECH XII GPS RECEIVER AND ANTENNA	TRACOR RUBIDIUM FREQUENCY STANDARD
IBM P70 PORTABLE COMPUTER	2 USCG LORAN RATE BLANKERS
2 GRID 1530 PORTABLE COMPUTERS	TSC GRI TRIGGER CIRCUIT
HYUNDAI A565D LAPTOP COMPUTER	TEKTRONIX C5C SCOPE CAMERA
EPSCO LORAN SIMULATOR	AC POWER LINE STABILIZER
DESKJET PLUS HP PRINTER	INMAC UPS POWER CONDITIONING SYSTEM
3 0-50 VOLT VARIABLE POWER SUPPLY UNITS	

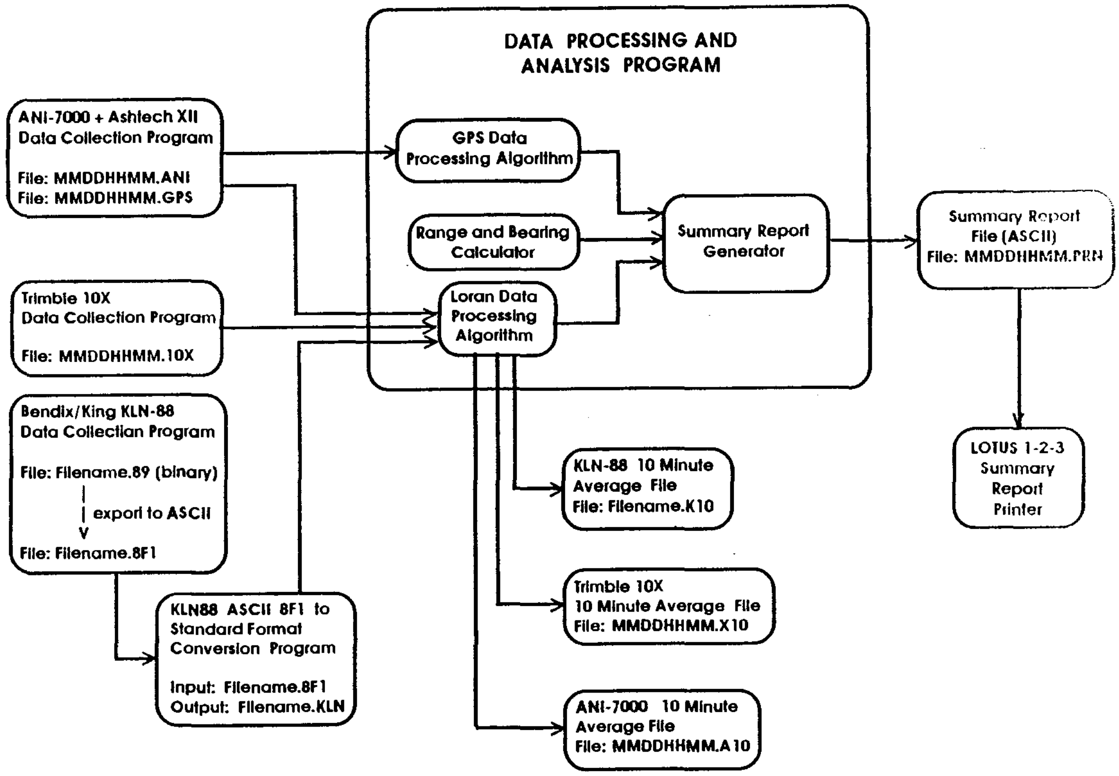


FIGURE 2 **DATA COLLECTION AND PROCESSING SOFTWARE BLOCK DIAGRAM**

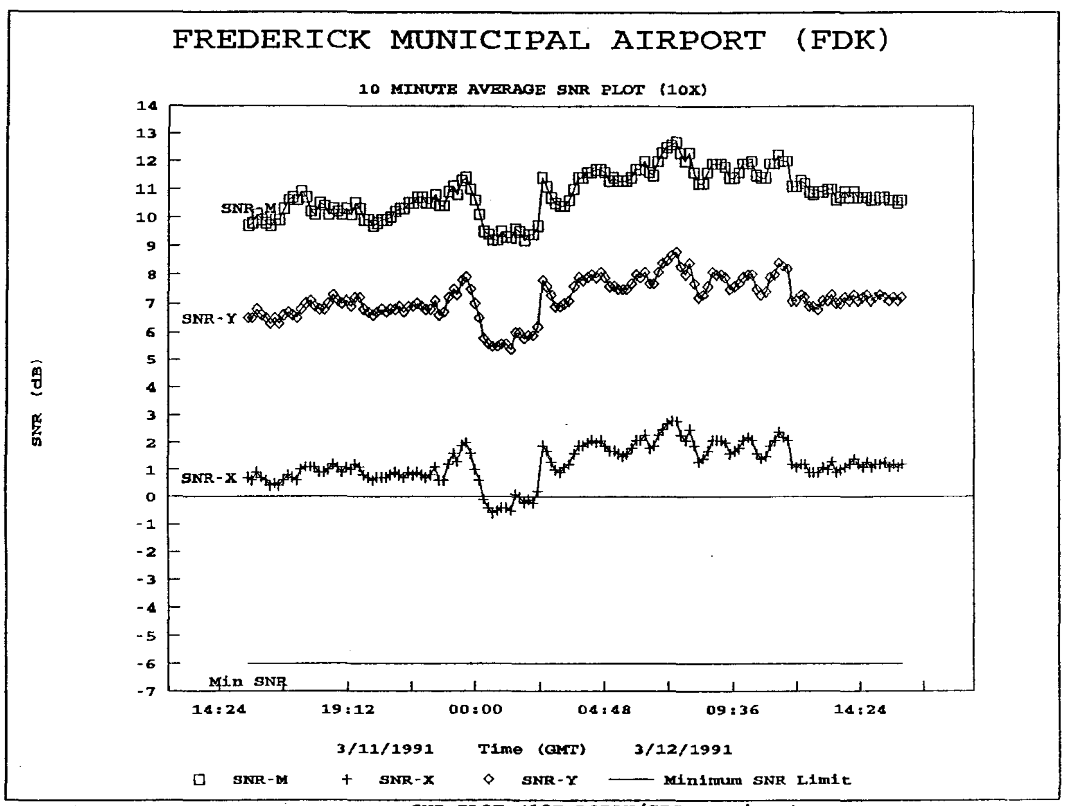


FIGURE 3 **SNR PLOT (10X LORAN/GPS receiver)**

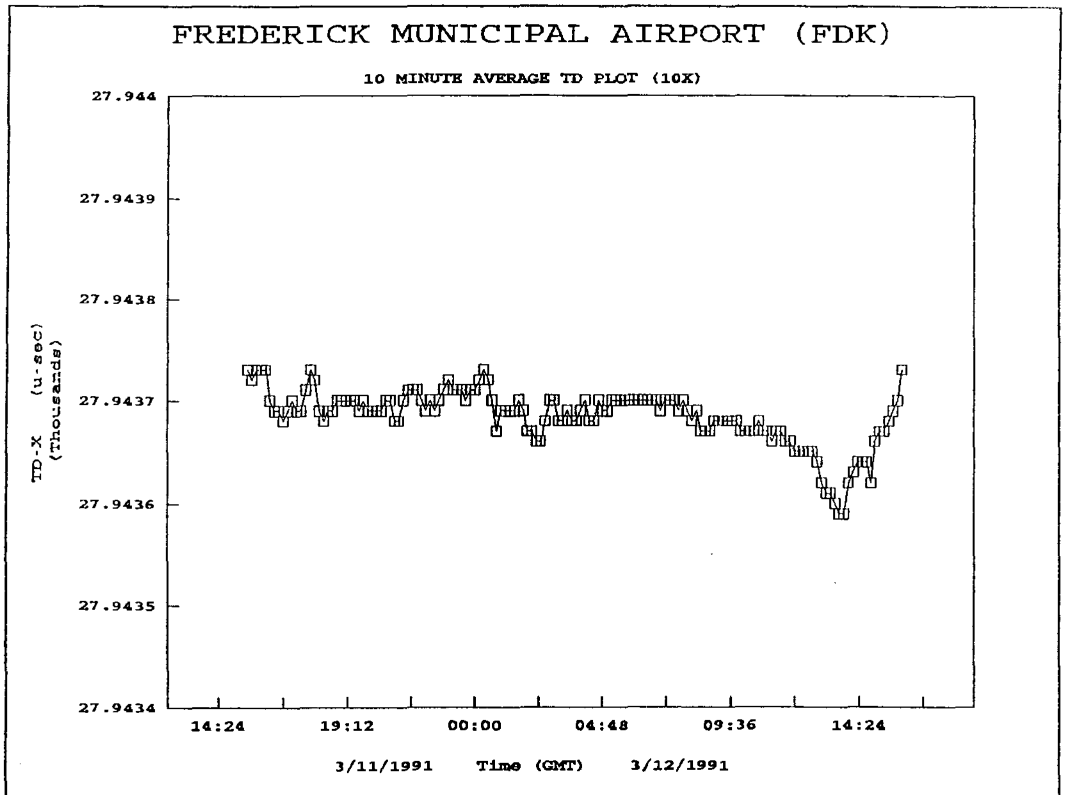


FIGURE 4 **TD-X PLOT (10X LORAN/GPS receiver)**

FIGURE 5 SUMMARY FOR THE 24 HOUR SITE

Frederick Municipal Airport (FDK) MD

Taxiway near state police hanger (24 Hour Data)

	LORAN Receivers						GPS Receiver	
Measured	ANI-7000 (WGS-72)		KLN-88 (WGS-72)		Trimble 10X (WGS-72)		Ashtech XII (WGS-84)	
Position	Latitude	Longitude	Latitude	Longitude	Latitude	Longitude	Latitude	Longitude
Mean	+39°25'10"	-077°22'38"	+39°25'12"	-077°22'39"	+39°25'13"	-077°22'34"	+39°25'15"	-077°22'40"
Max	+39°25'10"	-077°22'36"	+39°25'12"	-077°22'36"	+39°25'14"	-077°22'32"	+39°25'17"	-077°22'36"
Min	+39°25'09"	-077°22'40"	+39°25'11"	-077°22'41"	+39°25'13"	-077°22'35"	+39°25'14"	-077°22'41"
Var. (feet^2)	28.23	3322.80	139.66	1494.93	1662.36	1104.94	1788.18	21.55
Std. (feet)	5.31	57.64	11.82	38.66	40.77	33.24	42.29	4.64

Signal-to-Noise Ratio									
GRI - 9960	M - Seneca			X - Nantucket			Y - Carolina Beach		
	Master SNR			X - SNR			Y - SNR		
	ANI-7000	KLN-88	10X	ANI-7000	KLN-88	10X	ANI-7000	KLN-88	10X
Mean (dB)	9.00	18.03	10.82	8.19	13.73	1.22	8.99	16.94	7.17
Max (dB)	9.00	24.00	15.00	9.00	19.00	5.00	9.00	22.00	12.00
Min (dB)	6.00	14.00	7.00	0.00	6.00	-3.00	3.00	12.00	2.00
Var. (dB^2)	0.00	3.18	1.33	2.28	10.02	1.28	0.04	3.16	1.51
Std. (dB)	0.03	1.78	1.15	1.51	3.17	1.13	0.21	1.78	1.23

Time Difference						
GRI - 9960						
	TD - X			TD - Y		
	ANI-7000	KLN-88	10X	ANI-7000	KLN-88	10X
Mean (usec)	27943.59	27943.62	27943.68	42982.72	42982.68	42982.83
Max (usec)	27943.71	27943.81	27943.78	42982.82	42982.82	42982.93
Min (usec)	27943.45	27943.42	27943.56	42982.62	42982.53	42982.74
Var. (usec^2)	0.00	0.00	0.00	0.00	0.00	0.00
Std. (usec)	0.03	0.04	0.03	0.03	0.04	0.03

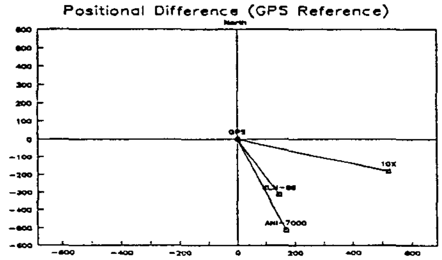
Total Data Samples		
LORAN		File
ANI-7000	38535	FDK-24HR
KLN-88	17524	FDK-24HR
10X	25187	3111533
GPS		File
Ashtech	24470	FDK-24HR

