THE WILD GOOSE ASSOCIATION

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The International Loran Radionavigation Forum

Proceedings of the Twenty-first Annual Technical Symposium

August 24 — August 27, 1992

Birmingham, England

Published by
The Wild Goose Association
P.O. Box 556
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Copthorne Hotel and City Library
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The Wild Goose Association

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

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We're just wild about Birmingham

I see no ships: Cmdr David Olsen and Cmdr Lee Gazlay find their way to Centenary Square

Landlocked navigators in town

Britain's most landlocked city proved an ideal conference venue for an international club which includes coastguards, lighthouse operators and ocean fishery officials.

That was how US Cost Guards Cmdrs David Olsen and Lee Gazlay found themselves high and almost dry in rainy Birmingham city centre yesterday.

They were amoung 100 delegates to the Wild Goose Association, an international body that aims to promote and preserve long-range navigation.

The meeting - the association's first outside the US - took place in the Josiah Mason Hall. Organiser Mr. John Beukers, a navigational writer with homes in Florida and Gloucestershire, decided on Birmingham after reading about its conference facilities.

The group was named after the Canada Goose because members admired the bird's ability to navigate over vast distances.

Courtesy: The Birmingham Post, Friday August 28, 1992

Courtesy:
The Birmingham Post, Friday, August 28, 1992

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Foreword

Since its inception in 1972, the Wild Goose Association, as an organization, has not ventured outside of the United States. In 1992 the Association took the plunge and held its 21st Annual Convention and Technical Symposium in Birmingham, England. There was a strong incentive to do this and the timing appeared to be just right, The United States government was nearing completion of transferring overseas Loran-C facilities and operation to host countries and there were strong indications that Loran-C agreements in Europe and the Far East would be concluded. In addition, Loran-C independent activities in China, Russia, India and other countries suggested that Loran-C was about to become a truly internationally accepted and funded terrestrial radionavigation system.

The decision by the WGA Board of Directors to make a move overseas was not taken lightly and without some trepidation. The North West Europe Loran-C Agreement was having a long, frustrating and bumpy ride and its signing was being repeatedly delayed by political, economic, legal and even language difficulties. However, noting that Loran-C technical integrity and performance were rarely in question, Board members were persuaded that the agreement would ultimately be signed and that the WGA's presence in Europe would serve as a focal point for disseminating Loran-C information. In fact the North West Agreement was signed just three weeks before the Convention and the Far East Cooperative Agreement between China, Korea, Japan and Russia was signed just one week after the Convention.

The Board of Directors also recognized the international rising tide of interest in satellite navigation as the 1994 operational date for the Global Positioning System approached. Firmly believing that a mix of national terrestrial and international satellite radionavigation systems will be required to provide the necessary integrity and redundancy to meet international performance and safety regulations, the Convention theme "Loran-C/GPS Mix, Sharing the Future" was adopted.

After almost two years of planning, the Convention convened at the Copthorne Hotel in the center of the City with the technical sessions being held at the City Library. The venue proved ideal and a comment about the hotel is warranted. The Copthorne is a relatively small, well managed, quality hotel ideally suited to a group of our number. The courteous and efficient staff went out of their way to make our stay comfortable and meet all our requirements in timely manner. For this we are appreciative.

The Convention was opened by WGA President Dr. Robert Lilley and the group welcomed by the Lord Mayor of Birmingham, Councillor Peter J. Barwell MBE. The Keynote Address, given by Mr. Jacques de Dieu from the Directorate General for Transport, Commission of the European Communities, was particularly useful in setting the stage for an excellent technical program and stimulating discussion on the future of international radionavigation policy. A number of significant current Management and Policy papers were presented and are contained within these Proceedings.

Being the first Loran-C Convention of its kind in Europe, emphasis was placed on tutorial material. We are indebted to Carolyn McDonald of Navtech Seminars, Inc. for arranging a Loran-C/GPS tutorial held on the day before the Convention and to the authors and presenters of material at the tutorial session held during the technical symposium. We are also indebted to Carolyn for her pep talks to speakers and her fine job in managing the technical sessions

Our special thanks go to the Technical Co-Chairmen, Session Chairmen and Speakers for making this one of the best technical programs conducted by the WGA. We also acknowledge with gratitude the support of industry for sponsoring the reception and for helping to defray Convention costs by exhibiting their products and services. Industry support is vital for a successful Convention and must receive additional encouragement for future Conventions.

Our Awards Chairman Jim Van Etten and his committee are recognized for a job well done in selecting deserving individuals for this year's awards. Recipient of the Medal of Merit was Norman Matthews, Secretary General of IALA, for his work in coordinating the support for the international use of Loran-C while the President's awards went to Andreas Stenseth and Kjell Enertstad, both of NODECA, for their work in connection with the North West Europe Loran-C agreement. Other awards are listed in these proceedings.

Judging by all the comments, the Ice Breaker and the event-filled Spouse & Guest program were thoroughly enjoyed. For this we must thank Marilyn Beukers for her time and effort in generating an interesting program and for making all the necessary arrangements.

Credit must be given to the Birmingham Convention and Visitor Bureau, in particular, Philippe Taylor, its Chief Executive, and Kim Bate, the Convention Officer. That the Convention ran smoothly and was conducted professionally is largely due to their organization and Kim's attention to detail. Many others contributed to the success of this Convention, the list is extensive and is included in these Proceedings.

We conclude by acknowledging the welcome and hospitality of the Lord Mayor and the City of Birmingham. The Civic Dinner given by the City to the WGA was an honor and an evening to be remembered. The presentation of an exquisitely engraved glass vase by the Lord Mayor to the WGA is indicative of the hospitality shown to the Association by this progressive city. Our warm hearted thanks to the Lord Mayor and the Councillors of the City of Birmingham for this recognition.

Next year, 1993, the Convention will be held in Santa Barbara under the Chairmanship of John Illgen, this year's Technical Chairman. The 1994 Convention will be chaired by Bahar Uttam in Boston, and, if you wish to look even further ahead, the Internavigation Committee of Russia have offered to be the hosts of the 1995 Convention in Moscow.

John D. Illgen
Technical Chairman

John M. Beukers
General Chairman

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Keynote Address

Jacques de Dieu

Directorate General of Transport
Commission of the European Communities

I am very glad and proud to be invited to give on behalf of the Directorate-General of Transport of the EC-Commission the keynote address to your twenty first annual Convention, in particular when it is the first time that the Wild Goose Association goes to Europe.

Mr. Chairman in your very kind invitation you asked the Commission to set the tome for the technical symposium because of the involvement and interest it is showing in radionavigation matters.

Being no technician I will restrict myself to political aspects.

When I joined the Commission three years ago, one of the first letters I received was an invitation to attend your nineteenth annual convention in Long Beach California.

Through the enclosed leaflet introducing your association I discovered the world and the friends of loran. Unfortunately for me, I could not convince my Director General to send me to Los Angeles without any evidence to justify the Commission presence.

Today, barely three years later, things have changed, especially on the European level.

Before giving you a brief review of the facts which led to the involvement of the commission, I owe our American friends a very short explanation of the role of the Commission on the European scene.

Together with the Council, consisting of the Ministers of the twelve EC-countries, - the U.K. is one of them and is now chairing the Council until the end of this year -, the directly elected European Parliament and the Court of Justice, the Commission is one of the four institutions forming the European Economic Community, which is a political and economic organization, ruled by the EEC-Treaty.

The task of the Community is to establish a common internal market and through the development of common policies. such as the one in the transport sphere, to promote throughout the Community an harmonious development of economic activities, expansion, an increase in stability, a high standard of living and closer relations between the states belonging to it.

One of the main institutional duties of the Commission, assisted by its technical departments, such as the Directorate general of Transport, is to propose appropriate measures to Council and Parliament for the realisation of the policies.

With the objective of ensuring the safety of navigation in Europe and neighbouring areas, the development and improvement of aids to navigation is one of the actions which the Community is currently concerned with. This concern dictates the role of the Commission.

For the benefit of my colleagues and friends of the EC-Member States I am prone to make already at this stage a reference to Maastricht and the magic word SUBSIDIARITY

The principle of subsidiarity requires that the Community should only exercise its powers where EC action is essential for the effective attainment of the Treaty objectives, and where measures by the Member States individually are insufficient to that end.

Fresh tasks are only to be taken on by the Community when they prove essential at that level, in order to protect its citizens and all those who travel through the European area without borders.

Although this principle of subsidiarity will only come into force at the beginning of next year, in accordance with the provisions added to the EEC Treaty by the Maastricht Treaty, I will demonstrate during this intervention that the Community and, in particular the Commission, have applied this principle avant la lettre, in advance and will still be guided by the same principle in the future.

With this background information it will now be easier for you to assimilate the key elements of the Community and Commission action in the radionavigation field.

The Commission was present at Trinity House in London in March 1987 where the International Association of Lighthouse Authorities called a radionavigation Conference after the announcement by the United States Coast Guard to cease funding and manning all its Loran-C stations outside of the US at the end of 1994, offering at the same time to transfer all or part of Loran-C station equipment to interested host nations, when these would not be needed by the US.

At that time the Commission had shown some interest in the development of a single European Loran-C system, but did not want to intervene leaving the responsibility for action for providing an answer to the US Coast Guard, direct to the concerned host nations.

Building up its policy with regard to aids to navigation the Commission took note of one of the main conclusions agreed by the Conference: the need to maintain, after the introduction of new satellite navigation systems, terrestrial radionavigation systems for the foreseeable future in appropriate national and regional areas.

Given the involvement of several EC-Member States in the international discussions on the US Coast Guard Loran-C proposal, and given the previous and potential interest of the Commission in the subject, two years later, the Commission was invited by the UK-government to comment and to give the

Commission's views on a consultative document on the future of marine radionavigation in United Kingdom waters.

The Commission took note that the UK Department of Transport was in favour, under certain conditions, of a change of terrestrial system in the UK and expressed its intention to participate in a North European Loran-C chain.

Answering the invitation of the UK the Commission stressed that given on the one hand the North-European developments and the interest shown by France, Italy and Spain for a similar Loran-C system in the Mediterranean area, it was very interested in the generalization of a terrestrial radionavigation system in Europe and made an offer to develop an initiative in this field.

At the request of IALA the Commission has participated since 1990 in an IALA working group which was set up to examine the technical, operational and organizational aspects of maintaining Loran-C in the Mediterranean area.

The Commission was also invited, as an observer to attend the meetings of the North-West European Loran-C Policy Group.

In September 1990 the Directorate General of Transport evaluated the situation and decided that time had come for European action.

This was based on the following determinants:

- the technical merits of Loran-C for marine, air and land navigation were demonstrated,
- the possibility to extend the system, at low costs, to the entire European area and to link it with other chains in the west and east,
- international developments and the IALA policy with regard to aids to marine navigation,

and, may be the most important one in our policy-building process,

- the fact that combined satellite/Loran-C coverage will offer the highest degree of system verification and continuity of radionavigation coverage, for the benefit of safety and environmental protection.

Without wishing to blame the US authorities, whose role was not to defend the loran technology, it must be said that their decision to abandon Loran-C in Europe for GPS created the impression that, in the era of satellites, an obsolete technology was offered to Europe.

This forum does certainly not need to be convinced that this was totally wrong.

Recent investments in the loran technology in the continental USA and in France, international developments and of course the merits of the system itself, were laid on the table as evidence. Objections against the system were overruled.

European action with regard to Loran-C was entirely justified due to:

- the risk of dismantlement of the basic infrastructure by the US Coast Guard, in the absence of a positive answer to their offer to the host nations,
- the intention of some Member States of the EC to withdraw from the North West European Policy Group,
- the lack of progress in the Mediterranean talks.

These elements my have seriously jeopardised the development of a European network.

Therefore, anticipating the outline of its general policy with regard to aids to navigation , the Commission decided in January 1991 to present a formal proposal for a Council decision on Loran-C.

The proposal was fully supported by the Economic and Social Committee, an advisory body in which the industry and the social partners are represented.

Taking note of a change in the policy in the UK and endorsing constructive amendments of the European Parliament, the Commission, in November 1991, amended and widened its proposal into a proposal on radionavigation systems for Europe.

With the formal adoption of the Decision on radionavigation systems for Europe on the 25th February of this year by the Council of Ministers of the European Communities the first decisive step into the establishment of the radionavigation policy in the European Community was taken.

The Decision taken is an example of subsidiarity.

The European Community, recognizing the need for a terrestrial radionavigation system, states that the establishment of regional Loran-C systems must ensure coherent and complete coverage of the European maritime area.

To this end the Member States and the Commission are obliged to support efforts to set up a worldwide radionavigation system, including European regional Loran-C chains, with the purpose of enlarging worldwide Loran-C coverage in order to improve the safety of navigation and the protection of the marine environment.

Member States are not required to abandon radionavigation systems such as Decca, and Omega, neither are they obliged, at this stage, to join regional Loran-C Chains. Nevertheless they have to strive and do their utmost for the realisation of regional Loran-C chains in Europe.

Respectful of the subsidiarity principle the Commission hopes that all Member States will, in due time, take the necessary steps to set up or join regional agreements on Loran-C. Those who decide to participate in such agreements are bound to seek to achieve the configurations which cover the widest possible geographical area in Europe and in neighbouring waters.

The Commission, which was charged by the Council to ensure coordination between Member States participating in regional Loran-C agreements, is very satisfied about the recent developments and commitments of the EC Member States with regard to the coverage of the northern European area. For this area no further action is necessary at this stage.

For the Mediterranean and the Iberian peninsula the situation is totally different.

Today there is still no formal political commitment of the states involved to set up a policy group for the realisation of a suitable chain in southern Europe.

The Commission will do its utmost to help Member States make a decisive step into the signature of such a commitment. I am making use of the presence of our American Coast Guard friends to appeal for joint efforts in this matter.

The Commission will evaluate the situation in the course of September and, respectful of the subsidiarity principle, will propose, if the need arise, the necessary measures as urged by Council.

The most important outcome of the Council decision for the Commission is the recognition at European community level of the need to set up a European radionavigation plan which takes into account the development of satellite systems, existing terrestrial systems and the radionavigation plans of the Member States.

Taking into account the US plan and the intentions of the Commonwealth of Independent States it is obvious that Loran-C will also play an important role in the European system.

With regard to satellite systems the Commission already has the responsibility to reflect on the development of civil and internationally controlled radionavigation system that will meet the requirements of transport in the 21st century.

Appropriate contacts with ESA, the European space agency and INMARSAT are envisaged.

The Commission supports also the idea of the establishment of a joint IMO-ICAO planning group, to which it intends to participate actively.

Coming back to the European radionavigation plan it is the wish of the Commission to present to the Council and parliament, as soon as possible, mid 1994 is a tentative date, an extensive report on radionavigation aids and a draft for a radionavigation plan for Europe.

At this stage the Commission Services are of the opinion that the provision of appropriate radionavigation aids, with suitable requirements, mandatory if necessary, on a European level, will be of the benefit to:

- control and monitor the safe, timely and efficient carriage of people and cargo by sea, air and inland transport modes,
- offshore exploitation, marine surveys, fishing and recreational crafts,
- fleet management and emergency rescue,
- protection of the environment in areas with high density traffic and marginal weather conditions.
- cost optimisation for the countries providing radionavigation aids,
- reduction of user's costs by the development of suitable low cost receivers.

Preliminary to the realisation of the European radionavigation concept the Commission Services will discuss the policy objectives and relevant aspects with the governments of the Member States and third countries with which the Community has signed cooperation agreements and will try to identify the real users' requirements.

Interests of the involved radiocommunication industry will not be neglected.

All these commitments and intentions represent a lot of work and money.

With regard to the financial aspects, it is worthwhile to refer again to the Maastricht Treaty. A specific chapter of this Treaty is of particular interest in assessing Community contribution to infrastructure for transport and telecommunication in the field of Transeuropean networks.

Under which conditions a future coherent European radionavigation system could be incorporated in the concept of Transeuropean network has to be investigated.

Within the Transeuropean network, projects identified of common interest and financed by the Member States, could receive some specific financial support from the Community and in addition some financial support from the, to be set up, Cohesion Fund, which applies to Spain, Portugal, Greece and Ireland.

About the recovery of investment costs for aids to navigation the Commission Services believe that the EC dimension is appropriate, in terms of both a coherent geographical area and an institutional framework for the application of the "user pays" principle. Investigation in this field will start soon. The first step will be the gathering of information from the Member States on the cost of providing marine navigation aids.

At the end of this review of our prospects for the future I want to stress that I am confident about the future of Loran-C, taking account of the international developments and the very interesting and important contributions that were made to the Loran-C/GPS tutorial and, last but not least, more especially as the Wild Goose will continue to foster and promote the art of loran.

I like to emphasize in this forum, that for the Commission, Loran-C has an additional merit, the one of being responsible for the start of the European radionavigation policy.

Finally, I wish you a fruitful, successful and pleasant convention and really hope to have another opportunity to report to your association on the progress accomplished at the European level.

Luncheon Address

August 25,1992

Radionavigation - The Outlook for Europe

Walter F. Blanchard F.R.I.N.

Radio aids to navigation have reached a watershed. After nearly 90 years many of their problems such as restricted range, inaccuracy, weather-dependence, propagation variability and the inability to site transmitters properly for best accuracy, have been eliminated by the advent of satellite-based technology. We have within our grasp the ability to provide a truly universal radionavigation aid capable of being used by all classes of navigator. In the long run it is inevitable that sheer technical superiority will cause satellite-based radionavigation aids to dominate and many other radio aid to disappear.

It is, however, most unfortunate from the civil users' viewpoint that the current breed of satnav systems are of military provenance and unlikely to be turned over to civil control. This will be the cause of so many non-technical problems of control, legislation, and organisation that it is doubtful whether they will ever be acceptable for civil use. It is not at all obvious how some of these problems might be solved, but they MUST be, and it is becoming increasingly urgent that they should be. Before many more years are past, there will be a large body of GPS users who will force a solution if one has not been found, and forced solutions are rarely optimum.

Civil Satellite Navigation - a Global Navigation Satellite System (GNSS)

What is under consideration is CIVIL SATELLITE NAVIGATION, not GPS, GLONASS, or any other specific system. While one cannot but admire the technical expertise that brought GPS and GLONASS about, they should be looked on only as technology demonstrators. They were developed for specific military applications that burdened them with costly facilities and features quite inappropriate for a civil environment. It would probably place the emphasis correctly if GPS satellites were regarded as military satellites that happen to carry a navigational package rather than as navigational satellites carrying other payloads. Their value lies in the active demonstration they provide of the successful development of satellite technology for navigation applications and the advantages it brings. This is not a very original statement; it was made by no less a person than the Administrator of the FAA last year.

GPS and GLONASS cannot, of course, be totally ignored. The investment put into them cannot be dismissed and in any case by the time any real decisions are made about a civil system there will already be large numbers of civil GPS users. Any GNSS will have to incorporate elements of GPS - but which, and how?

In the past, radio navaids (apart from Omega) had very limited coverage and could be truly regarded as national systems but the virtually unlimited coverage of satellite navigation transcends national boundaries and makes it unsuited to narrow national control. International control is required, but what type of institution is appropriate? And how would it interface with the multiplicity of existing organisations that already have a finger in the radionavigation pie?

Another feature peculiar to satnav is its universal applicability. It is equally usable by land, sea and air navigators, and the old divisions of responsibility no longer apply. Decisions taken by aviators on GNSS will affect mariners and land navigators, and vice-versa. They cannot be treated in isolation. If mariners'and aviators' interests clash, who will make a decision?

What is needed is a satnav system owned, operated and controlled by a civil international authority for the benefit of the world-wide civil community. There are already exemplars in other areas - INMARSAT, INTELSAT, EUTELSAT, etc., - supra-national organisations providing services for the benefit of many different countries.

The European Situation

The European Economic Community will in a few years be the largest economic bloc in the world, comprising all the major industrial countries of the West outside the USA.

On the basis of its projected GNP alone it should be easily capable of designing, building, launching and operating its own satnav system particularly in view of the fact that a solely civil-oriented system would cost less than 10% of GPS.

However, for reasons unconnected with finance it may prove difficult for the EC to go it alone on satnav, but it is certainly in a uniquely favourable situation to take the lead in making fundamental decisions about a civil satnav system. Here are some reasons.

The USA has put all its money on GPS. It has done so primarily for military reasons that have resulted in a system not well suited to civil use, a fact that will become increasingly evident in the next few years, Even when this is admitted and seen to be a major obstacle it will be impossible for the USA to ignore its own child and go ahead with a new specifically civil-oriented system. It MUST use GPS to its utmost and all its deliberations on civil satnav will be colored accordingly. US proposals for the civil use of GPS will be designed more with an eye for greater utilisation of GPS than for real civil needs. It will perpetuate split civil/military control that simply will not work internationally.

The other possible contender, GLONASS, is increasingly looking uncertain and indeterminate. It may be another 10 or 20 years before the political structure of the CIS (or Russia) becomes well enough defined and stable to place any reliance on it.

Europe has no such problems. It does not operate a satnav system and can look at the problems of instituting a civil satnav system from a detached viewpoint.

The GPS Situation

A common view is that GPS will inevitably sweep the board because it will cost civil users nothing and will satisfy the vast majority of their requirements. Those who have specialist applications can pay for specialist systems. After all, has not GPS been offered free for civil users for a least ten years?

Such a reaction ignores the fact that under the terms on which the US is offering GPS for civil use it is really only usable by uncritical "hobby" users. Any professional user who intends to base his economic survival and perhaps his safety on it needs solid guarantees of performance and availability that cannot possibly be forthcoming while it is controlled, even partially, by military authority. We have only to look at the constant reminders issued by the DoD on every conceivable occasion that civil users use it "at their own risk". Can the DoD ever afford to delete this and accept responsibility for CIVIL operations? FOREIGN civil operations.

The DoD will soon have to fulfill its promises that if it got GPS it would be such a powerful force enhancer that regular forces could be dramatically reduced and the saving in cost would easily outweigh the investment in GPS. When that occurs, the DoD will never be able to relinquish control over GPS. Rightly, they would never permit their military operations to be jeopardised by some international civil body that might not even be very favourably inclined to them.

There is another factor. The DoD, in company with some Ministries of Defence in other countries, considers that a totally independent civil satnav system providing accuracies the same as GPS P-code would provide an almost free and powerful force enhancer to third world dictators that might nullify some of the advantages GPS gives the US and its allies. Consequently it intends to bend considerable effort to prevent any such development taking place and to keep its deliberate degradation of GPS accuracy (S/A) permanently in place.

Similar arguments have been used about almost every technological development. When railways were invented it was claimed that they would enable robbers to travel about so freely that they would never be caught. Telephones would enable them to plot their robberies better; the development of modern motorways resurrected the rail arguments, and so on.

The flaw in all these arguments is the same. Technological development brings enormous benefits to the vast majority and its misuse is limited to a very few. Better to tackle those few directly than to deny the majority these benefits.

What this policy will do in practice is to give the USA a perpetual monopoly of high-accuracy navigation for commercial as will as military purposes. It will ensure permanent US control of the world's navigation services. This caries obvious dangers of its own and is of course quite unacceptable to non-US States, nothing of this will be heard in the major US fora.

Even if we ignore this and consider only the legislative situation, what of the legalities involved in internationally approved navigation systems? All existing major civil systems have been painstakingly approved and thoroughly tested and are closely regulated. Each country is responsible, under international law, for the correct operation and maintenance of its navaids, and can supervise them because they are located in their own country and are operated by them. How can legislation and liability be apportioned for a system not under their control; not located in their country; and subject to the over-riding requirements of a foreign military power? It is of course quite impossible. Even if GPS provided a civil service completely divorced from its military side it could only be used as an ancillary to an independent civil system.

INMARSAT's Role.

INMARSAT will provide navigation packages (as it happens, designed and built in Europe) aboard their Generation 3 satellites. They are doing so to provide facilities for experiments relating to a civil satellite navigation system, but who will carry out these experiments, and to what end.

Disorganised and sporadic experiments will get nowhere. An international group should be set up to proceed with tests and trials agreed as having a common objective. INMARSAT itself cannot force its signatories to organise themselves into a coherent satnav experimental group but this is what is really needed. A problem here is that many signatories know absolutely nothing about satnav. Who will educate them?

That group could well become the nucleus of an international body charged with examining these scenarios, facts, and, yes, suppositions, and determining the right path towards the establishment of a civil international satellite navigation system.

Policy and Technical Papers

SESSION A

Management and Policy

THE U.S. COAST GUARD AND LORAN-C TURNOVER OVERSEAS...
WHAT'S HAPPENING?

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ABSTRACT

Just what is happening with the U.S. Coast Guard and Loran-C overseas? This paper describes the efforts of the U.S. Coast Guard in withdrawing from overseas Loran operations. It also discusses the U.S. Coast Guard's reasons for leaving and the effects that the Global Positioning System (GPS) and Selective Availability (SA) have had and are having on the deliberations of those countries affected by the U.S. Coast Guard's withdrawal. Lastly, the paper addresses what the Coast Guard's plans are for Loran today and tomorrow...what, when and why.

BACKGROUND

The U.S. Coast Guard has operated Loran-C overseas for DOD since the early 1960's. Title 14 of the U.S. Code empowers the Coast Guard to provide such overseas service for and in behalf of any U.S. Federal agency. However, since the early 1980's, DOD has been looking forward to having its own, more precise navigation system -- the NAVSTAR GLOBAL POSITIONING SYSTEM (GPS).

Although beleaguered with past delays, it now appears that GPS will be completely up and operating with 21 Block II satellites by the end of 1994. Therefore, DOD need for Loran-C will end by December 31, 1994.

Without another federal sponsor for overseas Loran-C, the USCG is required to withdraw from operating and/or funding the Central Pacific Chain, the Labrador Sea Chain, the Icelandic Sea Chain, the Norwegian Sea Chain, the Mediterranean Sea Chain, and the Northwest Pacific Chain.

Since the late 1970's, GPS has been preceeded by considerable fanfare and enthusiasm. From President Reagan's pronouncement to ADM Busey's address at the ICAO meeting in Montreal, GPS has been offered to the world. True, DOD has suffered several delays. True, DOD has limited the predictable accuracy to 100 meters (95% of the time) worldwide. And, true, DOD has, on occasion, adjusted SA to well beyond 100 meters. After all it's a military system, controlled by and for the U.S. military. Aware of this, and knowing Loran-C offers a repeatable accuracy of better than 100 meters for much of its coverage area, the host nations have been struggling with the decision to adopt GPS or continue with Loran-C. This decision is not easily achieved. It comes down to several questions:

Are other nations comfortable relying on U.S. DOD control of GPS?
Is there an international need to warrant a system in addition to GPS?
Do the nations want the expense of operating and supporting Loran-C stations?
How will the nations cooperate to support continued Loran-C operations?
How can international cooperation be maintained?
What kind of initial and ongoing equipment and operational training is required and available?
What cost-sharing arrangements must be established?

GPS OR LORAN-C?

Let's address each of the foregoing questions before discussing the situation of each overseas chain operated by the Coast Guard.

Are other nations comfortable relying on U.S. DOD control of GPS? The short answer is no. To understand that we must review the rationale for its creation...it was not designed, funded and launched as a universally available, worldwide, navigation system. Rather, it was designed to meet the worldwide precise navigation needs and missions of the U.S. DOD. As a strategic asset, it must be assumed that DOD cannot limit the system's effectiveness by publishing or alerting in advance their intention to make the signal less useful to an adversary (and, hence, the world).

Is there an international need to warrant a system in addition to GPS? This question is answered by answering some other questions...What is the national navigation requirement? Will GPS meet and/or exceed it? If no, then an additional system is needed. If, however, GPS does meet or exceed national requirements, then an additional system may not be needed, but...

How comfortable is that nation in relying upon the DOD for continued, uninterrupted navigation information? If they're not, then regardless of national navigation requirements being met or not, the nation will want its own system. But...

Can it afford a supplement to GPS? Some will argue "Can it afford not to?" I think real-world cost considerations have a way of sobering us to the reality that it costs relatively large amounts of money to operate a navigation system...especially one that is more precise and accurate than GPS. GPS has cost over $10 billion to date. In addition, it has been estimated that it will cost the U.S. taxpayers somewhere between $500 million to $1.5 billion annually to maintain and operate the GPS. Can any nation or group of cooperating nations afford a similar amount for a satellite based system? Loran-C, on the other hand, has been costing about $60 million per year. But Loran-C is not global. True enough, but I'm not talking global. I'm proposing national or regional coverage. How much of the world is adequately covered by both Omega (at an approximate annual cost of $12 million) and Loran-C? How many new chains could be built and operated for less than $500 million each year?

Do the nations want the expense of operating and supporting Loran-C stations? As mentioned above, Loran-C costs the Coast Guard about $60 million annually for their more than 40 transmitter sites. New station costs include not only the transmitter, timing & control equipment, and tower, but also the necessary land, buildings, and communication circuits. Depending on location and size of both transmitter and tower, the cost to establish could vary from $5 million to over $20 million.

In contrast, GPS has been offered free of direct user charges for the next 10 years.

How will the nations cooperate to support continued Loran-C operations? Whereas GPS is operated and maintained by the U.S. DOD, international Loran-C requires international cooperation and support. Existing chains have stations located in more than one country. The MEDSEA Chain, for instance, has stations located at Estartit, Spain; Sellia Marina and Lampedusa, Italy; and Kargaburun, Turkey. For continued chain operation these three nations have to agree on 1) continued operation, 2) control philosophy and procedures, 3) capital replacement and annual operating cost sharing, and 4) continued logistic support (including supplies and training) procedures.

How can international cooperation be maintained? Once international agreements are in place, it is incumbent upon each cooperating nation to protect that agreement until such time as there is no need for coverage. This is just as true for Omega as it is for Loran-C. International liaisons stand because they are in the best interests of the signatories.

What kind of initial and ongoing technical and hands-on training is required and available? For Loran-C, this depends. For stations whose Coast Guard equipment will be replaced by commercial equipment, there is no Coast Guard technical training available. As long as nations continue to operate equipment which is the same as Coast Guard equipment, then Coast Guard technical training could be provided. The training would have to be negotiated and arranged through official Government to Government channels, but it could be made available. There are limitations on Coast Guard training, though; students have to have a specific knowledge and ability to speak, hear, and read English. They have to have a specific background in math, science or electronics. Further, students have to merge with existing class schedules. So, foreign-student training must be limited to 2 or 3 students, at most, per class.

On-the-job training (OJT) is limited by existing Coast Guard facility size and work load. Where it's convenient, arrangements can be made to have foreign technicians (of the country taking-over Coast Guard operations) work side-by-side with Coast Guard technicians and learn/practice command and control of the Loran-C signal.

What cost-sharing arrangements must be established? This depends. Some nations will want to replace transmitters to either increase capability (dual-rate or increase range) or allow for reduced staffing. That cost could be borne by the specific country or shared, with other capital investment costs, with the other cooperating nations. In addition, the costs to maintain each station could be shared using some predetermined prorata basis by the nations involved or simply borne by the hosting nation. Too, the personnel support costs for establishing and maintaining some type of control and general oversight group needs to be funded. This should be a shared expense of those nations working together to deliver the Loran-C signal.

CLOSURE AND TRANSFER OF COAST GUARD OVERSEAS LORAN-C OPERATIONS

With the previous questions answered, we're now in a position to discuss the specifics of each overseas Loran-C chain soon to be closed or transferred by the U.S. Coast Guard.

CENTRAL PACIFIC

With the declaration by DOD that overseas Loran-C would not be needed after 1994, the Coast Guard polled Loran-C users in Hawaii. The Coast Guard found that there were few civil navigation users of Loran-C in the Hawaii area. Some timing users were located, but their needs will now be met by GPS timing receivers.

The Coast Guard is always looking to reduce costs to the taxpayer. Therefore, the Coast Guard asked DOD if DOD needed Loran-C in Hawaii and whether the chain could be terminated before the end of 1994. DOD informed the Coast Guard of no present or continuing need for Loran-C and authorized terminating CENPAC coverage by the end of 1992. This closure affects only Kure, Johnston Island and Upolu Point Loran-C Stations. Since the Coast Guard announced its plans to shutdown its Central Pacific Loran Chain, the Coast Guard has received very few objections.

Kure and Johnston Island were turned-off 30 June 1992. To protect and provide only minimal disruption to wildlife, cleanup efforts at Kure will be delayed until summer 1993. Upolu Point will continue to operate through December 1992. All towers, buildings and equipment will be removed from each site.

NORTHWEST PACIFIC

Negotiations between the Japanese Ministry of Foreign Affairs and the Commander, U.S. Forces Japan (USFJ) are progressing well. Present plans call for the Japanese Maritime Safety Administration (JMSA) to takeover all existing, operating functions by the end of 1993 except the Loran-C station at Barrigada and the Guam monitor.

It's interesting to note that while the USFJ and JMSA have been holding discussions leading to transfer of Loran operations, International Association of Lighthouse Authorities (IALA) has been chairing Far East Loran-C Technical (FELT) meetings between the JMSA, the Korean Maritime and Port Administration (KMPA), Peoples Republic of China, and Russia. The purpose of these meetings has been to coordinate and encourage joint Loran-C and Chayka operations after Coast Guard withdrawal. Their plans call for connecting Loran-C/Chayka chains to provide continuous coverage from the Sea of Okhotsk to (but not including) the Philippines. They expect to sign their Agreement this September in Moscow.

NORTHWEST EUROPE

Norway, Iceland, Denmark, and Germany staff Loran-C stations for the U.S. Coast Guard. The intention of the U.S. Coast Guard to cease its Loran-C operations once DOD no longer needed Loran-C has been known since 1983. GPS delays have postponed the takeover until now. The end of 1994 has remained the takeover target for the last few years and appears to be viable.

To facilitate continued operations, these nations formed the Northwest European Working Group. The Working Group expanded from the original four nations to include Canada, France, the UK, the Netherlands, and Ireland. The U.S. Coast Guard has always participated as both an interested party and as technical advisor.

As various nations withdrew to support either GPS or their own national system, the remaining members have worked through the issues of funding, shared operations, and control, and an Agreement is expected to be signed in August 1992.

MEDITERRANEAN SEA

The Mediterranean Sea chain consists of Loran-C stations Sellia Marina and Lampedusa, Italy; Estartit, Spain; and Kargaburun, Turkey. These stations, unlike the Northwest European stations, are staffed and operated by U.S. Coast Guard personnel. Since 1986 These countries have known of our intentions to cease or turnover operations by the end of 1994. Since then they have formed a MEDSEA Working Group, which is chaired by IALA, to develop their takeover plans. Italy and Spain are already pursuing takeover. Turkey has not yet committed, but has expressed interest. Russia has also been involved in these Working Group meetings and has offered to work with the MEDSEA Working Group in finding an alternative to Kargaburun if Turkey elects not to continue operations beyond 1994.

The Working Group has a lot to accomplish before January 1995. Individual station plans need to be developed. These plans will have to be shared within the Working Group so the Working Group can develop its own plan and concept of operations. The Coast Guard has offered to assist with technical guidance and input.

It's relatively easy to take over Loran-C operations when you've already been operating the stations (as in Northwest Europe), but when you haven't it's another issue which needs to be addressed. To operate a Loran-C station will require training and actual hands-on, on-the-job experience, also.

The Coast Guard will be fielding a team to negotiate with each country for the turnover or cessation of operations. This negotiating team will be addressing similar, but not necessarily the same, issues with each respective country. This is true whether or not transfer of operations is anticipated or closure.

WHAT ABOUT CONUS LORAN-C PROGRAMS and PROJECTS?

IN GENERAL

Despite GPS eventual Fully Operational Capability (FOC), the number of marine and aviation users continues to expand. Therefore, the Coast Guard intends to operate and continue to improve U.S. Loran-C equipment well into the next century. Our plans are coordinated with both DOD and the other DOT modal agencies and published as part of the Federal Radionavigation Plan (FRP). Federal plans call for a 10 to 15 year transition before cessation of any national radionavigation signal. The following projects describe what we've done and are doing to improve the Loran-C program.

NORTH PACIFIC UPGRADE

The three, less-powerful tube-type transmitters at Attu, St. Paul, and Port Clarence are to be replaced with the newer, more powerful tube-type transmitters like the ones used in the West Coast Chain. This replacement will be accomplished beginning this year at Attu, then next summer at St. Paul, and, finally, summer 1994 at Port Clarence.

ELECTRONIC EQUIPMENT REPLACEMENT PROGRAM

The Coast Guard is presently studying the various Timing and Control equipments and designing replacement modules to replace existing cabinets of equipment. This will ensure continued operations in spite of certain electronics components no longer being available.

AUTOMATIC BLINK SYSTEM

Working closely with the Federal Aviation Administration (FAA), the Coast Guard has been helping to design an Automatic Blink System (ABS) for installation at Loran-C stations. The purpose of ABS is to monitor each station's Loran-C timing and automatically blink the Loran-C signal (within 10 seconds) when the timing error exceeds 500 nanoseconds. Although there have been some delays, the project is nearing the manufacture stage. Once installed, ABS will provide a margin of safety to the aviation user of Loran-C.

AUTOMATED OPERATIONS

Today's computer technology offers the promise of complete de-manning of existing Loran-C stations. Over the next few years the Coast Guard will continue to explore suitable methods of ensuring continued operations while completely de-manning the stations. Once successful, this will significantly reduce recurring costs.

CONCLUSION

Even though the U.S. Coast Guard is withdrawing from overseas Loran-C operations, it appears most host nations will continue to provide similar Loran-C coverage after 1994. Their decision to continue to operate Loran-C after Coast Guard withdrawal is a positive statement for the advantages of Loran-C and demonstrates the highest and finest attributes of international cooperation. I salute their resolve and look forward to working with them individually and in Working Group forums to assist in the smooth transfer of operations.

The closure and transfer of existing Coast Guard operated Loran-C chains will save the U.S. some $20 million dollars annually.

The Coast Guard will continue to, not only, operate, but continually look to improve, Loran-C operations in the Continental U.S. and Alaska. This will include examining ways to reduce station operating costs through automation and select equipment replacement.

DISCLAIMER

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

BIOGRAPHY

CDR WILLIAM J. THRALL serves as Assistant Chief, Radionavigation Division, Office of Navigation Safety and Waterway Services, Coast Guard Headquarters, Washington, D.C. As such, CDR Thrall oversees the Coast Guard sponsored radionavigation (RA) program, including Loran-C, Omega, Radiobeacons, and differential GPS. In addition, he provides technical advice and assistance to the Far East Loran-C Technical (FELT) committee, and participates on IALA's Radionavigation Technical Committee.

His initial involvement in the RA program came in 1976 when he assumed command of Loran Station St. Paul, Alaska. Since then he has served in and as Chief, Loran Branch, Radionavigation Division, Headquarters (1980-1985) and as Chief, Engineering Branch, Loran Division, Activities Europe, London, UK (1985-1988). Also between 1980 and 1985, he established TECC --Technical Education Consultant Corporation and founded the TECC School of Electronics, which successfully trained and placed over 300 hard-core unemployable men and women in the electronic field.

About Conception of employment and the prospects of radionavigation systems development in Russia and International cooperation in the field of marine, air, land navigation

V. DENISOV
Director of research centre
Deputy chairman of "Internavigation" Committee

I.

The basis to provide marine, air and land users with navigation is formed by a condition to guarantee accessible radionavigation information in all possible geografic regions at any time of a day with position determination accuracy providing users' safe movement.
This task may be solved by using domestic and foreign navigation systems and also establishing combined and joint ones in the interests of all users of world community.
In our approach to provide users with reliable navigation information we come out of the necessity to determine users' position with accuracy from some hundred metres to 10 m (in local zones -- up to 1m) with guaranteed radio signal availability for every radionavigation system (RNS) not worse than 0.997--0.998.
Domestic RNS are devided into two large classes: ground and satellite based navigation systems (SNS).
Here we are not going to make an overview of all existed and available RNS. We'll dwell upon those, which are widely used and on examples of which it will be possible to analyse a general trend of RNS development during last 30 years and for future.

1.1. Ground based RNS

RNS with ground based stations took their firm place among systems, providing navigation of marine and air vessels both as single aids to navigation and the means for correction of single ones.
A number of types of radionavigation means and systems are developed and operate in this country: marine and aircraft radio beacons, short range RNS, long range RNS and global RNS.

Short range RNS

BRAS -- "Kalmar" is used by different kinds of marine users. Operation range is 350--400 km. Accuracy of positioning is no worse than 50--60 metres. (Foreign analog -- "Hyperfix", Gr. Britain);
RSBN - (radiotechnical system of short range navigation) is a main aid for providing aircrafts flights along airways, their approach to airport and manoeuvring. Practically all airways of the country and considerable part of airports are equipped with RSBN. Range of system operation depends on the altitude of the flight and amounts to 400 km. Accuracy of bearing measurement is about 0.25 degree. (Foreign analog -- VOR/DME, TACAN -- USA).

Long range RNS

"Chayka" -- pulse-phased RNS (foreign analog -- "Loran-C", USA). It is widely used to provide navigation of marine, air and land users at present. Range of operation is 1.500--1.800 km and more. 15 "Chayka" stations are built. They are configurated into 4 chains:
EUROPEAN CHAIN consisting of stations located near the cities of Briansk (master), Petrozavodsk, Simferopol, Slonim, Sizran (secondaries).
EAST CHAIN consisting of stations located near the cities of Alexandrovsk-Sahalinsky (master), Petropavlovsk-Kamchatsky, Ussuriisk, Okhotsk (mini-"Chayka"), Kurilsk (mini-"Chayka").

NORTH-WEST and NORTH CHAINS consisting of stations in the regions of Dudinka, Taimilir, Inta, Pankratiev's Isl., Teriberka (Tumanniy). The chains were put into practice in 1991.
"Mars-75" -- RNS is intended for marine users. Range of operation is about 1.000 km. Accuracy of positioning is 60--350 m (depends on location of vessel relatively to transmitting stations).

Global navigation systems

VLF system -- widely used by marine and air users. Range of system operation is about 11,000 km. Accuracy of positioning is 1-5 km. (Foreign analog -- Omega, USA).
Domestic VLF system consists of 3 stations located near the cities of Novosibirsk, Krasnodar and Komsomolsk-on-Amur. Stations were constructed in the late 60-ties and put into operation in 1972.
Two new stations are still being built near the cities of Murmansk and Ashkhabad. They are to be put into operation in 1993-94.
System of 5 stations will allow to improve navigation service of marine and air users, especially while using Northern sea route and implementing conception of "Open Sky".

1.2. Satellite navigation systems

"Tsikada" -- fully operating low-orbit SNS (foreign analog "Transit", USA). Accuracy of positioning in any part of the world is about 50--100 m.
GLONASS -- medium orbit SNS (foreign analog -- GPS, USA) for continuous high precision determination of position, altitude and speed of moving object in any part of the world. Accuracy of positioning is about 100 m. The system is at the stage of deployment. At present it is deployed the system of 12 satellites. Full composition system will be of 24 satellites.

II.

Analising possibilities and main technical and economic characteristics of all types of RNS one can come to the conclusion that none of these systems, including SNS, is universal today to meet users' contemporary requirements for radionavigation provision. These requirements may be met only by combined employment of different systems on the basis of formation of a single united radionavigation field covering both the inner- and outer-country territories.
Given approach results, to our mind, in possibility of bringing radionavigation information of different RNS to unified coordinate system in real time scale. Enlarging efficiency of available and perspective RNS is connected with creation of integrated receiving equipment capable to operate simultaneously with a number of RNS.
A single whole radionavigation field must be a totality of separate radionavigation fields, transmitted by ground and satellite systems posessing common coordinate-and-time basis. To our mind in prospect medium-orbit GLONASS system should be a basis for it. Combined use of the systems will permit to eliminate many problems inherent to any separate system. For example, combined use of satellite system with "Chayka" will result in more reliable information of GLONASS. In its turn GLONASS will help to increase accuracy of time scale surveying of ground "Chayka" stations to universal time scale.
As for the prospects to use existing RNS and the ones under development each of them will play its own role in providing safe navigation in the sea, air and on land, based on the analysis of technical state, financial expenditures and so on.
Air and marine short range navigation systems like RSBN, BRAS and others with limited possibilities of use will, evidently, lose their importance as the market is saturated with navigation equipment of "Chayka", VLF and SNS type. VLF system will be operating at least up to complete introduction of GLONASS. And after that it may be used as a reserved global system. Tsikada system will be used up to a full deployment of GLONASS system. Its future will be a subject to considerate.
Under conditions of limited availability and high maintenance expenses of GLONASS type satellite systems and limited class of navigation tasks, which may be solved with the help of VLF systems, long range pulse-phased radionavigation systems like "Chayka" and "Loran-C" have been admitted all over the world and in this country as well. These systems are very efficient. They stay to be most popular in

spite of them to be eclipsed by the development of global satellite systems. We consider that "Chayka" and "Loran-C" will be the ones of important aids to navigation. According to forecasts they will be used at least up to 2010--2015 and then they will successfully supplement satellite systems. As for this our views are the same as to the opinion of International Association of Lighthouse Authorities (IALA).
It is desirable to consider in detail the prospect of "Chayka" and "Loran-C" use. Their integration with satellite navigation systems will become and important factor in providing safe marine and air navigation.
In our opinion there are three stages which may be conditionally distinguished:

2.1. Period of autonomous use and integration of "Chayka" and "Loran-C" systems
"Chayka"/"Loran-C" will be widely used by marine, air and land users of overwhelming majority of the countries. It is based on the following:
-- covering with field of these systems the regions of extensive marine and air traffic (Europe, America, Far East, Nothern parts of Atlantic and Pacific oceans);
-- high accuracies of position fix (the same order as satellite systems in the differential mode of operation), providing solving the large class of navigation tasks and real possibilities of accuracy improvement;
-- inexpensive on-board equipment (2--3 times less as compared with satellite equipment), what provides a possibility of these receivers installation on practically all classes of moving objects including small ones. At present time there are already about 500,000 marine and 100,000 air users;
-- lower (as compared with SNS) operational costs;
-- potential capabilities of improving the characteristics (accuracy improvement at the expense of differential mode introduction, more precise link of transmitting station radiosignals to common time scale, reduction of instrumental error of users receivers).

2.2. Period of "Chayka"/"Loran-C" with GLONASS/GPS systems integration includes:
-- link of signals of these systems to a single time scale;
-- using "Chayka"/"Loran-C" as additional systems to satellite systems;
-- using "Chayka"/"Loran-C" to transmit differential corrections of satellite differential sub-system.

2.3. "Chayka"/"Loran-C" operation period in united system of coordinate-and-time provision

Indicated stages do not represent any time succession. They have both horizontal and vertical links.
The results of investigations have revealed a tendency towards closing the methods of time and coordinate determination with simultaneous broadening a number of determined parameters. However, at present time a task of coordinate and time determination is carried out on the basis of separate use of aids to navigation and synchronization (common time). So, there is a necessity to combine aids to navigation (ground and satellite) and synchronization into a whole system of coordinate-and-time provision.
Being guided by Conception, which is being completed now, we are looking forward in cooperation with all countries to provide safe navigation in Ocean waters, of aircraft flights and on land.

III.

Cooperation in the field of establishment and use of joint navigation systems in the interests of world community users will result in expenses cuts for navigation provision and in higher efficiency of existing and perspective navigation systems.
Now when we have a large experience of joint Far East chain establishment as a model of future development of bilateral and multilateral agreement in radionavigation, one may say that we have all necessary conditions for "Chayka" and "Loran-C" joining in all regions of the world.
It's known that originally "Chayka" and "Loran-C" systems were designed mostly for military users and as a rule were used by marine users. Taking this into account we strive first of all to use existing stations to broaden coverage areas in coastal regions. Most complicated conditions for sailing are in the regions of East Asian, North, Baltic and Mediterranean Seas. Presence of a large number of islands, narrowness and

underwater obstacles makes navigation difficult and increases the possibility of ships accidents. On the other hand the ship traffic is very extensive in these regions. Comparative analysis of radionavigation coverage showes the absence of radionavigation field in some parts of these regions. For example, those are western part of Sea of Japan, bays of Yellow Sea (Liaodong and Vohaivan), South China Sea, Taiwan and Bashi straits, coastal waters and straits of Philippines and Big Zonds Islands.

Taking this into account, during international meetings in Tokyo in September 1990 and in Moscow in March 1991, chaired by IALA Secretary General Mr. Norman F. Matthews, "Internavigation" Committee made its proposals and Draft of International Agreement on a Programme of activities aimed at establishment of joint "Chayka"/"Loran-C" chains in Eastern Waters. These proposals and the Draft met full understanding of the participants of the meetings -- the USA, Japan, China, Republic of Corea. The Draft was polished up accounting an agreed calculation of radionavigation field configuration. It is stipulated several variants of establishing joint chains on the basis of existing stations of East "Chayka" chain, North Pacific chain (USA), East Asian Korean chain and South chain of China ("Loran-C"). In September 1992 proper Agreement is supposed to be signed in Moscow.

Implementation with slight expenses of the project will result in covering with radionavigation field the heavy marine traffic areas and this will provide both marine and air safe navigation.

In Europe we proposed to combine our "Chayka" stations with 'Loran-C" stations in Baltic, Mediterranean and Barents Seas.

In December 1990, "Internavigation" Committee and German Federal Waterways Administration with participation of US Coast Guard signed the Protocol of establishment of joint "Chayka"/"Loran-C" chain in the Baltic Sea consisting of "Chayka" stations from European chain and "Loran-C" station in Germany. Joint investigations were carried out by the experts. The results were discussed during the meeting of interested countries delegations in February 1992 in Moscow.

At international meetings in Bayonne and Paris (France) held on the initiative of IALA with US Coast Guard participation it was submitted proposals on coverage of the Mediterranean and the Black Seas with "Chayka"/"Loran-C" radionavigation field. These proposals were of good reference of the participants -- Italy, France, Egypt and others. At the same time, following the request of the participants our delegation appealed to Turkey Government to preserve "Loran-C" station in Kargaburun. We consider that use of Kargaburun station will allow to preserve radionavigation coverage area of Mediterranean region with less expenditures. Linking Simferopol station ("Chayka") with "Loran-C" station Esh-Shah-Humaid (Saud Arabia) and the construction with sharing expenses of a station in Egypt will make it possible to set up a new joint chain, which will cover the eastern part of the Mediterranean, and also eliminate the gap between the coverage areas of Saud Arabian and Mediterranean "Loran-C" chains.

Analysis shows that satellite systems (GLONASS, GPS) may be used together with "Chayka" and "Loran-C" stations for position fix, broadening their capabilities by improving synchronization, interstation communication, transmitting high precision differential corrections on radio wave propagation.

We consider it necessary to examine organizational and technical possibilities to use in common our VLF system and Omega. Our delegation at symposium of "Omega" Association in 1991 in Canada submitted this proposal.

At present time we are working out a Draft of agreement on joint use of GLONASS and GPS satellite systems. We hope that this agreement will be concluded in the interests of the world community.

Complex use of GPS, GLONASS, "Chayka", "Loran-C", "Omega" is possible only under the condition of uniting their signals at receiving equipment input. Creation of combined receivers, operating with all mentioned systems, practicaly solves the task to provide reliability, flexibility and navigation information abundance.

So, employment of "Chayka"/"Loran-C" and satellite navigation systems will increase and VLF system of "Omega" type will be supported.

Proceeding from the necessity to unite the efforts for improving navigation provision "Internavigation" Committee together with foreign partners is carrying out extensive work on establishment of International commercial economic association "Navigation", which in future may be transformed into joint-stock company "Navigation". Its main purpose is to unite efforts to set up radionavigation fields of all designations in the interests of safe navigation in the sea, air and on land.

Status and Plans of the Loran-C Program for Japan, Korea, China and the Mediterranean

Norman F. Matthews, Secretary General

International Association of Lighthouse Authorities

Introduction

The purpose of this paper is to give an update of recent developments in Loran-C in the Far East and the Mediterranean area.
Regrettably, representatives from China, Korea and Japan are unable to attend this 21st Annual Convention of the Wild Goose Association (WGA). However, the three services concerned have sent details of their future plans.
The first part of this paper is a compilation of the reports received, and due acknowledgement of their contributions is therefore made.

Japan

Mr. Masamitsu Kobayashi, Director of the Radio Aids Division of the Japanese Maritime Safety Agency (JMSA) reports as follows:

At present, Japanese waters are covered by a mix of Loran-C operated by the US Coast Guard, Loran-A and Decca, operated by JMSA

Fig. 1 shows the existing Loran-C coverage.

10 Loran A rates comprising 11 stations give the coverage shown in Fig. 2.

6 Decca chains comprising 22 stations are being operated with coverage shown in Fig. 3.

The Maritime Safety Agency proposes to establish new Loran-C coverage in three phases.

Phase 1

Japan will take over 4 stations of the Northwest Pacific Loran-C Chain (excluding the Guam Station) from the United States in July and October 1993 by stages.

Within this program the following Loran-A rates and Decca chains will be closed down around July 1993.

Loran-A:	2S1 Rate	(Ochiishi, Ookamazaki)
	2S2 Rate	(Ookamazaki, Hasaki)
	2S0 Rate	(Hasaki, Hachijyojima)
	2H6 Rate	(Hachijyojima, Gesashi)
Decca Chains:	Tohuku Chain	(4 stations)
	Kanto Chain	(4 stations)
	Shikoku Chain	(3 stations)
	Hokuriku Chain	(3 stations)

Phase 2

In the second phase, the US Coast Guard will shut down the Iwo-Jima master station at the end of 1994. This will be replaced by a new station being built by Japan at Nii-Jima. This new master station will commence operation in January 1995.

Phase 3

During meetings of the Far East Working Group, Japan has expressed the strong desire that the following two chains be established as soon as possible
Northwest Pacific Chain (Fig. 4)

Nii-Jima	Japan	master
Hokkaido	Japan	
Mina Mitori-Shima	Japan	
Geshashi	Japan	
Pohang	Rep. of Korea (RoK)	

Korea Chain (Fig. 5)

Pohang	RoK	master
Ussuriysk	Russia	
Nii-Jima	Japan	
Geshashi	Japan	
Kwangju	RoK	

On completion of the chains with neighbouring countries all remaining Loran A and Decca will be closed down.

At present, Japan and the Republic of Korea are carrying out technical discussions to enable the Japanese/Republic of Korea Chain to be brought into operation.

Korea

Mr. Jae Kuk Kim, Director of Navigational Aids Division, Korea Maritime and Port Administration (KMPA), provides the following information:

The US Air Force had operated COMMANDO LION CHAIN for military purpose since 1979. In 1988 there was no further military requirement and KMPA took over, and has since operated this chain which covers the entire Korean peninsula with the new name of East Asia Loran-C Chain (EALC). It is configured to have its master station at Pohang and secondary station at Kwangju, with two other secondary stations in Japan at Hokkaido and Gesashi. These two latter stations are currently operated by the US Coast Guard.
Monitor stations are located at Changsan and Osan, and the control station is at Yokota, Japan.

Currently, there are 8,000 Loran-C receivers in use out of 11,590 ships, which means 58% of Korean ships have receivers. As the importance of Loran-C in Korea, is realised, the old facilities AN/TRN-39 at Pohang taken over from the US Air Force are being replaced by new ones under a contract with Megapulse Inc. of December 31, 1991.
This contract will cover the manufacturing of one 16HCG transmitter, two monitor facilities, and one control facility. The installation of control/monitor equipment was completed during July 1992, and it is planned to take over the EALC control function from the Yokota station after a test period.

For the future, centering around the Korean peninsula in the East Asia region, Korea, Japan and China are operating or plan to operate Loran-C transmitters, together with the Russian Federation which also operates Chayka compatible with Loran-C. These four countries located in East Asia agreed to have a FELT (Far East Loran-C Technical Working Group Meeting) chaired by IALA in September 1990 with the mutual understanding that cooperation would be a very effective way to provide better coverage with less facility investment. The conclusion was reached that an international cooperative agreement would be the best solution.

The Government of the Republic of Korea is doing its best to have an international chain, by the end of 1994, as agreed at FELT.
Once the international cooperative chain is in place it will be configured as shown at Fig. 5.
After the completion of this chain, blind areas to the southwest of the Korean peninsula will disappear and a very reliable and accurate coverage for all ships around the Korean peninsula will be provided.

Overlapping coverage can also provide users with chain selection features. Currently, a second upgrade program is being planned for the replacement of old facilities and enhancement of output power, and this program will be implemented from 1993 to 1995. Through this program, old facilities at Kwangju will be replaced. As Korea is a peninsula almost all exports and imports are transported by ship and from this viewpoint marine safety and efficiency are very important to the national economy.
Loran-C as a navigation system with its excellent performance and convenience will have more users during the upcoming 25 years. For these users, Korea will do its best to achieve international cooperation through FELT.

The development of the Russian Chayka chain is dealt with in another paper, but its coverage is shown in Fig. 6. When the Japan, Russian and Korean chains are in place, there will be a total coverage as shown in Fig. 7.

China

Messrs. Gan Guoquiang, Yan Jiaping, Wei Qianzi and Bao Wuwei of the Xian Research Institute of Navigation Technology and Mrs. Guo Xin of the Chinese Ministry of Communications have provided the following information:

The first Loran-C chain along the coast of China, the South Sea Chain, was completed in 1988 (Fig. 8). The results from the inland and marine tests show that all 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 (Fig. 8).

Now China is building two other Loran-C chains along the coast of Northeastern China, the East Sea and the North Sea. Test transmission of signal is expected at the end of 1992 or a little later (Figs. 9 and 10).

According to a contract signed with the government department concerned, the Xian Reasearch Institute of Navigation Technology (XRINT) is in charge of all technical matters of the Loran-C project.

Up to now, the three Loran-C chains are mainly for the navigation of marine users. They began to make themselves attractive to other users in China, especially air users who realised the possibility of en-route navigation and non-precision approach by using Loran-C. Plans to extend Loran-C chains to cover the main airways of inland China are being discussed.

There are 6 transmitting stations along the Chinese coast with three dual-rated to form three chains and a control centre is co-located at the master station.

The three Loran-C chains along the Chinese coast can cover most sea areas of China. But around the Raoping station, there is a part of the sea area lacking satisfactory coverage.

The Chinese Loran-C system operates in the free synchronization method controlled by SAM. Every transmitter is equipped with a time-frequency rack (TFR) to supply the transmitter with time and frequency standard. The TFR is equipped with AC-DC automatic switching with which it can operate for 45 minutes to ensure the reference is not lost when AC failure occurs.

The 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 the SNR calculation are the atmospheric noise of 90% of Service Probability. The radiation power of transmitting stations (peak power) is 1200 KW.

For the future, the operation of the South Sea chain is popular with the users, and the construction of the East Sea chain and the North Sea chain are well in hand. The civil engineering was completed in 1991 together with the transmitter antennas. The equipment - including the solid-state transmitter - for the new chains, is manufactured by the Xian Research Institute of Navigation Technology.

The future development of Chinese Loran-C includes the expansion of coverage and the opening up of its applications.

Various plans concerning the inland configurations of chains are being discussed. The Loran-C stations along the coast have laid a solid foundation for the inland expansion of coverage. Two or three stations added will satisfy air coverage for the main economic zones of China. And the coverage for the whole of inland China needs only an addition of nine or ten stations.

The coverage of the coastal Loran-C needs to be perfected, especially at the junction between the South Sea chain and the East Sea chain. The filling of this gap will greatly benefit the marine navigation of the whole area.

The opening up of the Loran-C system has a very bright future in China. It is of great value for attaining high positioning accuracy of 50m by Differential Loran-C at areas with heavy traffic. The synchronization of the transmission time of the master stations of Loran-C to UTC, will be effected thus providing a time service.

In conclusion, China attaches great importance to the development of the Loran-C and is working hard to expand coverage and to open up its applications.

General

This paper gives only brief details of the plans of Japan, the Republic of Korea and China. However, it is sufficient to show that Loran-C coverage of the area will be in place in the foreseeable future.

It is anticipated that the FELT Agreement between Russia, Japan, the Republic of Korea and China, will be signed in Moscow during the week commencing 6th September 1992. The agreement will enter force on the day of signature and provides for the immediate establishment of a Council of the four countries concerned.

No cost sharing is involved as each party to the Agreement will be responsible for the costs of its own stations. IALA will act as the depository organization for the Agreement.

When the FELT Agreement is fully operational, the total coverage will be as shown in Fig. 12.

The Mediterranean

Progress is being made with regard to Loran-C coverage in the Mediterranean. France, Spain and Italy are discussing the technical problems that may arise and the next full meeting of the Committee is scheduled for 16th and 17th September 1992.

A key factor concerning coverage in the Eastern Mediterranean is the position of Turkey. The Author of this paper had a meeting with the principal officials in Ankhara during February 1992. At this meeting, the Turkish Administration expressed interest in maintaining the Kargaburun station after the withdrawal of the US Coast Guard at the end of 1994.

A fundemental problem that remains is the training of technical personnel, particularly in Italy, in the remaining 27 months before the US Coast Guard withdrawal. This will be a major issue at the next Committee meeting.

A draft Agreement between the concerned nations, including cost sharing, has been prepared, but as yet the agreement has not yet been finalised.

Conclusion

With the successful signing of the Northwest European Agreement in Oslo on 6th August 1992, and the anticipated signing of the Far East Agreement in Moscow on 8th September 1992, it can be said that Loran-C/Chayka has a very successful future.

Discussions between Germany, Norway and Russia with regard to the linking of Batlic states, and between Russia and the Mediterranean concerning Black Sea coverage means that Loran-C/Chayka will be available to a large body of users.
From an IALA point of view, we are in sight of the objective of offering Maritime Users a wide area terrestrial Radionavigation position fixing service as a back up to, or as an alternative to Satellite Systems, for the foreseeable future.

SESSION B

Management and Policy

THE NORTH WEST EUROPEAN LORAN-C SYSTEM - STATUS REPORT

ANDREAS STENSETH

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

Finally I am in the position to inform you that a North West European LORAN-C system will be realized. An International Agreement concerning the establishment and operation of such a system was signed in Oslo on the 6th August this year by the involved countries: Denmark, France, Germany, Ireland, the Netherlands and Norway. It has been a long and thorny road from where we started in 1987 to where we are today, and many of you have been able to follow the developments through briefs given in this forum over the years. For the benefit of those of you who are here for the first time I will give a short summary of events leading to where we are today and then look at the work ahead and some lessons learned in the process.

I have already mentioned 1987 - in May that year representatives from Denmark, Germany, France, Iceland, the Netherlands, Norway and the United Kingdom at a meeting in Oslo established themselves as the LORAN-C Policy Group. The basis was an initiative taken by IALA and a recommendation by a previous LORAN-C Working Group. The Policy Group was later joined by Canada and Ireland. The Group was to propose cost sharing arrangements, develop a system plan and produce the text of an agreement for further consideration by the involved governments.

As could be expected the different countries had different interests and requirements as basis for their participation in the Policy Group, and gradually it became clear that difficulties would arise in trying to accommodate all these interests and requirements within the established framework. These difficulties were ranging from financial considerations to the preference of other already available terrestrial systems - and of course GPS was all the time just round the corner. As a consequence of this some nations withdrew whereas others were given a special status resulting in the group of nations which have now signed the International Agreement I have already mentioned.

However, you will have to go back to 1981 to find the real origin of the North West European LORAN-C system - in that year the Acting Commandant of the USCG informed the nations hosting USCG LORAN-C stations in Northern Europe that the US would terminate support of these stations in the mid 1990's and offered to transfer the stations to the host countries if they so wanted. The date for this transfer has later been established at 31 December 1994. The background of course was the introduction of GPS which was expected to meet all US military requirements so far met by LORAN-C, and the US had no civilian interests in the area to justify continued operation of this system. From an European point of view the coverage offered by the USCG system was interesting, but not enough to meet civilian requirements, so enhancements of the system would be necessary. One enhancement will be the integration of two French stations at Lessay and Soustons. Secondly new stations will be introduced in Ireland and Norway to give a total coverage as depicted in this foil (Foil 1). Further enhancements are under consideration and I will come back to that in a minute.

Time of transmission (TOT) control will be used for the new North West European system although existing USCG stations will continue to be controlled via System Area Monitors (SAM) until the proposed handover date - 31 December 1994. The timing control of the transmitters will be executed from a control centre in Brest in cooperation with a similar centre in Norway, whereas the overall coordination of the operation of the system will be taken care of by the Coordination Agency - an Agency authorized by the Agreement and tasked among others to coordinate all activities necessary to have the system work as a system. Norway has accepted the role as Coordinating Agency and my organization -

NODECA - has been appointed executive agency under the political guidance of the Ministry of Fisheries. To take care of this task within NODECA a Coordinating Agency Office has been established for the day-to-day work of the Agency, and a Project Management Office is set up to coordinate and direct the establishment of the new system. Both these offices draw support from the overall NODECA organization. The overall direction of the system including decisions on economy, administrative and operational procedures etc., is left to a Steering Committee with representatives from all participating countries using the Coordinating Agency Office as secretariat. Decisions of the Steering Committee will normally have to be unanimous and are binding on all the parties.

The North West European and North Atlantic LORAN-C organization is as far as I know, the first of its kind and represents a step in the direction of a more conscious European approach to problems involving radionavigation systems, even if it presently only embraces 6 nations - I stress the word presently because indications are that both the UK and Iceland might reconsider their previous decision to withdraw from the group when it becomes clear that LORAN-C has come to stay and will cover their areas of interest. Furthermore the Internavigation Committee in Moscow on behalf of all the Independent States within the Intergovernmental Consultative Council, has displayed great interest in closer cooperation with the North West European Group and is accepted as observer to the Steering Committee. The background for this is their expressed policy of providing marine, air and land users global, reliable information on position at any time of day or year with required accuracy, and they see the CHAYKA/LORAN-C system as an important element of the mix of systems necessary to achieve this. This point of view is - I believe - shared by most members of the North West European Group.

In addition to this global aspect some members have local requirements which are not fully met by the presently planned LORAN-C systems as you will see from this prediction diagram (Foil 2 - 50-100-200 m). These deficiencies could be overcome by integrating some of the CHAYKA stations in operation today into the North West European LORAN-C system, giving enhanced coverage for the benefit of all involved parties. The proposal of most immediate interest in this regard today is the inclusion of the CHAYKA station at Slonim as a third secondary of the Sylt chain with Sylt as master, giving good coverage in the Baltics and strengthening the coverage in the south eastern part of Norway. Which organizational consequences this will lead to are yet to be seen, but the newly signed Agreement opens for new members.

Anyway, we will get a LORAN-C system in north west Europe to serve us for the next 15 to 20 years, what do we do about that? First it should be recognized that by and large LORAN-C today is a "terra incognita" in most of Europe for the simple reason that there has been and is very limited LORAN-C coverage available in Europe. We are therefore faced with a formidable task of informing potential users, and we have a long way to go to catch up with GPS in this respect - not that I see GPS as a threat or something to be defeated, but I would like to see the users having the same true and fair knowledge of both systems as basis for their choice. We in the North West European Group will have to do our bit in this regard, and we already have proposals in that direction on the Steering Committee table. However, we do not have the resources to do this job all by ourselves and hope that industry with interest in this potential market will see this as a challenge, remembering that LORAN-C should be sold as an universal system not limited to marine application, but of equal interest to land users and aeronautical users, particularly outside the ICAO sphere. Precise time, differential use of LORAN-C, meteorology and possible use of LORAN-C for carrying Differential GPS corrections are also potential areas of utilization of the system. And of course the Wild Goose Association should consider in what way they can use their experience and knowledge as their contribution towards a living and prosperous LORAN-C engagement in Europe. - I see this arrangement here in Birmingham as a flying start in this respect.

Secondly I believe that the "war" with GPS - if there ever was one - should be called off. GPS has already demonstrated its superiority in so many ways, and this or some other satellite based radionavigation system is here to stay and will be part of the radionavigation mix into the future, even if a number of difficult problems are yet to be solved. I hope therefore that industry will utilize this mix and for one thing introduce new hybride GPS/LORAN-C user equipment to satisfy what might be a fast growing market, even if prices presently are on the high side. In Norway we already have positive reports from users of such equipment.

I would also like to remind industry of the enhanced coverage that can be offered with cross chain receivers. This enhancement is probably not impressive by itself, but will in some critical areas improve accuracy and coverage of importance to many users.

So a few words about the implementation of the system. A provisional project team was set up and actually started its work more than a year ago so as to be prepared for signature on short notice of a contract with the vendor if the system was to be established. By signing the Agreement in Oslo on the 6th August authorization was given to go ahead with the project - this authorization included the formal establishment of the Project Management Office and opens for signature of a contract with the vendor.

A complicating factor is the fact that four of the involved stations are part of the existing US Coast Guard LORAN-C system in the area, and the tube transmitters at these stations are to be replaced by solid state equipment prior to handover of the stations to the host nations. This will have to be done without unacceptable interference with the operation of the USCG system and retaining the present System Area Monitor (SAM) control system until 1 January 1995. I would like to use this opportunity to say that by exceptional support and cooperation from USCG, both in Washington and London, we have established a basis for this operation which I feel will meet the needs of both parties, and further that we are grateful for the contribution USCG thereby has made towards the realization of the project.

Somewhere down the line it was realized that both hardware and software will have to be replaced at the Control Centre at Brest in order to get the maximum benefit from the new transmitters and the time of transmission concept of operation. A second Control Centre is also under consideration in Norway. A system requirement verification and specification phase will be one of the important near term activities within the overall program. The overall Project Implementation Schedule is illustrated in this foil (Foil no. 3).

Finally a few words on the Agreement which actually started as a draft Memorandum of Understanding in 1987, was upgraded to an International Agreement in 1989/90 and through numerous modifications signed in the Norwegian Government Guesthouse in Oslo - as I have already told you - on the 6th August this year. The signature was actually done by representatives from the appropriate Ministry or national Embassy in Oslo and for Norway by the Minister of Fisheries. This does not mean that the Agreement is in force - that happens only 30 days after signature, and for some countries - although considered a mere formality - the Agreement will have to be ratified by their Parliament before it is legally binding for them. The lesson learned from our work with this Agreement is that it needs a lot of guts and patience to get through with it, and the number of pitfalls are many. If I should dare to give you an advice based on our experience, it would be: be formal from the start, sooner or later you will meet the formalities anyway - remember that each country has its own interests to look after, and these interests do not always go in the same direction or are not always relevant to the prime purpose of the Agreement; shortcuts therefore can prove to be disastrous for the timetable established for the operation.

To conclude - once again I want to express how pleased I am that my report to you today is not just another story of setbacks and uncertainty. The LORAN-C Policy Group has finalized its mission. The program is now under way under the overall direction by the Steering Committee. Despite all difficulties experienced during the past 5 years I want to underline the excellent cooperation between the various countries; with their enthusiasm I believe we now have provided a good basis for establishing a reliable and accurate, multinationally controlled system for safe traffic at sea, on land and in the air.