Aggregate Coordinates									
	ANI-7000		KLN-88		10X			Ashtech XII	
LORAN	Latitude	Longitude	Latitude	Longitude	Latitude	Longitude	GPS	Latitude	Longitude
WGS-84*	+39°25'10"	-077°22'38"	+39°25'12"	-077°22'38"	+39°25'13"	-077°22'33"	WGS-84	+39°25'15"	-077°22'40"
WGS-72	+39°25'10"	-077°22'38"	+39°25'12"	-077°22'39"	+39°25'13"	-077°22'34"			

* - Converted Position

Positional Differences (WGS-84)				
(Range feet) (Bearing deg)	GPS	ANI-7000	KLN-88	10X
GPS		539.1	343.3	551.7
		161.9	155.4	109.4
ANI-7000	539.1		201.8	482.4
	341.9		353.0	46.9
KLN-88	343.3	201.8		398.6
	335.4	173.0		71.1
10X	551.7	482.4	398.6	
	289.4	226.9	251.1	

Positional Difference (GPS Reference)



Data Collection Period					
Start Time:	Date:	Mar. 11, 1991	Stop Time:	Date:	Mar. 12, 1991
	Time:	16:03:27 GMT		Time:	16:00:15 GMT

Data Samples Above Minimum SNR Limit			
Receiver	ANI-7000	KLN-88	Trimble 10X
SNR Samples ≥ - 6 dB	100 %	100 %	100 %

Design, Development and Testing of a Loran-C AUTOMATIC BLINK SYSTEM (ABS)

MARTIN C. POPPE
Cambridge Engineering
P. O. Box 3099
Burlington, VT 05401-3099

ROBERT B. GODDARD
Megapulse, Inc.
8 Preston Court
Bedford, MA 01730-2380

Abstract

The Loran-C radionavigation system has been designated by the FAA as a supplemental approach aid in the NAS. In order to utilize Loran-C as a navigation aid for nonprecision approaches, the FAA has determined that improvements in the Loran-C ground equipment are required. Specifically the improvements are required in order to meet the aviation integrity requirement, which states that "during nonprecision approaches, the pilot must be warned of faulty Loran-C signals within 10 seconds of detection of the error." This paper describes the design, development and testing of a Loran-C Automatic Blink System (ABS). The ABS system monitors the time position of both the transmitter trigger pulses, and the standard zero crossing of the antenna current with respect to the stations three Cesium time references. Out of tolerance conditions cause the system assert Secondary blink, or to stop transmission of the Master signal until all Secondaries are blinking.

Introduction

The Federal Aviation Administration (FAA) has been conducting a program to investigate the potential of supplemental navigation aids in the National Air Space (NAS). The Loran-C radionavigation system has been designated by the FAA as a supplemental approach aid in the NAS. In order to utilize Loran-C as a navigation aid for nonprecision approaches, the FAA has determined that improvements in the Loran-C ground equipment are required. Specifically the improvements are required in order to meet the aviation integrity requirement, which states that "during nonprecision approaches, the pilot must be warned of faulty Loran-C signals within 10 seconds of detection of the error."

Furthermore the FAA has determined that the Loran-C system "blink" capacity can be utilized to meet the integrity warning requirement provided that equipment is installed which performs the blink function automatically when an out-of-tolerance condition occurs. The basic out-of-tolerance condition is considered to be a Loran-C baseline timing error in excess of 500 nanoseconds.

Objectives

The objectives of the Automatic Blink System (ABS) project were: to survey Loran-C transmitter ground equipment existing in the NAS in order to determine the detailed requirements for an ABS; to design and build an ABS prototype; to test the prototype using the Loran-C transmitting equipment available at the USCG Engineering Center (EECEN); and to prepare an engineering specification for production units of an operational Automatic Blink System.

The survey determined that a single ABS design would be compatible with all Loran-C transmitters used to obtain Loran-C signal coverage over the NAS.

The selected design concept is based on measuring the Loran-C timing errors "locally." Specifically, the error should be determined by comparing the timing of the transmitted signals with time references derived from the three frequency standards installed at each transmitting station. Designs based on measuring the Loran-C signals from remote stations could not respond quickly enough and still provide satisfactory false alarm and missed detection performance.

The prototype was tested at EECEN on a solid-state transmitter and on two tube-type transmitters. The compatibility of a single ABS with all three transmitter types was verified. The prototype require approximately two seconds to turn on blink after the introduction of an out-of-tolerance condition. No false blink turnons occurred. The ABS was successfully integrated into the USCG TTY communications system, thus providing a link between the ABS and the local watchstander and the Chain Control Center.

Survey of Loran-C Transmitter Site Equipment

The NAS includes 10 chains. The Canadian East Coast, Northeast U.S., Great Lakes, Southeast U.S., and South Central U.S. are under the command of the Atlantic Area Regional Manager. The U.S. West Coast, Canadian West Coast, North Central U.S., Gulf of Alaska, and North Pacific are under the command of the Pacific Area Regional Commander.

The transmitter survey showed that a single ABS design would be compatible with all of the Loran-C transmitter stations covering the National Air Space. The electrical interfaces involved are: Connections to the frequency references; input connections to receive the (MPT) and output connections to route the MPTs to the transmitter; connection to a Pearson transformer which provides a sample of the OPRF; and a standard RS-232 connection to the TTY loop.

The detailed results of the survey are presented in reference (1).

Design Approach

Three design approaches were considered. One was based on using the System Area Monitors (SAM) to obtain baseline timing information. The second was based on using a receiver at each secondary to measure the time of arrival of the signal from its master. At first glance one might ask, "Since we are looking for baseline timing anomalies and existing SAM's measure baseline timing, why not use them as the sensors for the ABS system?" A short second glance quickly dispenses with this possibility: (1) the SAM receivers for good reason have time constants longer than those required for the quick reaction time required by ABS; (2) when an abnormality is detected it would have to automatically and promptly be communicated to the ABS for blink activation. In general direct links between SAM sites and transmitters do not presently exist; (3) Monitor site data is unavailable for significant periods of time. The April 1990 report for the Great Lakes Chain shows Plum Brook Ohio unusable for 1018 minutes, Dunbar Forest Michigan unusable for 1447 minutes, New Orleans unusable for 4389 minutes, and Destin Florida unusable for 6074 minutes.

A far more attractive approach is to locate a receiver at each Secondary which tracks the Master signal. This is done now as a backup method of timing control using Austron 2000 receivers. With this approach the baseline timing information would be available right at the secondary transmitter where it is needed. Furthermore there would be no need for equipment at the Master transmitter.

Both of these were shown to be unfeasible because of the signal-to-noise ratios involved. If long-term smoothing of the