Thank you for your attention!

BIOGRAPHY

Mr. Andreas Stenseth serves as the Deputy Director Greneral of the Norwegian Defence Communications and Data Services Administration (NODECA). As such he is responsible for the overall coordination and supervision of all activities in NODECA comprising planning, implementation and operation of strategic communication networks and radio systems for national defence and NATO, command, control and information systems for military headquarters as well as administrative EDP systems for central defence institutions.

He has been involved in LORAN-C since the early 70's and was Chairman of the LORAN-C Working Group from 1984 to 1985, member and Chairman of the North West European LORAN-C Policy Group from 1987 to 1992, and he was recently elected Chairman of the Steering Committee.

Mr. Stenseth holds degrees in Electrical Engineering (Telecomms.) as well as in Business Administration. He attended the Norwegian Defence College in 1978 and is a member of the Association of Chartered Engineers.

FIG. 1

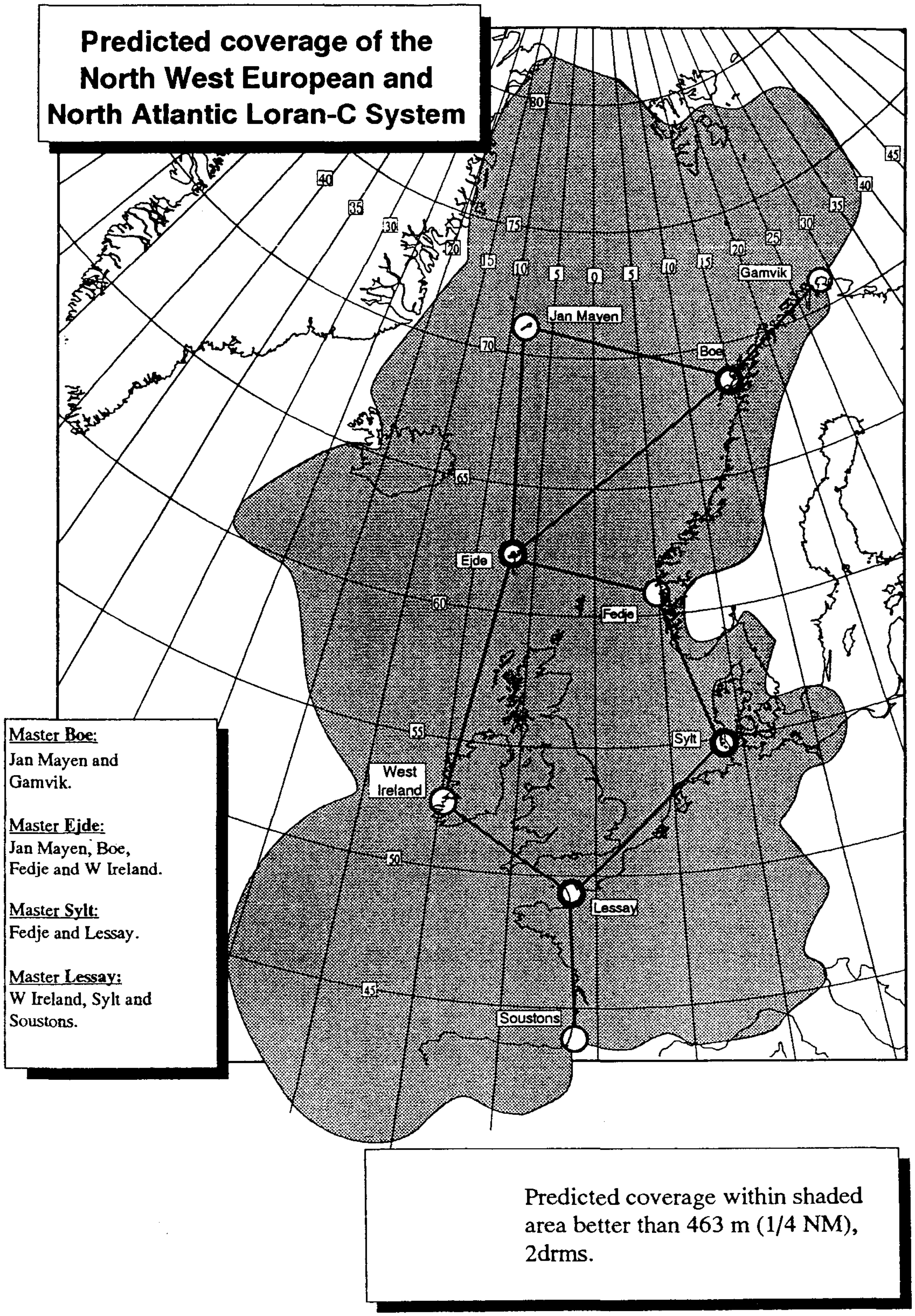
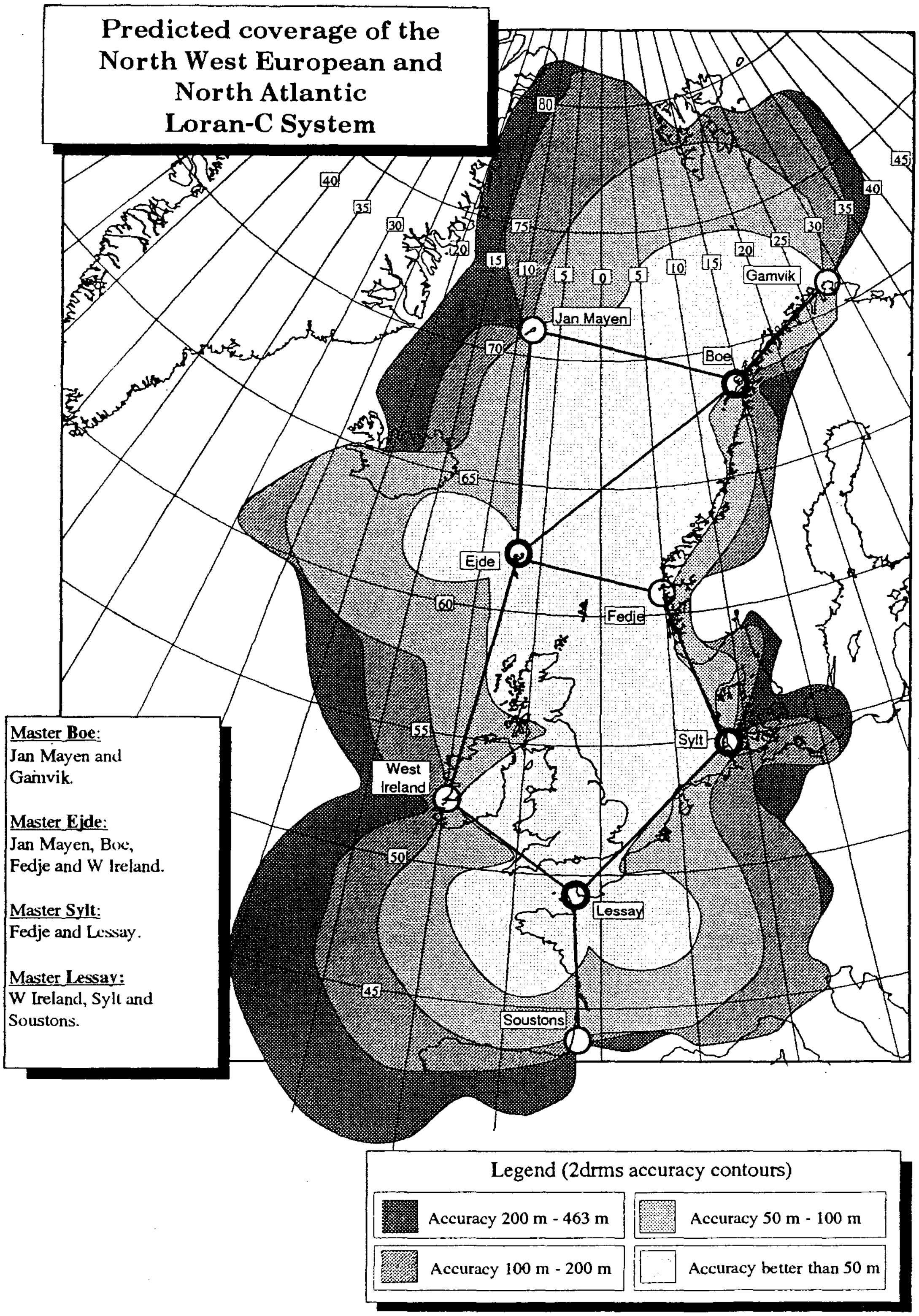

Predicted coverage of the North West European and North Atlantic Loran-C System
Jan Mayen
Gamvik
Boe
Ejde
Fedje
Sylt
West Ireland
Lessay
Soustons
Master Boe:
Jan Mayen and Gamvik.
Master Ejde:
Jan Mayen, Boe, Fedje and W Ireland.
Master Sylt:
Fedje and Lessay.
Master Lessay:
W Ireland, Sylt and Soustons.
Predicted coverage within shaded area better than 463 m (1/4 NM), 2drms.

FIG. 2


Predicted coverage of the North West European and North Atlantic Loran-C System
Jan Mayen
Gamvik
Boe
Ejde
Fedje
Sylt
West Ireland
Lessay
Soustons
Master Boe:
Jan Mayen and Gamvik.
Master Ejde:
Jan Mayen, Boe, Fedje and W Ireland.
Master Sylt:
Fedje and Lessay.
Master Lessay:
W Ireland, Sylt and Soustons.
Legend (2drms accuracy contours)
Accuracy 200 m - 463 m
Accuracy 50 m - 100 m
Accuracy 100 m - 200 m
Accuracy better than 50 m

North West Europe and North Atlantic Loran-C System

System Implementation Schedule

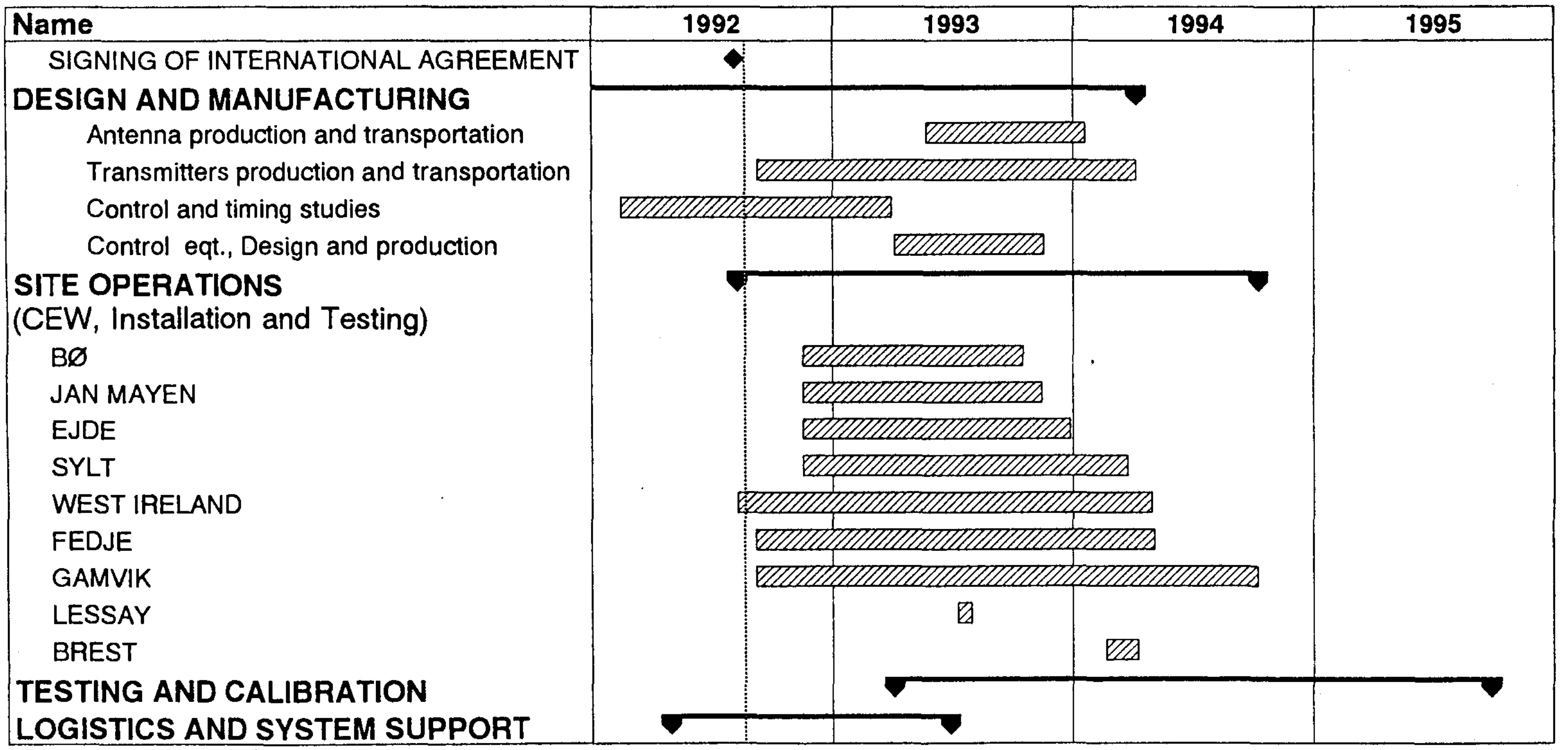


FIG. 3

MARITIME RADIONAVIGATION IN THE UK AND THE FUTURE OF DECCA

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Trinity House Lighthouse Service,
England

The paramount operational requirement for maritime radionavigation systems is "Safety of Navigation". Do the present and future systems contribute to the improvement of Safety of Navigation and will, as a result, the accident rate decrease? These factors are discussed in this paper together with the UK maritime radionavigation systems available in UK waters and especially the terrestrial systems, Decca Navigator and Loran C.

The paper is prepared by Trinity House and does not necessarily represent the views of the United Kingdom government.

1. Introduction

In these sessions on Management and Policy we are concerned not so much with the technical aspects of maritime radionavigation systems but with the operational requirements and my paper, therefore, concentrates on these matters. The main and overriding operational requirement is, and always will be, "Safety of Navigation". Can improved maritime radionavigation systems improve safety at sea?

I believe this point is dealt with in the second report prepared by the UK House of Lords Select Committee on Safety Aspects of Ship Design and Technology. In Section 4 dealing with Navigation and Traffic Control it states that:

The state of the art of navigation has changed dramatically in recent years, as described for us by witnesses from the Royal Institute of Navigation. The skill of the navigator used to consist of, reducing uncertainty to an acceptable level using landmarks, star sights and more recently, the two low-frequency radionavigation systems, Decca Navigator owned by a British company and Loran C owned by the US armed forces. Now, using high-frequency satellite-based radionavigation systems, ships' officers may receive their position at the touch of a button to an accuracy adequate for all purposes except perhaps harbour navigation.

The Institute's witnesses acknowledged that progress in this field is not without its pitfalls. Traditional skills are obsolete, and a new approach to training is needed; in untrained hands, the new systems are "almost a liability". There are difficulties to be overcome in using satellite positions in conjunction with the old Admiralty charts which are still relied upon for most areas. The fact that GPS (Global Positioning System), the leading satellite navigation systems, belongs to the US Department of Defense presents special problems; the service is subject to no civilian or international control, and may be modified or withdrawn at any moment in response to US military requirements.

However, the Salvage Association considered that the new systems "will no doubt reduce groundings and strandings". The Institute went one better, and claimed that the benefits of improved navigation systems can already be seen in Lloyd's Register's tables of total losses attributed to collisions or wrecks for 1981-90. (They acknowledged that some losses in these categories might be due to weather rather than to failures of navigation).

The Symposium may recall two horrendous accidents that occurred in UK coastal waters in past years. During 1967 an oil tanker of 61,000 tonnes foundered on the Sevenstones Reef off the coast of Cornwall resulting in serious oil pollution to the adjacent coastline.

In January 1971 four vessels were involved in a disaster in the Dover Straight area of the English Channel. On January 11th, the 20,500 tonne Texaco Caribbean collided with the 10,000 tonne Paracus. The Texaco Caribbean exploded and sank claiming eight of her crew. The Paracus was towed to port for repairs and suffered no casualties. On January 12th the Brandenburg, a 3,000 tonne cargo ship struck the submerged bow section of the Texaco Caribbean, she was ripped open end to end and sank leaving 21 dead. The area of wrecks was carefully marked with buoys and additional light vessels and still vessels continued to sail through the buoyed danger area until on February 27th the Niki, a 400 tonne cargo vessel sailed across the wreck, was ripped open and sank with 22 of her crew.

These sort of accidents continue to occur, and it is clearly the view of the Salvage Association and the Royal Institute of Navigation that the new radionavigation systems will reduce accidents.

In these two cases would accurate radionavigation have prevented the accident, would accurate radionavigation with audible warning of danger have assisted the navigators of these ships? May I go one further and suggest to this Symposium that there may well be simple methods of warning navigators when the vessel is proceeding into danger using the new radionavigation systems.

What then is the operational requirement for a suitable radionavigation system? What does the user/navigator require? May I suggest that he requires a "black box" which indicates latitude and longitude to two decimal places of minutes, anywhere in the world, in all seasons and preferably does not place total reliance on a single system. It should also provide a clear indication of system or equipment malfunction. The navigator is not interested whether it is Loran C, GPS or Decca. All he requires is a reliable and accurate position. It is a very similar situation to the navigator on the bridge of a vessel fitted with 'X' and 'S' band radars. He is not interested and quite often does not know which radar display is 'X' or 'S', but is only interested in the system which provides the display he requires in the environmental conditions prevailing at the time.

We are now at a significant milestone in the progress of maritime navigation, the navigator has never before had available a radionavigation system that is accurate, reliable and cheap. The user, the navigator, is beginning to realise that such systems are possible and available, but I suggest that it will take a few more years to convince the maritime service that navigational reliance can be placed on such a system or systems. Furthermore if the maritime service can and does place reliance on a radionavigation system, what monitoring and control of such systems needs to be put in place to ensure that the performance is maintained and how will this affect the provision of conventional navigation aids, i.e. lights, fog signals etc.?

2. The General Lighthouse Authorities

In order to meet the obligations set by the International Maritime Organisation (IMO) to ensure the continuous availability of an acceptable and assured maritime navigation system British and Irish law has vested the superintendence and management of all lighthouses, buoys and beacons throughout Britain and Ireland, the Channel Islands, the Isle of Man, and the adjacent seas in three statutory bodies known as the General Lighthouse Authorities (GLAs), having jurisdiction in England and Wales, Scotland and the Isle of Man, and Ireland respectively. The exceptions are certain seamarks which are maintained by local lighthouse authorities, which are mainly harbour undertakings.

Under the British and Irish Merchant Shipping Acts all expenses relating to lighthouses, buoys and beacons maintained by the GLAs, are met out of a self-supporting common fund known as the General Lighthouse Fund (GLF). The GLF's principle revenue is the light dues levied on ships using the GLAs' services in Britain and Ireland. The accounting for these dues is centralised and controlled by Trinity House, (the GLA having jurisdiction in England and Wales) on behalf of the 3 GLAs.

The Secretary of State for Transport is responsible for setting the level of light dues in the UK to maintain the GLF at a level commensurate with the approved estimates of expenditure of the GLAs. In the Republic of Ireland the dues are set by the Minister of the Marine.

Light dues are payable per voyage in respect of ships arriving at or departing from ports in the United Kingdom or the Republic of Ireland, unless they come within the scope of the exemptions laid down in the relevant Regulations; tugs and fishing vessels of 10 metres and over and pleasure craft of 20 tons and over are required to make periodic payments on account of light dues.

The GLAs have a formal process which involves regular consultations with all national maritime bodies including the ports, on developments in aids to navigation and changing user requirements. This extends internationally through the UK Department of Transport (DOT) and the Irish Department of the Marine who report the views of their respective countries to IMO and ensure the implementation of internationally agreed traffic separation schemes in their areas. The GLAs also play an active role in the various committees of the International Association of Lighthouse Authorities (IALA) which represents lighthouse authority interests worldwide.

3. UK Maritime Radionavigation Policy

There is no formal UK government document setting out its policies concerning maritime radionavigation in its coastal waters. However, as a member Administration of the IMO, the DOT complies with the Conventions of that organisation, and in relation to navigation in coastal waters the DOT formulates its policies on the provisions of Chapter V of SOLAS 74.

The GLAs provide a broad mix of traditional aids to navigation including lighthouses, lightvessels, buoys, fog signals and beacons. Radionavigation systems include radar beacons (racons), maritime radiobeacons and the radio terrestrial system, Decca Navigator.

Let us now examine in more detail the radionavigation systems provided in the UK and more especially the two systems of prime interest to the Symposium, Loran C and Decca Navigator. How do these systems fit into the future overall UK maritime navigation picture and can they enhance safety of navigation in our coastal waters.

3.1 Radar Beacons

Radar Beacons (racons) are receiver/transmitter devices operating in the maritime radar frequency bands and intended for improving identification of radar targets. A racon responds by sending a characteristic pulse when triggered by a received radar pulse. The response can appear on the display of the triggering radar thereby providing range, bearing and identification information. The displayed response has a length on the display corresponding to a few miles and is often coded as a morse character for identification. The advantage of a racon over a light is that its signal can be received under nearly all circumstances, in particular reduced visibility. A racon can be used for one or more of the following purposes:

- ranging of and identification of positions on inconspicuous coastlines
- identification of aids to navigation, both seaborne and land based
- landfall identification
- centre and turning point identification in precautionary areas or Traffic Separation Schemes
- to mark new and uncharted hazards
- to indicate navigable spans under bridges
- as leading line racons

In addition it has been accepted that:

- user selectable services are not required in the UK at present
- when a radar beacon is provided it should be capable of both 'X' and 'S' band transmission.

Racons have, in practice, proved to be a reliable device requiring little or no attention once fitted. The mariner has a high regard for this simple and reliable radar presentation and it is expected that more rather than less radar beacons will be provided in the future.

IMO Resolution A 615(15) makes recommendations on the marine use of radar beacons and transponders and includes operational characteristics and operational standards.

3.2 Radar Enhancer

Navigators, using radar, have reported that during rain storms an echo from a buoy can be obscured on the radar display by rain clutter. This can be particularly troublesome when buoys are located at crucial turning points or at the start and finish of buoyed channels.

To this end a simple radar enhancer is under development which will automatically re-transmit the received radar pulse and thus ensure that a clear signal is displayed on the radar indicating the location of a buoy. It is intended that the enhancer will be cheap so that it will be applicable to a large number of buoys.

3.3 Non-Directional Maritime Radiobeacons

Based on the requirements set out in Regulation 14 of Chapter V of the SOLAS 74 Convention, the following criteria have been used to provide the maritime radiobeacon service around our coastline.

3.3.1 It is necessary to provide an independent system of maritime radiobeacons in order to comply with the SOLAS Regulations.

3.3.2 Although some aeronautical radiobeacons can be used for maritime purposes, they may have serious drawbacks in that the propagation path is over land and sea which can cause bearing errors.

3.3.3 The service will enable navigators to obtain a "line of position" and not in all cases a "position fix".

To this end the number of maritime radiobeacons around the UK and Irish coastline has been reduced from 51 to 31, seven of which are provided for calibration purposes. Also the mode of operation has recently changed from a carrier modulated by a keyed audio tone (A2A) to a simple keyed carrier signal (A1A). The channel spacing has been reduced from 2.3 kHz to 500 Hz, creating more channels in the band and enabling each station to operate continuously. Under the previous arrangement most radiobeacons operated on a time shared basis in groups of 3 to 6 stations.

The accuracy of a bearing will usually lie between 2° and 10°, but the 95% accuracy is generally better than 5°. The higher accuracy would be expected if the direction finding receiver in use had recently been calibrated by visual means. The accuracy will be subject to propagation conditions, and will usually worsen at night time. Bearings can also be seriously affected by the passage of the signal over certain types of terrain and by transitions from land to sea and vice versa.

It is expected that the reduced service will be maintained until the SOLAS Regulations, with regard to radionavigation, are amended.

3.4 Terrestrial Systems (Decca Navigator & Loran C)

During the early 1980s, Racal-Decca Marine Navigation Ltd (RDMNL) found difficulty in obtaining sufficient rental income from receivers to support the continued operation of the UK Chains of the Decca Navigator System (DNS). Following representations made to the Secretary of State for Transport by RDMNL, an agreement was negotiated with the company for the GLAs to assume responsibility for DNS at the expense of the GLF. This was enabled by an Order made in the exercise of the powers conferred on the Secretary of State under Section 34(3) of the Merchant Shipping Act 1979. An agreement between the GLAs and the company came into effect on 27th February 1987. The agreement covered all matters relating to the operation of the DNS Chain including performance levels, maintenance, monitoring, costs, frequencies and transmission format plus the fixed assets. There was provision for the continued operation and maintenance of DNS by RDMNL until 27th February 1994 with an option to extend for a further 3 years.

In NW Europe and the N. Atlantic, the US Coastguard - which operates the US Department of Defense LORAN-C installations in Norway, Greenland, Iceland, the Faroes and Germany - gave notice to the host states of their intention to cease operation of the system at the end of 1994 once GPS had become fully operational. Denmark, Iceland, Norway, Germany, France and the UK agreed to examine the implications of establishing a NW European LORAN-C network. International discussions proceeded among these countries, together with Canada, the Netherlands and the Republic of Ireland, to assess the technical feasibility and suitability of such a system, and the means by which it could be established and financed. Included in the proposed comprehensive regional coverage were two new transmitters, one in NE England and another in SW Ireland.

The Secretary of State issued a statement in April 1990 following 10 months of public consultations, saying that in principle, and subject to certain conditions, the UK should not stand aside from the opportunity to adopt LORAN-C as a European regional terrestrial radionavigation system under independent control.

This system had been preferred over DNS the existing equipment of which was nearing the end of its useful life and which does not have similar potential to interface fully with other LORAN-C systems, whose coverage was increasing in may parts of the world. The greater range of LORAN-C meant the possibility of high quality radionavigation service to many additional areas outside UK waters and would have overcome the technical limitations of DNS. DNS's variable technical effectiveness arising from seasonal changes and *night effect* (sky-wave interference) are inherent problems remaining since the development of the system over 40 years ago. Indeed, it was a recognition of these problems which led to the development of the Loran A and later Loran C signals. Nevertheless, mariners have found and continue to find the performance of DNS acceptable for general navigation purposes. The cost to the GLF of running DNS was in excess of £4.5M per annum.

After considerable international discussion beginning in 1988, a cost-sharing formula was eventually agreed in principle at a meeting in Ottawa in January 1991. A draft international agreement was also produced incorporating the financial aspects and providing, inter alia, for the new transmitter installations.

The Secretary of State in his announcement in April 1990 had made the UK's final commitment to the NW Europe LORAN-C subject to a number of conditions. These included:

3.4.1 acceptable cost sharing arrangements,

3.4.2 the location, acquisition and clearance of suitable sites for the new transmitter stations in the UK and Ireland

3.4.3 an adequate transition period for DNS users

3.4.4 ratification of the associated international agreement no later than mid-1991 to permit such a transition.

The UK has also always made it clear to the other countries involved that its participation was conditional on any alternative system being of lower cost to its users who fund the costs of all the general navigational aids through light dues. This latter point is of particular significance and is perhaps not fully appreciated outside the UK. Trinity House was asked to provide technical advice and to take forward - acting in the capacity of agent for the Secretary of State - matters leading up to the establishment of a UK transmitter. A similar role was carried out by the Commissioners of Irish Lights for the proposed new Irish station.

It was proposed that LORAN-C would be under the control of the participating countries, divorced from the pressures of a purely commercial environment. In the UK it would have cost about £0.7M annually to run subject to a single capital contribution of up to £11M from the UK to establish the NW European network. Recent innovations include low-cost receivers with significantly higher performance, using technology operating under quite new principles. Techniques have also been developed for computer mapping of ground conductivities and signal propagation speeds which substantially improve absolute accuracy. It was planned that the NW European system would implement these latest techniques. In contrast, the same degree of technical development of DNS has not taken place. DNS has been withdrawn from N. America, France, the Persian Gulf and is being withdrawn from India, all in favour of LORAN-C. It is, however, being retained in Denmark and the Netherlands in Europe.

The intention was for a minimum transitional period of about 3 years with DNS and LORAN-C running in parallel, to allow sufficient time for all necessary notifications of the proposed change and also any alterations to the marine users' equipment. No difficulties or major disruptions to the marine radionavigation user community were anticipated due to the long changeover period envisaged, although not all users, particularly the fishing industry, were persuaded of this. Many users would, in any event, have changed their receivers at least once in the period to 1997, to take advantage of improvements in receiver technology with expected reductions in the retail cost.

Early in May 1991, RDMNL publicised its intention to re-submit to the Secretary of State (after an earlier proposal had been rejected in 1988) their offer in revised form to modernise the UK Chains of DNS at lower cost. The GLAs commented on this to the DOT.

The Secretary of State subsequently announced in Parliament on 21st June 1991 his decision to retain DNS in UK waters following consideration of the revised proposals from RDMNL for automating the UK Decca Chains.

Two main factors led to this conclusion. First, the UK had received no assurances that the international agreement could be concluded and implemented on a time scale which would meet the UK's transitional requirements. Secondly, the revised RDMNL offer had significantly changed the economic appraisal and the effects on UK light dues. The dues payers had made it clear that they were not prepared to pay more to change to LORAN-C, and the fishing and electronics industries had strongly represented against a change of system. The other European participants including France, German, Norway, Denmark, Ireland and the Netherlands were informed of the UK's decision on 21st June.

Realistically, there can be no doubting the great weight carried by economic, user costs and other practical factors in such matters as these. The GLAs, too, are concerned about the cost to the user, but they are also concerned with measuring the advantages in terms of improvements in the safety of navigation. Trinity House remains of the opinion that from the point of view of safety of navigation, LORAN-C would give the mariner a better service than DNS and merits consideration as the long term terrestrial back-up system for a suitable satellite service for world-wide operation. In seeking to preserve their system RDMNL were able to offer a cheaper package and so the GLAs were requested by the DOT to negotiate a new agreement with RDMNL.

As requested by the DOT a new agreement was negotiated to replace old transmitting equipment, provide for fully automatic operation and thus remove the requirement for operating staff. Decca would also provide and man a new control centre at the Northern Lighthouse Board office in Edinburgh and maintain the system. A new agreement was signed on 11th February 1992 to cover a period up to 31st March 2014. There would be no improvements in the coverage or accuracy of the system which would remain as specified in the Decca Data Sheets for the system.

Included in the Agreement are provisions for the GLAs to terminate

3.4.5 on March 31st 2004 or 31st March 2009 at no extra cost.

3.4.6 on 31st March from 1998 to 2003 with at least 2 years prior notice and payment of an Early Termination Payment which is established from an agreed formula.

In the meantime the GLAs are monitoring the progress of the European LORAN-C Committee and the provision of the proposed modified European system. This system as planned would exclude a transmitter in the UK but is expected to provide complete coverage of UK coastal waters and the following advantages over the present Navigator system.

3.4.7 improved accuracy in some areas

3.4.8 negligible skywave interference

3.4.9 accurate modelling of fixed errors

3.4.10 greater range

3.4.11 cheaper to operate

But of course very substantial capital investment is required.

It is understood that the International Agreement has now been agreed by all participating countries and was signed in Oslo on August 6th 1992. Iceland and Russia are also considering participation in the scheme.

3.5 Worldwide Radionavigation Systems

IMO Resolution A666 (16) presents a report of the current situation of a study on a world wide radionavigation system. This provides a basis on which regulation V/12 of the 1974 SOLAS Convention might be amended to include a requirement that ships should carry means of receiving transmissions from a suitable radionavigation system throughout the intended voyage.

The Resolution provides operational and technical details of candidate radio systems, does not make a recommendation but invites member governments to keep IMO informed of developments so that the report can be adjusted as necessary. However, section 3.13 of the Resolution does lay down the criteria which IMO should consider in deciding whether or not to adopt a radionavigation system.

At the recent meeting of the IMO Sub-Committee on Safety of Navigation - 38th Session, the Government of the United States submitted a statement which contained the following details:

In making GPS available to civil users around the world, we will offer what we call the standard positioning services (SPS) with an accuracy of 100m 2drms (95% probability). Starting in 1993 (based on present projections), SPS will be available to all GPS users on a continuous, world-wide basis with no direct charge affixed by the United States Government to the users of this system for at least the initial ten years of service.

GPS has been offered to the International Civil Aviation Organisation (ICAO) as a candidate component of the Global Navigation Satellite System (GNSS). After GPS is declared fully operational, which is expected to occur in 1993, the United States will consider proposing it for adoption by IMO as a component of the world-wide radionavigation system detailed in resolution A 666 (16).

This represented a retraction of an earlier US statement to IMO in May 1992 which had said more positively that GPS would be proposed for IMO adoption.

The problem with GPS is that although the system is being used, and will in future be increasingly used by mariners, there is still no formal offer to IMO by the US for GPS to be considered as a component in a future world-wide system. Until that happens, no mandatory carriage requirements can be made and no real control can be exercised over its use. Nevertheless, it is clearly important that mariners should be aware of its limitations and the possibility of malfunction of the system or the on-board equipment, in the same way as for other shipborne equipment. For the present it is considered that the accuracy of the GPS signals is sufficient for general marine navigation, and provided that a method of promulgating navigation warnings can be implemented.

It is accepted that the present advance Bulletin Board Systems do not provide the mariner with an acceptable warning of a system malfunction and the provision of a suitable Integrity Monitoring System is now being considered.

At the present time GPS, which is provided and funded by the US Department of Defense appears to be the only satellite system to have the necessary funding and support to provide an effective and reliable world-wide service, although Glonass (Russian) may also be a possible candidate system. Apart from Omega there are no terrestrial radio systems that will provide complete global coverage but Loran-C could provide complete global coverage of the most used areas of maritime navigation.

There are a number of important milestones that should be borne in mind during the next few years which will affect the final mix of radionavigation systems adopted for the future in UK waters. Any UK decisions will need to take account of both the user requirements and the costs falling on users.

1992 - European Loran C Agreement signed in August.

1993 - SPS will be available to all GPS users on a continuous basis with no direct charges for at least 10 years. Controlled by US Department of Defense.

1993 - GPS declared fully operational. Will the system be offered to IMO as a candidate system for world-wide navigation? Will the system meet the criteria laid down by IMO?

1994 - USCG cease to operate Loran C stations outside the US.

1994 - European changeover to new Loran C system.

1995 - European Loran C system fully operational.

1996 - If GPS is adopted by IMO, UK need to reaffirm whether a terrestrial system should be provided as a backup. If so, or if GPS is not adopted by IMO, UK will need to decide whether to continue with DNS or to change to LORAN-C. If the latter, will need to give notice of closure of DNS.

3.6 Differential GPS

A great deal of work is taking place within the US and Europe to agree a common method of transmission and signal format for a Maritime Radionavigation Differential GPS service. This service would enhance the present 100 to 300 metre accuracy obtained for the civil GPS service to 5 to 10 metres and be available to any user free of charge.

However, within the UK the view is that a differential GPS service is not required for general navigation and is only needed for specialised purposes, i.e. cable laying, surveying etc.

To this end channels have been provided on a selected number of Maritime Radiobeacons to transmit differential data signals provided by a private company. The Company rents the service and pays a fee based on the use of the equipment to seaward. The equipment on the vessel is provided by the Contractor and the signals can be encrypted to ensure that only registered equipment users have access to the system.