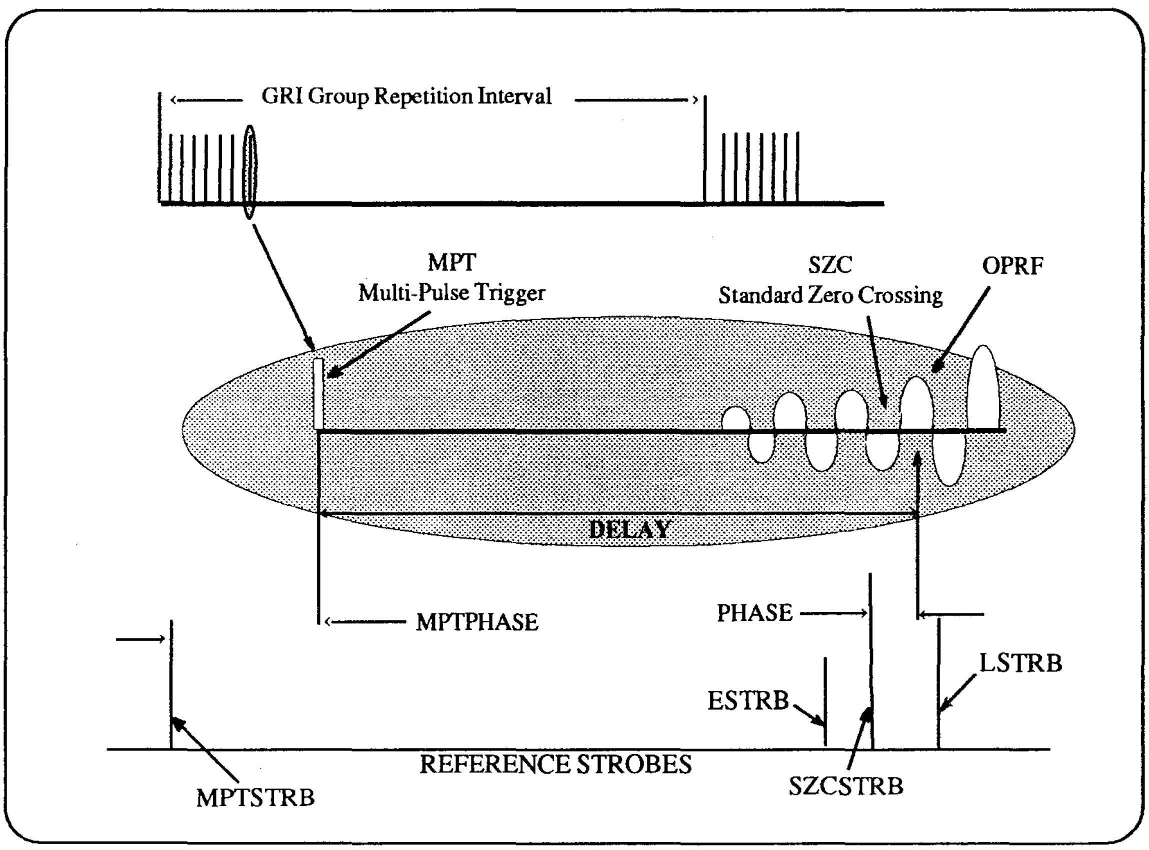


FIGURE 1 - ABS Timing

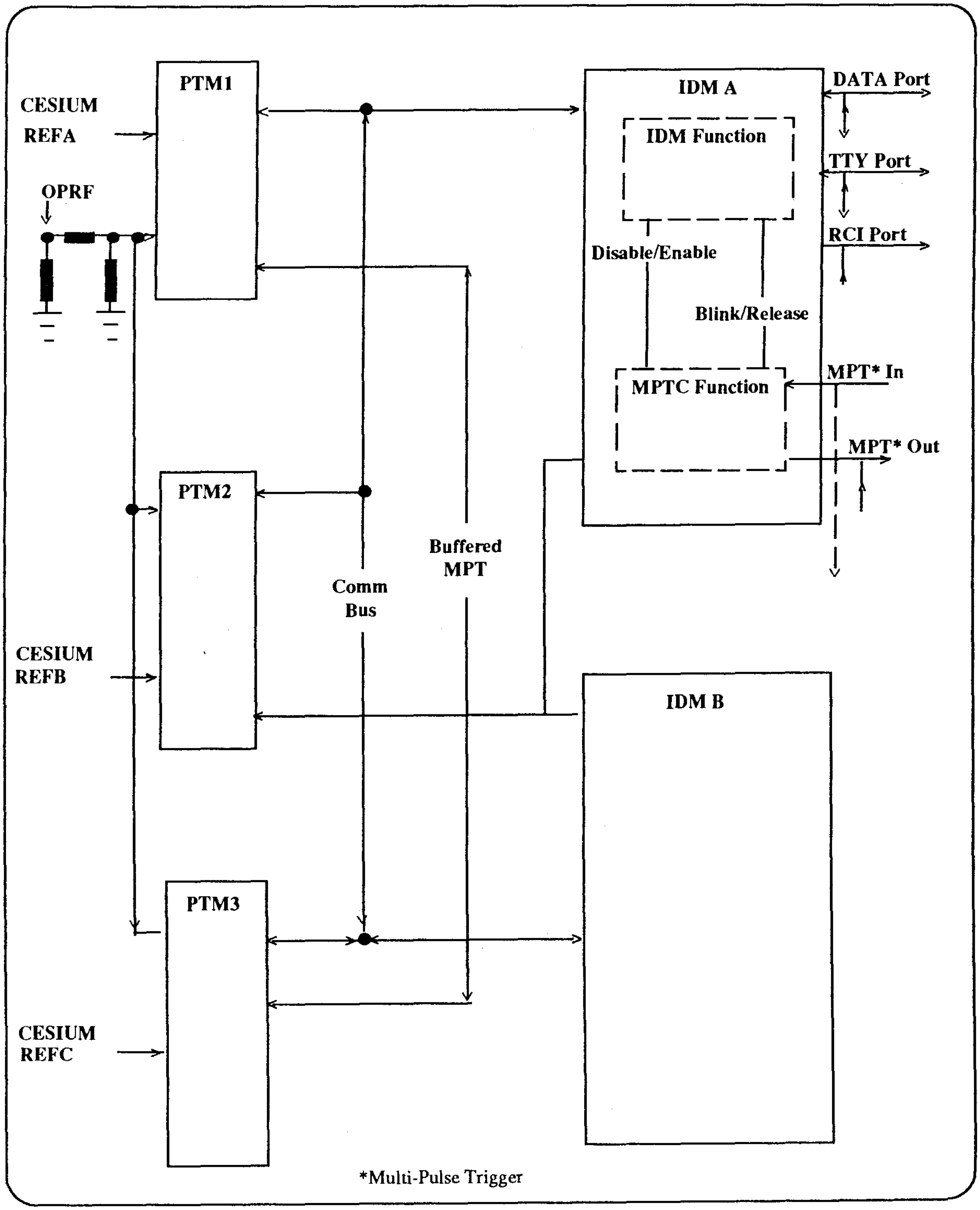


FIGURE 2 - A Block Diagram of the Selected Approach

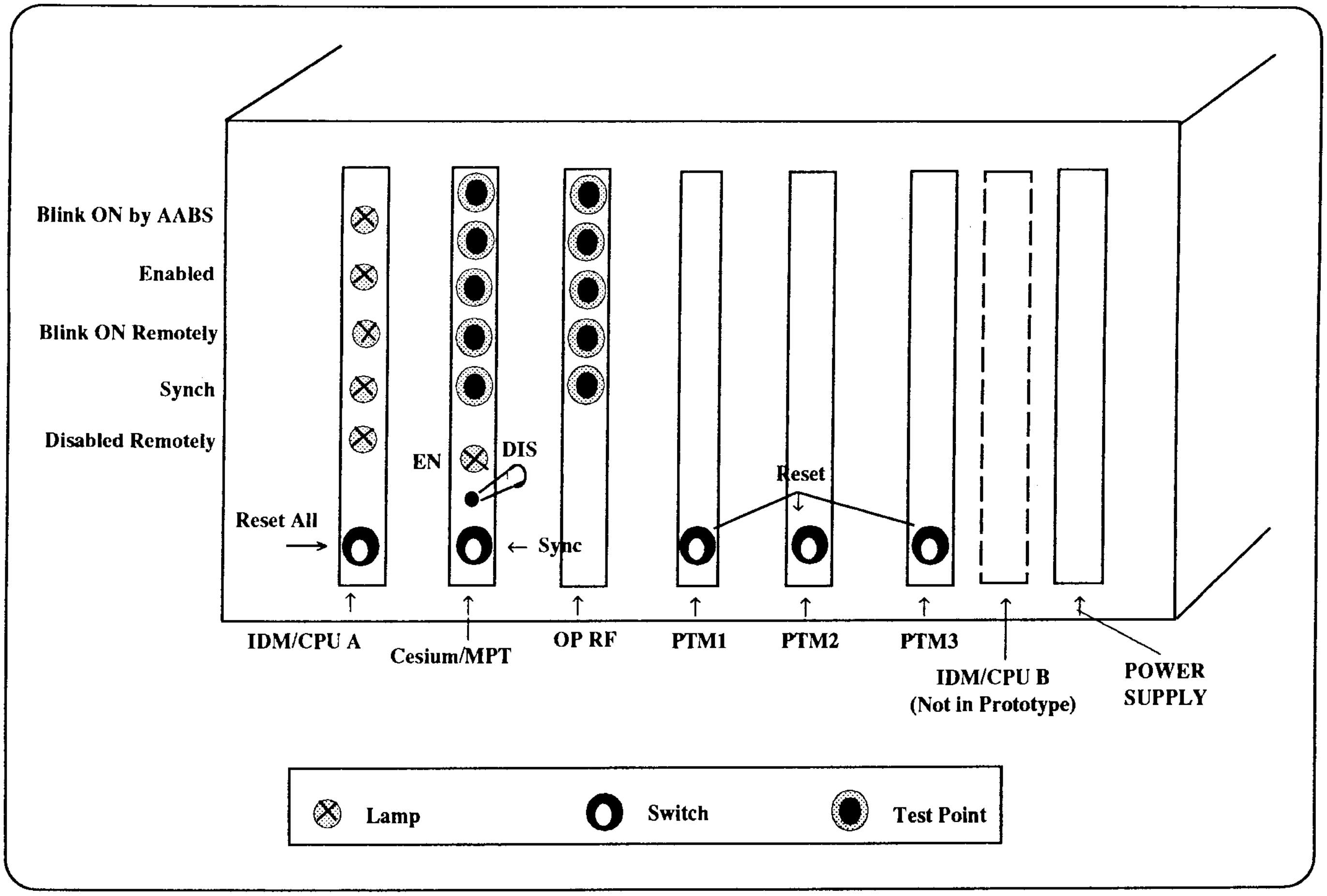


FIGURE 3 - ABS Prototype Chassis

data is used, then the reaction time of the receivers would be too slow. Short smoothing times would result in excessive false alarms or missed detections.

The selected measurement technique accepts five input signals: (a) A phase shifted 5 MHz signals which originate from three separate cesium oscillators; (b) A sample of the antenna return current (OPRF) which is a replica of the transmitted Loran-C signal. (If the transmitter is being run in dual-rated mode then Loran-C pulses from both rates will appear in the OPRF.); (c) A waveform which is termed the multi-pulse trigger waveform (mPT). This waveform consists of one trigger pulse for each Loran-C pulse to be transmitted on a given rate. Each MPT pulse initiates the transmission of a Loran-C pulse and hence determines the timing of the radiated signals.

Loran-C receivers are designed to track the 'third' positive going zero crossing of the Loran-C pulse. This is termed the standard zero crossing (SZC). Each MPT pulse precedes the SZC by about 500 microseconds in a solid state transmitter (SST) and by about 40 microseconds in a tube type transmitter (TTX). Figure 1 shows the timing.

The ABS measures the timing of the SZC of the OPRF with respect to strobes derived from each of the 5 MHz references. This measurement is designated as the PHASE. Any change in PHASE is designated as the OFFSET. The ABS is synchronized at a time when the baseline timing is known to be correct, at which time the three OFFSETS are set to zero. Any subsequent change in PHASE will be reflected in the OFFSET. Three OFFSET measurements are made, each using one of the three frequency references. If at least two of the three measurements do not agree that the OFFSET is less than a specified limit, then the ABS must impose blink. The ABS will do this by gating out the appropriate pulses from the MPT waveform before the MPT waveform is sent to the transmitter. Specifically the first two of each group of eight MPT's are gated out for 3.75 seconds and allowed through for 0.25 seconds. The ABS will stop imposing (release) blink when two OFFSET measurements agree that the OFFSET has returned to within a specified limit and certain other conditions are met.

The reference strobes used to measure the PHASE are termed SZCSTRB's. To ensure that the PHASE is measured with respect to the third positive going zero crossing, the SZCSTRB must occur between the second and third positive going zero crossings of the OPRF. The ABS must include a means of determining that the SZCSTRB is properly positioned during initial acquisition. Subsequent to the initial acquisition the ABS must also be able to determine that the OPRF has not moved such that the PHASE is being measured with respect to the wrong zero crossing or has moved the pulse out of the measurement window. This can be accomplished by using a second reference strobe (MPTSTRB) which occurs just prior to the MPT and measuring the time between the MPTSTRB and the MPT. This measurement is termed MPTPHASE and any change in MPTPHASE from its value at synchronization is termed MPTOFFSET. Thus blink is initiated whenever the OFFSET exceeds a limit of about 400 nanoseconds or when the MPTOFFSET exceeds a limit of about 7 microseconds. Both OFFSET and MPTOFFSET must return to a value within limits before blink can be released.

A block diagram of the selected design approach is illustrated in Figure 2. The antenna current (OPRF) is compared with references from each of the three cesiums in the three Pulse Time Monitor modules. The two Intelligent Decision Modules (IDM) are redundant. Each obtains the measurement results from the PTMs and decides whether or not blink should be activated. The Multi-Pulse Trigger (MPT) waveforms are generated in the USCG timers. Each MPT pulse initiates the transmission of a high-powered Loran-C pulse. Since the MPT pulses pass through the ABS, the ABS can invoke blink by gating out the appropriate MPT pulses so that they do not reach the transmitter.

A major advantage of the chosen approach is that the signals being used all have very low noise and decisions can be made quickly and with a high degree of certainty. Its disadvantage is that it does not yield a direct measurement of the baseline Time Difference (TD) and hence must be periodically synchronized when the baseline timing is known to be in limits.

Hardware Design

The basic design approach shown in Figure 2 was adhered to except that the prototype does not contain a redundant IDM CPU. The circuitry was contained on six PC boards as shown in Figure 3. The six modules, along with a power supply module, plug into a custom motherboard which serves as the rear panel of a card cage. All connectors except module debug ports are located on the rear of the motherboard.

The PTM modules and the IDM CPU module were slightly modified version of designs that had been done previously for the Omega Navigation System Center on the Omega Transmitter Upgrade project. The three PTM modules are identical. The PTM and CPU modules are designed around a Motorola 68HC11 microprocessor. The 68HC11 contains a built-in SPI bus which is utilized for intermodule communications.

The Cesium/MPT and OPRF modules were custom-designed. The Cesium/MPT module buffers the incoming frequency references and divides them down to 1 Mhz. It also buffers the incoming MPT waveform and provides the gates and relay contacts for controlling the blink function. The OPRF module provides hard limited OPRF to each of the three PTM modules. The OPRF module also contains six sample and hold circuits which provide 'early,' 'late' and 'diff' sample to each PTM module. These samples are used by the PTM modules to locate the standard zero crossing of the Loran-C pulses.

Each PTM module measure the time between a strobe generated from its frequency reference and the standard zero crossing of its hard limited OPRF. The CPU module queries the PTM modules for this and other data and makes the blink/noblink decisions. The CPU module also communicates with the TTY loop to receive commands and send status information.

Software Design

Programming was done primarily in 'C' on PCs using an Introl Corp. C11 cross-compiler version 3.06. Both PTM and IDM software utilize a multi-tasking environment. The structure of the PTM software is depicted in Fig. 4. The IDM tasks and their functions are illustrated in Fig. 5. Flow diagrams for the software can be found in reference (2). The final software differs slightly from the diagrams, but the basic logic was retained.

Prototype Testing

The prototype was tested at EECEN July 15-19, 1991. Reference (3) is the test procedure used. Test were run on the FPN-42, FPN-44, and SSX transmitters. Not all tests were run on all transmitters because of limitations in the transmitter equipment. A summary of the tests, test results, and corrective measures follows.

- Acquisition Tests

The purpose was to determine whether or not the ABS will reliably locate the standard zero crossing of the Loran-C pulses under a variety of signal conditions. In all cases but one the ABS successfully acquired the Loran-C signal within 15 seconds.