3.7 Conclusions

In considering the Radio Aids to Navigation that can be provided for the future, will their ability to display the vessel's position accurately contribute to the improvement of safety of navigation. Can these new systems be integrated with other on-board equipment to provide a visual and audible warning of danger? Can these systems provide a warning to the navigator of equipment malfunction? The clear answer to all the questions is YES and if this equipment can be produced cheaply and operate reliably it will certainly ensure that vessels throughout the world proceed about their business in a safer, more reliable and effective manner. Then the navigator will be well satisfied.

With regard to a world-wide radionavigation system acceptable to IMO and thus the mandatory requirements for on-board equipment, at this moment in time the matter is still unresolved. GPS, the prime candidate system is still under military control and therefore a back-up terrestrial system is still required. The only UK candidates are Decca Navigator and Loran C.

REFERENCES

IMO Resolution A529(13)
IMO Resolution A615(15)
IMO Regulation 14 (Aids to Navigation), Chap. V of Solas Convention
GLA Radiobeacon Plan - May 1991
IMO Resolution A666(16)
IALA Recommendation on Maritime Radar Beacons (Jan 1990)
IALA Recommendation on Maritime Radiobeacons, (June 1990)
IALA Policy on Terrestrial Radionavigation Systems (1991)
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THE U.S. COAST GUARD GPS INFORMATION CENTER (GPSIC) AND ITS FUNCTION WITHIN THE CIVIL GPS SERVICE (CGS)

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Abstract

In 1987, the U.S. Department of Defense (DOD) formally requested the Department of Transportation (DOT) assume responsibility for establishing and providing an office that would respond to nonmilitary user needs for GPS information, data, and assistance. In February 1989, the Coast Guard assumed the responsibility as the lead agency within DOT for this project. Since that time, the U.S. Coast Guard has worked with the U.S. Space Command to develop requirements and implement a plan to provide the requested interface with the civil GPS community. The Civil GPS Service (CGS) consists of four main elements: the GPS Information Center (GPSIC) which provides GPS status information to civilian users of the system; the PPS Program Office (PPSPO) (once established) will administer the program allowing qualified civil users to have access to the PPS signal; the Civil GPS Service Interface Committee (CGSIC) which was established to identify civil GPS user technical information needs in support of the CGS program; and the Coast Guard's Differential GPS (DGPS) Project. This paper will provide details about the services these organizations provide.

Overview Of The Civil GPS Service (CGS)

Background

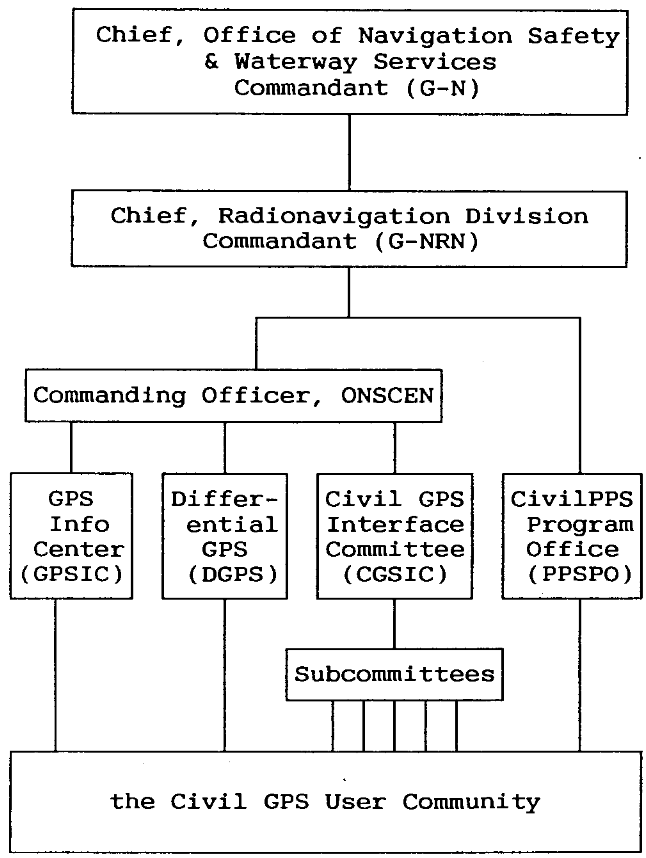
In 1987, the Department of Defense (DOD) formally requested the Department of Transportation (DOT) assume responsibility for establishing and providing an office that would respond to nonmilitary user needs for GPS information, data, and assistance. In February 1989, the Coast Guard assumed the responsibility as the lead agency within DOT for this project. Three areas requiring interaction were identified:

- ♦ Near real-time operational status reporting
- ♦ Distribution of the precise satellite ephemerides
- ♦ Civil use of the precise positioning service

In 1988, the U.S. Space Command (USSPACECOM) invited the U.S. Coast Guard to assist in the development of the DOD Operational Capability (OPSCAP) reporting system. Since that time, the U.S. Coast Guard Radionavigation Division has worked with USSPACECOM to develop requirements and implement a plan to provide the requested interface with the nonmilitary GPS community. Most of these civil GPS services are now in place; others are planned to be ready by the time GPS is fully operational.

Structure

As the Department of Transportation (DOT) operational agency, the U.S. Coast Guard is responsible for the oversight and management of the Civil GPS Service. The function is implemented by the following organizational elements:



Chief, Office of Navigation Safety & Waterway Services (G-N), located at Coast Guard Headquarters, provides top-level oversight and management of the CGS program. The primary responsibility is the provision of broad, high-level policy guidance. This direction is provided in support of:

- ♦ DOT positions
- ♦ Congressional mandates
- ♦ Federal Radionavigation policies

This office is the focal point for information feedback from the Civil GPS Service Interface Committee. Members of this staff interface with the heads of other Federal agencies with an interest in the Civil GPS Service program.

Chief, Radionavigation Division (G-NRN), also located at Coast Guard Headquarters, is the program manager responsible for the activities of the PPSPO and the GPSIC operations. This office assists with the budgetary planning for these services.

The Civil GPS Service consists of four main elements:

The GPS Information Center (GPSIC) is the operational entity of the CGS which provides GPS status information to civilian users of the Global Positioning System based on input from the:

- GPS control segment
- Department of Defense (DOD)
- Other sources

The PPS Program Office (PPSPO) is responsible for administering the program which will allow qualified civil users to have access to the Precise Positioning Service (PPS) signal. This program office is currently under development in the Radionavigation Division of the Office of Navigation Safety and Waterways Service (G-NRN-2) located at Coast Guard Headquarters in Washington, D.C.

The Civil GPS Service Interface Committee (CGSIC) was established to identify civil GPS user technical information needs in support of the Civil GPS Service program. Its purpose and goal is of an information exchange nature only.

The Coast Guard's Differential GPS (DGPS) Project was established to develop an extension of GPS to enhance the Standard Positioning Service (SPS) for civil users in the maritime regions of the United States.

The DOT Navigation Council and the DOT Radionavigation Working Group will continue in their traditional roles in the oversight of navigation including radionavigation.

Two other DOT agencies have Civil GPS Service functions:

The Federal Aviation Agency (FAA) handles aviation issues, including Notices to Airmen (NOTAM), the National Aviation Standard for GPS, and GPS integrity as it relates to aviation.

The Research and Special Programs Administration (RSPA) handles intermodal navigation issues and planning.

Although DOT has been given the principal oversight and management responsibilities for the Civil GPS Service, other federal agencies will play a role. The involvement of Federal agencies, other than those under DOT, will be particularly appropriate with regard to users outside of the navigation community.

The Global Positioning System Information Center (GPSIC)

The GPSIC began providing basic services on a test and evaluation basis in March 1990. Since then, the GPSIC has improved these services, formalized the information gathering processes and expanded GPSIC operations to meet GPS user needs.

Operated and maintained by the U.S. Coast Guard for the Department of Transportation, the GPSIC is a branch within the U.S. Coast Guard Omega Navigation System Center (ONSCEN) located in Alexandria, Virginia.

The development of the GPSIC is evolving as an extension of the Coast Guard's existing involvement in providing information on worldwide radionavigation systems. The GPSIC will continue to be responsive to the needs of the user and remain flexible to ensure that the user's needs are considered when implementing new information services or changing existing ones.

The GPSIC is currently in a test and evaluation phase, which means:

- Some services are not on line yet
- Details of information content and format have not been finalized
- Changes may be made without prior notice
- Operational standards have not yet been established for continuity of operation, and allowable time delays

Users of GPS are also cautioned that the Global Positioning System is not yet fully operational. Signal availability and accuracy are subject to change without warning due to an incomplete satellite constellation and operational test activities.

In general, the GPS Information Branch personnel are responsible for the day-to-day operations of the GPSIC. This includes collecting the information and data required to create the Operational Advisory Broadcast (OAB) and then transforming this information and data into required formats for the various information services accessed by the GPSIC. The GPSIC branch consists of the following personnel:

- Branch Chief
- Electronics Officer
- Operations Officer
- Navigation Information Specialist
- Telecommunications Specialist
- Navigation Information Clerk
- Watchstanders

The GPSIC Mission

The mission of the Global Positioning System Information Center (GPSIC) is to:

- gather,
- process, and
- disseminate

timely GPS status information to civil users of the global positioning satellite navigation system. Specifically, the functions to be performed by the GPSIC include the following:

- Provide the Operational Advisory Broadcast Service (OAB)
- Answer questions by telephone or written correspondence
- Provide information to the public on the GPSIC services available

- ♦ Provide instruction on the access and use of the information services available
- ♦ Maintain tutorial, instructional and other relevant handbooks and material for distribution to users
- ♦ Maintain records of GPS broadcast information, GPS data bases or relevant data for reference purposes
- ♦ Maintain bibliography of GPS publications
- ♦ Maintain and augment the computer and communications equipment as required
- ♦ Develop new user services as required

Gathering GPS Information

A Memorandum of Agreement (MOA) establishes policies and procedures for the exchange of GPS status information between the U.S. Space Command (USSPACECOM) and the Coast Guard. This agreement addresses relative roles and responsibilities of each organization. A similar MOA is being drafted between the Air Force and the Coast Guard.

The U.S. Air Force Second Satellite Operations Squadron (2SOPS), which operates the GPS Master Control Station (MCS) in Colorado Springs, provides the following GPS information for the GPSIC:

Notice Advisory to NAVSTAR Users (NANUs) are near real-time operational status capability reports. They contain information about future, current, or past satellite outages, system adjustments, or any condition which might adversely affect users. 2SOPS issues NANUS as events occur.

GPS Status Messages contain general information that is downloaded daily from the 2SOPS's bulletin board. The message contains information about the satellite orbit (plane/slot), clocks, and current or recent NANUS. Status Messages are generated by 2SOPS once a day Monday through Friday.

Almanacs contain the orbital information and clock data of all the satellites. The almanac for all satellites can be obtained from downloading the continuously transmitted data stream from any satellite.

Precise Ephemeris In addition to receiving information from the MCS, the GPSIC works with representatives of the National Geodetic Survey (NGS) to offer NGS computed precise GPS orbit data to the public via the GPSIC bulletin board. This data is called precise ephemeris data.

NGS provides data products "SP3" (in ASCII format) and "EF18" (in binary format). In the past, NGS distributed this information on diskettes by mail to some users.

Precise ephemeris data describes the orbit of each satellite as observed by numerous ground stations. It is useful in making a refined determination of where the satellites were at some time in the past. The time lag for this information is now about five weeks, but NGS plans to reduce it to two weeks eventually. For more information about Precise Ephemeris Data contact:

National Geodetic Information Branch (N/CG174)
Charting and Geodetic Services
National Ocean Service
National Oceanic and Atmospheric Administration
Rockville, MD 20852

Telephone: (301) 443-8631

Disseminating GPS Information

The GPSIC sends GPS status information to civil users through Operational Advisory Broadcasts (OAB). These broadcasts contain the following general categories of GPS performance data:

- ♦ Current constellation status
- ♦ Recent (past) outages
- ♦ Scheduled (future) outages
- ♦ Almanac data
- ♦ Precise ephemeris data

The OABs consist of textual matter containing the GPS performance data listed above. Conditions that impair the GPS for navigational purposes receive special attention and wide distribution.

The Operational Advisory Broadcast is updated by the GPSIC staff at a minimum of once per day Monday through Friday except Federal Holidays. OAB's are updated more frequently if information on changes in the constellation are received prior to 4:00 p.m. Eastern time. The following table outlines the update schedule for sources of GPS information received by the GPSIC:

SOURCE	UPDATE SCHEDULE
NANU	The GPSIC staff processes NANUS received during GPSIC working hours as soon as possible. NANUS received after hours or on week-ends are processed immediately the next normal workday morning.
STATUS MESSAGE	The GPSIC watchstanders post a new message daily (usually around 1 pm, Eastern time) Monday through Friday, except Federal holidays.
ALMANAC	The almanac is updated once a week, plus whenever changes that appreciably affect system coverage occur.
NGS	Precise ephemeris data is updated weekly, since each data set covers one week, but some variations occur due to differences in processing time at NGS.

The Operational Advisory Broadcast is disseminated through the following media:

- ♦ GPSIC Computer Bulletin Board System (BBS)
- ♦ GPSIC 24-Hour Status Recording
- ♦ WWV/WWVH worldwide high-frequency radio broadcasts
- ♦ Coast Guard Marine Information Broadcasts (MIB)
- ♦ DMAHTC Broadcast Warnings
- ♦ DMAHTC Weekly Notice to Mariners
- ♦ DMA Navigation Information Network (NAVINFONET)
- ♦ NAVTEX Data Broadcast

Some of these services have limited time or space available for GPS information. The following paragraphs describe each service and the GPS information available.

GPSIC Bulletin Board System (BBS)

Any user who has access to a computer and a modem can call the GPSIC BBS for information. The BBS is free and open to all; however, users have to pay their own connection charges (long distance telephone or public data network costs). First-time callers are asked to register online (provide their names, addresses, etc.) before proceeding to the BBS main menu.

Through the BBS, a wide range of information is available 24 hours a day. BBS information is updated whenever the other GPSIC sources are (see schedule); note that updates are limited to GPSIC working hours.

Users may call the BBS via either telephone or SprintNet (a public data network). Ordinary telephone is the easiest for most people, but SprintNet offers a high speed error-free alternative for those (especially international callers) who may have difficulty in getting a good data connection over the voice phone lines.

The BBS phone number is (703) 866-3890. Modem speeds of 300 to 14,400 bps and most common U.S. or international protocols are supported. Communications parameters should be set to: 8 data bits, No parity, 1 stop bit (8N1), asynchronous comms, full duplex. We have eight phone lines at this number, and two auxiliary numbers to accommodate modems which may be incompatible with the ones on 866-3890.

The BBS SprintNet number is 311020201328.
(Or abbreviate to 202 1328 if accessing SprintNet via telephone to one of their modems.) For SprintNet access, users must set up their own accounts with Sprint or a similar public data network which has a "gateway" to SprintNet. For more information, call: (800) 736-1130 (U.S.) or (913) 541-6876 (international).

Users who need further information or assistance may call the GPSIC watchstander, at (703) 866-3806.

GPS information on the BBS includes:

- NANUs
- Status Messages
- Almanacs
- Precise Ephemeris Data
- Coast Guard DGPS Project Updates
- CGSIC Meeting Announcements, etc.

The BBS also contains information about other radionavigation systems:

- Omega Status Messages
- Loran-C User Notification Messages

In addition, the BBS has areas set aside for general information about radionavigation and associated topics:

- The text of the Federal Radionavigation Plan[1]
- U.S. Naval Observatory "series 4" timing messages
- The Coast Guard's Radionavigation Bulletin
- The GPSIC Users Manual[10] (includes a BBS users manual)
- Other items which may be of interest to the GPS/radionavigation community

The BBS is menu-driven and has an extensive set of on-line help utilities. Users can page the system operator (/p Sysop) to request more personalized assistance.

GPSIC 24-Hour GPS Status Recording

The 24-hour status recording provides information in voice format. The amount of information is strictly limited since the maximum tape length is 92 seconds long.

The telephone number for this recording is: (703) 866-3826

The following information is available on the 24-hour status recording depending on the space available. The information is prioritized as listed below:

- Cautionary Statement
- Current system status
- Forecast outages
- Historical outages
- Other changes in the GPS

Other Distribution Media

GPS information available from each of these additional sources is prepared and assembled at the GPSIC. These sources were chosen because they were already established to provide other types of information. Most of these service are already used by a portion of the GPS user community, primarily marine navigators. These services offer significant advantages in coverage and accessibility. The following section provides:

- Description of each information source
- Type of GPS information available
- How the user can obtain the GPS information

WWV/WWVH: Since 1923, the National Institute of Standards and Technology (NIST), formerly National Bureau of Standards, has provided a highly accurate time service to the national and international time and frequency community. NIST currently broadcasts continuous signals from its high frequency radio stations. Services provided by WWV/WWVH include:

- Time announcements
- Standard time intervals
- Standard frequencies
- Geophysical alerts
- Marine storm warnings
- Omega Navigation System status reports
- Universal Time Coordinated (UTC) time corrections
- BCD time code
- GPS information

GPS information is broadcast in voice on WWV/WWVH at the following times and frequencies:

STATION	LOCATION	FREQUENCY	TIME
WWV	FT COLLINS COLORADO	2.5, 5, 10 15, 20 MHz	Minutes 14 and 15
WWVH	KAUAI HAWAII	2.5, 5, 10 15 MHz	Minutes 43 and 44

The time for the WWV/WWVH GPS broadcast is strictly limited. Depending on the space available the GPS information is prioritized as listed below:

♦ Cautionary Statement
♦ GPSIC operating hours and phone number
♦ Current system status
♦ Forecast outages
♦ Other changes in GPS Status

USCG AND DMA Marine Information Broadcasts (MIBs): USCG Marine Information Broadcasts and DMA Broadcast Warnings are methods by which important maritime navigation information is disseminated in the most expedient manner. This system covers a variety of topics of interest to mariners including:

♦ Status of navigation aids
♦ Weather
♦ Search and Rescue (SAR) operations
♦ Military exercises
♦ Marine obstructions
♦ Ice reports
♦ Changes in channel conditions
♦ Important bridge information

Within the United States, the U.S. Coast Guard and the Defense Mapping Agency Hydrographic/Topographic Center (DMAHTC) are responsible for broadcasting navigation information described above. Each agency has a particular geographic area of responsibility:

<table>
<tr><th>AGENCY</th><th>AREA OF RESPONSIBILITY</th></tr>
<tr><td>USCG</td><td>Local and coastal navigation info broadcasts from sources within the U.S. & its possessions</td></tr>
<tr><td>DMAHTC</td><td>Long-range navigation broadcasts from countries within NAVAREA IV and NAVAREA XII.<table><tr><td>NAVAREA IV</td><td>Covers the Atlantic coast eastward to 35 degrees W.</td></tr><tr><td>NAVAREA XII</td><td>Covers the Pacific coast westward to 172 degrees E.</td></tr></table></td></tr>
</table>

The Coast Guard provides vital maritime information in voice format via an established system of VHF and HF radio broadcasts. These Marine Information Broadcasts (MIB) include the following types of messages:

Urgent Messages concern the safety of a person, ship, aircraft or other vehicle.

Safety Messages contain important navigational or meteorological warnings that cannot be delayed because of hazardous conditions.

Scheduled Broadcasts include:

♦ Notice to Mariners (NTM)
♦ Hydrographic information
♦ Storm warnings
♦ Advisories
♦ Other important marine information
♦ Safety and urgent messages which remain in effect

Cancellation Messages are sent by the originator to cancel previous broadcast when action is no longer necessary.

USCG Marine Information Broadcasts are issued via voice and continuous wave (CW) transmissions. The following table outlines the MIB frequencies:

STATION	COVERAGE
VHF-FM Cha 16 Cha 22A	Information that applies to inland waters seaward to 25 nautical miles.
MF 2182 KHz 2670 KHz	Duplicate VHF-FM broadcasts and additionally cover waters out to 200 nautical miles.
HF-CW 500 KHz	Info that applies to waters from the coastline to 200 nautical miles offshore.

Broadcasts are scheduled several times a day depending on the location of the broadcasting site. Stations designated to make regularly scheduled broadcasts are listed in the *Coast Guard Radio Frequency Plan*. The length of messages broadcast is kept to a minimum.

DMAHTC is responsible for broadcasting navigation information concerning the "high seas". Information is provided in message format via an established system of message dissemination. DMA broadcasts are known as NAVAREA, HYDROLANT, or HYDROPAC and are generally geared to the deep draft mariner.

DMAHTC also publishes a weekly Notice to Mariners (NTM) containing USCG Marine Information Broadcasts and DMA Broadcast Warnings for a seven day period.

GPS status information is found in Section III of the Notice to Mariners, which summarizes voice or data broadcast warnings.

Additional information on the DMA Notice to Mariners Information is available from:

Director, Defense Mapping Agency
Hydrographic/Topographic Center
Attention: MCNM
6500 Brokes Lane
Washington, DC 20315-0030

Telephone: (301) 227-3126

DMA NAVINFONET: In carrying out its mission to produce Notices to Mariners, DMA has developed a data base called Automated Notice to Mariners System (ANMS). This data base contains information dealing with navigational safety. It is a supplemental source of up-to-date maritime information for the user. The software developed for this data base provides remote query capabilities which DMA makes available to the entire maritime community through the Navigation Information Network (NAVINFONET). NAVINFONET provides information in data format via telephone modem.

Information includes:

- ♦ Chart Corrections
- ♦ Broadcast Warnings
- ♦ MARAD Advisories
- ♦ DMA List of Lights
- ♦ Anti-Shipping Activities Messages
- ♦ Oil Drill Rig locations
- ♦ Corrections to DMA Hydrographic Product Catalogs
- ♦ U.S. Coast Guard Light Lists & GPS

The following GPS information is available from the DMA NAVINFONET under item 8 in the bulletin board menu:

- ♦ Cautionary Statement
- ♦ Current system status
- ♦ Forecast outages
- ♦ Historical outages
- ♦ Almanac data
- ♦ Civil GPS Service information

Users must register for the NAVINFONET bulletin board off-line before they will be granted access to the system. For a user ID and information book contact DMA at the address listed above:

Attention: MCN/NAVINFONET

Telephone: (301) 227-3296

NAVTEX: NAVTEX is a an internationally adopted radio telex system used to broadcast marine navigational warnings and other safety related information to ships. This system assures worldwide coverage by transmitting on an international frequency of 518 KHz. Vessels' NAVTEX receiver/teleprinters are permanently tuned to the worldwide frequency and remain on standby to receive and print out all the messages automatically. Navigation information broadcasted through NAVTEX includes:

- ♦ Notices to mariners
- ♦ Weather warnings and forecasts
- ♦ Ice warnings
- ♦ Other marine information

Coast Guard Atlantic and Pacific Area Commanders coordinate NAVTEX broadcasts transmitted by all Coast Guard Communications stations. NAVTEX messages are normally broadcast four times a day which may be increased to six broadcasts with a maximum duration of 40 minutes.

NAVTEX messages are categorized by subject area. GPS status messages were recently changed from category "K" to category "J". GPS information available from NAVTEX includes the following:

- ♦ Cautionary Statement
- ♦ Current system status
- ♦ Forecast outages
- ♦ Other changes in GPS Status

Additional GPSIC Services

The GPSIC publishes documents which provide detailed information about GPS, other radionavigation systems, the GPS Information Center and how to obtain these services. The following table describes the GPSIC publications available:

PUBLICATION	DESCRIPTION
GPSIC BROCHURE	Describes information services provided by the GPSIC.
GPSIC USERS' MANUAL	Provides detailed instruction on the access & use of services available at GPSIC
GPS FACTS & FIGURES	Describes the system, its concept, accuracies and applications.
OMEGA FACTS & FIGURES	Describes the Omega radionavigation system.
LORAN-C FACTS & FIG	Describes LORAN-C.
RADIOBEACON FACTS & FIG	Describes Radiobeacons.

The GPSIC distributes documents provided by other GPS interested organizations. The following table describes other GPS publications available through the GPSIC:

PUB	PUBLISHER	DESCRIPTION
NAVSTAR GPS USER EQUIP	JPO	Describes the system, equipment, applications & capabilities.
GPS NAVSTAR OVERVIEW	JPO	Provides general information about GPS.
ICD 200	JPO	Technical information about the GPS signal-to-receiver interface

The GPSIC responds to individual user inquiries, comments, and concerns about civil access to, and use of the GPS. The GPSIC fields requests for information Monday though Friday from 8:00 a.m. to 4:00 p.m. Eastern time. Most inquiries can be answered immediately over the phone. Some technical questions or requests are referred to a more authoritative source.

If you would like to comment on any of these services or ask questions about present or future services write to:

Commanding Officer (GPSIC)
US Coast Guard Omega Navigation System Center
7323 Telegraph Road
Alexandria, Virginia 22310-3998

Or call (703) 866-3806

An answering machine records messages after working hours. Messages are normally returned the following workday.

Future Plans For GPSIC

The Coast Guard plans to evaluate the possibility of expanding the GPS Information Center into a Radionavigation or Navigation Information Center. As such, the Information Center would provide navigation information on all navigation systems involving the Coast Guard both nationally and internationally.

Information concerning other radionavigation systems the Coast Guard is involved with would be posted on the BBS. As a first step in this direction, the GPSIC currently provides Omega and Loran-C status information on the BBS.

Differential GPS (DGPS)

Consistent with its role as the civil interface for GPS, the U.S. Coast Guard has a research and development project to develop an extension of GPS, known as differential GPS (DGPS). This is an enhancement to the Standard Positioning Service (SPS) which should achieve accuracies of 10 meters or better for civil users in the maritime regions of the United States.

Based on encouraging results of operational testing of a prototype reference station, a project has been initiated to implement DGPS in U.S. near-coastal areas to improve upon current harbor and harbor-approach navigation accuracy. Project plans are being formulated. Additional prototypes began operation during September/October 1991. If fully funded, an operational system is expected by 1996.

For additional information on DGPS, contact:

Commandant (G-NRN)
U.S. Coast Guard
2100 2nd Street, S.W.
Washington, DC 20593

Telephone: (202) 267-0283
Fax: (202) 267-4427

Precise Positioning Service Program Office (PPSPO)

The Precise Positioning Service Program Office (PPSPO) will administer civil applications and collect fees for access to encoded Precise Positioning Service (PPS) capabilities.

The Government will publish detailed guidance for users interested in requesting access to PPS once policy is established for the following:

- Submitting applications
- Granting approval for user access
- Establishing operational procedures and compliance requirements for accessing data from the GPS PPS

The Federal Radionavigation Plan (FRP) contains general criteria for qualified civil use of PPS. Access determination will be made on a case by case basis. The following criteria may be refined as Government policy is developed:

- Access is in the U.S. national interest
- Security requirements can be met
- There are no other means reasonably available to the civil user to obtain a capability equivalent to that provided by the GPS PPS

For additional information on the PPSPO, contact Commandant (G-NRN) at the address listed above or telephone: (202) 267-0298

Civil GPS Service Interface Committee (CGSIC)

The roles of the Civil GPS Service Interface Committee (CGSIC) are to:

- Provide a forum for exchanging technical information in the civil GPS user community regarding GPS information needs
- Identify types of information and methods of distribution to the civil GPS user community
- Identify any issues that may need resolution by the CGS program office

The CGSIC will work with the following organizations:

- U.S. Coast Guard Office of Navigation Safety and Waterway Services (Civil GPS Program Office)
- DOT Navigation Working Group
- Joint DOD/DOT Radionavigation Working Group

The Civil GPS Service Interface Committee is comprised of representatives from relevant private, government, and industry user groups, both U.S. and international.

The CGSIC consists of:

- General Committee
- Five Subcommittees

The Committee is jointly chaired by the U.S. Coast Guard and the DOT Research and Special Programs Administration (RSPA). The joint chair is based on the USCG being DOT's lead agency for the civil GPS service which includes the government's interface with civil GPS users, and RSPA's responsibility to coordinate intermodal navigation planning with DOD.

The Civil GPS Service Interface Committee may create subcommittees to identify specific areas of civil GPS user information needs and facilitate technical information exchange as required. Standing subcommittees have been established for:

- Surveying and Positioning Information
- Timing Information
- International Information
- Reference Station, Technology, and Applications
- Real-time Carrier Phase Applications

The International Information Subcommittee (IISC) of the Civil GPS Service Interface Committee is investigating the feasibility of a regional international information media. The GPSIC would provide the OAB into an electronic mailbox designated, controlled, and financed by the IISC.

The Civil GPS Service Interface Committee meets as necessary to exchange technical information regarding civil GPS information needs.

For additional information on the CGSIC, contact:

Volpe National Transportation Systems Center (VNTSC)
55 Kendall Square
Cambridge, MA 02142-1093

Telephone: (617) 494-2432
Fax: (617) 494-2628

Federal Radionavigation Plan (FRP)

The Federal Radionavigation Plan[1] contains the official statement of government policy on civil use of GPS. This plan covers other government operated radionavigation systems in addition to GPS. Information provided includes:

♦ Policy and plans for the future radionavigation systems mix
♦ GPS System description
♦ Table of SPS and PPS signal characteristics
♦ Various other topics

The text of the Federal Radionavigation Plan (minus tables and illustrations) is available on the GPSIC electronic bulletin board. To obtain a paper copy (including tables and illustrations), write:

Superintendent of Documents, Order Section
U.S. Government Printing Office
Washington, DC 20402

Ask for the Federal Radionavigation Plan, stock number 008-047-00402-8. The price is $10.00. Checks or money orders should be made payable to "Superintendent of Documents".

Or, to order by telephone, call: (202) 783-3238
... and pay by credit card.

References

1. Department of Defense & Department of Transportation, *Federal Radionavigation Plan*, U.S. Government Printing Office, 1990.

2. Bennett, CDR Verne and David J. Pietraszewski, *The U.S. Coast Guard Civil GPS Program*, 1990.

3. Civil GPS Service Interface Committee, *Charter For The Civil GPS Service Interface Committee (CGSIC)*, 1991.

4. Defense Mapping Agency Hydrographic/Topographic Center, *Navigation Information Network Users Manual*, 1990.

5. Defense Mapping Agency Hydrographic/Topographic Center, *Notice to Mariners No. 32*, 1991.

6. Omega Navigation System Center, *GPS Operations Manual*, ONSCEN Instruction 16575, Coast Guard Omega Navigation System Center, 1991.

7. Radio Technical Commission For Maritime Services, *Maritime Navigational Safety Information Sources*, RTCM, 1991.

8. U.S. Coast Guard, *Global Positioning System Program Plan Civil GPS Service*, U.S. Coast Guard Printing Office, 1991.

9. U.S. Coast Guard GPSIC, *GPS Information Center*, U.S. Coast Guard Printing Office, 1990.

10. U.S. Coast Guard GPSIC, *GPS Information Center Users Manual*, U.S. Coast Guard Printing Office, 1990.

11. U.S. Coast Guard, *Telecommunications Manual (TCM)*, COMDTINST M2000.3B, U.S. Coast Guard Printing Office, 1988.

12. U.S. Space Command, U.S. Coast Guard, *Memorandum of Agreement: Distribution of NAVSTAR Global Positioning System (GPS) Status Information*, 1990.

SESSION C

Panel Discussion

Panel Discussion - Why Loran-C in Europe?

Panel Chairman: Dr. Peter Ryder, U.K. Meteorological. Office

Panel Members

Wally Blanchard:	Radionavigation Consultant
John Butler:	Canadian Coast Guard
Vladimir Denisov:	Internavigation Committee, CIS
Norman Matthews:	International Assoc. of Lighthouse Authorities
Ed McGann:	Megapulse
Mike Moroney:	U.S. Dept. of Transportation
Andreas Stenseth:	NW Europe Loran-C Committee

Chairman's Introduction

In setting up the panel for discussion, the Chairman suggested that there were two basic reasons for adopting Loran-C in Europe:

(a) because there are relevant operational requirements deriving from defense, safety and economic considerations and;

(b) because Loran-C provides a cost-effective; technically, politically and administratively sound and competitive solution to meet these requirements in Europe.

The Chairman requested that the panel take into consideration European requirements that could be satisfied by loran's validated technical performance, signal availability, and ease of use. He further requested that both primary users for navigation and secondary users who are able to exploit the system's capabilities be considered, addressing possible cost savings that might materialize through the use of loran over current systems.

The Chairman suggested that the panel also concern itself with system control authority, investment and funding arrangements, vested interests in current systems, loran's demonstrated performance, volume of users and the existence of alternative solutions. He then gave his personal views.

Panel Comments

Peter Ryder: Peter Ryder described a secondary use of Loran-C involving the United Kingdom's land-based wind finding operation. He stated that loran offered useful cost savings over other candidate solutions such as secondary radar. He further indicated that while the Omega system was acceptable for synoptic oceanic wind measurements, Loran-C is the only know viable solution for aircraft dropsondes to determine fine grain wind structure of the atmosphere.

Mike Moroney: Loran-C use in General Aviation was the subject addressed by Mike Moroney. He stressed that integrity and availability of the signals was the most stringent requirement for Loran-C use, stating that neither Loran-C nor the GPS would deliver performance to satisfy sole means navigation. He said that there was every indication that a combination of Loran-C and GPS would satisfy aviation signal integrity and availability criteria. He also stressed the need for minimum performance specifications for equipment.

John Butler: Canada selected Loran-C initially for marine operations but other needs followed. John Butler stated that compatibility with the United States was an important consideration and that Loran-C met user needs for accuracy and reliability, provided cost savings in operations, and went a long way in meeting the wide area coverage required by

Canada. He also acknowledged the complementary use of Loran-C and GPS would be beneficial in many applications.

Wally Blanchard: Wally Blanchard took the position that it would take many years to bring satellite navigation systems into general operational use, citing funding and control as being hurdles to be overcome. He felt that Loran-C is a good interim system for use during the next 10-15 years

Norm Matthews: The wide area under the control of individual governments was stressed by Norman Matthews. He felt that Loran-C filled an important gap until satellite technology could be accepted internationally.

Andreas Stenseth: Confirming the issue of national government control, Andreas Stenseth stated the six countries of North West Europe made their decision and commitment based on the requirement for independence from a single country for funding and control.

Ed McGann: The reliance upon a single system under the control of one country was the issue raised by Ed McGann. He suggested that Loran-C could meet most user requirements for the foreseeable future. He felt that Loran-C and satnav complemented each other and stressed that GPS was primarily a military system and could not be relied upon to satisfy civil navigation requirements.

Vladimir Denisov: Mr. Denisov stated that the CIS saw no effective alternatives to Chayka and that the CIS equivalent to Loran-C met all requirements of land, sea and air navigation. He further stated that no other system in Russia had the potential to solve that country's navigation requirements for the foreseeable future.

From the Floor:

At this time the Chairman asked for contributions to the discussion from the floor.

The point was made that there was a real need for education, selling and marketing of loran in Europe and that this should start soon.

It was stated from the floor that the U.S. Coast Guard's involvement with Loran-C would be reduced while Europe and the Far East use of the system will grow.

The need for the control for Group Repetition Rate (GRI) assignments was raised. Norm Matthews suggested that IALA will probably take this responsibility. It was recommended that Don Feldman's work, performed while he was with the U.S. Coast Guard, on this subject be taken into account.

It was pointed out that in the United States 120,000 of the 173,000 electrically-equipped General Aviation aircraft carry Loran-C receivers but that in Europe the number of GA aircraft was only 3600. Receivers in the U.S. are only certified for VFR conditions.

It was stated that Eurocontrol was looking at GPS for air navigation and not Loran-C primarily because of weather-related electrical noise and precipitation static on aircraft.