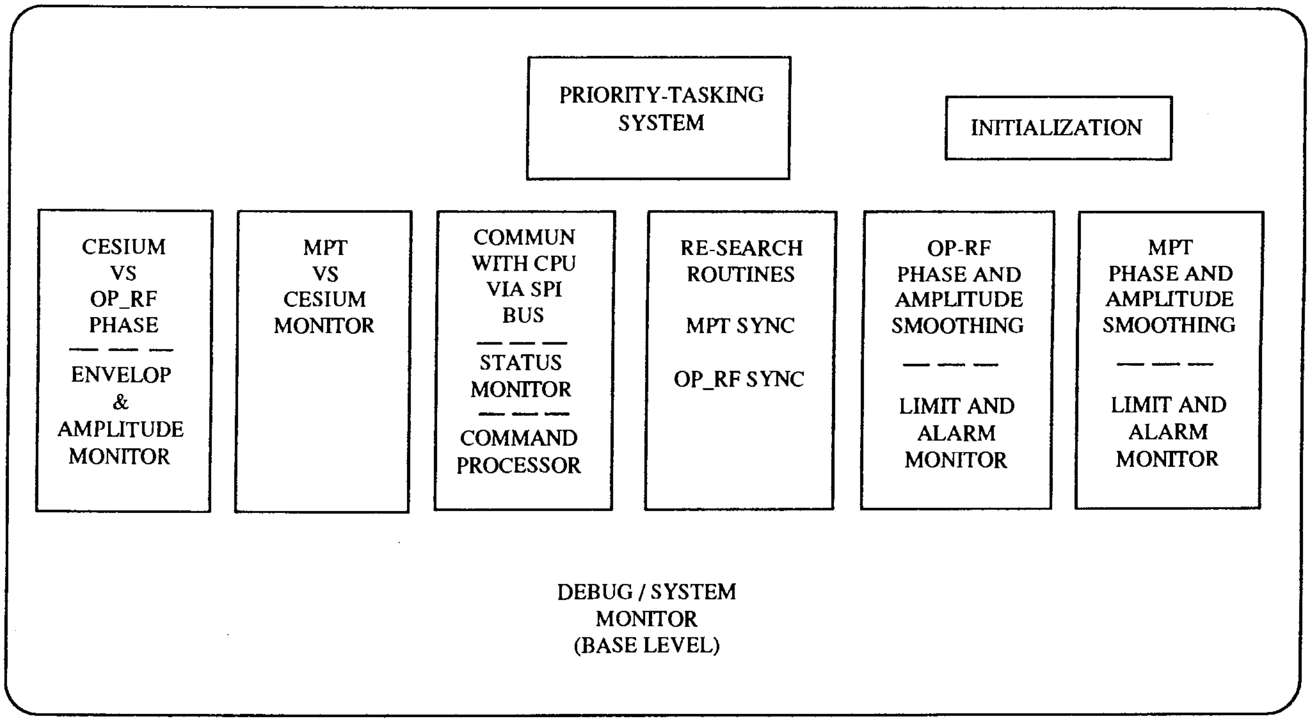


FIGURE 4 - PTM Software Structure

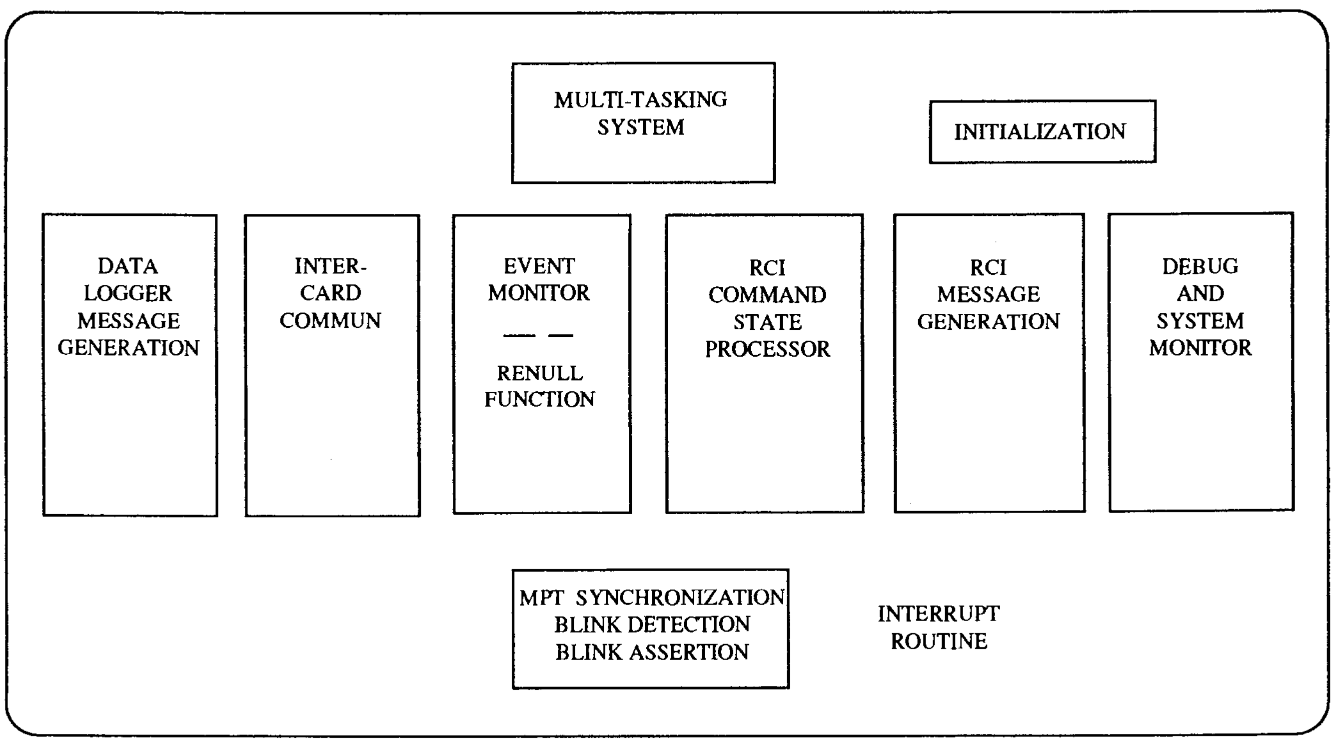


FIGURE 5 - IDM Software Structure

The exception was when the FPN-42 was run at low power. It is believed that this problem was caused by the pulse shape of the FPN-42 being out of specification at the low power level. Presumably this condition would not be allowed to exist in operation.

• Offset Measurement and Self-Synchronization

The purpose was to determine the accuracy with which the ABS measures the offset between the frequency reference and the standard zero crossing and to determine that the self-synchronization function of the ABS works correctly. Accuracy was limited by the resolution of the clock (42 nanoseconds). Thus the results were generally within +/- one bit of error. The self-synchronization functioned correctly.

The clock resolution has been specified as 20 nanoseconds in the Engineering Specification. Accuracy of the offset measurement will be carefully specified over the range of signal conditions. The required accuracy is well within the state of the art.

• Blink Tests

The purpose was to determine that the ABS correctly initiates blink when a variety of perturbing conditions are introduced into the transmitter. The ABS initially failed to blink properly when a large (20ms) timing jump was introduced. After a software change, all tests were passed.

It was observed that when ABS blink was asserted, the transmitter cycle compensation loops did not behave properly. The ABS software was changed so that the ABS would not blink when it saw that the MPT's generated by the USCG were blinking. It is believed that EECEN personnel later found the cause for this behavior. Presumably the USCG will also correct the cycle compensation circuitry.

• Noblink Tests

There are events that can occur at a transmitter that should not cause the ABS to initiate blink, for example, switching coupling networks, 'clean' timer switching, and the loss of the standby or tertiary cesium. When induced, none of these events caused unexpected blinks.

• Disable/Enable Tests

One of the requirements is that it must be possible to disable the ABS either locally or remotely via the TTY communication loop. These tests were designed to show that the disable/enable function did indeed disable the ABS and to show that USCG commanded blink still functioned properly.

The disable/enable function worked correctly except that the ABS sent a blink command to the local Remote Control Interface (RCI). A small software change will correct this problem. The Engineering Specification states that the blink command must not be sent when the ABS is disabled.

• Local Blink Tests

The purpose of these tests was to show that if blink is started locally and then stopped quickly (15 seconds) the ABS will extend the blink period to a minimum of 30 seconds. The ABS functioned properly.

• Master Blink

The purpose of this test was to demonstrate that the ABS functions properly using the Master phase code and to demonstrate that when a blink condition exists the ABS shuts off all Master pulses and sends TTY messages that it has turned Master off and requesting that ABS be disabled. That latter message implies that the USCG is to take control of the chain until the problem is corrected. The ABS functioned properly.

• EECEN Test Summary

The ABS prototype successfully demonstrated that it is compatible with all three transmitter types. It can reliably detect a timing anomaly of 500 nanoseconds or greater and can initiate blink within two seconds. The self-synchronization functioned properly. No false blink events occurred. It is compatible with the USCG TTY communications system, and it does not interfere with the normal USCG methods for detecting and initiating blink.

The resolution of the clock used to compare the frequency reference with the standard zero crossing needs to be improved for the production units.

A number of minor problems having to do with message protocols, use of the data port, blink event details and the like came to light as a result of the testing. Several of these were corrected by software changes to the prototype. They have all been dealt with by proper additions to the Engineering Specification.

Engineering Specification

Task 5 of the Statement of Work (SOW) calls for the preparation of an "Engineering Specification for Loran-C Automatic Blink Operation Units" conforming to MIL-STD-490A. However, MIL-STD-490A does not define an 'Engineering' specification; therefore, a Type C2a, Critical item product function specification, was selected as the type best suited to this stage of the ABS development. This type is described as "applicable to a critical item where the critical item performance characteristics are of greater concern than part interchangeability or control over the details of design, and a 'form, fit and function' description is adequate."

Para. 3.1 of the specification is entitled Critical Item Definition. Subpara. 3.1.3, General Functional Description, is a description of how the ABS prototype, and presumably the production unit, is organized, and what functions it performs to accomplish the overall goal. The intent is that an understanding of this section will lead to a better understanding of the performance specification section which follows.

Para 3.2, Characteristics, with its subparagraphs, details the performance and physical specifications of the ABS. For the general requirements such as maintainability, environmental, design and construction, etc., the specification states that the ABS shall meet the requirements of similar equipment built for monitoring and control of Loran-C transmitters. The final specification is contained in reference (4).

He also holds three patents, has an MSEE degree from Northeastern University, and is a member of IEEE, ION, and the Wild Goose Association.

REFERENCES

[All References prepared for Volpe National Transportation Systems Center under Contract DTBS-57-89-D-00045, TTD CA1029.]

Reference 1: Task 1 Report - February, 1991

Reference 2: Automatic Aviation Blink EECEN Test Plan - 04/30/91

Reference 3: Handouts from 05/01/91 Critical Design Review

Reference 4: Critical Item Product Function Specification for Automatic Blink System, 08/30/91

BIOGRAPHY

MARTIN C. POPPE
Cambridge Engineering
P. O. Box 3099
Burlington, VT 05401-3099

Mr. Poppe is an electronic 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 18 years ago, Mr. Poppe has worked on various navigation systems including Loran-C, Omega, and Differential GPS in addition to Mr. Poppe's work on the Automatic Blink System (ABS).

Recent projects include the design of a DSP-based timer for the USCG Omega navigation transmitters, and the design of radiobeacon receivers to demodulate MSK modulated differential GPS data.

ROBERT B. GODDARD
Megapulse, Inc.
8 Preston Court
Bedford, MA 01730-2380

Mr. Goddard joined Megapulse Inc., in 1981 and was subsequently named Manager of Software Engineering and later Manager of Systems Engineering. In these positions, Mr. Goddard managed and actively contributed to several major development projects.

At Megapulse, Mr. Goddard managed the Automatic Blink System program, the program to develop, implement, and install the timing and control system for the French Navy Loran-C chain, and the effort which obtained acceptance of the Loran-C subsystem of the Vessel Traffic Control System by the Suez Canal Authority.

Mr. Goddard was a principal contributor to many studies on such topics as Loran-C/GPS Interoperability, precision time transfer techniques for remote synchronization, design of a timing and control system for the proposed NW European Loran-C System, and the propagation time behavior in Europe.

Mr. Goddard is the author of numerous technical papers including, "Use of Radiobeacons to Broadcast Differential GPS Corrections," delivered at the 1987 Annual Meeting of RTCM. He also holds three patents, has an MSEE degree from Northeastern University, and is a member of IEEE, ION, and the Wild Goose Association.

NAVY COMBAT SEARCH AND RESCUE OPERATIONS IN SUPPORT OF OPERATIONS DESERT SHIELD/STORM

Neil T. Kinnear
Sonalysts, Inc.
Virginia Beach, VA

ABSTRACT

This paper will discuss the U.S. Navy's efforts in the Joint Combat Search and Rescue (CSAR) arena during Operation Desert Shield and, later, Desert Storm. After an introduction to "set the stage" of where the Navy's CSAR program was at the invasion of Kuwait, the paper will discuss:

* 2 AUGUST UNTIL DEPLOYMENT IN MID DECEMBER
* DEPLOYMENT UNTIL THE OUTBREAK OF HOSTILITIES, 17 JANUARY
* OPERATIONS DURING DESERT STORM
* THE NAVIGATION PROBLEM
* CONCLUSIONS

Emphasis will be placed on the technical difficulties encountered and the solutions developed to solve the associated problems. Special emphasis will be given to the navigation problem and the use of GPS and LORAN C.

INTRODUCTION

Prior to October 1988, Helicopter Combat Support Squadron Nine (HC 9) out of Naval Air Station (NAS) North Island, CA was the Navy's only dedicated CSAR asset. This reserve squadron had, for years, kept the CSAR capability developed in Vietnam alive and well and ready for use by the Fleet Commanders. The "Protectors" of HC 9 were flying the same HH-3's that had performed the CSAR mission in the skies over Vietnam in the 60's and 70's. The aircraft were old and their capability severely limited. Under certain conditions, their combat radius was as little as 30 miles. Two other squadrons, also reserve, had kept alive another capability that was deemed no longer needed by Fleet squadrons - light attack. Helicopter Attack Light Squadrons Four and Five (HAL 4 & HAL 5) out of NAS Norfolk, VA and NAS Pt. Mugu, CA respectively operated HH-1K's Huey gunships that had seen action in the Mekong Delta of Vietnam. The "Redwolves" of HAL 4 and the "Bluehawks" of HAL 5 had evolved a direct support role for Navy SEAL's, the special operations branch of the Navy. This type of flying included long range, low level, day/night navigation flights that culminated in either the insertion or extraction of these Navy commandos using a variety of methods to and from some rather unorthodox landing zones (LZ), as well as their traditional mission of light attack.

All three of the squadrons had been using night vision goggles (NVG) for night operations since the early 80's and had developed an exceptional operational capability with an impressive and enviable safety record - collectively, over thirty years of safe NVG operations.

In order to have a successful program, three elements are necessary. First, people must either be identified or trained with the prerequisite skills needed to accomplish that mission. Second, you must have equipment capable of performing the specific mission; and, third, a training program that can mold the men and machines into a unit that will yield the necessary capability. The CSAR program plan adopted by the Navy in the mid 1980's identified a pool of readily trained personnel available in HC 9, HAL 4 and HAL 5. The plan called for these three squadrons to form the nucleus of the two new squadrons, both reserve, charged with the CSAR mission as well as Special Operations support. Since these were reserve squadrons, more active duty reserve personnel would be assigned to allow the squadrons the flexibility to respond to Fleet requirements on very short notice. The remaining reserve personnel would give the squadrons their sustainability.

HAL 5 was decommissioned in October 1988 and the "Firehawks" of Helicopter Combat Support Special Squadron Five (HCS 5) were commissioned the same day at Pt. Mugu. They were followed by the HCS 4 "Redwolves" in October 1989 who grew out of what had been HAL 4 at Norfolk, VA. HC 9 was decommissioned in June 1990 and its highly trained and experienced personnel were shared between HCS 4 and HCS 5.

As previously stated, people are only one third of the program - equipment and training round out the equation. The airframe selected through a competitive bid process was a variant of Sikorsky Blackhawk and was designated the HH-60H. The first aircraft was delivered in June of 1989 to HCS 5. HCS 4 received its first airframe in January 1990. Aircraft delivery, pilot, aircrew and maintenance personnel training was on-going when Iraq invaded Kuwait in August of 1990. HCS 5 had five aircraft on board while HCS 4 had only three. To say the Navy's CSAR program was in transition in August 1990 was an understatement. On the day of the invasion, only one two-aircraft detachment belonging to HCS 5 was certified fully combat capable. HCS 4's first detachment was not scheduled to come on line until October 1990.

2 AUGUST UNTIL DEPLOYMENT IN MID DECEMBER

When the order came through in early August to prepare two detachments (dets) for deployment, the second detachment was molded from the trained personnel and equipment of Fire Hawk Det Two and Redwolf Det One. The combined detachment was formed at Pt. Mugu, CA and reported ready to deploy on 10 August. By the end of October Redwolf Det One was declared ready and the men and equipment were returned to NAS Norfolk to await possible recall and deployment. Early in August, HCS 5 sent one officer to ride over with the Saratoga Battle Group to help RADM Gee and his staff with the CSAR contingency planning. That pilot also took advantage of the opportunity of being in country to do site surveys in both eastern and western Saudi Arabia. At that time it was not yet known if the detachments would be based ashore, aboard ship, in the Red

Sea or Persian Gulf or some combination of those options. In September, both HCS 4 and HCS 5 provided one pilot each to the Naval Central Command staff (NAVCENT) embarked aboard the USS BLUE RIDGE to man the Rescue Coordination Center (RCC) so support to the Fleet was early into the problem.

The immediate concern was insuring that the dets were ready to go in every way possible. The original transition plan had called for additional equipment improvements in the out years. This list included such items as the Downed Aviator Locator System (DALS), an upgrade to the on-board Tactical Navigation (TACNAV) system; and, of more immediate concern, the Global Positioning System (GPS). It was immediately apparent that equipment installation, especially the GPS, would need to be accelerated. All this was going on at the same time the thousand and one other details and problems that needed to be addressed and solved to get a detachment deployed were happening.

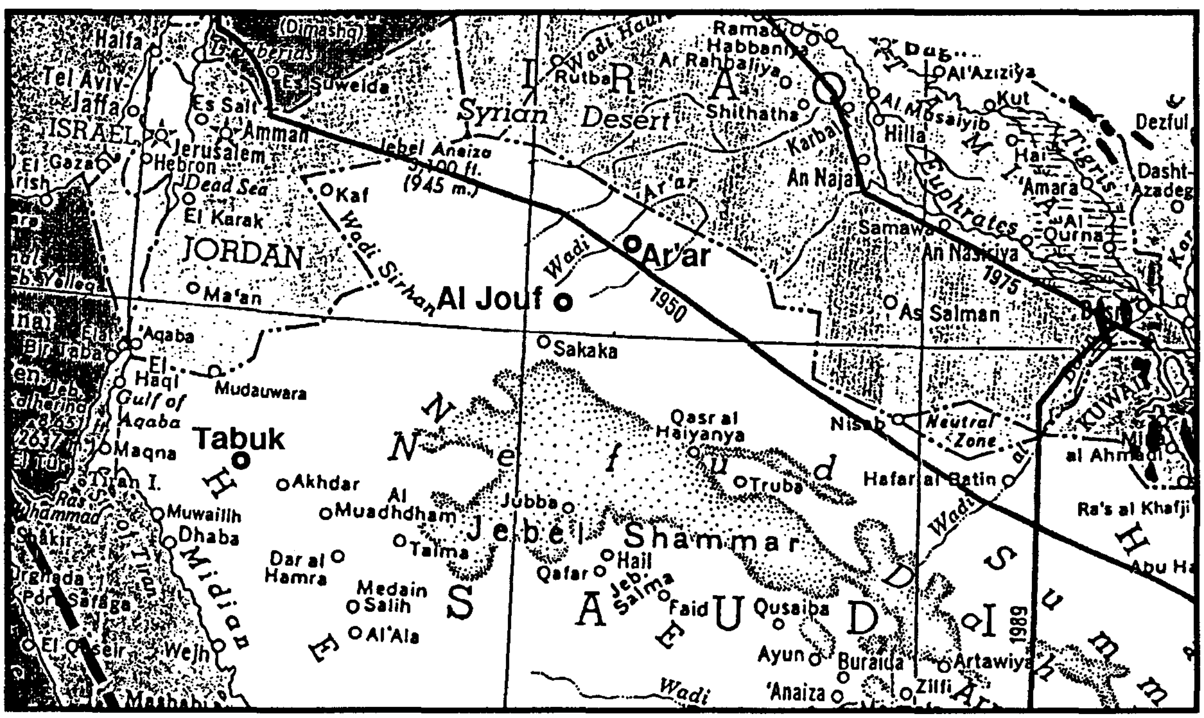
The original concept of operations for the CSAR detachment had conceived of operations in and around the carrier battle group based aboard ship and under the supply umbrella of the battle group with operations seen projected ashore in a more woodland environment. The many variables around exactly where and when the detachments would deploy made contingency planning very difficult. To say that things were a little hectic at both squadrons would be an understatement.

The Kuwaiti Theater of Operation (KTO) and the eastern part of Saudi Arabia had numerous coalition forces capable of performing SAR operations. In the western sector of Saudi Arabia, the only SAR asset available was the 4th Flight of the Royal Saudi Air Force based at Tabuk. They were flying UH-1N Hueys capable of day-only SAR operations out to a radius of 125 nautical miles. Due to the large distances involved in the western sector and the fact that the coalition forces would have three carrier battle groups in the Red Sea as well as numerous air assets at every available airfield in western Saudi Arabia, the need for an increased SAR capability was identified.

The detachments were activated 30 November 90 under the President's call up of Guard and Reserve forces and tasked to provide combat search and rescue support in western Saudi Arabia to meet this requirement. Placing both detachments at Tabuk would provide 24 hour a day SAR coverage to the western sector as well as allowing mutual support.

DEPLOYMENT UNTIL THE OUTBREAK OF HOSTILITIES, 17 JANUARY

HCS 4 Det One left its home base of NAS Norfolk, VA and arrived via an Air Force C-5 aircraft on 10 DEC 90. HCS 5 Det One left NAS Pt. Mugu, CA on 11 DEC 90 and after what can be described as the "C-5 flight from hell" arrived 15 DEC 90. The Fire Hawks had to change aircraft three times before arriving in country. Both detachments set up operations at King Faisal Air Base in Tabuk, Kingdom of Saudi Arabia. The two detachments worked out of tents next to the hangar which housed 4th Flight, the Royal Saudi



The Western Sector
Saudia Arabia & Iraq

Air Force search and rescue squadron, which flew the UH-1N. Operations remained autonomous since each detachment was required to be capable of self-sustained operation. By being colocated at Tabuk, the dets were able to provide each other technical as well as supply support.

Both dets developed and executed training plans that honed their readiness to a fighting edge prior to hostilities. Contingency plans were developed, site locations surveyed and liaison established with both the Central and Air Force Special Operations Command, SOCCENT and AFSOC respectively, to support forward basing of the detachments. It was determined that the detachments would be best used if placed under Air Force control. RADM Mixson, Commander Red Sea Battle Force, was to retain operational control but tactical control would pass to AFSOC.

OPERATIONS DURING DESERT STORM

On 16 JAN 91, orders were received to move forward to Al Jouf, 200 miles northeast of Tabuk. Anticipating the opening of hostilities, an advance party of two officers and one chief petty officer had established a presence by 1800 on the 15th. The maintenance personnel and the supply pack-up moved by flatbed truck into position by 1600 with the aircraft arriving by 1800. At 0200 on the morning of the 17th, the first Navy combat search and rescue package moved 90 miles north to a forward arming and refueling point at Ar' Ar airfield to join elements of the 55th and 20th Special Operation Squadrons of the U.S. Air Force flying MH-60J Pavehawks and MH-53J Pavelows.

During the course of the war, the Redwolves and Firehawks molded themselves into an integrated, fully combat capable detachment under the callsign of "Spike" working out of "Spike Alley" at Al Jouf. Operations at Al Jouf were sustained around the clock for 51 days. The aircraft were operated from a perimeter road and all necessary maintenance was accomplished under less than ideal conditions - sandstorms where visibility past 100 feet was impossible, hot days, cold nights, wind in excess of 30 knots, rain and the inescapable and ever present dust. To be blunt, living conditions were spartan - sleeping and working spaces were tents and a blockhouse, twenty people lived in a 25 foot by 35 foot space, hot showers and hot food were non-existent - food was initially MRE's; halfway through the war, the Air Force put in shower tents and a messhall which greatly improved the quality of life. All this coupled with the constant threat of SCUD and terrorist attack placed an extra strain on all hands.

Fortifications consisting of barbed wire or earthen berm, bunkers and bomb shelters were constructed at both Tabuk and Al Jouf. The dets became very proficient at filling sandbags, building bunkers, bomb shelters and providing our own security force.

Upon the cease fire, the dets returned to Tabuk. On 17 MAR 91, HCS 5 Det 1 loaded into a C-5 for the return home arriving at NAS Pt. Mugu on the 18th. HCS 4 Det 1 left on the 22nd and returned to NAS Norfolk on 23 MAR 91.

THE NAVIGATION PROBLEM

As HCS 4 was making preparations to deploy, we tried to get maps of the region from the Defense Mapping Agency (DMA). Basically we were told they did not have any to give us - due to the huge demand for maps of that area there were none to be had. The fall back position until the map supply caught up with the demand was to scrounge through back issues of National Geographic. Not the best way to get ready to go to war but the best we could do under the circumstances. When we did get our maps, someone had put a disclaimer that said something to the effect that "contour lines should be considered unreliable and not used for navigation". This turned out to be the understatement of the war.