At this point, recognizing that time had run out, the Chairman ended the discussion and adjourned the session for a break before the Industry Sponsored Reception.

SESSION D

Loran-C Coverage and Use (1)

Loran-C Coverage of the East Mediterranean

E. Rubiola

Politecnico di Torino, Dipartimento di Elettronica

Abstract

This paper will present a technical study of some possible developments of the Mediterranean Loran-C chain after the end of 1994, when the U.S. support will cease.

Some alternative solutions are studied, with an evaluation of the S/N ratio and GDOP for a few new sites suggested by a preliminary selection. The coverage based on master-independent and crossed-chain operations are also considered.

1 Introduction

The Mediterranean Loran-C chain, in its current configuration, consists of four stations, two in Italy (M and X), one in Turkey (Y) and one in Spain (Z). While agreements are in progress, supported by official decisions, in order to keep in operation stations M, X and Z, when the U.S. support will cease, station Y could be switched off after the 1994 deadline. The consequence would be the unavailability of the system in the eastern Mediterranean, about half of the present coverage.

The aim of this paper is to analyze a few alternative solutions for replacing the Y station with a new one, in order to ensure the coverage of the eastern Mediterranean area. The link to the russian Chayka is also considered.

Some geographical and technical criteria concerning the site choice are discussed in the next section. The evaluation of signal-to-noise ratio and geometric effects are presented in sections 3 and 4. Results are discussed in section 5, in which the possible new configuration are presented together with some possible improvements based on master-independent and crossed-chain operations.

2 Proposed Sites and Existing Stations

As well known, a Loran-C transmitter is to be placed in an high soil conductivity site. This is due to the ground wave propagation behaviour and to the radiation efficiency, which relies on the ratio of radiation to grounding resistence. Practical antennas are small (200 m) compared to the wavelength (3 km), thus showing a "low" resistance; consequently, the overall resistance of the grounding system should be kept as small as possible, thus excluding many places.

When geometrical considerations are included (i.e., baseline length of 800–1200 km and angles between baselines of 60°–90°, hardly suitable to the Mediterranean shape), only a few convenient locations remain. Political considerations, not taken into account, could furtherly reduce the set of sites.

Some places are considered here, summarizad in Fig. 1, together with the existing transmitters sites.

Stations M, X, Y and Z constitute the Mediterranean sea chain in its current configuration. Their powers have a conventional value of 250 kW, which is in agreement with the decisions taken for easy comparison between results by the Working Group set by IALA in order to discuss these problems [1]. The actual power of these transmitters [2] is 1.8 dB lower than stated except for X, which is 1.6 dB stronger.

Transmitter U is a part of the russian Chayka

IDENT.		LAT. (deg)	LON (deg)	POWER kW		BASELINE (km)	SITE	COUNTRY
M	¶	38.9	16.7	250	‡	n. a.	Sellia Marina	Italy
X	¶	35.5	12.5	250	‡	525	Lampedusa	Italy
Y	¶	41.0	27.9	250	‡	980	Kargaburun	Turkey
Z	¶	42.1	3.2	250	‡	1195	Estartit	Spain
C	†	35.2	24.5	250		800	Creta	Greece
T	†	40.8	24.6	250		710	North East	Greece
E	†	31.5	26.2	250		1190	North West	Egypt
U	¶	45.0	34.0	550		1580	Simferopol	Russia
†replaces Y ¶ existing ‡conventional value								

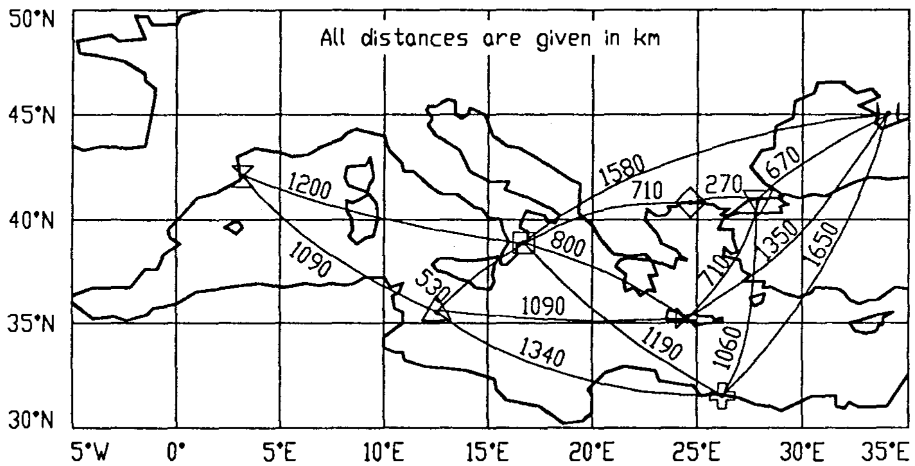


Figure 1: Existing and proposed Loran-C transmitters in the Mediterranean area.

chain. Its approximate coordinates have been derived from a map published in a IALA report [3]. The actual power (550 kW) has been used in simulations. If the Simferopol transmitter could operate in double rate mode, or if it could be used by multichain receivers, it could contribute to the Mediterranean chain.

Stations C, T in Greece or E in Egypt are proposed as possible replacements for the turkish station Y. The proposed stations are assumed to be based on the new solid state transmitters (250 kW) with 190 m top loaded monopole antennas, similar to the existing ones.

As pointed out by the IALA Technical group [4], four stations are not sufficient for full coverage of the Mediterranean sea. If station Y were kept in operation, E appears to be a good candidate to improve the coverage of the eastern Mediterranean. Under this hypothesis, links to Chayka, through Y, and to the Egyptian chain, through E, are worthy of consideration.

3 S/N Ratio

3.1 Noise

An earlier analysis [5], based on the CCIR reports [6] showed that in a central point of the Mediterranean area, and in the worst case for season and daytime (Summer and Autumn, 00–04 local time), the average value of the atmospheric noise is 47.5 dB/(μV/m) in a 20 kHz band centered around 100 kHz. Depending on season and daytime, the average noise spans in a range of 35 dB; upper and lower deciles depart from the average values by 10–15 dB. When considering the whole Mediterranean sea, the noise level is substantially the same as for the central point, with differences within than 2–3 dB.

The U.S. Coast Guard coverage map [7] for the Mediterranean sea chain is based on the assumption of a noise level of 51 dB/(μV/m).

For north-western Europe, in quite similar conditions as regards the atmospheric noise, it was suggested [8] that the combined effect of coherent inter-

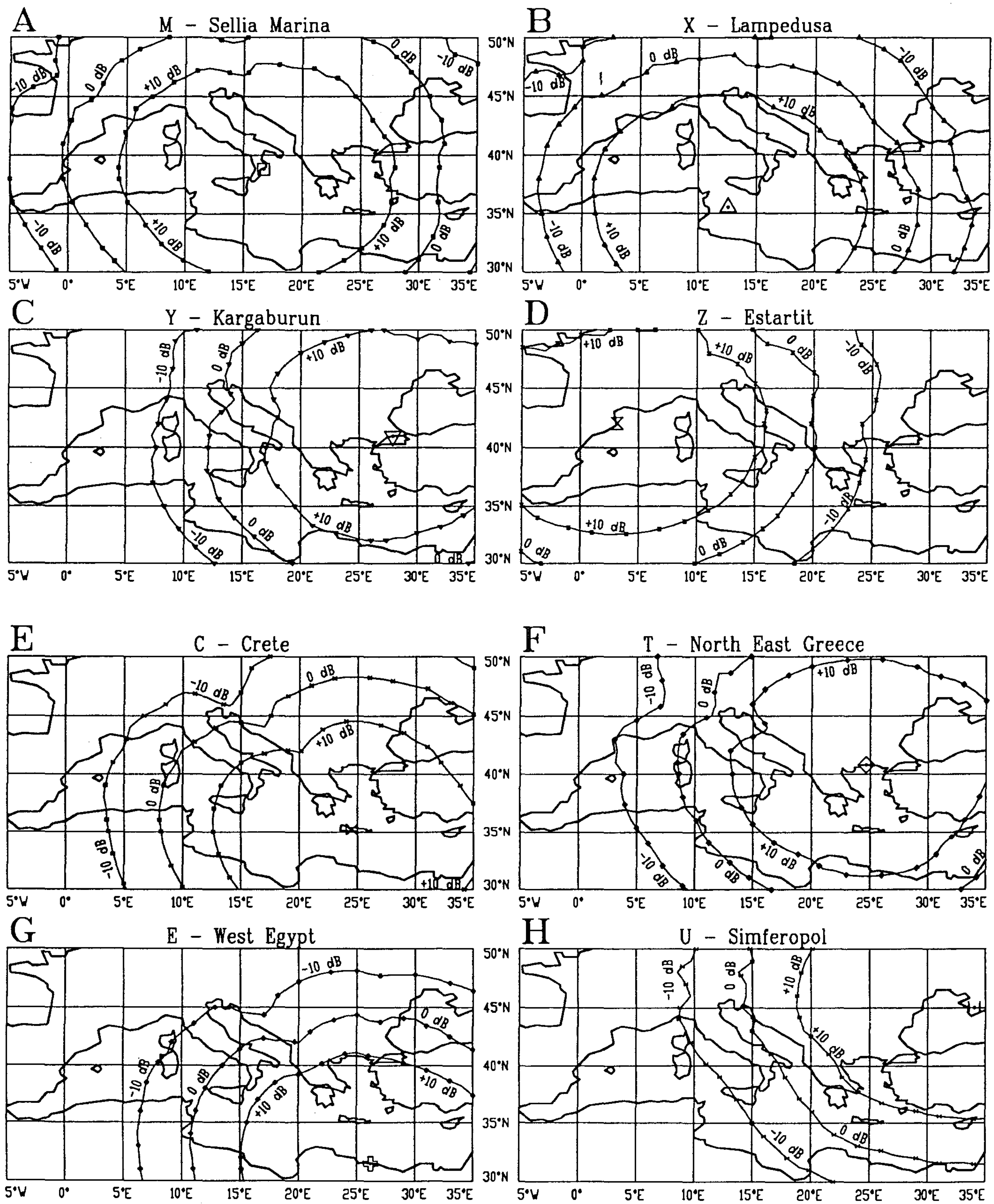


Figure 2: S/N ratios for the existing and proposed stations.

ferences and atmospheric noise can be represented by a field strength of 61 dB/(μV/m).

In agreement with the suggestion of the IALA Loran-C Working Group [1], a conventional value of 50 dB/(μV/m) has been used in this work.

3.2 Signal Strength

The main source of information is the CCIR report 717 [9], which provides maps of ground conductivities, attenuation curves for uniform soil paths, and a clear explanation of the evaluation algorithm for mixed paths, based on the Millington method.

The CCIR maps are stored in a disk file as a matrix representing the Mediterranean area quantised in 0.5° wide regions, both in latitude and longitude. The conductivity quantisation is the same as for the CCIR maps, in steps of a factor of three from 10 μS/m to 30 mS/m for the ground, plus 5 S/m for the sea.

Excluding Italy, where a very accurate study is available [10], some doubt still remain about the accuracy of some of the CCIR maps and about the availability of detailed maps for other European zones.

A computer program evaluates the propagation attenuation from the transmitter to all of the points on a $0.5° \times 0.5°$ grid. The attenuation is combined with the radiated power, thus providing a matrix of signal strengths.

3.3 Results

The electric field matrix is combined with the noise by a program which converts results in Autocad *script* format. Results are shown in fig. 2 as curves of equal S/N ratios for +10, 0 and −10 dB.

A comparison with some measurements performed in Spain was done during a meeting of the IALA Mediterranean Loran-C Working Group [11]. Experimental values agreed to the calculated ones within 0 to −3 dB if the whole wave path is over the sea, while the measured S/N ratio was lower by about 10 dB if waves cross long land paths.

Taking into account the sensitivity of the new receivers, which work with S/N ratios as low as −10 dB, and some possible corrections to calculated S/N ratios, the stations should ensure a good coverage inside the area where S/N $\geq$ +10 dB, and a fair coverage as far away as the 0 dB curve.

4 Geometric Dilution of Precision

When the position is derived from time difference, timing errors produce position discrepancies. This is the well known problem of geometric dilution of precision (GDOP), which relies on the following concepts:

1. When considering two transmitters, which originate one hyperbola at the receiver site, the sensitivity S is given by the ratio of the positioning error vector p divided by the timing error t. S is a vector perpendicular to the hyperbola, whose modulus is given by $|S| = c/(2\sin\alpha)$; c is the speed of light, and α is the angle at the receiver site between lines directed towards the transmitters.

2. Since the position is obtained as the intersection of two hyperbolae, each generated by a couple of transmitters, its error is the sum of the two vectors given by sensitivities and timing errors.

When adding error vectors originated by time jitter, the standard deviation of the evaluated position is constant on an ellipse. The excentricity of the latter depends on the angle between the two hyperbolae. Errors due to time biases, i.e. errors originated by the finite conductivity of the ground, can also be added as vectors.

In this work the geometric errors have been evaluated as the 95% probability position uncertainty radii ($2\mathrm{d_{rms}}$) assuming a unique value of the time jitter (σ = 100 ns). In this way the geometry is evaluated separately from the signal to noise ratio. The uncertainty radius is given by

$$2\mathrm{d_{rms}} = \frac{2k\sigma}{\sin\gamma}\sqrt{\frac{1}{\sin^2\frac{\alpha}{2}} + \frac{1}{\sin^2\frac{\beta}{2}} + \frac{2\rho\cos\gamma}{\sin\frac{\alpha}{2}\,\sin\frac{\beta}{2}}}$$

where:
k is the half speed of the light, about 150 m/μs,
γ is the angle between the two hyperbolae,

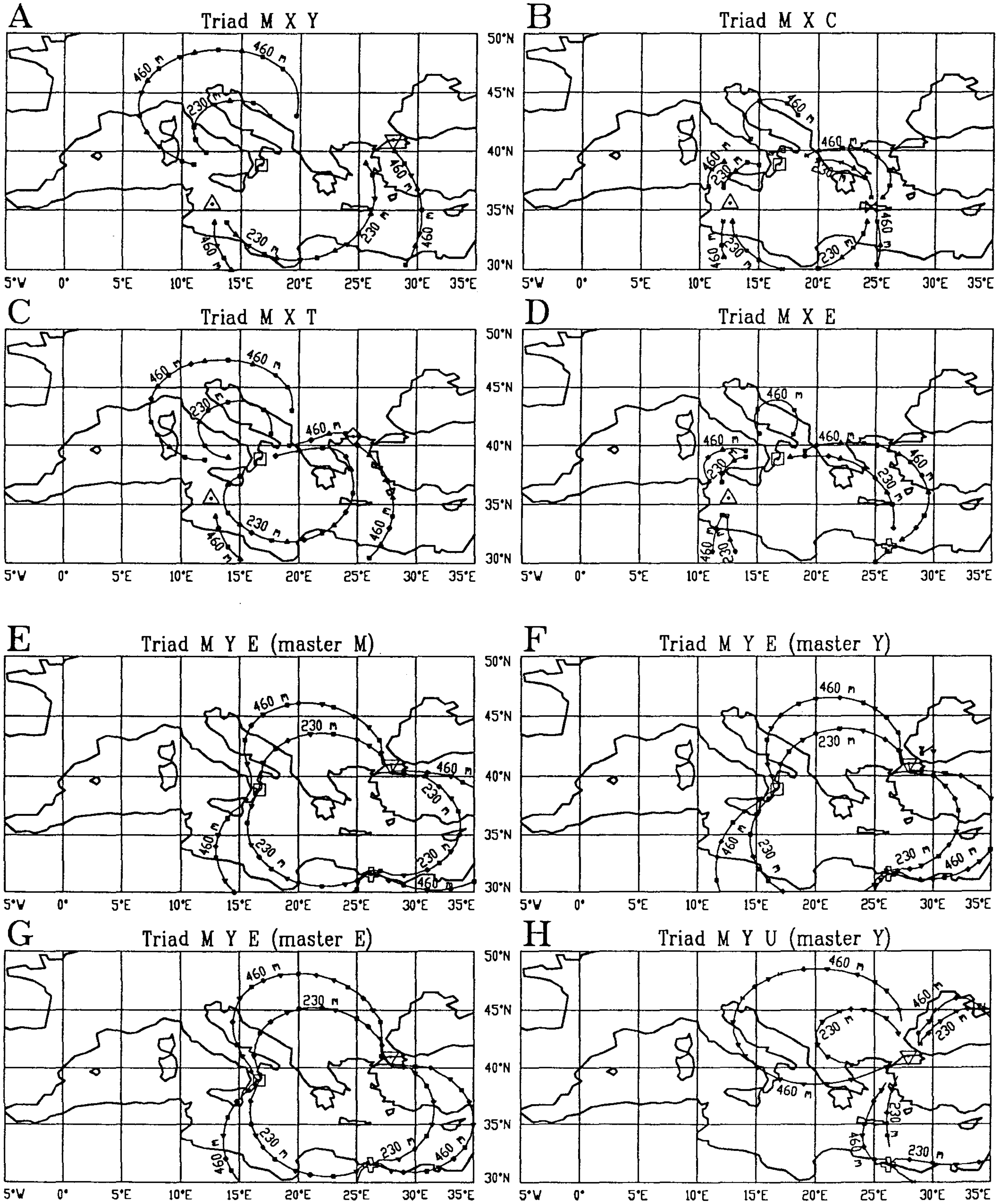


Figure 3: Geometrical dilution of precision for the existing and proposed triads.

ρ is the noise correlation between noise contributions of the two time differences, each one generating an hyperbolic locus of position. Since propagation time for the master station is the same for the two hyperbolae, then $\rho = 0.5$,
α and β are the angles between lines joining the receiver to master and each of the secondary stations,
σ is the standard deviation of the time differences measured by the receiver.

Results are reported in Fig. 3, where the areas within curves represent position uncertainty radii ($2d_{rms}$) less than 1/4 nm (460 m) and 1/8 nm (230 m).

5 Coverage

In this section the coverage of the proposed chains is presented. Assumptions are that the S/N ratio should not be less than 0 dB and that the consequence of a 100 ns time jitter should be a position uncertainty smaller than 1/4 nm, or 460 m.

In the present system configuration the eastern coverage is based on stations M, X and Y. Comparing figures 2 A, B and C, availability of signals is seen limited in the east direction by station X. This limit can't be overcome by replacing Y.

Comparing figures 2 B (S/N Y) and 3 A (geometry M-X-Y), the most important limitation can be seen to arise from the S/N ratio of station X.

All of the proposed stations ensure a good S/N ratio coverage in all the east Mediterranean area (Figs. 2 E, F and G).

When analyzing new chain configurations, the south Adriatic is worthy of consideration because it is not covered at the present time. This lack of coverage is due to the M-X baseline direction, and it can't be overcome by simply replacing the Y station.

5.1 Replacements for Y

5.1.1 Crete (C)

The eastern coverage is limited by geometry, as results from the GDOP plot of Fig. 3 B. The system is almost useless in hyperbolic mode at longitudes farther east than 25° E.

As regards the central-eastern Mediterranean, the C station ensures higher S/N ratios than Y (see Fig. 2 C and D).

5.1.2 North East Greece (T)

When replacing the Y station by T, the baseline direction remains about the same, its length is reduced by about 30%. Consequently, small changes in the GDOP are forseen (Figs. 3 A and C); the main difference is the loss of 3° of longitude in the region between Crete and Cyprus. However, by taking into account also the S/N limit of X (Fig. 2 B), this loss of coverage is seen to be smaller than what results from the geometry.

5.1.3 West Egypt (E)

Transmitter E ensures a good geometry in the east Mediterranean, farther than the limit due to the S/N ratio of the X station, as results from Figs. 3 D and 2 B. Consequently, this solution allows the present coverage to be kept.

5.2 Improved Chain

The eastern coverage of the system could be improved by adding station E, without switching off Y. Sites C and T are not considered because of baseline lengths, as results from Fig. 1.

By adding station E, the coverage is based on the triad M-Y-E, thus overcoming the eastern S/N limit due to X, which is replaced by the limit of M (Figs. 2 A and B). The stations Y and E ensure a good S/N noise in all the eastern Mediterranean (Figs. 2 C and G).

By comparison of Figs. 2 A and 3 E, the eastern coverage appears to be limited by the M S/N ratio. An improvement of 5° in the east direction is achieved with respect to the present situation. The coverage of the south Adriatic is also ensured, as results from Fig. 3 E.

The adoption of master-independent receivers allows a better use of the triad M-Y-E (Fig. 3 E, F and G). A fair coverage of the region around 30°–35° N, 12°–15° E, which is on the M-X baseline extension, is possible when Y plays the master role. The best GDOP in the south Adriatic area is achieved by using E as the master.

A multi-chain receiver can take advantage from the Simferopol signals. The triad Y-E-U ensures good S/N ratios in the whole east Mediterranean (Figs. 2 C, G and H), even farther than the maps limit. An optimum GDOP is ensured when using this multichain triad in the eastern Mediterranean, as results from Fig. 3 H.

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Loran-C Receiver Performance in the Presence of Carrier-Wave Interference

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Abstract

Carrier Wave Interference (CWI) has been shown to be a serious problem which affects the operation of all Loran-C receivers in Europe, and aviation and land mobile receivers in the US and Canada. The designers of Loran-C systems for use in Europe have been obliged to pay considerable attention to CWI in predicting their coverage. This paper contains a unified analysis of the effects of the phase-coding of the signals and integration in receivers on CWI and it provides a quantitative assessment of receiver performance under CWI conditions. The analysis includes synchronous, near-synchronous and asynchronous interference. It shows that synchronous and near-synchronous CWI, in contrast to asynchronous, are attenuated by phase-decoding and integration within periods of 2GRI and that longer periods of integration do not improve performance. Front-end filtering is incorporated into the analysis by considering not only the attenuation of interference which it provides but also the delay and distortion it causes to Loran-C signals. Both the phase-tracking and the cycle-selection functions of receivers are examined and their relative sensitivities to interference are compared. The results of the analysis, which have also been confirmed by computer simulation, are presented in a form that will be of direct use to the designers of both receivers and systems.

1 Introduction

Loran-C receivers work in noisy environments. The problem of extracting position information from time-of-arrival (TOA) measurements, corrupted by noise and interference, has been at the heart of the efforts of Loran-C system designers and receiver manufacturers for many years. Interference studies, including sky-wave, cross-rate interference (CRI), and carrier wave interference (CWI), are as old as Loran-C itself.

The current development of Loran-C in Europe, where the numbers and levels of interferers are exceptionally high, has stimulated this study of Loran-C receiver performance in hostile CWI environments. The aim of the study is to provide data based on a realistic assessment of the problem to aid receiver and system designers.

Reduction of CWI was one of the initial incentives for introducing phase coding [1]. Later, a mathematical model which could be used to predict the effects of interference, both CRI and CWI, on the basis of sound frequency-domain concepts was described by Feldman [2] in 1975. Van Etten [3] extended Feldman's work and attempted to eliminate CWI of certain frequencies, plus all CRI, through the use of a unique family of Group Repetition Intervals (GRIs). Van Etten's method requires Loran-C receivers to be modified to utilize a balanced phase code, for example by omitting certain sampling strobes.

Renewed interest in CWI, especially from power-line carriers (PLC), was triggered by Arnstein in 1986 [6]. Shortly thereafter, theory and measurement techniques for interference, especially for narrow-band CWI, were presented by Peterson and Hartnett [7]. Their model simplifies exact calculation of the Loran-C spectrum and predicts the effects of interference on measured time differences. They assessed the effects of common types of existing narrow-band interferer, such as naval communications stations, time-dissemination signals, and PLCs. In 1990, Meranda & Winslow [8] proposed two simple modifications to receivers, selective pulse sampling and multiple strobes, aimed at improving their CWI attenuation capabilities.

The complex nature of the disturbance of the phases and envelope shapes of Loran-C signals by CWI makes accurate understanding of the problem difficult. Van Willigen and others have developed a vector-analysis method which has greatly improved our understanding of the effects of CWI on *phase tracking* [4]. They have also demonstrated the disturbance caused by CWI to the phase and cycle loops, by means of their LOran Simulation Program, LOSP [9]. The first attempt to perform a detailed analysis of synchronous CWI effects on cycle identification was made by Beckmann [9] in 1990. He warned that synchronous CWI is potentially more likely to cause serious position-measurement errors by virtue of cycle identification failure than by unacceptable phase-tracking errors.

However, quantitative analysis on the errors caused by CWI has been limited to either neglecting Loran-C phase coding or by restrictions to specific frequencies. Receiver front- end filtering is also commonly ignored. Filters may be specified in terms of their amplitude transfer functions alone, and quantitative analysis of their effects concentrated on the attenuation of CWI and at most the amplitude distortion of the Loran-C signal. This is unsatisfactory since designers of Loran-C systems must make realistic assessments of receiver performance under hostile CWI conditions in order to be able to predict areas of coverage with confidence [10]. The quantitative investigation described in this paper, which takes all the principal mechanisms of CWI attenuation into account, is designed to meet that need.

2 Loran-C receiver operation and the effects of CWI

2.1 Loran-C signal

Loran-C signals consist of trains of 16 phase-coded pulses. The leading edge of each pulse is formally defined by the United States Coast Guard (USCG) [11] as $x_0(t)$:

$$x_0(t) = A(t-\tau)^2 exp\left[\frac{-2(t-\tau)}{65}\right] sin(0.2\pi t + PC) \quad (1)$$

where A is a normalization constant related to the peak amplitude, t is time in microseconds, τ is the envelope-to-cycle difference (ECD) in microseconds, and PC is the phase-code parameter in radians. PC is 0 for a positive phase code and π for negative.

Signals from the master and the secondary stations employ different phase codes [11]. Two groups of phase codes, that is 2GRI, constitute a period of the Loran-C signal. The transmitted Loran-C pulse train can thus be expressed as the convolution of $x_0(t)$ with a train of impulses which describe the start time of each pulse.

2.2 Structure of the Loran-C receiver

A simplified, typical receiver structure is shown in Fig. 1. The bandpass filter passes the Loran-C signal but rejects noise and interference outside its pass-band. Its bandwidth is usually between 15 and 60 kHz [12,13]. Notch filters are commonly employed to provide further rejection of specific CWI. The attenuation of CWI by the front-ends of such receivers is directly related to the amplitude transfer functions of these cascaded filters.

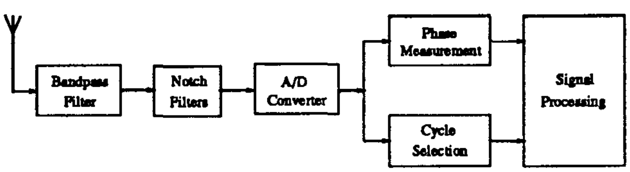

Fig.1 Simplified structure of a typical Loran-C receiver

The output signal from the front end filter is sampled by an analogue-to-digital converter under the control of a receiver clock. Samples are taken from each pulse in order to track the zero-crossing of an individual cycle (for input to 'phase-tracking loop') and for determining the sampling point by reference to the shape of the envelope (by the 'cycle-selection loop'). The choice of the bandwidths of these loops, which are generally second-order digital phase-locked loops (DPLLs), is related to the receiver's intended application. A typical phase-tracking bandwidth is 0.01-0.5 Hz, and for cycle-selection, 0.01 Hz.

2.3 The effects of CWI on Loran-C receivers

CWI may cause errors in TOA measurements because of its effect on phase tracking. It may also cause incorrect cycle selection, which then leads to at least 10 μs TOA measurement error. Previous research has shown that CWI can be classified in terms of its frequency relationship to the Loran-C signal. The Minimum Performance Standards (MPS) [15] specifies three types of CWI: Synchronous, near-synchronous, and asynchronous CWI.

These three types of CWI produce errors of different character. Synchronous CWI causes a fixed offset in TOA measurement, near-synchronous CWI an oscillating offset, and asynchronous CWI a noise-like effect. It is synchronous and near-synchronous CWI which most frequently cause unacceptable receiver errors and so reduce the coverage of Loran-C systems [4].

2.4 Method of TOA measurement

Loran-C receivers make TOA measurements by choosing a certain cycle of the received pulses and measuring the zero-crossing time of that cycle. The zero crossing chosen for this measurement must be sufficiently early in the Loran-C pulse to ensure that the groundwave-propagated signal is being measured and not the less stable skywave signal which arrives at least 37.5 μs after the ground wave [14,15]. The earlier this cycle, the less the skywave contamination. However, later cycles have greater amplitudes and better signal-to-noise ratios. Conventionally the zero-crossing at the end of the third cycle, 30 μs after the start of the pulse, is chosen as the timing reference.

CWI can alter the time of the zero-crossing being measured. The time error is a function of the signal-to-interference ratio (SIR) and of the phase of the interferer relative to the Loran-C cycle. This relative phase may change, pulse-by-pulse, for different kinds of CWI with consequent variations in the time error.

An important feature of the Loran-C signal which helps reduce CWI errors is its phase coding (Section 2.1). Consider a synchronous CWI at 100 kHz. If there were no phase coding, the zero-crossing errors of each of the 16 pulses within 2GRI would be equal. Integrating the measurements would make no difference. In contrast, the shifts of the positive and negative phase-coded pulses are in opposite senses and tend to cancel each other when integrated. Loran-C stations transmit 10 positive and 6 negative phase-codes in each 2GRI period, so the reduction of the error is (10-6)/16=1/4; that is, 12 dB.

More generally, the reduction of the effect of CWI due to phase coding varies with frequency in a complex fashion which will be analysed in Section 3.

2.5 Mechanism of cycle selection

Cycle selection is the process by which the receiver identifies the cycle on which the zero-crossing measurement is to be performed. Most receivers use the principle that the ratio of the amplitudes of the two half-cycle peaks either side of each zero crossing is unique. By measuring these 'half cycle peak ratios (HCPR)' the correct zero crossing may be identified.

Fig. 2 illustrates this principle; the dots, which represent the discrete HCPRs of an ideal Loran-C pulse, are stored in the receiver. After initial signal acquisition, a zero-crossing is found. Its HCPR is then measured by taking two samples, 2.5 μs before and 2.5 μs after it. By comparing this ratio with the stored ratios the zero crossing is identified and an appropriate time adjustment (a multiple of 10 μs) is applied so that the correct zero crossing is selected.

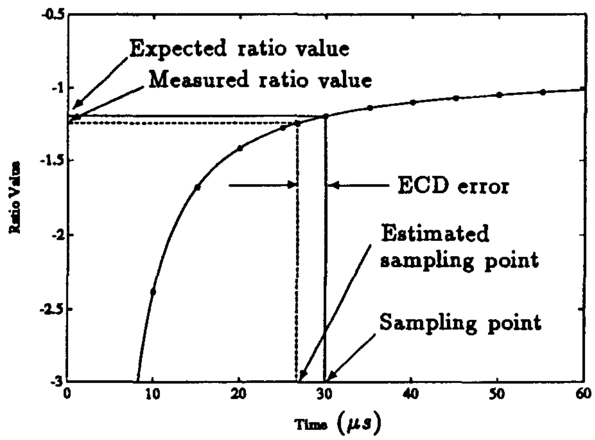

Fig.2 The half cycle peak ratio of a pure Loran-C pulse

In the presence of CWI, the pulse envelope shape may be altered substantially. This causes an error in the measured HCPR which corresponds to an incorrect 'estimated sampling point' (Fig. 2). The error between the estimated and true sampling points is termed the 'measured ECD error', using 'ECD' to mean the time discrepancy between the carrier of the Loran-C pulse and its envelope. Specifically, it may be thought of as the discrepancy between the zero crossing used for phase tracking and the corresponding point on the envelope. If the magnitude of this measured ECD error exceeds 5 μs, the wrong cycle will be chosen. This type of error will be analysed in Section 5.

3 Attenuation of CWI by integration and phase decoding

Although Loran-C signals are infinite pulse trains, receivers in practice process the measurements made on the pulses from a limited number, N, of periods, each of 2GRI. The signal within these N periods may be represented explicitly by the summation of the convolution of a train of impulses with a standard Loran-C pulse:

$$x_L(t) = \sum_{n=1}^{N} \left[\sum_{m=1}^{16} x_0(t) * \delta(t - t_m)\, pc(m) \right] * \delta(t - t_n) \quad (2)$$

where $x_0(t)$ is the Loran-C pulse, δ the Dirac function, t_m the time of each pulse within the 2GRI:

$$t_m = \begin{cases} (m-1)T & for \quad 1 \le m \le 8 \\ (m-1)T + GRI & for \quad 9 \le m \le 16 \end{cases} \quad (3)$$

and t_n the start time of that 2GRI:

$$t_n = 2GRI(n-1) \quad (4)$$

Phase decoding is represented by the multiplier $pc(m)$. The number N is related to the tracking bandwidth and is, of course, different for the phase-tracking and cycle-selection loops. Appropriate (and widely-different) values of N are employed in marine, airborne and land mobile receivers.

In the presence of CWI the receiver experiences the sum of the Loran-C signal $x_L(t)$ and the interference $x_{int}(t)$:

$$x_c(t) = x_L(t) + x_{int}(t) \quad (5)$$

$$x_{int}(t) = I\, sin(2\pi f_{int} + \varphi_{int}) \quad (6)$$

where I and f_{int} are the amplitude and frequency, respectively, of the interference, and φ_{int} its phase relative to that of the Loran-C signal. In the real world, CW interferers are generally amplitude or frequency modulated signals. Our assumption of a simple carrier will result in an over-estimate of the effects of modulated interferers.

The operations of integration and phase decoding of the received Loran-C signal are carried out on this composite signal. Integration is performed by summing corresponding points of successive pulses. Phase decoding is achieved by multiplying each pulse by its phase code. This integrated composite signal may then be expressed by:

$$y(t) = \frac{1}{16N} \sum_{n=1}^{N} \left[\sum_{m=1}^{16} x_c(t + t_m + t_n)\, pc(m) \right] \quad (7)$$

The linear relationships in equations (5) and (7) allow us to decompose $y(t)$ into two parts: y_1, the portion due to the Loran-C signal, and y_2, the portion due to the interference. It is easy to verify and understand that $y_1(t) = x_0(t)$, by substituting equation (2) into (7). Substituting equation (6) into (7), we have:

$$y_2(t) = \frac{1}{16N} \sum_{n=1}^{N} \left\{ \sum_{m=1}^{16} [x_{int}(t) * \delta(t + t_m + t_n)\, pc(m)] \right\} \quad (8)$$

In order to evaluate $y_2(t)$, we take the Fourier Transform of both sides of equation (8) (see [18] for details). The attenuation of the CWI due to phase-decoding and integration can therefore be obtained by taking the modulus of the division of $Y_2(f)$ by $X_{int}(f)$:

$$Rejection(f_{int}) = R_1(f_{int})\, R_2(f_{int}) \quad (9)$$

where

$$R_1(f_{int}) = \left| \frac{1}{N} \sum_{n=1}^{N} exp(+j2\pi f_{int} t_n) \right| \quad (10)$$

$$R_2(f_{int}) = \left| \frac{1}{16} \sum_{m=1}^{16} exp(+j2\pi f_{int} t_m)\, pc(m) \right| \quad (11)$$

Both $R_1(f_{int})$ and $R_2(f_{int})$ are frequency-dependent. However, the phase-decoding term appears only in $R_2(f_{int})$.

Equations (9), (10), and (11) are useful tools for studying the effects of CWI of various kinds and the ability of receivers to reject them (see [18] for details). The physical significance of these equations is that the rejection of CWI consists of two parts: $R_2(f_{int})$, the attenuation due to integration over a single 2GRI, and $R_1(f_{int})$, that due to integration over N periods of these 2GRI. Fig. 3 plots $R_2(f_{int})$ against frequencies from 95 to 105 kHz, taking GRI=99600 μs as an example. It shows a rejection ratio which varies in a complex fashion with frequency. The average value is approximately 0.25, equivalent to an attenuation of 12 dB. The crosses represent the synchronous frequencies which correspond to the spectral lines of the Loran-C transmission. Fig. 4 plots $R_1(f_{int})$ for frequencies between two arbitrarily chosen adjacent synchronous frequencies. It shows that long integration periods may provide significant additional attenuation for asynchronous CWI.

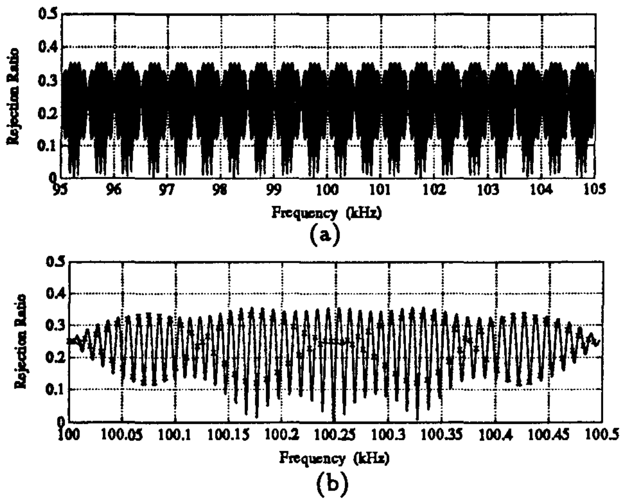

Fig.3 The rejection of CWI due to phase decoding. The crosses represent synchronous interference frequencies, the dots the line connecting them represent asynchronous frequencies, (a) 95 - 105 kHz (b) 100 - 100.50 kHz

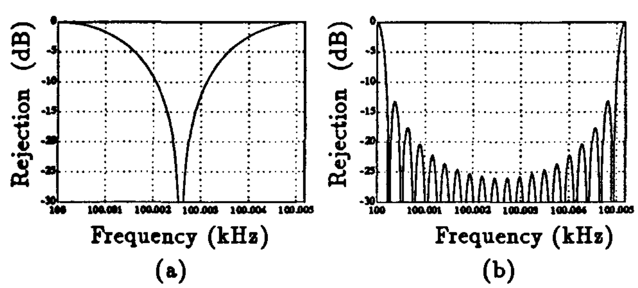

Fig.4 Rejection of asynchronous CWI due to integration over N periods of 2GRI, (a) N = 2, (b) N=20. Note that, for this GRI (99600 μs), 100 kHz and 100.005176 kHz are adjacent synchronous frequencies.

4 Time-of-arrival errors

The TOA measurement error is determined by the strength and the phase of the CWI relative to the Loran-C signal. According to [9], a single CWI results in the following TOA measurement error (in μs):

$$TOA\ error = \frac{10}{2\pi} sin^{-1}\left[\frac{I}{C} sin(\varphi_{int})\right] \qquad (12)$$

where φ_{int} is the phase of the CWI relative to that of the Loran-C signal, I is its amplitude, and $C = \sqrt{I^2 + S^2 + 2IS\ cos(\varphi_{int})}$, S being the amplitude of the Loran-C signal at the sampling point.

When $I/S \ll 1$, equation (12) can be simplified; when φ_{int} is $\pi/2$, the TOA error reaches its maximum value:

$$(TOA\ error)_{max} = \frac{10}{2\pi}\frac{I}{S} \qquad (13)$$

The maximum TOA error is frequency-independent but is a function of SIR. The dotted line in Fig. 5 shows the TOA error calculated according to equation (12). The solid line shows the TOA error due to a (synchronous) 100 kHz CWI after adding the attenuation due to phase decoding calculated by the method developed in Section 3.

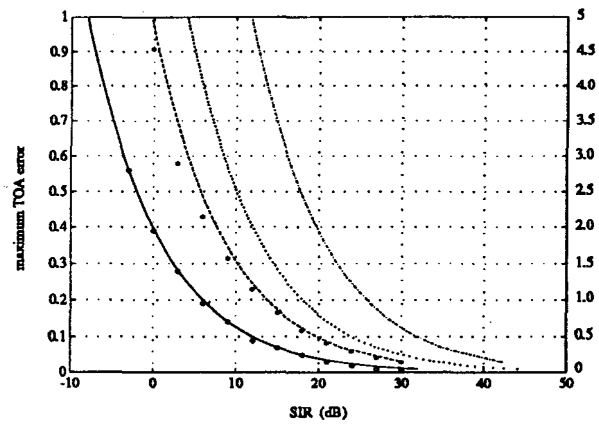

Fig.5 The maximum values of TOA and ECD errors due to a 100 kHz CWI. The solid and dotted lines are analytical results for TOA error, the dashed and dash-dot for ECD error. The circles and stars are TOA and ECD errors by the computer simulation, respectively

In practice, receiver designers commonly set a maximum TOA error which can be tolerated and need to know the corresponding minimum SIR. The result is, of course, frequency-dependent. Fig. 6 shows the SIR values which cause a 100 ns maximum TOA error at interference frequencies between 85 kHz and 115 kHz.

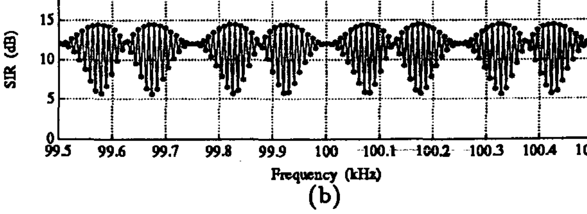

Fig.6 SIR values of CWI which result in 100 ns maximum TOA error, (a) 85-115 kHz, (b) 99.5-100.5 kHz

5 Cycle selection errors

Section 2.5 described how the 'measured ECD error', is determined by the HCPR measured, the two being related by the curve of Fig.2.

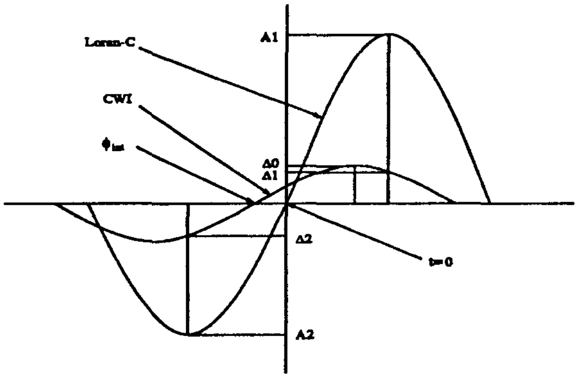

Fig.7 Definition of Loran-C signal and CWI parameters for analysis of error due to effect of interference on cycle selection process

Fig. 7 shows a single cycle of a Loran-C pulse and a single CWI. The HCPR which is measured in the presence of the CWI is:

$$Ratio = \frac{A_1 + \Delta_1}{A_2 + \Delta_2} \tag{14}$$

where A_1 and A_2 are the half cycle peak amplitudes of this cycle of the pure Loran-C pulse and Δ_1 and Δ_2 are the error contributions of the CWI. The amplitude of this CWI relative to the Loran-C signal is Δ_0.

Under the conditions $\Delta_0 \ll A_1$ and $\Delta_0 \ll A_2$, the error in this ratio caused by CWI equals

$$\begin{aligned} Ratio_e &= -\Delta_0 \frac{A_1}{A_2}\left[\left(\frac{1}{A_1}+\frac{1}{A_2}\right) sin(5\pi f_{int})\, cos(\varphi_{int}) \right. \\ &\quad \left. + \left(\frac{1}{A_1}-\frac{1}{A_2}\right) cos(5\pi f_{int})\, sin(\varphi_{int})\right] \end{aligned} \tag{15}$$

The maximum ratio error is:

$$\begin{aligned} \mid Ratio_e \mid_{max} &= \Delta_0 \frac{A_1}{A_2}\left[\left(\frac{1}{A_1}+\frac{1}{A_2}\right)^2 sin^2(5\pi f_{int})\right] \\ &\quad \left[+\left(\frac{1}{A_1}-\frac{1}{A_2}\right)^2 cos^2(5\pi f_{int})\right]^{-\frac{1}{2}} \end{aligned} \tag{16}$$

which is achieved when:

$$tan(\varphi_{int}) = \frac{\frac{1}{A_1}-\frac{1}{A_2}}{\frac{1}{A_1}+\frac{1}{A_2}}\, cot(5\pi f_{int}) \tag{17}$$

Equation (37) shows that, in contrast to the maximum TOA error, the maximum ratio error depends on both the SIR and the frequency of the CWI. Fig. 2 may be used to calculate the maximum 'measured ECD error' which is equivalent to the maximum ratio error.

The frequency-dependence of the measured ECD error may conveniently be illustrated by calculating the SIR value which gives a certain maximum measured ECD error. Fig. 8 (solid line), plotted for a maximum error of 5 μs, covers the frequency range from 50 kHz to 150 kHz. (Note that phase decoding and integration have not yet been taken into account).

The result is very surprising: it shows that, contrary to what is generally accepted, the closer a CWI is to 100 kHz, the *less* interference it causes and the less SIR is required. This result may be explained by reference to Fig. 7 which illustrates the way in which a CWI affects the half cycle peak ratio measurement. If the CWI is at 100 kHz, the two peaks will both be either increased or decreased together. In contrast, a CWI at 200 kHz which caused one peak to increase would cause the other to decrease, resulting in a much greater change in the HCPR. Thus we see that 100 kHz is the frequency at which a given *SIR* results in *minimum* error.

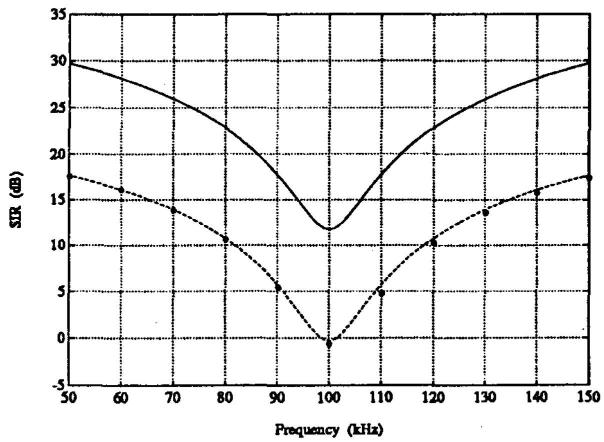

Fig.8 SIR values of CWI which result in 5 μs maximum measured ECD error. The solid line is the value when phase coding and integration are ignored. The dashed line is the theoretical prediction of SIR values of computer simulation. The circles are results by simulation.

The effects of integration and phase decoding may now also be taken into account, using the method of Section 3. The dashed line in Fig. 5 shows the maximum value of the ECD error for a CWI of 100 kHz. This is, of course, a synchronous frequency so the CWI is not attenuated by integration over 2GRI. However, phase decoding has reduced the effect of the CWI by 12 dB.

6 Effects of front end filtering

6.1 Criteria for filter performance assessment

The effects of front-end filtering may be summarized as the attenuation of CWI and the distortion of the Loran-C pulse. The final criterion for assessing the performance of a filter has to be its contribution to the improvement in the timing measurement accuracy of the receiver.

Conventionally, only the amplitude transfer function of a filter, and the resulting attenuation of CWI, have been considered. Recently, van Willigen has pointed out the need to take into account the distortion of the pulse, and in particular the reduction of signal amplitude at the sampling point compared with that of a standard pulse [4]. The SIR at the input of the receiver is always calculated with respect to the 30 μs of a standard pulse. Thus an indirect result of the pulse distortion is to reduce the SIR at the sampling point for a given input SIR.

To calculate the TOA error, both the attenuation of the interference and the reduction of the signal amplitude at the sampling point (and hence the reduced SIR there) have to be calculated. The TOA uncertainty can then be determined from this sampling point SIR. Estimating the cycle selection performance requires an additional factor to be considered: the change in the HCPRs around the sampling point due to the filters. In every case the reduction in SIR and the change in HCPR both depend on which zero-crossing is selected as the timing measurement point.

6.2 Generating filtered signals

In calculating the TOA and ECD errors due to CWI, the filtered Loran-C pulses and CWI must be employed. An analytical method of achieving this is to calculate the Laplace transform of the input signal, multiply it by the transfer function of the filter and take the inverse transform [5]. In contrast, we implement the filters digitally in a computer and use them to filter the input signal and interference.

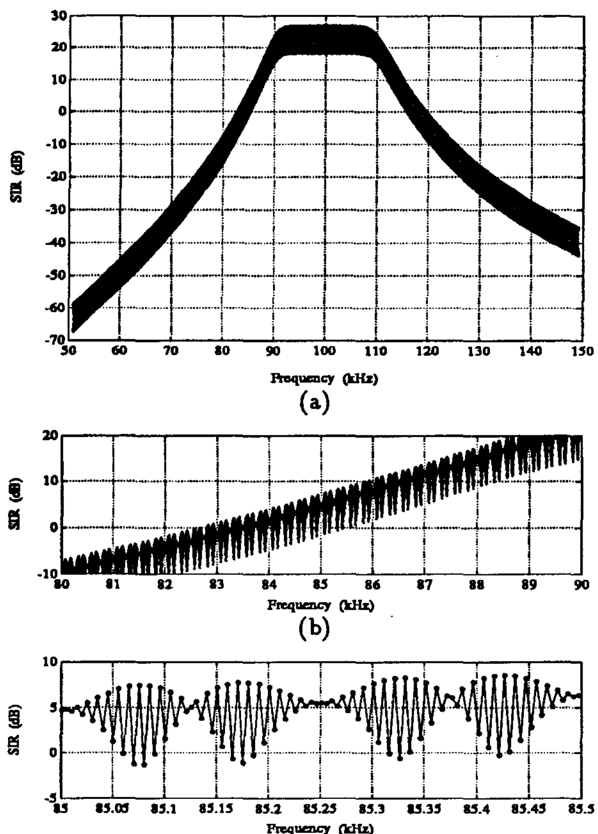

Fig.9 Minimum SIR at the receiver input for 100 ns maximum TOA error. A 5th Butterworth filter with 20 kHz bandwidth is used. The sampling point is approximately 65 μs after the start of the pulse at the receiver input. (a) 50 - 150 kHz, (b) 80 - 90 kHz, (c) 85 - 85.5 kHz

7 Results

7.1 TOA errors

Fig.9 shows the minimum SIR at the receiver input which results in 100 *ns* maximum TOA error when a 5th order Butterworth bandpass filter is used and the zero-crossing is approximately 65 *μs* from the start of the pulse at the input of the receiver. The effect of varying the sampling point from 45 to 80 *μs* is shown in Fig.10, for a CWI of 100 kHz. As expected, the earlier the zero-crossing, the higher the SIR required. The other lines illustrate the reduction in the performance of the receiver due to the pulse distortion caused by notch filters. The dashed lines are produced by a single notch filter set successively to the 6 frequencies cited. The top solid line shows the combined effect of all 6 notch filters operating simultaneously. The results show clearly that the pulse distortion caused by notch filters does not seriously degrade the performance of the receiver; the maximum effect is only 2 dB.

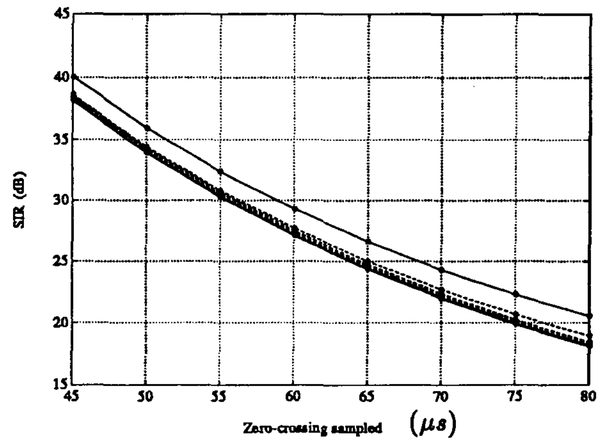

Fig.10 SIR limits for 100 ns maximun TOA error. Lower solid line: bandpass filter alone. Other lines show effects of pulse distortion due to notch filters. Dashed lines: single notch set to 75, 85, 95, 105, 115 and 125 kHz. Top line: notches at all those frequencies simultaneously

7.2 Cycle selection error

The fine structure of the frequency dependence of the ECD error results is identical with that for TOA results shown in Figs.9 and 10. The overall shape of the curves from 50-150 kHz in the two cases may be compared in Fig.11 below.

8 Comparison between phase tracking and cycle selection

This section will compare the errors caused by CWI in phase tracking and cycle selection. The question of which imposes the more critical limit on SIR will be answered.

The maximum allowable TOA and ECD errors must be defined. The MPS and the US Coast Guard both set a time-difference (TD) limit of 100 *ns* rms [5,7]. Since the TD error is the sum of two TOA errors (of opposite signs) we take ±50 *ns* as our limiting TOA error. The maximum measured ECD error allowed is ±2.6 *μs* .

This is calculated as follows: cycle identification failure occurs when the total ECD error is $\pm 5\ \mu s$. The receiver specification, however, permits a maximum ECD error in the received signal of $\pm 2.4\ \mu s$ and the CWI contribution makes up the rest. In neither case is any allowance made for noise; if this is present, in addition to CWI, both TOA and ECD limits would be reduced. The reduction would normally be expected comparable in the two cases and their relative importance would then be little affected.

We choose to consider only synchronous CWI since this is invariably the most serious form of interference. Also, although the attenuation due to phase coding varies with frequency between 10 and 18 dB, for simplicity we take it to be 12 dB, the value at 100 kHz and at all other multiples of 5 kHz for all existing GRIs. This assumption does not affect the comparison result since the reduction of CWI due to phase-decoding is the same for both phase-tracking and cycle-selection loops. If the interference is asynchronous, this simplification gives a first estimate of the relative importance of the TOA and ECD errors; it is, however, necessary for an exact solution to take into account any differences between the integration times of the two loops.

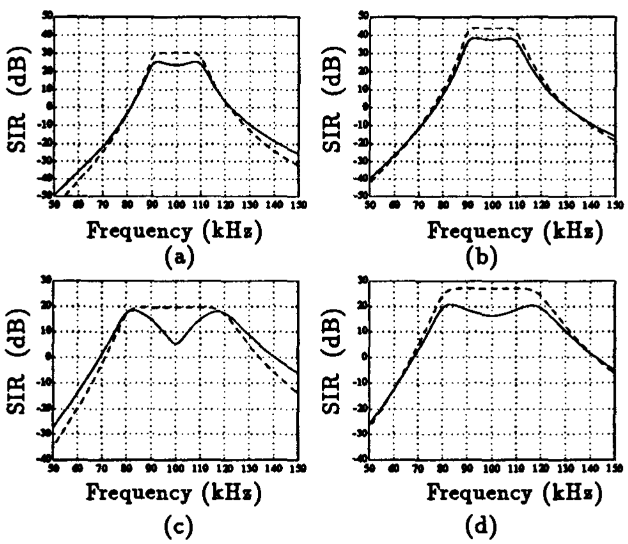

Fig.11 Comparison of SIR limits due to TOA error of 50 ns (dashed line) and ECD error of 2.6 μs (solid line). Timing point: (a) and (c) 65 μs, (b) and (d) 45 μs. Filter bandwidth: (a) and (b) 20 kHz, (c) and (d) 40 kHz.

Fig. 11(a) shows the variation of the SIR limits with frequency; the timing measurement point is at approximately 65 μs. Between approximately 82 and 117 kHz the dashed line is the higher: that is, the TOA measurement has the greater sensitivity to CWI. Outside this frequency range, interference is more likely to cause unacceptable *cycle-selection* errors.

The result is relatively insensitive to the choice of the timing measurement point over the full range of practically-usable values. Fig.(b) shows the qualitatively-similar results obtained when the timing measurements are made at 45 μs. The later the zero-crossing used, the safer the phase-tracking relative to the cycle selection.

Increasing the bandwidth of the bandpass filter from 20 to 40 kHz produces the curves in Figs. 11(c) and (d). It is seen that the wider the bandpass filter, the safer is cycle selection relative to phase-tracking. These results comfirm further that it is not only the SIR at the sampling point which determines the cycle-selection performance but also the HCPRs there.

We may conclude overall that, since interference is likely to be present over the whole frequency range 50-150 kHz and the two curves lie close together over large parts of this range, both kinds of error need to be considered. However, given that the greatest sensitivity to interference is at frequencies within the filter passband, the TOA limit is likely to be the more significant in practice.

9 Computer simulation

A computer program which simulates Loran-C receiver operation has been developed to verify the analysis above. This demanding computational task has been implemented using the highly computationally-efficient package, Pro-Matlab, running on a Sun Workstation. Standard routines have been drawn from the Matlab Signal-Processing Toolbox to simulate each of the individual functions of a linear receiver having the structure shown in Fig. 2. The input to the program is the Loran-C signal and the interference. The outputs monitored are the TOA measurement error and the measured ECD error. Sample results, calculated at multiples of 10 kHz, are marked on Figs. 5 and 8. Differences between calculation and simulation average only 0.5 dB and never exceed 1.4 dB for either the TOA or ECD error curves.

10 Conclusions

Carrier Wave Interference, especially at frequencies synchronous with spectral lines of the transmission, is a major threat to Loran-C operation. The analysis developed in this paper examines this problem, taking into account for the first time all major signal processing operations performed by the receiver. The main results of this theoretical analysis have been confirmed by computer simulation. The principal conclusions are that:

1. Both integration and phase decoding provide substantial attenuation of CWI.

2. CWI attenuation by integration and phase decoding is frequency-dependent. The controlling equations are the same for the phase-tracking and cycle-selection functions. In practice the cycle selection loop invariably has longer integration time and hence a narrower bandwidth, and so offers greater attenuation to asynchronous CWI, than the phase tracking loop.

3. Synchronous and near-synchronous CWI are attenuated by phase decoding within each period of 2GRI. This attenuation varies from 10 to 18 dB, depending on the frequency of the CWI. The attenuation at 100 kHz is 12 dB. No further attenuation is provided by integrating over periods significantly longer than 2GRI.

4. ECD error due to CWI depends on both frequency and SIR even before integration and phase decoding are taken into account. Unexpectedly, the cycle selection process is less sensitive to CWI at 100 kHz than to interferers at other frequencies in the range 50-150 kHz.

5. The improvement in performance the fornt-end filters provide depends not only on their attenuation of the CWI but also on the distortion they cause to the Loran-C signal. Notch filters are especially useful for attenuating individual high-amplitude interferers. The distortion they cause is greatest when the notch frequency is close to 100 kHz. Neither single nor multiple notch filters distort the signal sufficiently to require an increase of more than 2 dB in the SIR at the receiver input.

6. The relative sensitivity of the phase tracking and cycle selection functions of the receiver to CWI is a complex question. The answer depends quantitatively on the bandwidth of the bandpass filter, the zero-crossing chosen for timing measurements and the limits set for the measured TOA and ECD errors. It has been shown that, although the two limits are never greatly different and should both, therefore, be considered, it is the phase-tracking loop which demands the greater SIR when subject to the least-attenuated interferers close to the Loran-C band. Also, the wider the bandpass filters, the safer is cycle selection relative to phase-tracking; the later the zero-crossing used, the safer is phase-tracking relative to cycle selection.

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SESSION D

Loran-C Coverage and Use (2)

Coverage and Performance Predictions for the North-West European Loran-C System

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Abstract

In December 1991 six European nations, Denmark, France, Germany, Ireland, The Netherlands and Norway, agreed to co-operate in deploying a Loran-C system to cover North-West Europe and the North Atlantic Ocean. The system will comprise 9 stations (6 existing stations and 3 new ones) arranged in 4 chains. In estimating the coverage which will be provided, the effects of signal attenuation, atmospheric noise, carrier-wave interference, skywave propagation, the change of envelope-to-cycle difference with range and transmitter timing uncertainty have all been taken into account. Contours of repeatable accuracy have been predicted for both conventional hyperbolic receivers, which employ the signals of a master and two secondary stations of a single Loran-C chain, and receivers which work in the semi-circular, cross-chain and master-independent modes.

Because of the complexity of carrier-wave interference effects, and their sensitivity to the nature of the receiver employed, a standard receiver with specified bandpass, notch filter and tracking loop characteristics has been adopted as the basis for coverage and performance assessment. Further, in planning the system, a rigorous search was carried out for group repetition interval (GRI) values which minimised the numbers of synchronous and near-synchronous interferers in the area covered by each chain. The very substantial variations of coverage with choice of GRI were explored and optimal GRI values selected.

This paper sets out, and explains, the assumptions adopted by the planning group for the North-West European system in estimating coverage and it illustrates the performance to be expected using the GRI values chosen.

1 Introduction

In December 1991, six European nations, Denmark, France, Germany, Ireland, The Netherlands and Norway, agreed in principle to cooperate in deploying a Loran-C system to cover North-West Europe and the North Atlantic Ocean. The political and financial aspects of this agreement will be found in the paper in this Symposium by Mr. Stenseth of NODECA [1]. The purpose of this present paper is to explain and record some of the the technical decisions which were made in designing the system and to present predictions of its coverage and performance.

The new system will comprise 9 stations (6 existing and 3 new ones) arranged in 4 chains. In estimating the coverage that will be provided, the effects of signal attenuation, atmospheric noise, carrier-wave interference, skywave propagation, the change of envelope-to-cycle difference with range, transmitter timing uncertainty, and receiver operating mode and location have all been taken into account.

The system has been designed using a coverage and performance prediction model developed at the University of Wales, Bangor (the 'Bangor model'). At an earlier stage in its development the Bangor model was described in a paper in the 1990 Technical Symposium of the Wild Goose Association [2]. Since that publication there have been major advances in the scope of the model, especially in respect of skywave effects, carrier-wave interference, geometry and receiver operating modes. The principles and results of the skywave analysis embodied in the model were discussed in detail in a paper in the 1991 WGA Symposium [3]. That Symposium also contained a paper on the techniques used to assess the severity of carrier-wave interference, taking into account the locations and frequencies of the interfering stations [4]. These techniques have been further developed since the date of that publication.

The Bangor model works by estimating conditions at each of a large geographical array of points which span at least the area to be covered by the Loran-C system. First, each transmission is considered in turn. Its field strength at the point is estimated. The atmospheric noise level is also determined, using CCIR and USCG techniques, and the signal-to-noise ratio calculated. The strength of each of the large number of potential carrier-wave interference (CWI) sources is estimated, taking into account both groundwave and skywave propagation. The filtering and signal-processing effects of a 'standard receiver', adopted by the North-West European Technical Working Group (TWG), are taken into account. Then an overall signal-to-interference ratio (SIR), covering the whole ensemble of interferers, is established. The uncertainty of the time-of-arrival (TOA) measurements of the transmission due to atmospheric noise and to CWI are calculated.

Independently, the interference to the signal caused by unwanted skywave propagation is estimated, both its strength and its delay being taken into account. The envelope-to-cycle difference (ECD) of the signal is also predicted. If either the skywave interference or the ECD falls outside the limits set by published Minimum

Performance Standards (MPS) for receivers that signal is flagged as unsuitable for use at the point.

Each possible triad of the Loran-C stations whose signals are acceptable is now considered in turn. Taking into account the TOA uncertainties of the individual transmissions (including a factor to account for transmitter timing uncertainties) the repeatable accuracy of the position fix is estimated. The overall fix accuracy at the point is taken to be that of the triad with the highest repeatable accuracy. In making this selection, the operating mode of the receiver (hyperbolic, semi-circular, cross-chain or master-independent) is taken into account. Contours of accuracy may now be plotted which represent the coverage and performance of the Loran-C system under consideration.

Sections 2-5 of this paper will present further details of these aspects of the prediction model. Table 1 summarises the principal assumptions it embodies.

2 Field strength, atmospheric noise and ECD

2.1 Field strength

Techniques for estimating the field strengths of groundwave signals in the low-frequency band are well established. Bremmer [5] and Norton [6] have published families of curves which relate groundwave attenuation to range over surfaces of various values of conductivity. Millington [7] has developed a method of dealing with inhomogeneous paths. CCIR Report 717-2 describes these techniques in full [8]. The Bangor model employs the CCIR method to map the groundwave field strengths of Loran stations point-by-point throughout a large array of locations spaced by 0.5° of latitude (56 km) by 1° of longitude (typically 70 km) [9].

The model employs a database of ground conductivity values, at intervals of 0.1° × 0.1° of latitude and longitude (typically 11x7km), which covers much of Europe and North Africa. This database has been built up by combining data from the CCIR World Atlas of Ground Conductivities with information from national administrations and from geological sources. The current version of the map is dated 3 January 1991.

2.2 Atmospheric noise

The model determines the atmospheric noise at the point by reference to the nearest stored value in an array of points spaced at intervals of 10° × 10° of latitude and longitude (typically 111x70km). This spacing has been chosen to ensure that the difference between adjacent values does not exceed 2 dB. The data source is CCIR Report 322-3 [10]. These atmospheric noise field strength levels are the averaged 95-percentile values over the year, calculated in accordance with the USCG method set out in COMDTINST 16562.4 [11].

Parameter	Value/Source
Field strength	
Groud conductivity	Bangor map 3 Jan91
Attenuation curves	CCIR Rep. 717-2
Atmospheric Noise	
Source of data	CCIR Rep. 322-3
Calculation method	COMDTINST 16562.4
Element size	10° × 10° lat/long
Carrier-wave interference	
Source of data	IFRB
Band omitted	90-110 kHz
Modification	Decca stations
Summing rule	RSS
Notch filters used to calculate CWI signals	
Number	3 + 3
Tuning ranges	50-100/100-150 kHz
Notch filter model	Triangular
Center depth	30 dB
Width	+/-1kHz
Tuning strategy	Select worst after receiver filters
Reciever filters	
Bandpass filter	Butterworth 5th order
Tracing loop bandwidth	+/-0.1Hz
Geometrical limit	
Accuracy contours	2σ
TD standard deviation	Based on SNR and SIR
ECD limit	
Source of data	Sherman's curve
Limiting ECD values	+/-2.4μs
Skywave interference limit	
Skywave delay data	USCG
Skywave field strength	USCG/Decca (95%ile)
Time period	Winter Day
Operating limits	RTCM70, IEC80

Table 1: *Delft-Bangor table of assumptions*

2.3 Envelope-to-cycle difference

The envelope-to-cycle difference (ECD)is calculated by reference to Sherman's curve [12]. Sherman's curve relates the rate of change of ECD with distance from the transmitter to the conductivity of the ground. The conductivity database (Section 2.1) is used again in this calculation. Normally the ECD in the near far-field close to the transmitter is positive. Its value falls with distance, ideally reaching zero at the range limit. Poor ground conductivity could, in principle, cause excessively-low ECD which would result in receivers experiencing cycle selection errors. The limiting ECD values used in the Bangor model are those specified in the MPS of both the Radio Technical Commission for Marine Services (RTCM) and the International Electrotechnical Commission (IEC): +/-2.4 μs [13]. Transmissions whose ECD values lie outside this range are deemed unusable.

3 Skywave interference

With increasing range from the transmitter, the strength of the groundwave signal used for Loran-C navigation falls. The strength of the unwanted skywave component, in contrast, changes little with range over distances between 100 and 2000 km from the station. Thus there is a range at which the skywave interference becomes unacceptable in relation to the groundwave. Maximum levels of skywave interference which receivers are required to tolerate are laid down in the RTCM and IEC MPS documents [13]. They are expressed in terms of the skywave-to-groundwave ratio (SGR) and the skywave delay with respect to the groundwave. The Bangor model calculates both of these parameters at each point in the array and compares them with the MPS limits to determine whether or not the point lies within the boundary of acceptable skywave interference.

SGR is a parameter which varies randomly with time over short periods. Its expected root mean square (rms) value at any time of day and season of the year is a function of distance from the transmitter. A detailed study has been carried out of USCG sources and records of skywave propagation of Decca Navigator, a system which operates in the same frequency band as Loran-C. From this information, the relationships between rms skywave field strength and range have been established for each time and season.

USCG sources also contain authoritative measurements of skywave delay as a function of range, under day and night propagation conditions, which have been built into the model. When the estimated SGR and delay values are compared with the MPS limits it is seen that the most serious skywave interference is experienced during daylight on winters' days. The North-West European Loran-C Technical Working Group (TWG) have set this as the period of limiting skywave interference for coverage prediction purposes. Additionally, they have adopted the 99-percentile (a value 7dB above the rms) as the limiting skywave intensity.

A full presentation of the skywave analysis embodied in the Bangor model is available in [3].

4 Carrier-Wave interference

4.1 Introduction

The analysis of the effects on Loran-C receivers of the large numbers and high levels of carrier-wave interference sources experienced in Europe is exceptionally complex [14]. When the coverage of the first Loran-C chains to be installed in the region was estimated by the USCG, carrier-wave interference was ignored. The North-West European TWG first allowed for the reduced coverage due to CWI by assuming an artificially-high level of atmospheric noise, 61dB/μV/m. The reason for choosing this value was that it caused the model to predict a coverage area for the Norwegian Sea Loran chain which, in their judgment, most closely resembled that experienced by users. Subsequently, more sophisticated analyses have been developed and incorporated into the Bangor model which are based on a list of known European interferers and an understanding of the behaviour of Loran-C receivers when subject to CWI.

It must be recognised that this behaviour, and consequently the effective coverage areas of the Loran chains, depend upon many factors specific to the design of the type of receiver employed; there is no simple, single coverage boundary. For this reason the TWG decided to define a standard form of receiver to which the coverage and performance contours it published corresponded. This receiver was intended to be broadly representative of receivers of good quality. Other types of receiver might have greater or lesser coverage.

4.2 List of interferers

No complete, up-to-date list exists of the locations, frequencies, emission classes and power levels of all interferers which affect European Loran-C receivers at any time: details of some interferers are classified and so unavailable; other known interferers operate only infrequently; the picture changes constantly, especially as transmissions are removed from the 90-110 kHz band in order to reduce interference to Loran-C. However, a brave attempt has been made by Beckmann at Delft University of Technology in The Netherlands to assemble the best possible information. Beckmann's list is based on the records of the International Frequency Registration Board (IFRB). It includes all transmissions between 50 and 150 kHz in the region bounded by latitudes 30°N and 90°N and longitudes 70°W and 60°E.

The list has been amended to incorporate updates and corrections supplied by the PTT authorities of certain of the countries represented. Further, where entries in the list are known to be incorrect or misleading, they have been modified: in particular, the list actually contains the output powers of all Decca Navigator transmitters, rather than the much lower radiated power levels which are required for calculating their field strengths. Finally, surveys have shown [15] that there is now negligible interference in the crucial 90-110kHz band and so the interferers listed there have been deleted.

The Bangor model assumes conservatively that all interferers transmit continuously and that winter night propagation conditions apply. Again employing the ground conductivity database (Section 2.1), the field strength of the groundwave component of each interferer is computed at each point in the coverage array. The field strength of the skywave component of the interference (the value which is not exceeded for more than 5% of the time) is also estimated and the variances of the groundwave and skywave components are summed. The resulting composite interfering signal is then assumed to be attenuated by the receiver factors specified in Section 4.3. Finally, the variances of the individual signals of the whole ensemble of interferers are summed.

4.3 Receiver specification

Each interfering signal may effectively be attenuated within a Loran-C receiver by the bandpass filter, the phase sampling process and the phase decoding operation. In addition, notch filters may have been set to provide further attenuation.