In the days of flying Hueys, the HAL pilots had become very proficient at navigating low level using both dead reckoning, i.e. time/distance checks, and the "lay of the land" as a primary means of navigation. The first day in Saudi, it became readily apparent that this form of navigation would just not work. The desert environment encountered offered little more in the way of terrain to navigate from than the sea would provide. Unlike the sea, the sand had a way of gradually growing in height and could "reach up and touch you" in a disastrous way.

Initial reports back from the Gulf talked of the problems associated with tactical navigation. For a helicopter to survive on a modern day battlefield, the need to stay low (100 feet or less) was imperative. In order to effectively recover a downed airman, his position needed to be known to within a mile or less. The HH-60's had both a TACAN and Doppler with their inherent drawbacks. The aircraft would not be able to operate at altitudes to give sufficient TACAN coverage and the doppler did not have the needed accuracy. This fact drove the need for the accelerated incorporation of the ARN-171 Global Positioning System (GPS) into the aircraft

Very early in August, the decision was made to accelerate the GPS installation. This effort involved one officer and one enlisted man from HCS 4 traveling to American Electronics Laboratory, Inc. in Farmingdale, NJ to "get smart" on the system to be the trainer and maintainer. They later supervised the installation and training at both squadrons. In order to install the GPS, the improved software was required. This upgrade meant the actual "black boxes" had to be returned to the vendor for upgrading and re-installed in the aircraft. At that time, there were hardly enough "black boxes" to go around. The GPS installation and software upgrade took an almost unbelievable effort on the part of Naval Air Systems Command, Rockwell and Sikorsky Aircraft to get one full system to go in each of the four deploying aircraft. They all did a magnificent job in record time. However, on the down side, there would be little left in the way of spare parts to go along with the detachments.

There was a also a prediction program for the GPS that operated on a personal computer. That program projected approximately eight hours loss of coverage on a daily basis. This was due to the actual position and availability of the satellite constellation coverage. Prior to the outbreak of the war, an additional satellite was put into orbit that shaved coverage loss to around four hours a day which greatly improved the navigation situation.

The GPS was integrated into the aircraft through the 1553 data bus so information was presented on the Tactical Navigation (TACNAV) display. When the GPS was working, it gave a figure of merit of 26 yards or less.

In early August when the GPS issue was far from solved, one officer from HCS 4 happened on the idea of a LORAN backup using a unit capable of being held in your lap. With a velcro arrangement, it could be "mounted" to the side of the pedestal next to the copilot. Power would be supplied through an outlet already in the cabin of the HH-60 with an external antenna that attached to an eight inch oval of sheet metal that was used as a fairing in the vicinity of the cargo hook. All of this meant that the installation would not be permanent and could be easily removed. The Saudi's had spent a lot of money on a chain of LORAN stations and it looked like an opportune time to make use of that LORAN chain. When that officer deployed to Pt. Mugu in August as part of Det Two, this idea was offered to HCS 5. It was rejected at that time so as not to jeopardize the GPS installation.

When the offer was made to HCS 4 in November, the GPS upgrade was well on its way but was not a yet for certain. A decision was made to take two LORAN units "just in case". Northstar Avionics of Acton, Massachusetts and ARNAV, Inc. of Portland, Oregon each provided one complete unit. After arrival in Saudi, they were installed in the aircraft under a Rapid Action Maintenance Engineering Change with no modifications to the basic airframe.

Due to a number of reasons, one of which was the GPS spare parts situation, a request was made for additional units to provide a precise backup to the GPS navigation system. Four units were received from Foster Air Data System, Inc. of Columbus, Ohio and installed in the aircraft. This was an "add on" unit; and, as such, was not integrated into the 1553 data bus. It was separate from the on board computer system and would continue to provide navigation information in the unlikely event of a dual computer failure. The redundant systems gave the pilots a nice warm "fuzzy". It was a great comfort to look at the latitude and longitude (LAT/LON) and see them within a few minutes of one another especially when the figure of merit of the GPS was high or unavailable.

CONCLUSIONS

The impact on both squadrons and the Strike Rescue program in the Naval Reserve may never be either fully understood or quantified but we can all rest assured that it is in all respects positive. The squadrons will never be the same again. Each and every member of the "Spike" det should be proud of what was accomplished. The numbers speak for themselves.

	HCS 4	HCS 5	SPIKE
Sorties	234	227	461
NVG Hours	154.4	109.9	264.3
Total Hours	396.7	353.3	750.0

The detachment also obtained a full mission capable (FMC) rate of 85.0 % and a mission capable (MC) rate of 94.7%. These rates would be excellent at home base. Considering they were for a deployed detachment at the end of a long supply support chain they are fantastic!

Our accomplishments made us proud to be American fighting men defending the ideals that have made this country great and softened the impact of being in a foreign land in harms way. The "Spikes" of HCS 4/5 came to the Kingdom of Saudi Arabia to participate in Operation Desert Shield; and, later Desert Storm, to help do a job that was going to have to be done sooner or later. We can be proud that we didn't leave this problem to the next generation.

ACKNOWLEDGMENTS

I would like to thank the American people for their support which was nothing short of outstanding. Let's take a moment to talk about the Any Serviceman/Servicewoman Mail. To say it was overwhelming would be an understatement. No one, and I mean no one, every lacked for toilet articles, munchies, cookies, games, cards or books while at Desert Shield/Storm - not to mention the abundance of letters, posters, valentines and cards that wished us well. The only thing we were really short of was time to answer the avalanche of mail. Support was received from such diverse places as a nursing home in Vermont, second grade class of an inner city school in Chicago, Sunday school class in Iowa, loan office in California, American service families in Germany and England - the list goes on. The support made a big difference to morale. One could even say it showed in the results - we won this one!

It would also be an oversight to not recognize the support we received from the homeguard of HCS 4. The ones we left behind busily preparing for a second detachment, moving parts and other necessary material our way. Knowing they were behind us and preparing to take our place if this conflict had become drawn out was always a comfort. A salute to them and a sincere, heartfelt thank you.

I would like to thank the following organizations for their support throughout the crisis:

Commander Naval Air Forces Atlantic and Staff
Commander Naval Air Forces Pacific and Staff
Commander Naval Air Reserve Force and Staff
Commander Helicopter Wing Reserve and Staff
HCS-5
Naval Air Systems Command
Sikorsky Aircraft

I would also like to thank the following companies for the equipment they provided:

Sikorsky Aircraft
American Electronics Laboratory
Northstar Avionics Division, Digital Marine Electronics Corporation
ARNAV, Inc.
Foster Air Data System, Inc.

Neil Kinnear graduated from the U.S. Naval Academy with a BS in Systems Engineering in 1971 and also holds a MS in Engineering Management from Old Dominion University. After six years as a Cobra pilot in the Marine Corps, Neil left active military service and is currently working for Sonalysts, Inc. of Waterford, CT in Norfolk,Virginia as a senior engineer performing a variety of aviation related projects such as the cockpit integration of the V-22 OSPREY. CDR Kinnear is an eleven year veteran of the Naval Reserve where he has served in both HAL 4 and HCS 4, where he is currently the Commanding Officer. CDR Kinnear deployed to Saudia Arabia with HCS 4 Detachment One in support of Operation DESERT SHIELD/STORM and writes from his personal experiences.

Hospitality Sponsors

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Product Line: Avionics and instruments for the aerospace industry; best known for its gyroscopic products.

NavCom Systems, Inc.
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Manassas, VA 22110
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Product Line: Navigation and communication engineering, manufacturing, and management services.

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Exhibitors

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Product Line: Navigation and communication engineering, manufacturing, and management services.

U.S. Coast Guard Electronics Engineering Center
Wildwood, NJ 08260-0060
(609) 523-7275
Product Line: Loran-C system design and modernization.

Terrastarr, Inc.
10353 South 1300 West
South Jordan, UT 84065
(801) 254-3303
Product Line: Navigation, emergency location, and proximity warning systems based on loran or GPS positioning, for air and marine applications.

U.S. Coast Guard GPS Information Center
7323 Telegraph Road
Alexandria, VA 22310-3998
(703) 866-3806
Product Line: Loran-C, Omega and GPS status information and user documentation.

Electronic Devices, Inc.
3140 Bunch Walnuts Rd.
Chesapeake, VA 23322
(804) 421-2968
Product Line: Loran and depth simulators/test sets.

Convention Awards

The WGA Constitution authorizes the presentation of a number of non-monetary awards to further the aims and purposes of the Association. The following awards were presented during the convention banquet:

Medal of Merit — Jesse Pipkin

The Medal of Merit is awarded for a particular contribution of outstanding value to the development or fostering of loran. This award is normally given only after the exceptional nature of the contribution is clearly recognized.

The Medal of Merit was awarded to Jesse Pipkin for his contributions to the development and fostering of Loran-C by pioneering and promoting simplified microcomputer-based Loran-C receivers which are manufactured and sold at reduced costs and prices. A copy of the citation appears on the next page.

President's Award — David C. Scull

The President's Award is given to persons or organizations designated by the President of the Association.

The President's Award was presented to David C. Scull for his outstanding dedication and perseverance in managing the business operations for WGA and facilitating a smooth transition from his predecessor.

Best Paper Award — Martin Beckman

The Best Paper Award is given for the best papers published on any aspect of loran.

The Best Paper Award was presented to Martin Beckman, a student at the Delft University of Technology, The Netherlands, for *Interference Detection and Suppresion Methods for Loran-C Receivers* in the Proceedings of the 19th Annual Technical Symposium, October 1990, in Long Beach, California.

Service Awards

Service Awards are given to persons who distinguish themselves by service to the Association.

<u>James F. Culbertson</u> — For service as WGA President from October 1989 to October 1991

<u>James O. Alexander</u> — For service as General Chairman of the 19th Annual Convention in Long Beach, California, October 1990

<u>Robert H. Miller and Larry O. Cortland</u> — For service as Technical Co-Chairmen of the 19th Annual Convention in Long Beach, California, October 1990

Wild Goose Association

Citation on the award of the MEDAL OF MERIT to

JESSE PIPKIN

The Medal of Merit of the Wild Goose Association is awarded to Jesse Pipkin in recognition of his extensive contributions to the development and fostering of Loran-C including pioneering and extensive promotion of simplified microcomputer-based Loran-C receivers which are manufactured and sold at reduced costs and prices.

Working as an independent consultant, Mr. Pipkin designed systems which formed the basis for a number of receivers produced by various manufacturers, culminating in recent designs where all the digital processing is performed by a single-chip off-the-shelf microcomputer package aided by a few additional simple digital chips. We are informed that there have been more than 100,000 receivers representing more than a dozen different brands built with one type of microprocessor and its derivatives. Mr. Pipkin has documented his design ideas in three Wild Goose Association Technical Symposia papers.

The Wild Goose Association believes these contributions have had a most favorable effect on the stature of the Loran-C system and its expanded use and applications on land, sea, and in the air, and for this we are forever grateful to him.

Awarded this Second day of October, 1991,

James F. Culbertson, President.

Opening Day

WGA President Jim Culbertson

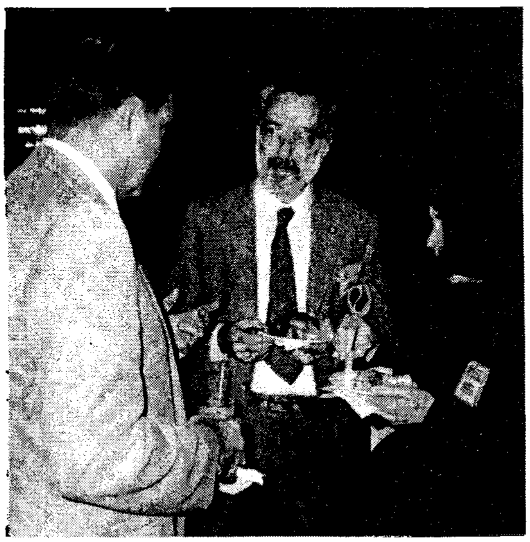
Dr. Frank Tung — Keynote Address

Technical Chairman Dave Scull

Tuesday Luncheon

Guest Speaker RADM William Ecker

Hosted Reception



Conference Coordinator Carolyn McDonald

Frank Boynton, Audio-Visual Aids

Banquet

Dinner is Served!