The 'standard receiver' is assumed to have a 5th-order Butterworth bandpass filter with zero attenuation at 100kHz and approximately 3dB at 90 and 110kHz [16]. Each interferer is weighted in accordance with that characteristic. The effect of the phase sampling process is to create a comb filter matched to the Loran-C spectrum. Synchronous interferers are not attenuated by this filter; the attenuation of each near-synchronous or non-synchronous interferers, however, depends on the proximity of its frequency to that of the closest spectral line. In the standard receiver, the effect of the sampling process is assumed to be equivalent to a comb filter with a -3 dB bandwidth of +/-0.1Hz and a 6dB/octave roll-off [16]. The phase reversals applied by the receiver to the signal in order to remove the Loran-C phase coding also attenuate the interference by an amount which is a complex function of frequency. In the standard receiver, interfering signals of all frequencies are assumed to be attenuated by a fixed value, 12 dB, which is typical of attenuation due to phase decoding.

The number of notch filters with which Loran-C receivers are equipped varies greatly. In addition, some receivers employ manually-adjusted notch filters; others automatically set their filters to the strongest interfering signals emerging from the bandpass filter. Loran-C receiver performance under European interference conditions depends critically on the number, bandwidth and depth of the notch filters and on whether or not they are optimally set to reject the most serious interferers. The standard receiver is assumed to be equipped with six notch filters, three being restricted to frequencies in the range 50-100kHz and three to frequencies from 100-150kHz. The attenuation of the notches at their centre frequencies is 30dB. It falls linearly (on a dB scale) to zero at +/-1 kHz. It is assumed that the notches are set to remove the most serious interferers, taking into account the effects of bandpass filtering and phase sampling and decoding described above.

4.4 Choice of GRI

A further factor which has a crucial effect on Loran-C coverage and performance, when these are limited by carrier-wave interference, is the choice of GRI. Setting the GRI determines the frequencies of the spectral lines of the signal and the corresponding frequencies of the matching comb filter which results from the sampling process in the receiver. The severity of the effect caused by an interferer of a given level depends upon the proximity of its frequency to these spectral lines. Beckmann has shown that, by prudent choice of GRI, the effects of the whole ensemble of European interferers can be substantially reduced [16].

Using the modified IFRB list, Lincklaen Arriens and Beckmann [16] have selected optimum GRIs for the set of candidate Loran-C chains selected at the Delft meeting of August 1991 (see Section 6). The GRI values chosen are specified in Figs. 3-6.

5 Calculation of fixed repeatability

5.1 Time-of-arrival uncertainty due to atmospheric noise

The signal-to-atmospheric-noise ratio of the signal received from each Loran-C transmitter is calculated at each point in the array from the estimates of field strength (Section 2.1) and atmospheric noise (Section 2.2). The rms value of the resulting uncertainty in the measured time-of-arrival of the signal is then calculated using the following equation [17]:

$$\sigma_{atmos} = \sqrt{\frac{5 \times 10^7}{samples \times SNR \times 4\pi^2}} \qquad (1)$$

'samples' = receiver integration time (secs) $\times 8 \times 10^5$/GRI. A typical receiver integration time of 10 seconds is used in the coverage model.

SNR is the signal voltage divided by the noise voltage.

5.2 Time-of-arrival uncertainty due to CWI

Two separate mechanisms in a Loran-C receiver are affected by CWI:phase-tracking and cycle-identification. Theoretical analysis [14] has demonstrated that, normally, the errors in phase-tracking reach the MPS limit before cycle-identification failure becomes unacceptable. Phase-tracking errors,therefore, are employed to define coverage limits. The uncertainty of TOA due to CWI depends on the signal-to-interference ratio; it is a complex function of frequency. A recent study [14] has shown that, on average over all frequencies, a 100ns rms TOA error results from an SIR of +11dB. Further, providing the strength of the signal significantly exceeds that of the interference, the variation of this rms value is approximately proportional to the SIR. Section 4.2 described how the strength of the interference due to the ensemble of interfering signals is calculated at each point in the array. The SIR at the point is then computed from this value, together with the strength of the Loran-C signal. In this way the rms value of the TOA of the transmission due to CWI is estimated.

5.3 Geometrical factors

Sections 5.2 and 5.3 have described how the TOA uncertainties of each Loran-C transmission due to atmospheric noise and to CWI are estimated at each point in the geographical array. These uncertainties are now combined, by summing their variances, to give the total TOA uncertainty of the signal. We can now derive the repeatable accuracy of the position fix obtained using a triad of Loran stations. The calculation takes into account the customary geometrical factors: the lane expansion factor of each time-difference (TD) pair of TOA measurements and the angle of cut of the pair of hyperbolic lines-of-position (LOPs). These calculations are embodied in the following equation:

$$2DRMS = \frac{2k}{\sin\gamma} \times \sqrt{\frac{\sigma_a^2+\sigma_b^2+\sigma_s^2}{\sin\frac{\alpha}{2}^2} + \frac{\sigma_a^2+\sigma_b^2+\sigma_s^2}{\sin\frac{\beta}{2}^2} + \frac{2(\sigma_a^2+\sigma_s^2)\cos\gamma}{\sin\frac{\alpha}{2}\sin\frac{\beta}{2}}} \quad (2)$$

σ_a, σ_b and σ_c are the individual TOA uncertainties of stations A,B and C.

σ_s is the standard deviation of the transmitter timing control which is 36ns for a modern Loran-C transmitter [17],

γ is the acute crossing angle between the LOPs,

α and β are the angles subtended at the receiver between stations A and B, and B and C, respectively.

k is the scaling factor, 149.8455

In this way we compute the 2drms uncertainty of the fix from the individual TOA uncertainties of the transmissions received from the triad of stations. The use of these equations represents a significant change in the method of dealing with TOAs and geometrical factors in coverage prediction from that adopted previously by the TWG in North-West Europe [2] (although a similar approach has been used elsewhere). Formerly the TWG had followed the USCG method: this assumes that, at the coverage boundary, the SNRs of all three of the stations which contribute to the fix are the same, -10dB. The resulting rms uncertainty in each TD measurement is 100ns, equivalent to 70ns in each of the three individual TOA measurements. The 2drms position uncertainty is then computed by including the effect of the geometrical factors. The USCG limit is 0.25 nm (463m) at the coverage boundary.

This USCG assumption resulted in a modest underestimate of the coverage since it excluded those areas in which the SNR of one or more of the signals is a little poorer than -10dB and the others a little better but where the combined effect of the three signals produces a position uncertainty within the USCG limit. As contours of ever-greater greater precision (200m, 100m, 50m, etc.) are plotted, however, the effect of the new technique becomes progressively more significant. These boundaries lie relatively close to the transmitters, in regions of good SNR, and to assume (as had been done previously) that the TOA uncertainties remained at 70ns and only the geometrical factors improved was unreasonably pessimistic. The new analysis replaces this assumption with more precise estimates of the uncertainties of the TOA and position measurements.

The coverage boundary is the line at which either the fix repeatability attains the USCG limit (463m, 95% confidence) or, alternatively, one or more of the transmissions reaches its skywave or ECD limit.

Mode	First TD pair	Second TD pair
Hyperbolic	M1+S1	M1+S1
Semi-circular	M1+S1	M1+M2 or M1+S2
Cross-chain	M1+S1	M2+S2
Master independent	Any two stations	Any two (not more than 1 of first TD pair)
M1=Master from first chain M2=Master from second chain S1=A secondary from first chain S2=A secondary from second chain		

Table 2: *Receiver operating modes*

5.4 Receiver operating modes

Customarily, the three stations employed to give a Loran-C position fix are the master and two secondaries of the same chain. However, certain types of receiver employ other operating modes which may result in improved performance or enhanced coverage and the model has been extended to cope with a range of additional possibilities. These are set out in Table 2. This Table should also help to clarify the nomenclature since the distinctions between these modes are fairly subtle and different manufacturers sometime employ different names for the same mode.

In Figs.1 and 2, the Bangor model has been used to compare the coverage of an earlier configuration of Loran chains when receiver operate in the hyperbolic, semi-circular and cross-chain modes.

6 Design of the Loran-C system for North-West Europe

As a result of the withdrawal of the United Kingdom from the North-West European Loran-C Consortium in June 1991 it was necessary to re-design the system. A major constraint was the loss of the planned transmitting station in North-East England. On the other hand, the technique of GRI optimisation, developed at Delft, had opened up the possibility of significantly reducing the effects of CWI on receivers and so increasing the coverage of each chain.

A working meeting of the TWG was held at Delft from 20-24 August 1991. Using an interim version of the model described above, the group generated and examined coverage diagrams for some 40 alternative configurations with different master-secondary relationships and transmitter powers. The principal technical problems to be overcome as a result of the loss of the British station were poor coverage off the west coast of Ireland and in the south of Norway. An additional new constraint was that the station at Sylt (Germany) was expected to be required as a master station for the later Baltic expansion of the system; given that no more than dual rating of stations is desirable, Sylt could only act as a secondary station in a single chain of this system. The interim version of the model used at Delft assumed that the GRI of all chains was 7777, a value chosen to minimise CWI over the whole region. Once the preferred configurations had been selected, the GRI for each individual chain was optimised.

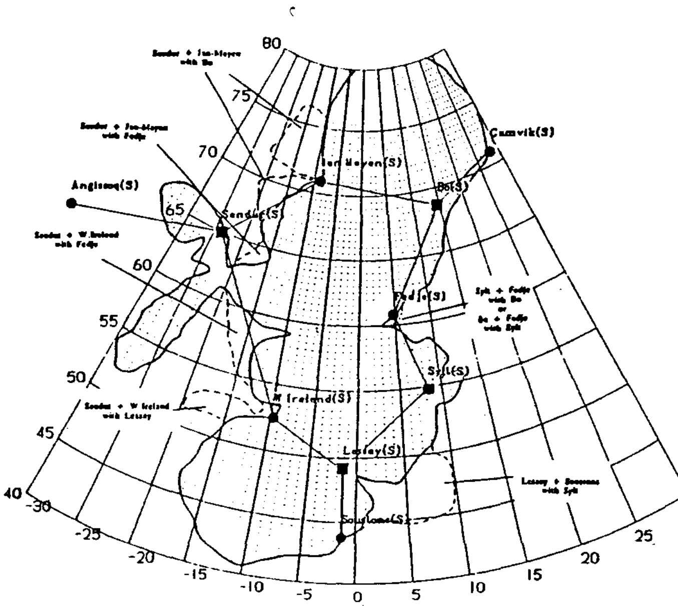


Figure 1: *Coverage showing the effect of semi-circular mode receiver operation*

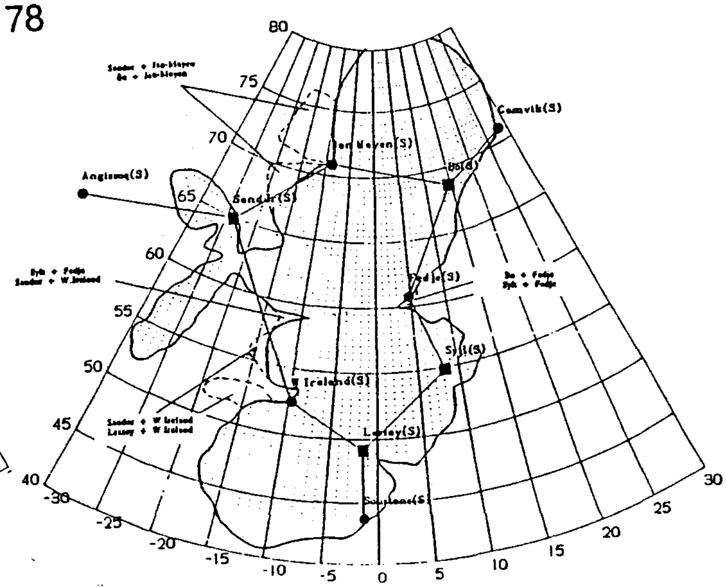


Figure 2: *Coverage showing the effect of cross-chain receiver operation*

Two preferred alternative options (Figs.3 and 4) emerged, which were costed in detail. A third option (Fig.5), which dispensed with the Sandur (Iceland) and Angissoq (Greenland) stations, was also prepared to meet the contingency of an Icelandic withdrawal from the Consortium.

These alternatives embody two different solutions to the problem of coverage west of Ireland. In Alternative 1, Ejde is a master station. The Irish station has been moved north to Blacksod which is within range of Sandur without skywave problems. Two triads, Ejde(M)-Sandur-Blacksod and Lessay(M)-Blacksod- Soustons, provide overlapping coverage. The power of Soustons has been increased to 500kW. In Alternative 2, the west of Ireland is served by the triads Lessay(M)–West-Ireland–Soustons,Lessay(M)–West-Ireland–Ejde or Sandur(M)–Ejde–West-Ireland. The power of Lessay is increased to 500kW. Alternative 3, is a modification of Alternative 1, the Sandur chain being deleted and with Jan Mayen as a secondary to Ejde. In all three alternatives, southern Norway is served by the Sylt(M)-Fedje-Lessay triad.

The final selection was made by the policy group at a meeting in Oslo in December 1991. It was based on Alternative 3, but, in response to the wishes of particular nations, it incorporated a number of changes including the further optimisation of the GRIs, the feasibility of which was demonstrated by using the Bangor model. The station in the west of Ireland was returned to Loop Head and the power of Lessay restored to 250kW.

The following are the chain configurations and transmitter powers for the coverage alternatives of Figs. 3-6:

Alternative 1: <u>Bo Chain</u> (GRI 4219): Master Bo: (400 kW), Secondaries: Gamvik (250 kW), Jan Mayen (250 kW). <u>Ejde Chain</u> (GRI 7223): Master: Ejde (400 kW), Secondaries: Jan Mayen (250 kW), Blacksod (250 kW), Fedje (250 kW), Bo (400 kW). <u>Sylt Chain</u> (GRI 7643): Master Sylt (250 kW), Secondaries: Fedje (250 kW), Lessay (250 kW). <u>Lessay Chain</u> (GRI 5641): Master: Lessay (250 kW), Secondaries: Souston (500 kW), Blacksod (250 kW), Sylt (250 kW).

Alternative 2: <u>Sandur Chain</u> (GRI 7307): Master: Sandur (400 kW), Secondaries: Jan Mayen (250 kW), Ejde (400kW), Angissoq (400 kW), W Ireland (250 kW). <u>Bo Chain</u> (GRI 6001): Master Bo: (400 kW), Secondaries: Gamvik (250kW), Jan Mayen (250 kW), Fedje (250 kW). <u>Sylt Chain</u> (GRI 7643): Master: Sylt (250 kW), Secondaries: Fedje (250 kW), Lessay (500 kW). <u>Lessay Chain</u> (GRI 7223): Master: Lessay (500 kW), Secondaries: Souston (500 kW), W Ireland (250 kW), Sylt (250 kW), Ejde (400 kW)

Alternative 3: <u>Sandur Chain</u> (GRI 6001): Master: Sandur (400 kW), Secondaries: Jan Mayen (250 kW), Ejde (400 kW), Angissoq (400 kW). <u>Bo Chain</u> (GRI 4219): Master Bo: (400 kW), Secondaries: Gamvik (250kW), Jan Mayen (250 kW). <u>Ejde Chain</u> (GRI 7223): Master: Ejde (400 kW) Secondaries: Sandur (400 kW), Blacksod (250 kW), Fedje (250 kW), Bo (400 kW). <u>Sylt Chain</u> (GRI 7643): Master: Sylt (250 kW), Secondaries: Fedje (250 kW), Lessay (250 kW). <u>Lessay Chain</u> (GRI 5641): Master: Lessay (250 kW), Secondaries: Souston (500 kW), Blacksod (250 kW), Sylt (250 kW).

Final option: <u>Bo Chain</u> (GRI 4219): Master Bo: (400 kW), Secondaries: Gamvik (250kW), Jan Mayen (250 kW). <u>Ejde Chain</u> (GRI 7223): Master: Ejde (400 kW) Secondaries:Jan Mayen (250 kW), W Ireland (250 kW), Fedje (250 kW), Bo (400 kW). <u>Sylt Chain</u> (GRI 7643): Master Sylt (250 kW), Secondaries: Fedje (250 kW), Lessay (500 kW). <u>Lessay Chain</u> (GRI 5641): Master: Lessay (250 kW), Secondaries: Souston (250 kW), W Ireland (250 kW), Sylt (250 kW).

Figure 3:
Coverage of Alternative 1.

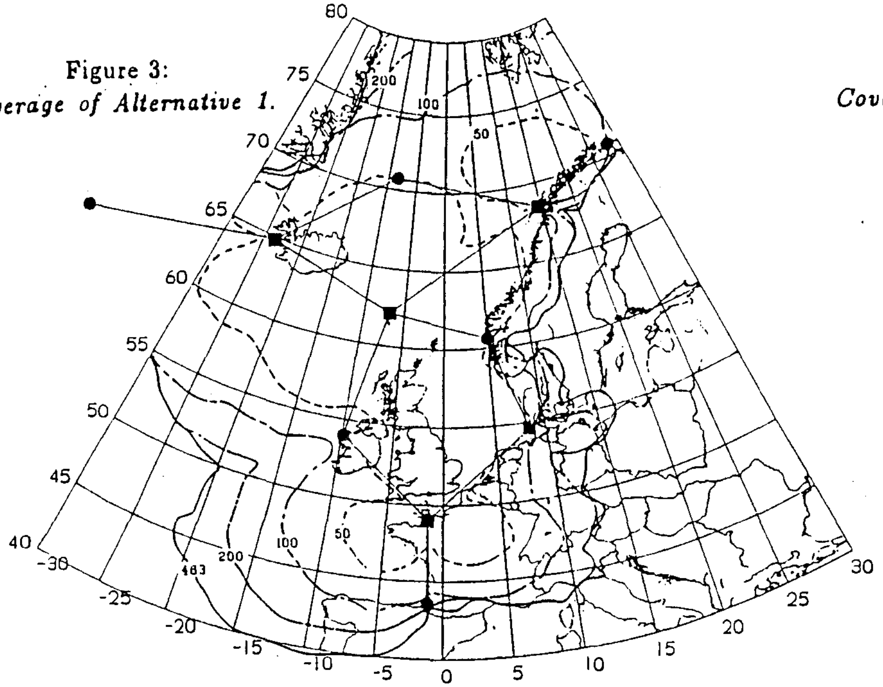


Figure 5:
Coverage of Alternative 3.

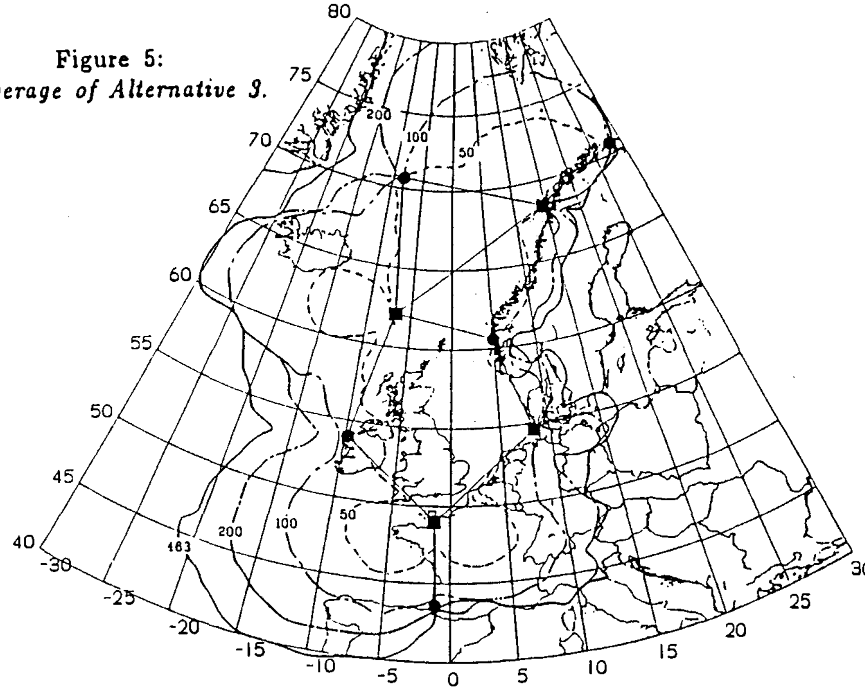


Figure 4:
Coverage of Alternative 2.

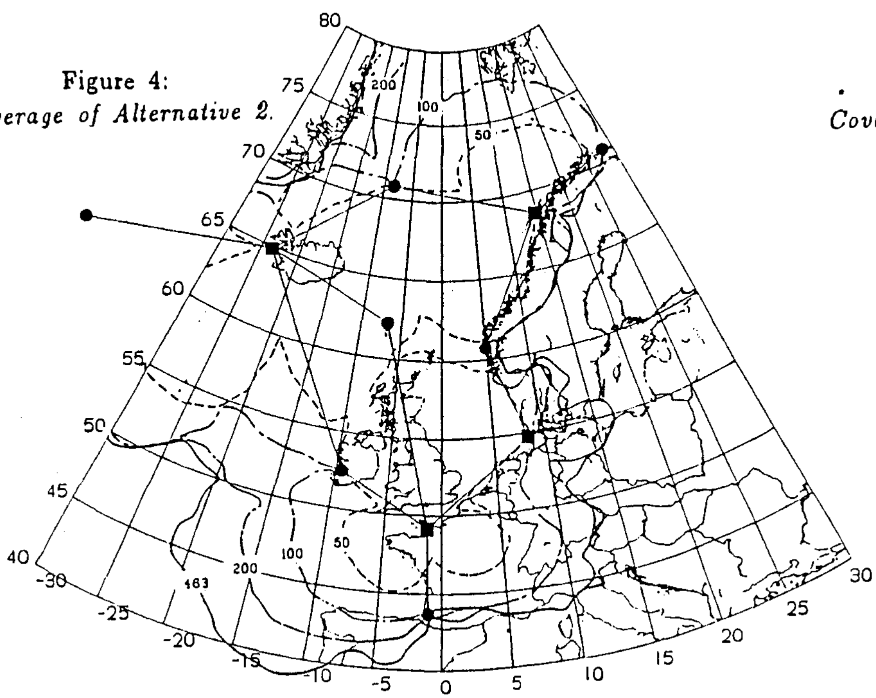
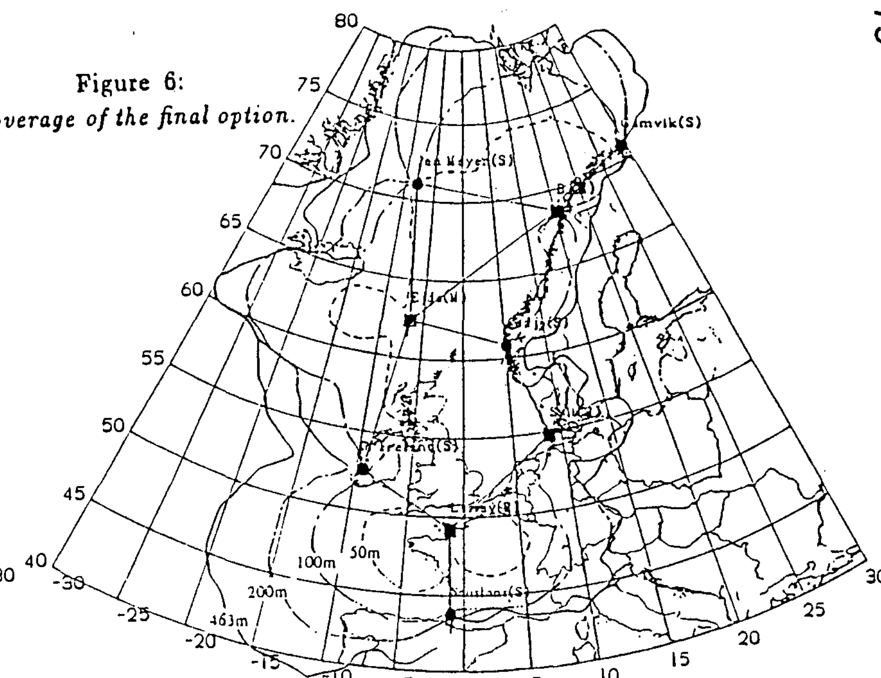


Figure 6:
Coverage of the final option.



7 Conclusions

The paper has described the model used to design the North-West European Loran-C system. This model predicts the coverage and performance of candidate configurations of stations. The paper has presented in detail the assumptions which it embodies and the methods it employs. Finally, the fixed repeatability contours of a short-list of alternative schemes and of the system chosen have been presented.

8 Acknowledgements

Although the coverage prediction model was designed by the Radio-Navigation Group at the University of Wales, Bangor, it embodies the knowledge built up by a large number of members of the Loran-C community. The authors pay special tribute to their colleagues and friends at the Delft University of Technology. They are also indebted to Megapulse, Inc. for their assistance and advice. The guidance, criticism and encouragement of all the members of the North-West European Loran-C Technical Working Group throughout the development of the model was invaluable.

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EXPERIENCE IN THE USE OF LORAN-C WINDFINDING IN THE UNITED KINGDOM

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Operational Loran-C windfinding systems were installed at four sites in the United Kingdom (UK) during 1991. Upper winds are observed by tracking meteorological balloons using Loran signals received by a radiosonde suspended underneath the balloon. The Loran signals are retransmitted from the radiosonde to a Vaisala PC-CORA ground system at the launch site, where the Loran signals are processed to produce winds using a Vaisala SPL11 tracker. Winds obtained with the Loran-C system were compared with those derived from radar tracking during installation tests at each site. Although certain intermittent deficiencies were identified in the Vaisala Loran system, the tests demonstrated that Loran wind measurements were of similar accuracy to those produced by radar tracking. Reprocessing the original observations with the signals from individual Loran transmitters excluded, demonstrates that cross-chain operation has clear advantages over single chain operation at all the sites using Loran windfinding in the UK.

Meteorological Requirements for wind

Upper wind observations are essential for successful weather forecasts. The winds are measured several times per day from a worldwide network of stations, usually by tracking the path taken by meteorological balloons ascending through the atmosphere at about 6 $m.s^{-1}$ to heights between 20 and 35 km above the surface. These observations are supplemented by wind reports from commercial aircraft and winds derived by tracking cloud motion from geostationary satellites.

Wind observations between the surface and heights of about 16 km are made at a vertical resolution of around 300m in the UK. The random errors (1 s.d.) in each component of wind velocity at this resolution must be less than 1 $m.s^{-1}$ between the surface and a height of about 2 km and less than 1.5 $m.s^{-1}$ at heights between 2 and 16km. If the observed wind components are averaged over layers about 1 km thick for global numerical forecasts random errors should alsobe less than 1 $m.s^{-1}$ at levels centred between the surface and 16 km. At heights above 16 km the forecasting requirements for winds are less stringent both in terms of accuracy and vertical resolution. However, longterm scientific investigations quantifying the influence of gravity waves on atmospheric circulations benefit from wind observations of similar quality and resolution to those at the lower levels. Thus, the vertical resolution of wind observations in the UK operational network is kept constant throughout the balloon ascent, i.e. winds are computed from the horizontal displacement of the balloon during 1 minute in flight. All the winds considered in this paper were measured at this resolution.

Operational observations in the UK

From 1965 until 1991 all upper wind observations from land-based stations in the UK were derived by tracking targets suspended under meteorological balloons with Cossor WF MkIV primary radars. Observations were made at 6 hourly intervals from eight UK stations. Pressure, temperature and relative humidity were also measured at midday and midnight by a radiosonde suspended at least 20m under the radar target. The radiofrequency signals from the radiosonde were received at the ground station by a dedicated antenna. Prior to 1978, operators computed the upper air observations manually from the incoming signals. However, since 1979 the radiosonde and radar signals have been automatically processed into the meteorological variables required for the upper air observation. The Cossor radars are unable to track the balloon from launch because the minimum range for automatic tracking is 300m. Hence, 2 members of staff are essential at launch to ensure timely and accurate radar lock onto the target. In 1990 a Vaisala PC-CORA system replaced the original UK RS3 automated ground equipment. PC-CORA is relatively easy to operate. If radar windfinding is replaced, one person rather than two is sufficient to make the upper air observation.

With a Loran-C windfinding system the motion of the radiosonde suspended 20 to 30m under the balloon is tracked using Loran-C signals received by an antenna and receiver mounted in the radiosonde. These signals are then retransmitted by the radiosonde to the ground equipment by suitable modulation of the radiosonde carrier frequency. At the ground the Loran signals are stripped out and processed using a suitable Loran receiver. see Lange [5]. . The Loran tracker is synchronised prior to launch so no special operations are required from the operators at launch. Without a radar target beneath the balloon, single man launching and operation is feasible. The cost of consumables for Loran windfinding is higher than for radar windfinding in the UK operational observation schedule, since Loran radiosondes must be flown on all four flights per day. Loran-C windfinding systems replaced radar windfinding systems at three UK upper air stations during 1991, where the saving in staff resources outweighed the increased consumable costs. These were, Shanwell (03170) [moved to Boulmer 03240 in March 1992], Aughton (03322) and Long Kesh (03920). Figure 1 shows the station locations relative to the nearest Loran-C transmitters. Initial Loran-C windfinding tests were performed at Crawley (03774). This paper describes earlier UK Loran windfinding tests and the experience gained during the operational change from radar to Loran tracking.

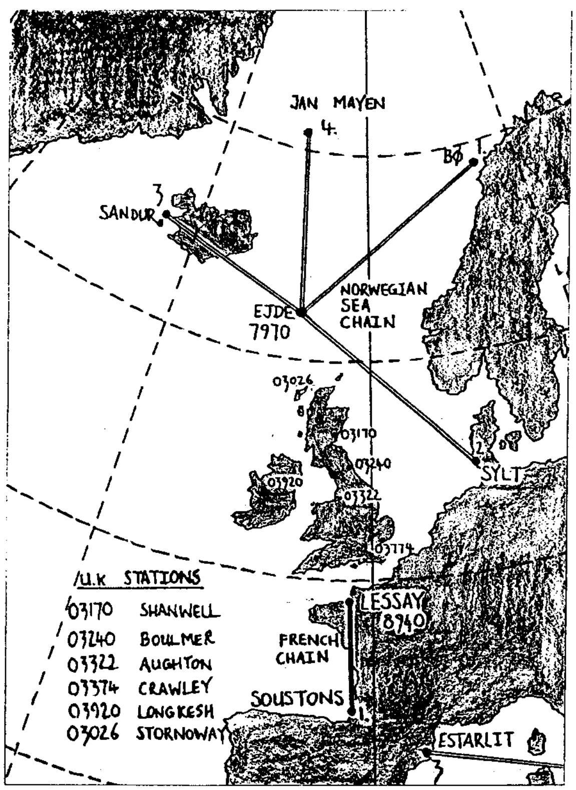

Fig.1 Locations of Loran transmitters relative to UK upper wind observation sites

History of Loran-C wind observations in the UK

Meteorological Research Flight Dropsonde

During the 1970s the UK undertook the development of a dropsonde to be ejected from the Meteorological Research Flight C130 aircraft. The dropsondes fell through the atmosphere suspended from parachutes designed to follow atmospheric motion in the horizontal. Loran signals received by the sonde and retransmitted to a receiver on the aircraft were used to derive winds from the horizontal displacement of the dropsonde. The system used on the aircraft was only capable of single chain operation and was described in Ryder, et al [8]. The quality of Loran signals was monitored at several surface locations in the UK prior to development. Ryder used the results from these static tests to predict the accuracies of single chain Loran wind observations in the north Atlantic and around the British Isles.

OWS Lima

The UK used Loran windfinding for routine operational observations on the Ocean Weather Ship (Starella) stationed at Lima (57°N, 20°W) to the northwest of Ireland from 1976 until 1985. Two Beukers Locate ground stations were used on the ship in conjunction with VIZ radiosondes transmitting at 403 MHz. The Locate systems required the operators to select three Loran stations (i.e. master and 2 slaves from a given chain) prior to flight and to insert the position of balloon launch. Computations were produced from both of the Loran chains available at the weather ship location.

A time of arrival difference from a pair of Loran transmitters defines a line of position (LOP), i.e. the locus of all the possible radiosonde positions for the given time difference. The rates of change of the time of arrival differences from the given pair of transmitters received at the radiosonde are proportional to the velocity of the radiosonde perpendicular to the LOP, the constant of proportionality being termed the scale factor. With a single chain Loran tracker, such as the Locate system, the errors in wind velocity are determined by the signal to noise ratios of the Loran signals received, the scale factors of the Loran pairs and also the angle between the LOP of each Loran master-slave pair at the radiosonde position. With three station Loran tracking, the component of wind velocity perpendicular to the LOP of the Loran pair with the most favourable scale factor and signal to noise ratios will be determined with higher accuracy than the component of wind velocity parallel to this LOP. This effect will be more pronounced if the LOP from the second Loran pair crosses the first LOP at an angle less than 45°.

In 1985, the weather ship was anchored close to the radiosonde station at Stornoway, in the Hebrides, see Fig.1. Simultaneous Loran and radar wind measurements were compared by tracking balloons launched from the weather ship, Kitchen, McLeod and Edge,[3]. Observations were obtained mostly between 0600 and 1800 GMT. This test revealed a flaw in the weather ship Loran wind measurements. The wind velocity component perpendicular to the Ejde-Sylt LOP was underestimated by 5 per cent. This led to a systematic bias in Loran wind speed observations during the test that would have been considered unacceptable against current observational requirements. By the time the test results were processed OWS Starella had been taken out of operation so the exact origin of the error remained unidentified. However, this experience highlighted the need for thorough testing of operational windfinding systems before operations commence rather than at the end of useful life.

The LOP of the Ejde - Sylt pair at Stornoway is aligned approximately southwest to northeast. Static monitoring by Ryder (unpublished Met.Office memorandum) demonstrated that the signals from this pair had more favourable signal to noise ratios than those from Ejde-Sandur, the other pair used. Loran signals received from Ejde and Sylt at Stornoway were dominated by the ground wave. Sandur observations had much weaker ground wave and a higher proportion of skywave with the first hop skywave predominant at nighttime. The results of the weather ship test indicated a random error in Loran wind component meausurements of 0.5 $m.s^{-1}$ perpendicular to the Ejde-Sylt LOP and 1.5 $m.s^{-1}$ parallel to the Ejde-Sylt LOP. These random errors were larger than the 0.3 $m.s^{-1}$ rms vector errors predicted for daytime observations in the Stornoway area by Ryder.

Benbecula

In 1984 a Loran windfinding system manufactured by Vaisala was purchased for use at the military range at Benbecula, Hebrides. The acceptance trial for the equipment was performed at Stornoway, see Kitchen and Nash [4]. Test flights were mainly performed during the day. The best agreement between radar and Vaisala Loran winds was obtained between heights of about 1.5 and 3.5 km. Here, the rms vector errors in the Loran wind observations were estimated as 0.7 $m.s^{-1}$, with a random error in the wind component perpendicular to the Ejde-Sylt LOP of between 0.2 and 0.3 $m.s^{-1}$, and in the component parallel to the Ejde-Sylt LOP of about 0.6 $m.s^{-1}$. The asymmetry in the random errors of these Loran winds was similar to that found for the weather ship system. However, the absolute magnitude of the errors was a little smaller than for the weather ship as the average rms vector error between the surface and 16km for the Vaisala observations was about 1.2 $m.s^{-1}$.