The Head Table

Guest Speaker Phil Boyer
President, Airline Owners and Pilots Association (AOP)

General Chairman Zeke Jackson
Recognizes the Technical Chairmen

Awards

Jesse Pipkin
Medal of Merit

Dave Scull
President's Award

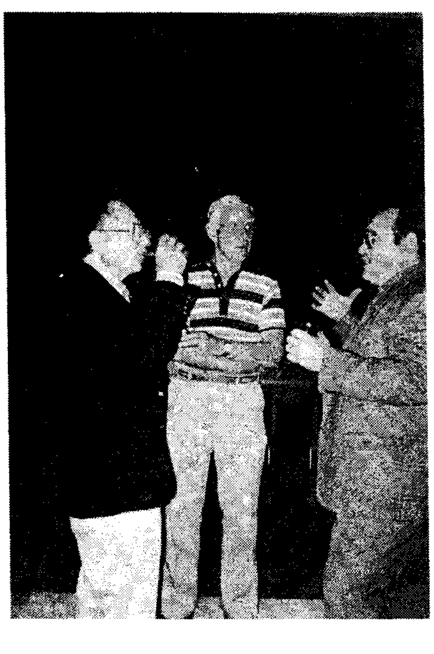
Martin Beckman (Durk van Willigen Accepting)
Best Paper Award

Bob Miller and Larry Cortland (Dale Johnson Accepting)
Service Awards

Hospitality





Board of Directors

The Directors at Work

Top Row: Lilley, Andren, Amos, Van Etten ... Scull, Cassidy, Jackson, Moroney, Culbertson

Bottom Row: Dean, Enerstad, Morgenthaler ... Marx, Hensel, McGann, Frank

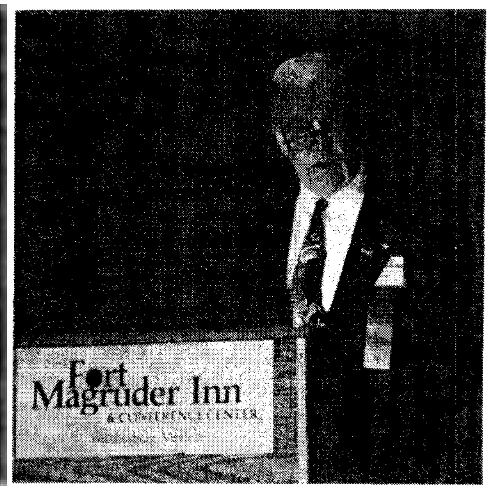
Carl Andren delivers Treasurer's Report at Wednesday General Membership Meeting

Technical Sessions

Apologies to those speakers whose photos do not appear.

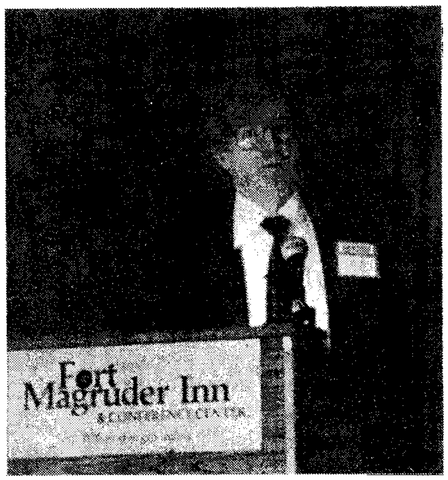
Ed McGann
Session 1 Chairman

Kjell Enerstad
Presenting for Andreas Stenseth

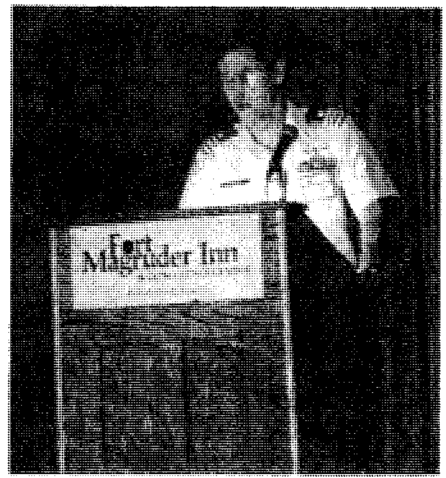


Mike Moroney
Session 2 Chairman

Liz Carpenter



Cal Culver



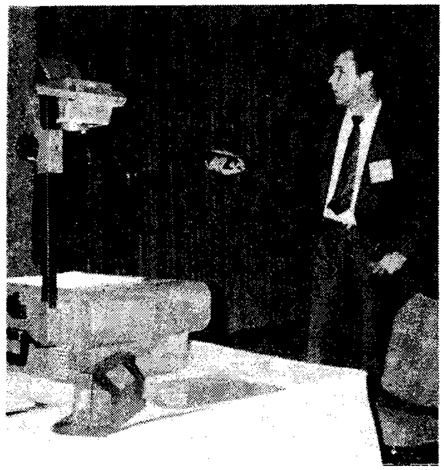
Denny McLean

Paul Burket

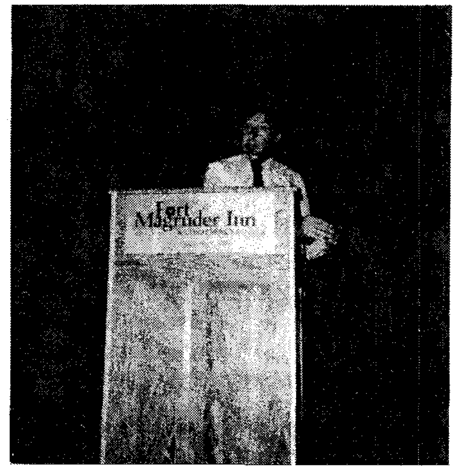
Jim Bland

Durk van Willigen

André Nieuwland



Bryan Townsend

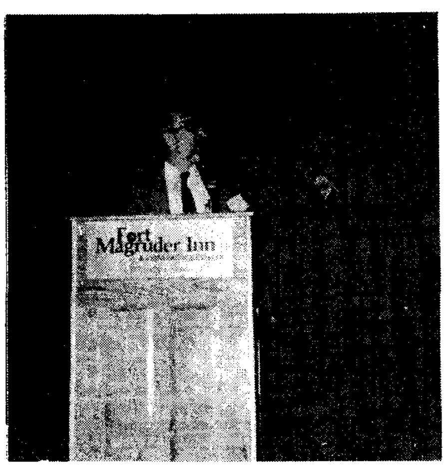


David Last

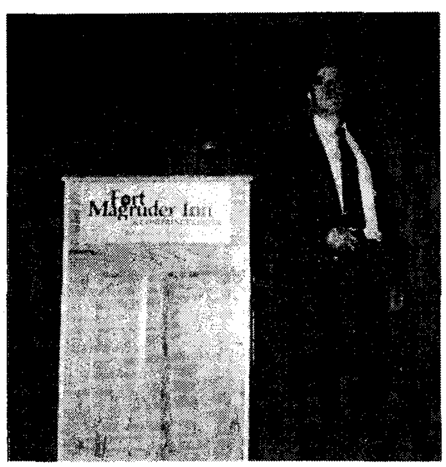
Frank Coyne

Ben Peterson

Chic Longman
Session 6 Chairman



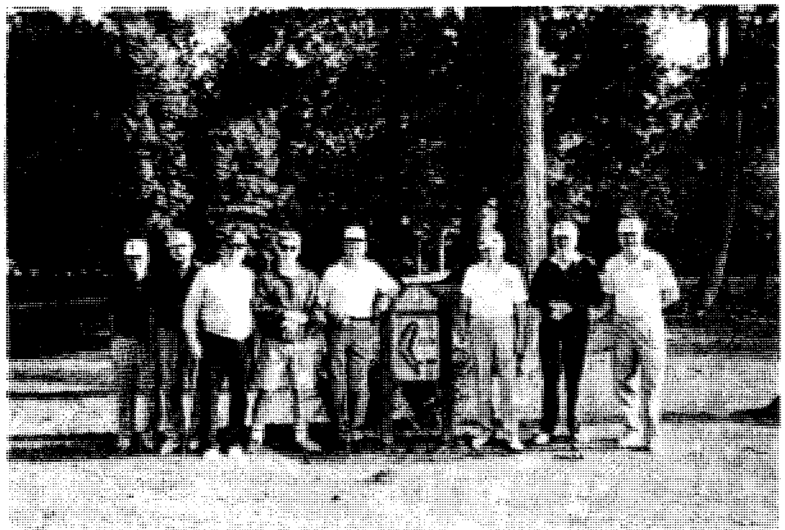
Jim Carroll



Marty Poppe

Neil Kinnear

Golf Tournament



The Players
Higginbotham, Roll, Bencivenga, Lupton, Moroney, Dean, Culbertson, Olsen

Winners Dave Lupton (Low Gross) ...

... and Vinny Bencivenga (Low Net)

Authors

Registered Attendees

Mr. Raymond Agostini
U.S. Coast Guard
Electronics Engineering Center
Wildwood, NJ 08260
(609) 523-7242

Mr. David Allison
CellTrac (MS 345)
4815 W Braker Lane, Suite 502
Austin, TX 78759
(512) 338-4651

Mr. David Amos
Synetics
540 Edgewater Dr.
Wakefield, MA 01880
(617) 245-9090

Mr. Carl S. Andren
Racal Marine Group
2000 M St. N.W., Suite 820
Washington, DC 20036
(202) 331-9097

CDR Richard Armstrong
USCG HQ (G-NRN-1)
2100 Second St. S.W.
Washington, DC 20593
(202) 267-0292

Mr. Vincent L. Bencivenga
FAA (AND-30)
Springfield, VA 22152
(202) 267-7504

Mr. John Beukers
Beukers Technologies
East Ridge, Longborough, nr.
Moreton-in-Marsh Glos.
GL 56 OQL **ENGLAND**
44-451-870777

CAPT William. J. Brogdon
506 W. Washington Ave.
Kinston, NC 28501
(919) 527-9349

Mr. Paul E. Burket
Aviation Consultant Services
545 Joseph St. S.E.
Salem, OR 97302
(503) 362-5126

CWO P.J. Calpin
U.S. Coast Guard Atlantic Area
Bldg 333
Governors Island, NY 10004
(212) 668-7880

Mr. Edward Campbell
U.S. Coast Guard
Electronics Engineering Center
Wildwood, NJ 08260
(609) 523-7274

Mr. Michael Campbell
U.S. Coast Guard
Electronics Engineering Center
Wildwood, NJ 08260
(609) 523-7274

CDR Perry W. Campbell
U.S. Coast Guard Atlantic Area
Bldg 333
Governors Island, NY 10004
(212) 668-7880

CDR George A. Capacci
U.S. Coast Guard 17th District
P.O. Box 3-5000
Juneau, AK 99802
(907) 463-2245

Ms. Elisabeth Carpenter
Volpe National Transportation
Systems Center (DTS-52)
55 Broadway, Kendall Square
Cambridge, MA 02142
(617) 494-2126

Mr. James Carroll
Volpe National Transportation
Systems Center (DTS-52)
55 Broadway, Kendall Square
Cambridge, MA 02142
(617) 494-2908

Mr. Frank Cassidy
Datamarine International
53 Portside Dr., P.O. Box 1030
Pocasset, MA 02559
(508) 563-7151

Ms. Pamela K. Charles
Helicopter Association
International
1619 Duke Street
Alexandria, VA 22314
(703) 683-4646

Ms. Laura Charron
U.S. Naval Observatory
34th & Massachusetts Ave., N.W.
Washington, DC 20392-5100
(202) 653-1529

Mr. Kam F. Chin
Volpe National Transportation
Systems Center (DTS-52)
55 Broadway, Kendall Square
Cambridge, MA 02142
(617) 494-2529

Mr. Francis J. Coyne
Volpe National Transportation
Systems Center (DTS-502)
55 Broadway, Kendall Square
Cambridge, MA 02142
(617) 494-2228

Mr. Bob Crowell
U.S. Coast Guard R&D Center
Avery Point
Groton, CT 06340
(203) 441-2682

Mr. James F. Culbertson
Coastwatch
15781 Exeter St
Westminster, CA 92683
(714) 531-7974

Mr. Calvin Culver
Micrologic
9610 Desoto
Chatsworth, CA 91311
(818) 998-1216

Mr. Walter N. Dean
Waldean Engineering, Inc.
8060 Sacajawea Way
Wilsonville, OR 97070
(503) 694-1443

Mr. Bill DeGeorge
NSS
3334 Bullfrog Road
Fairfield, PA 17320
(717) 642-6397

ENS Roberto DeVarie
USCG HQ (G-TTF-2)
2100 2nd Street S.W.
Washington, DC 20593-0001
(202) 267-1241

Mr. Kjell Enerstad
NODECA
Oslo Mil/Akershus
N-0015 Oslo 1
NORWAY
47-2-402400

Mr. Robert Erikson
FAA Technical Center (ACN-270)
Atlantic City, NJ 08405
(609) 484-5750

Mr. Richard Farnworth
University of Wales School of EE
Dean Street, Bangor
Gwynedd LL57 1UT
UNITED KINGDOM
44-0248-351151 Ext 2737

Mr. Ken Foret
Northstar Avionics
30 Sudbury Road
Acton, MA 01720
(508) 897-6600

Mr. Robert L. Frank
30795 River Crossing
Birmingham, MI 48025
(313) 645-9848

Mr. Edward Fraughton
Terrastarr, Inc.
10353 South 1300 West
South Jordan, UT 84065
(801) 254-3303

Mr. David Gay
Navigation Systems Specialists
RD 1 Box 2145
Felton, PA 17322
(717) 993-5226

Mr. Jeffrey Girsch
JHU/APL
Johns Hopkins Rd Room 8-280
Laurel, MD 20723
(301) 953-5107

Mr. Ed Goudie
Canadian Coast Guard
Atlantic Area
St. Anthony, Newfoundland
CANADA
(709) 454-2392

CWO Jonathan D. Graeb
USCG MLC Atlantic
Bldg 333 1st Floor
New York, NY 10004
(212) 668-6381

LT Kurtis Guth
U.S. Coast Guard LORSTA
Kodiak
110-A Avenue E
Kodaik, AK 99615
(907) 487-5183

Mr. Bruce Hensel
Jet Electronics and
Technology, Inc.
5353 52nd Street S.E.
Grand Rapids, MI 49588-0873
(616) 285-4396

CWO Richard Hoffman
USCG Pacific Area (PTL)
Coast Guard Island
Alameda, CA 94501
(415) 437-3226

Mr. S. Ito
Japan Assoc. for Nav. Aids
1-3 Nishishinbashi I Chome
Minato-K4 Tokyo 105
JAPAN
03-3502-0588

Mr. Elijah "Zeke" Jackson
NavCom Systems
7203 Gateway Ct.
Manassas, VA 22110
(703) 361-3186

Mrs. Mary Jackson
NavCom Systems
7203 Gateway Ct
Manassas, VA 22110
(703) 361-3186

CPO Joe Jester
USCG LORSTA Boise City
P.O. Box 232
Boise City, OK 73937
(405) 426-2221

Mr. Dale Johnson
II Morrow, Inc.
2343 Turner Rd. SE
Salem, OR 97302
(503) 581-8101

Mr. Vernon Johnson
17 Maple Drive
North Caldwell, NJ 07006
(201) 228-2642

ETC Vern Jones
U.S. Coast Guard Training Center
Petaluma, CA 94952
(707) 765-7442

Mr. Charles J. Justice
USCG HQ (G-NRN-1)
2100 2nd St SW
Washington, DC 20593-0001
(202) 267-0284

Mr. Bud Kaczor
Sea Dog Marine, Inc.
5971 W 217th St.
Fairview Park, OH 44126
(216) 734-4011

Mr. Ray B. Kauffman
Electronic Devices Inc.
3140 Bunch Walnuts Rd.
Chesapeake, VA 23322
(804) 421-2968

Mr. Richard Keating
U.S. Naval Observatory (TSSP)
34th & Massachusetts Ave., N.W.
Washington, DC 20392-5100
(202) 653-1549

Mr. Clyde B. Kirlin
USPS
P.O. Box 2161
Walnut Creek, CA 94595
(415) 934-0607

LCDR Gregory Kmiecik
U.S. Coast Guard
Electronics Engineering Center
Wildwood, NJ 08260
(609) 523-7274

Dr. Gérard Lachapelle
The University of Calgary
2500 University Drive, N.W.
Calgary, Alberta T2N 1N4
CANADA
(403) 220-7104

Dr. David Last
University of Wales School of EE
Dean Street, Bangor
Gwynedd LL57 1UT
UNITED KINGDOM
44-0248-351151

Mr. Bill Law
Ministry of Transport
159 King St
Weston, Ontario M9N 1L6
CANADA
(416) 235-4927

Dr. Robert Lilly
Ohio University
College of Engineering
Athens, OH 45701
(614) 593-1514

Mr. Chick Longman
Air Navigation Consulting
6100 Lakeway Drive
Oklahoma City, OK 73132
(405) 728-1883

Mr. Jerry Lozano
CellTrac
4815 W Braker Ln
Austin, TX 78759
(512) 338-4651

CWO Angus J. MacFeeley
U.S. Coast Guard
99-651 Aliipoe Dr.
Aiea, HI 96701
(808) 541-2323

LT George S. Mahlum
USCG MLC Atlantic
Bldg 333 1st Floor
Govenors Island, NY 10004
(212) 668-6210

Mr. Duane Marshall
Megapulse, Inc.
8 Preston Court
Bedford, MA 01730
(617) 275-2010

CDR G. "Nino" Martini
U.S. Coast Guard
Electronics Engineering Center
Wildwood, NJ 08260
(609) 523-7221

Capt. Henry E. Marx
Landfall Navigation
354 West Putnam Ave
Greenwich, CT 06830
(203) 661-3176

LT Andrew "Norm" Mason
USCG HQ (G-NRN-1)
8455 Brass Knob Ct.
Annandale, VA 22003
(202) 267-0294

Mr. Norman F. Matthews
IALA
20, rue Schnapper
74100 St. Germain-en-Laye
FRANCE
33 1 34 51 70 01

Mr. Edward L. McGann
Megapulse
8 Preston Court
Bedford, MA 01730
(617) 275-2010

Mr. Robert V. McKeown
RVM Industries, Inc.
27 Waterbury Road
Upper Montclair, NJ 07043
(201) 746-5737

CDR Dennis McLean
USAF Space Division
P.O. Box 92960 WPC
Los Angeles, CA 90009-2960
(213) 363-0354

LCDR Dick McMahan
COCO SEUS/SOCUS
Box 387
Malone, FL 32445
(205) 899-5225

Mr. Ian McWilliams
Volpe National Transportation
Systems Center (DTS-52)
55 Broadway, Kendall Square
Cambridge, MA 02142
(617) 494-2244

Mr. Edwin Mengel
Johns Hopkins University
Applied Physics Laboratory
Johns Hopkins Road
Laurel, MD 20723
(301) 953-5421

Mr. James Meranda
39875 Camino Del Vino
Temecula, CA 92592
(714) 676-2168

Dr. Robert Miller
II Morrow, Inc.
P.O. Box 13549
Salem, OR 97302
(503) 581-8101 x3842

Mr. Francis W. "Bill" Mooney
Mitre Corp.
2907 Bay-to-Bay Blvd Suite 303
Tampa, FL 33629
(813) 831-5535

Mr. Mark Morgenthaler
Trimble Navigation
645 North Mary Ave.
Sunnyvale, CA 94088-3642
(800) 874-6253 or (408) 481-2960

Mr. M.J. "Mike" Moroney
Volpe National Transportation
Systems Center (DTS-52)
Kendall Square
Cambridge, MA 02142
(617) 494-2026

Mr. Robert Newman
Systems Control Technology
1611 N Kent St. Suite 910
Arlington, VA
(703) 243-3633

Mr. André Nieuwland
Delft University of Technology
EE Dept., P.O. Box 5031
2600 GA Delft
THE NETHERLANDS
31-15-782845

Mr. Tom Nolan
Navconsult, Inc.
P.O. Box 375
Linthicum Hts, MD 21090
(301) 544-8996

CDR Dave Olsen
DOT/RSPA/DRT-20
400 7th Street S.W. Room 9402
Washington, DC 20590
(202) 366-4354

Mr. Hank Patel
Ross Engineering Co.
12505 Starkney Road Suite E
Largo, FL 34677
(813) 536-1226

CAPT Ben Peterson
USCG Academy Engrg.
Department
New London, CT 06320
(203) 444-8541

LCDR M. Piccioni
COCO NEUS/GLKS
P.O. Box 28
Romulus, NY 14447
(607) 869-5393

Mr. Jesse Pipkin
2173 E 8th Street
Chico, CA 95928
(916) 342-8518

Mr. Robert Pizzuti
Code Alarm
950 E. Whitcomb
Madison Hts, MI 48138
(313) 583-9620

Ms. Dorothy Poppe
Cambridge Engineering, Inc.
P.O. Box 3099
Burlington, VT 05401
(802) 860-7228

Mr. Marty C. Poppe
Cambridge Engineering, Inc.
P.O. Box 3099
Burlington, VT 05401
(802) 860-7228

Mr. Kendall E. Post
LocUS, Inc.
1842 Hoffman Street
Madison, WI 53704
(608) 244-0500

Mr. Richard S. Rich
Falcon Reconnaissance Systems
2670 Mineral Point Road
Friday Harbor, WA 98250
(206) 378-3900

Mr. Ronald G. Roll
3804 Kelsey Street
Silver Spring, MD 20906
(301) 942-7959

Dr. G. Linn Roth
LocUS, Inc.
1842 Hoffman Street
Madison, WI 53704
(608) 244-0500

Mr. Dan Sage
FAA/ANM - 461 A
1601 Lind Avenue SW
Renton, WA 98055
(206) 227-2353

LT Gary A. Schenk
U.S. Coast Guard
Loran Station
Middletown, CA 95461
(707) 987-2911

Mr. William Schorr
NavCom Systems, Inc.
7203 Gateway Ct
Manassas, VA 22110
(703) 361-0884

Mr. David C. Scull
NavCom Systems, Inc.
7897 Wellington Drive
Warrenton, VA 22186
(703) 349-9310

Dr. Mark Searle
University of Wales School of EE
Dean Street, Bangor
Gwynedd LL57 1UT
UNITED KINGDOM
44-0248-351151

ETCM Chuck Severance
U.S. Coast Guard
Training Center Petaluma
Petalum, CA 94952
(707) 765-7474

CAPT James J. Shaw, Jr.
USCG Far East Section
PSC 78 Box 3713
APO AP 96326
81 425 52 2511 ext. 8405

Mr. Martin W. Shuey
AOPA
421 Aviation Way #11
Frederick, MD 21701
(301) 695-2209

LCDR Louis R. Skorupa
USCG Pacific Area (PTL)
Coast Guard Island
Alameda, CA 94501
(415) 437-3232

LCDR Doug S. Taggart
U.S. Coast Guard
Electronics Engineering Center
Wildwood, NJ 08260
(609) 523-7273

LCDR C. A. Teaney
U.S. Coast Guard
Electronics Engineering Center
Wildwood, NJ 08260
(609) 523-7275

CDR William Thrall
USCG HQ (G-NRN)
2100 2nd St. S.W.
Washington, DC 20593-0001
(202) 267-0283

ETC Dan Tominia
U.S. Coast Guard
Training Center Petaluma
Petaluma, CA 94952
(707) 765-7473

Dr. Bryan Townsend
The University of Calgary
2500 University Drive N.W.
Calgary, Alberta TN2 174
CANADA
(403) 220-7104

Mr. Jon Turban
U.S. Coast Guard R&D Center
Avery Point
Groton, CT 06340
(203) 441-2600

Mr. Christopher Vale
Spectrum Management Sciences
5360 Landing Road
Elk Ridge, MD 21227
(301) 796-8165

Mr. James P. Van Etten
230 Rutgers Place
Nutley, NJ 07110
(201) 661-0876

Dr. Durk van Willigen
Delft University of Technology
EE Dept., P.O. Box 5031
2600 GA Delft
THE NETHERLANDS
31-15-786186

ENS E.V. Vogt
U.S. Coast Guard Atlantic Area
Bldg 333
Governors Island, NY 10004
(212) 668-7880

Dr. Nicholas Ward
Trinity House Lighthouse Service
East Cowes, Isle of Wight
PO32 6RE
UNITED KINGDOM
44-983-292651

Mr. Patrick Warr
Racal-Decca Canada Ltd
71 Selby Road
Brampton, Ontario L6W 1KS
CANADA
(416) 457-8720

Mr. Dave Waters
Canadian Coast Guard
344 Slater Street Bldg 333
Ottawa, Ontario K1A ON7
CANADA
(613) 998-1549

LCDR Gary Westling
USCG Activities Europe
PSC 802 Box 50
FPO AE 09499-1400
44 71 872 0943

Mr. Steve Wilson
Jet Electronics and
Technology, Inc.
5353 52nd Street S.E.
Grand Rapids, MI 49588-0873
(616) 949-6600

Mr. James M. Wood
The Boeing Co.
27415 8th Ave. South
Kent, WA 98032
(206) 941-9241