Crosschain Loran tracking

In 1987, a windfinding system using cross-chain Loran tracking was tested at Crawley upper air station under a contract for Vaisala Oy . The system was based on fully automated Vaisala DigiCora ground equipment. With this system, rms vector errors for the Loran wind measurements were 0.7 $m.s^{-1}$ between the surface and about 16 km and there was no significant asymmetry in the random errors. During the same year, Clough et al [unpublished Met. Office memorandum] developed a similar system with cross-chain tracking ability for use with the Metorological Research Flight dropsondes.

As the test results for both cross-chain systems indicated winds of similar quality to those obtained by radar tracking, Loran systems were ordered from Vaisala Oy in 1990 to allow single man operation to commence at four of the UK land stations in 1991/2.

Vaisala PC-CORA system

The Vaisala PC-CORA ground system, Lister and Pettifer [6] and Nash [7] was introduced in the UK in 1990 using tracking data from the Cossor radars to compute winds. However, the system was also designed to accommodate Loran or Omega navaid windfinding, if additional navaid trackers and software were purchased from Vaisala. In the Loran windfinding configuration a Vaisala SPL11 Loran-C receiver is added to the PC system together with a whip antenna for local Loran signal reception. The local Loran signals are used to synchronise the Loran receiver prior to radiosonde launch. The Loran receiver acquires data from the standard UHF (403 MHz) receiverfor the incoming radiosonde signals . The rates of change of the time of arrival differences derived by the Loran receiver are output at 10s intervals to the Vaisala SPU11 card in the PC system. The independent microprocessor on this card computes winds from the Loran tracking data using, , see Karhunen [2],:-

$$\bar{\dot{x}} = (K^T Q^{-1} K)^{-1} K^T Q^{-1}\bar{\dot{t}}$$

where

$\bar{\dot{x}}$ is the wind vector

K is the matrix of Loran-C geometry

Q is the weight matrix computed from the variances of the rates of change of the time of arrival differences

and $\bar{\dot{t}}$ is the vector of the rates of change of time of arrival differences

This formulation allows all the available Loran signal pairs to be used in the wind computation. In the UK there can be as many as 5 independent Loran time differences available. The variances and rates of change of the time of arrival differences are determined as the Loran tracking data update by fitting a polynomial to the data in a given time window. If time of arrival data from a given Loran pair in the time window are too noisy, they are dropped from the computation. Winds are computed and output from the SPU11 to the PC system for use in the reported observation if the quality of the Loran geometry, as represented by the determinant of the matrix $(K^T.Q^{-1} K)^{-1}$ is adequate. The precise details of the algorithms and the limits used in the computations have not been disclosed by Vaisala. In the following sections, comparison against simultaneous radar wind observations and recomputation of flights using different combinations of Loran stations have been used to judge the skill of the Vaisala procedures.

Comparisons of PC-CORA radar and Loran winds

A typical comparison between radar and Loran winds between the surface and about 18 km can be seen in Fig. 2. This was obtained during installation testing at Shanwell. Agreement between the two sets of observations is close, but even at the lower levels the Loran winds indicate a smoother vertical structure in the v component than the radar winds.

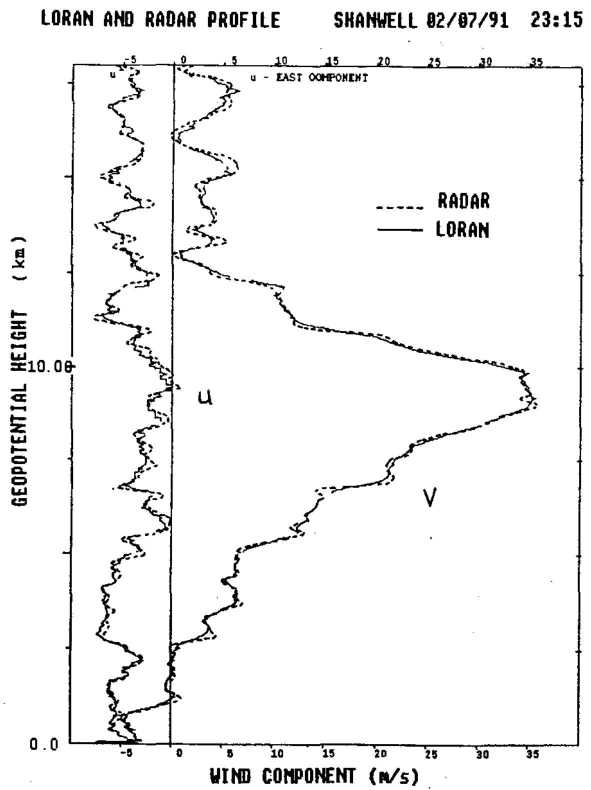

Fig.2 Typical profiles of Loran and radar wind observations .

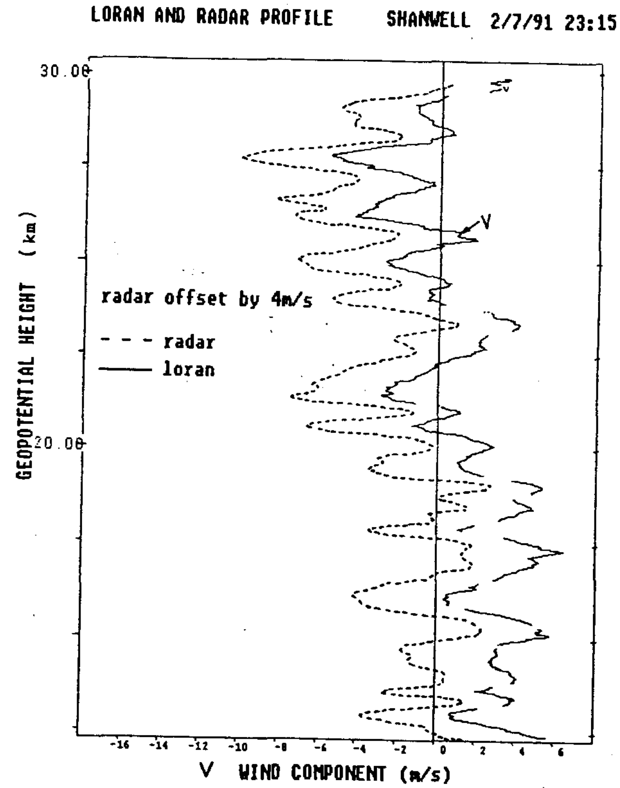

Fig.3 Typical profile of loran and radar northerly wind components in the stratosphere.

In the summer , winds are usually weak in the stratosphere,(e.g. at heights above the jetstream maximum in Fig.2), but gravity waves cause substantial variation in the vertical in each wind component. Loran and radar tracking indicate similar structure in the vertical , but the amplitude of the variations in the Loran winds is typically smaller than that of the variations in the radar winds, see Fig.3. Either the Loran tracking data are overdamped or smoothed for longer than the nominal 1 minute sampling period during processing or the radar tracking data are underdamped. This requires further investigation.

The gaps in the Loran winds in Fig.3 are caused by the quality control procedures applied to the Loran signals during the computations. The operator has to accept the machine decision. He is not presented with an estimate of wind component error or an error message to query why so many wind observations are being rejected. The Loran signals do not appear to be close to a critical noise threshold since the vertical structure in the Loran winds has a very close correlation with the structure in the radar winds. There is no indication of excessive noise in the observations near the data gaps. There are usually enough viable wind reports that the gaps in the reported Loran winds can be tolerated in operational practice. However, at heights close to the jetstream maximum gaps in reported Loran wind data often occur in regions of very strong wind shear and these do lead to misrepresentation of significant vertical wind structure.

Loran and radar windfinding systems were operated simultaneously for about four weeks before Loran operations commenced at all the new installations in 1991. Typical comparison statistics between Loran and radar wind components are presented as a function of time into flight, in Fig.4, for an initial test at Shanwell performed in July 1991. The horizontal displacement of the balloons from the launch site in the Shanwell test was not large (less than 50 km on average) and so the radar tracking errors probably did not vary very significantly with time into flight. The random errors (1 s.d.) in each of the wind components observed by the Cossor radar could be expected to be about 0.3 ± 0.1 $m.s^{-1}$ at close ranges increasing to nearer 0.5 ± 0.1 $m.s^{-1}$ at 50 km slant range, see Edge et al [1]. Hence, the results in Fig.4 indicate that random errors in each orthogonal component of the Loran winds were most probably in the range 0.2 to 0.5 $m.s^{-1}$ between minutes 6 and 40 into flight. These are similar in magnitude to the radar tracking errors. There was no evidence of asymmetry in the random error distributions in the Shanwell data set. The strongest signals received at Shanwell were predominantly ground waves from Ejde, Sylt and Lessay. Both Loran pairs available from these signals would have similar signal to noise ratios and the LOPs would cross at angles near 90°. Single chain tracking at Shanwell would give poorer wind accuracy in the direction parallel to the Ejde-Sylt LOP than perpendicular to this LOP (see earlier Stornoway tests), because of

Table 1

Statistics of [Vaisala Loran - Cossor radar] wind components obtained during operational installation tests in the United Kingdom (note: wind component u is positive for a westerly wind and wind component v is positive for a southerly wind .

Station	Launch hour GMT	Elapsed time minutes	u mean $m.s^{-1}$	u s.d $m.s^{-1}$	v mean $m.s^{-1}$	v s.d $m.s^{-1}$
Crawley	0,6,12,18	6-10	0.0	0.6	0.0	0.6
Shanwell	0,6,12,18	6-10	0.2	0.5	0.0	0.5
Aughton	0,6,12,18	6-10	0.1	0.6	0.0	0.5
Long Kesh	0,6,12,18	6-10	0.0	0.9	0.1	0.6
Crawley	0,6,12,18	21-30	0.0	0.9	0.0	0.8
Shanwell	0,6,12,18	21-30	0.2	0.5	0.0	0.5
Aughton	0,6,12,18	21-30	0.2	0.7	0.1	0.7
Long Kesh	0,6,12,18	21-30	0.0	0.8	0.2	0.8
Crawley	0,6,12,18	41-80	-0.1	1.1	0.0	1.0
Shanwell	0,6,12,18	41-80	0.1	1.0	0.0	1.0
Aughton	0,6,12,18	41-80	0.2	1.1	0.0	1.1
Long Kesh	0,6,12,18	41-80	-0.1	1.2	0.3	1.5
All	0	41-80	0.1	1.0	0.1	1.1
All	6	41-80	0.1	1.0	0.1	1.1
All	12	41-80	0.0	1.2	0.1	1.3
All	18	41-80	0.0	1.1	0.1	1.1

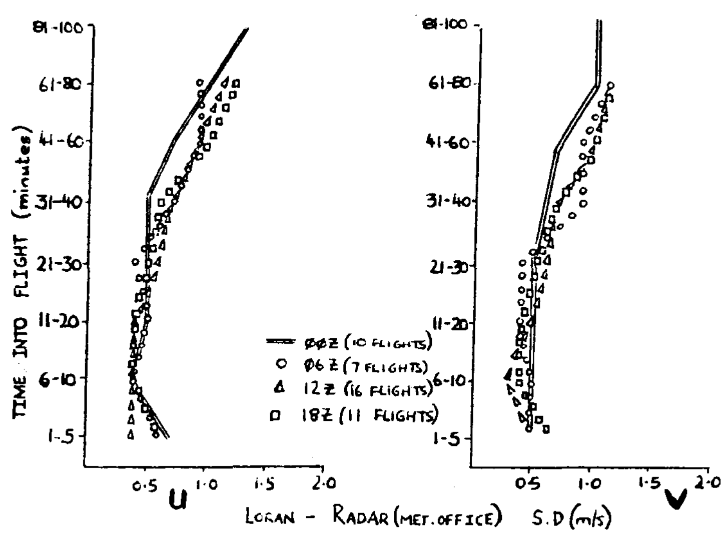

Fig.4 Summary of the standard deviation between simultaneous Loran and radar winds at Shanwell.

the need to rely on the Ejde-Sandur pair in the Norwegian chain. Crosschain Loran tracking avoids this degradation. .

Near the surface ,i.e. minutes 1 to 5 in Fig.4, Loran winds (poor signal reception immediately after launch) have slightly larger errors.

The increased scatter between the Loran and radar winds from minute 41 onwards was not just the result of degradation in radar tracking accuracy.

The signal to noise ratios of the Loran tracking data received at the ground decrease in the later stages of the balloon ascent. This should lead to increased random error in the Loran winds. The Vaisala system does not record information on the signal to noise ratios in a useful fashion for the operator during or after the flight. An error estimate would be of more practical use than the current indication of whether a given Loran station is used in each wind computation or not. The number of signals exceeding the threshhold of usefulness applied by the Vaisala software does not give a reliable indication of the magnitude of the random error expected in the reported wind. The different response of the two tracking systems to smaller scale wind variations in the vertical, see Fig.3, must also play a part in increasing the random scatter between the two sets of winds .

Table 1 summarises the results of Loran - radar system testing at four UK sites. The 1991 tests were performed at Crawley in February/March, at Shanwell June/July, at Aughton September/ October and at Long Kesh November/Decmber. In the first time band in Table 1, i.e. 6 to 10 minutes into flight, radar tracking errors should be a minimum in all data sets and should be 0.3 ± 0.1 $m.s^{-1}$ in both components. The second time band, 21 to 30 minutes into flight, can be used to judge if any substantial degradation in wind accuracy has taken place when the balloon has reached jetstream heights. In the final time band, horizontal balloon displacents may be large. Average displacements were largest for the Long Kesh data This offers a partial explanation of why this data set has the largest standard deviations between loran and radar winds.

Long Kesh was the only site where there was an indication of significant asymmetry in the random differences between the two sets of wind observations. It is unlikely that the asymmetry was associated with the radar wind observations.

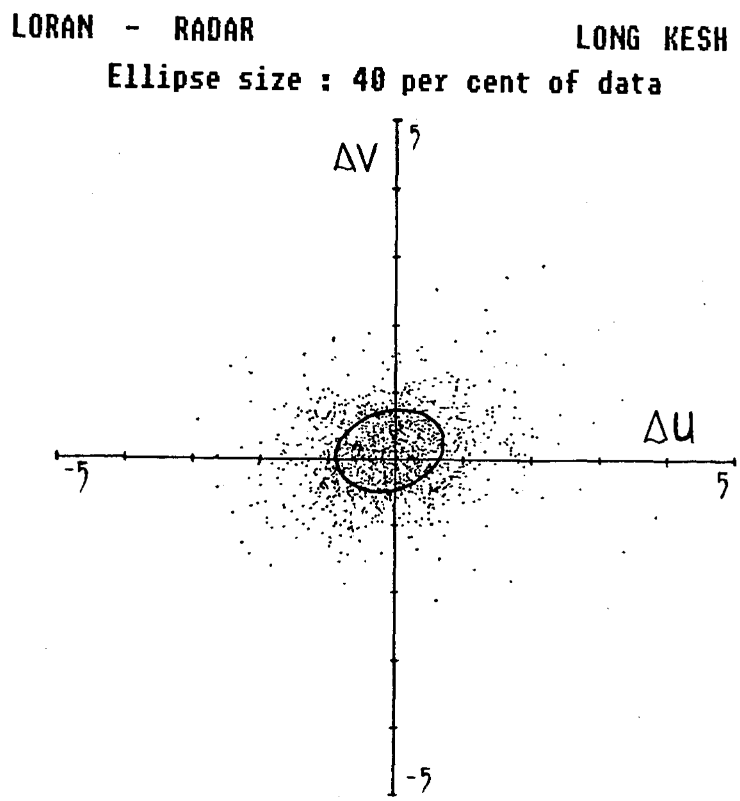

Fig. 5 Scatter plot of vector differences [$m.s^{-1}$] between Loran and radar winds at Long Kesh, for minutes 5 to 25 into flight.

The scatter plot of the vector differences between Loran and radar winds between minutes 5 and 25 into flight can be seen in Fig.5. The major axis of the ellipse fitted to the random error distribution is aligned parallel to the Ejde - Lessay LOP at Long Kesh. The random errors in the Loran wind velocity in this direction were estimated to be in the range 0.7 to 0.9 $m.s^{-1}$. The Loran receivers used at Long Kesh were found to have intermittent errors in the timing assigned to the tracking data. It is possible that these errors increased the scatter between the Loran and radar winds. However, the asymmetry suggests that the Ejde- Lessay station pair was providing better Loran tracking accuracy than the Ejde-Sylt and Lessay-Sylt pairs.

Ryder found substantial increases in Loran tracking noise during static Loran monitoring at Stornoway. This was attributed to enhanced skywave propogation at night. The combined comparison results split according to time of observation in Table 1 do not indicate a substantial diurnal variation in Loran observational error. The poorest agreement between Loran and radar winds was found in midday measurements, particularly at Long Kesh.

Vaisala system faults

Intermittent faults

Operational testing identified several intermittent faults in the Loran system.

On occasions, the time assigned to the Loran tracking data would reset to zero during launch preparations. This led to a mismatch with the PC system times of up to 10 minutes and winds were assigned to heights up to 3 km in error. Additional symptoms of this fault were identified so operators could identify when the fault had happened, and reinitiate the flight.
In a limited number of test flights (particularly at Long Kesh, but also at Aughton and Crawley) the timer in the Loran tracker updated too rapidly so that by the end of the flights Loran times differed from the PC and radar times by more than 1 minute. Vaisala claim to have identified the origin of this fault. No diagnostics are available to warn the operator if it occurs.

Communication between the Loran receiver and the SPU11 card would often lock when operating with early versions of PC-CORA software. This has largely been overcome with updated software.

System deficiencies

As noted earlier, the system would be improved substantially if wind error estimates were derived from the Loran tracking data and output into the data archives. The operators could then recognise poorer quality measurements. Fault investigations would be eased. The tests have shown that Vaisala quality control

Table 2
Statistics for reprocessed wind components
[Vaisala Loran, 1 transmitter excluded] - Vaisala Loran, all stations]

Loran signal excluded	Launch site	Elapsed time minutes	u mean $m.s^{-1}$	u s.d $m.s^{-1}$	v mean $m.s^{-1}$	v s.d $m.s^{-1}$
Ejde	Shanwell	1 - 5	0.0	0.5	0.0	0.2
Bø	Shanwell	1 - 5	0.0	0.2	0.0	0.1
Sylt	Shanwell	1 - 5	-0.7	2.7	0.0	0.5
Lessay	Shanwell	1 - 5	-0.1	0.5	-0.1	0.4
Soustons	Shanwell	1 - 5	0.0	0.2	0.0	0.1
Ejde	Shanwell	11 - 20	0.1	0.3	-0.1	0.3
Bø	Shanwell	11 - 20	0.0	0.2	0.0	0.1
Sylt	Shanwell	11 - 20	0.0	1.4	0.0	0.3
Lessay	Shanwell	11 - 20	0.0	0.4	0.0	0.5
Soustons	Shanwell	11 - 20	0.0	0.1	0.0	0.1
Ejde	Shanwell	61 - 80	0.0	0.3	-0.1	0.3
Bø	Shanwell	61 - 80	0.0	0.2	0.0	0.2
Sylt	Shanwell	61 - 80	-0.1	1.0	0.0	0.3
Lessay	Shanwell	61 - 80	0.0	0.4	0.1	0.5
Soustons	Shanwell	61 - 80	0.0	0.1	0.0	0.1
Ejde	Crawley	1 - 5	0.0	0.3	0.0	0.2
Sylt	Crawley	1 - 5	-0.3	1.6	0.1	1.0
Lessay	Crawley	1 - 5	0.1	0.9	0.1	1.2
Soustons	Crawley	1 - 5	0.1	0.8	0.1	1.2
Ejde	Crawley	11 - 20	0.0	0.2	0.0	0.1
Sylt	Crawley	11 - 20	-0.1	0.6	0.0	0.2
Lessay	Crawley	11 - 20	0.1	0.3	0.0	0.1
Soustons	Crawley	11 - 20	0.0	0.2	0.0	0.1
Ejde	Crawley	61 - 80	0.0	0.3	0.0	0.3
Sylt	Crawley	61 - 80	-0.2	1.0	0.0	0.2
Lessay	Crawley	61 - 80	0.1	0.2	0.0	0.2
Soustons	Crawley	61 - 80	0.1	0.2	-0.1	0.1

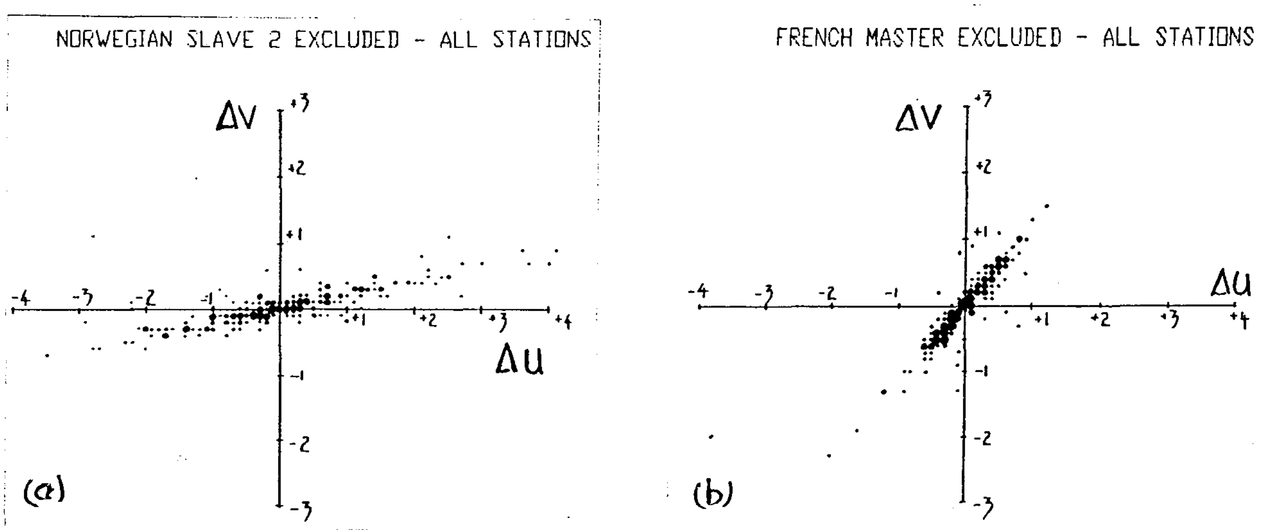

Fig.6 Vector differences [$m.s^{-1}$] between reprocessed Shanwell winds and the original multistation Loran observations.
(a) Sylt excluded, (b) Lessay excluded.

procedures do allow fairly large wind errors if Loran signal reception is poor. In the UK, poor Loran reception is usually caused by a faulty radiosonde transmitter or Loran receiver. This does not occur very often in practice, since the Vaisala radiosondes have relatively few failures. However, the operator needs to decide whether to abandon a flight and launch a replacement radiosonde.

In practice , stations using Loran windfinding have been making more repeat flights (typically 2 to 3 per month) than at the stations using radar windfinding, usually because Loran tracking has failed during flight. On several occasions Loran signals have been lost when radiosondes have been flying through active weather fronts. The origins of this signal loss are under investigation.

If the radiosonde has a faulty Loran receiver, this does not become apparent to the operator until the radiosonde is launched. Then no Loran signals are received from the radiosonde although the pressure ,temperature and relative humidity observations are present. It would be more cost effective if Loran reception via the radiosonde antenna could be checked prior to launch and faulty radiosondes returned to the manufacturer for repair.

During the first year of operation, each of the three sites using Loran has encountered problems with the SPL11 Loran receiver supplied by Vaisala. The receivers seem to gradually become detuned from the Loran signals and so the Loran signal strengths detected from the radiosonde are not always adequate for windfinding. The reason for this is currently under investigation. If a spare Loran receiver had not been available at each site, Loran wind observations could not have been sustained.

Reprocessed winds

The PC-CORA system allows winds to be recomputed using archived Loran time of arrival data reprocessed by the SPL11 Loran receiver. The PC-CORA system parameter file can be adjusted to exclude signals from nominated Loran stations during the reprocessing. The necessary archives are available from all the test flights , but the reprocessing is extremely time consuming and only a limited sample has been reprocessed to date. The statistics in Table 2 compare wind components computed with given Loran signals excluded to the original computation using all available signals. The flights were chosen arbitrarily and consist of 10 flights from Crawley at 18.00 GMT and 10 from Shanwell at 12.00 GMT. Data from three time bands are represented in Table 2. Minutes 11 to 20 were chosen to represent optimum Loran signal reception conditions, with minutes 1 to 5 and 61 -80 expected to have poorer Loran signals.

The removal of a Loran signal that has little impact in the original computation produces winds with a standard deviation of between 0.1 and 0.2 $m.s^{-1}$ relative to the original computation, e.g. see the impact of the exclusion of Soustons or Bø signals from Shanwell observations.The exclusion of Sylt signals has the biggest impact on wind computations at both Crawley and Shanwell. This indicates that the quality of operational Loran winds in the UK depends strongly on the operation of this transmitter. Fig.6(a) contains a scatter plot of the differences between Shanwell winds computed with Sylt excluded and the original winds. With Sylt excluded the increased errors in the reprocessed winds are aligned parallel to the Ejde-Lessay LOP at Shanwell. The equivalent plot for winds with only Lessay excluded is included at Fig. 6(b). The increased random errors are then aligned parallel to the Ejde-Sylt LOP at Shanwell.

The redundancy in the multistation wind computation at Crawley means that the loss of any of the Loran signals apart from Sylt does not lead to a significant degradation in Loran wind quality, if the radiosondes are more than 1.5 km above the surface.The situation is not so favourable at Shanwell, where the loss of either Sylt or Lessay Loran signals does lead to degradation of Loran wind observations. It is undesirable for an operational system to rely heavily on one particular Loran transmitter for satisfactory operation. Thus, in the long term, the installation of an additional Loran transmitter in southern Ireland would probably offer significant advantages to the UK.

Conclusions

After extensive testing , satisfactory operational windfinding systems have been established at four sites in the UK. The quality of the wind observations is similar to the quality of winds obtained from the radar tracking systems that were replaced. The current Loran wind observations are of better quality than those obtained with earlier single chain Loran systems. Crosschain Loran operation has benefits at all the UK installations. Small scale variations in the vertical in Loran winds have smaller amplitude than in radar winds .The Vaisala system would be substantially improved if wind error estimates were derived from the Loran tracking data used to compute the winds.

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ANALYSIS OF ENVELOPE-TO-CYCLE DIFFERENCE (ECD) IN THE FAR FIELD

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ABSTRACT

With the recent mid-continent expansion of LORAN in the United States and the worldwide increase in the use of LORAN in terrestrial and aviation applications, the understanding of propagation over land of LORAN signals has received renewed attention. This study focuses on two aspects of the ability of a LORAN receiver to select the correct zero crossing to track. First, it has long been thought that the negative change in ECD is more rapid over land than seawater. Recent data has shown this not to be true and one purpose of this study is to develop a more accurate model of the variation of ECD with distance and ground conductivity. As opposed to using stationary monitor receiver data, we use flight data covering virtually the entire continental United States.

Second, with more groundwave attenuation over land than over seawater, skywave to groundwave ratios are larger and skywaves are potentially more of a problem. Also, in Europe, with the very large number of interfering signals in the adjacent LF bands, some receivers have very narrowband front ends which further complicates the skywave problem. In our study we have developed a highly accurate model of pulses from solid state transmitters which allows the isolation of skywave from groundwave. This allows us to collect statistical data on skywave to groundwave ratio, skywave delay, and skywave ECD. These statistics, together with a knowledge the frequency response of the receiver front end and the ECD estimation method, allow us to predict ECD bias and cycle selection problems due to skywave interference.

INTRODUCTION

Starting in 1991, 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. 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. At the 1991 Wild Goose Association (WGA) Symposium [1], we discussed such issues as: With present technology, how is ECD measured? What are the statistics of the measurement? What sources of bias exist? In particular it was shown that cross rate interference could be a significant source of bias in the ECD measurement. In this paper we analyze ECD changes over land using flight data, which unlike monitor data, should not contain bias due to cross rate interference. Also, at the same meeting, David Last and others [2], suggested that skywave interference in many cases may be the limiting factor in a receiver's ability to select the proper zero crossing for tracking. At the 1987 WGA Symposium, [3] we had suggested methodology for systematically studying skywaves but we had only collected a small amount of data. In this paper we present a revised method and much more extensive data. For an earlier and longer version of this paper containing many more graphs of the data, the reader is referred to [4].

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GROUND CONDUCTIVITY ANALYSIS AND ECD

One type of shape change which can cause a receiver to cycle slip is the Envelope-To-Cycle Difference (ECD) of the pulse. One model for ECD is a phenomena which results from a difference between the group velocity, the speed at which the envelope propagates, and the phase velocity, the speed at which the zero-crossing propagates. This difference between group and phase velocities is because different frequencies within the LORAN band propagate at different phase velocities. Assuming the most experience in phase velocities near the LORAN band would be related to the DECCA navigation system, we contacted Mr. Alf Ramsay with RACAL DECCA, formerly DECCA NAVIGATOR COMPANY LIMITED and he provided us with an internal DECCA memo from 1950 [5]. This contained plots of phase velocity vs ground conductivity for the various DECCA frequency bands.

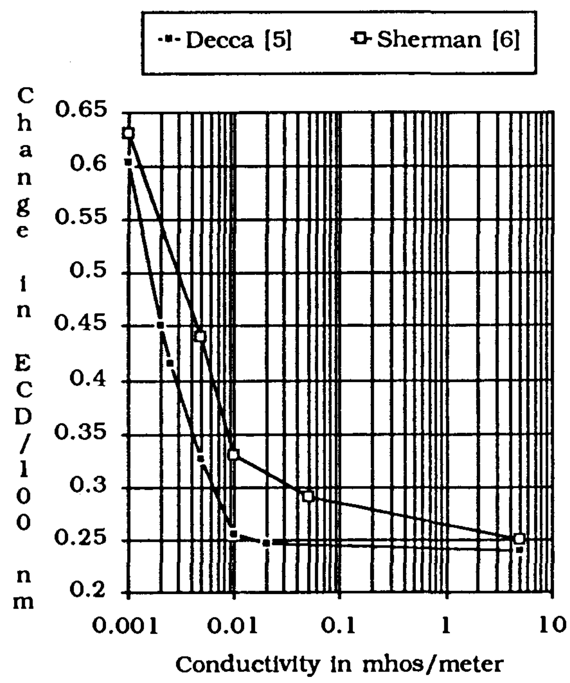

Figure 1. Predicted change in ECD per 100 nm vs ground conductivity.

Using the standard expression for group delay (derivative of phase with respect to frequency), it can easily be shown that the change in ECD per 100 nm is approximately 7.27 x 10^{-6} μsec times the difference in phase velocities at 85 (Master) and 113.3 (Red) kHz in m/sec. Since this difference is approximately 33,000 m/sec over seawater, this implies about 0.24 µsec of negative shift per 100 nm and agrees very well with the generally accepted value of 0.25 µsec. In [6], Sherman using Coast Guard monitor data fit this data to a curve Figure 1 compares Sherman's model [6] to that predicted by the curves of phase velocity in [5]. The two curves show reasonable agreement and both predict much larger changes over land than over seawater. It is worth noting that the DECCA data suggests virtually the same rate of change for good ground conductivity (10 mmhos/m or greater) as for seawater while Sherman's data suggests faster change for these conductivities. In [7], Taggart conducted further analysis of Coast Guard monitor and suggested a least squares method for the analysis and we use essentially his method in the analysis below.

Anecdotal results indicate that these models do not accurately predict the change in ECD over

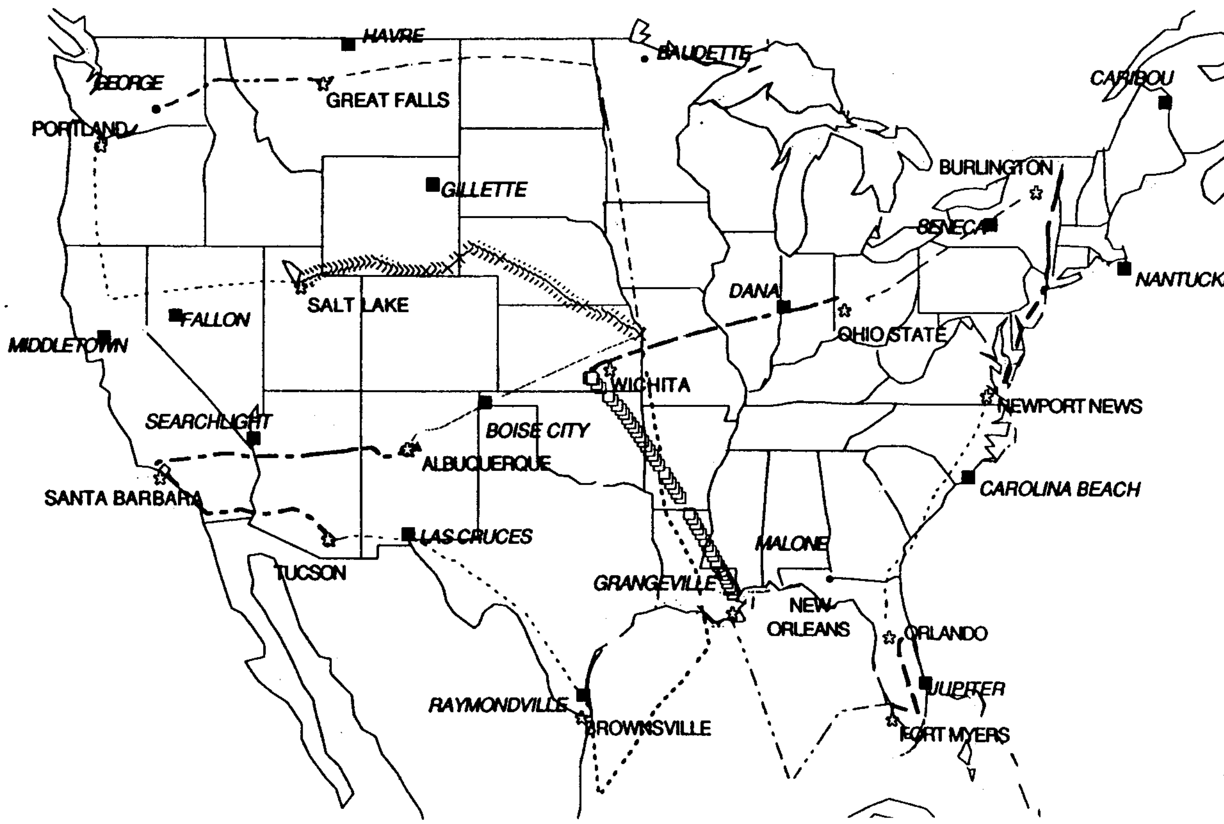

Figure 2. Paths of BENDIX KING flights.

ground paths. BENDIX KING corporation provided us LORAN data collected from airplane flights across the US. These paths are shown in Figure 2. We plotted the ECD of these paths against the distance the receiver was from the transmitter to try and determine the rate of change of ECD. Figure 3 is a typical plot plot where the data was collected over a ground path. This data was collected from the Baudette transmitter in a flight between Kansas City and Great Falls.

Although the model predicts that ECD should change faster than .25µsec/100nm, it actually changes slower. We noticed that few of the paths over land conform to Sherman's model. Using the BENDIX KING LORAN data and a data base of the ground conductivity for the United States. We partitioned the conductivity of the US into 7 discrete values: 1, 2, 4, 8, 15, 30, 5000(seawater) mmho/meter. For each point along one of the airplane paths, we calculate the distance a pulse traveled over each value of conductivity. Using this information and the ECD at each coordinate we can calculate in a least squares sense the rate of change of ECD for various conductivities. For example:

Assuming ECD can be written as a function of ground conductivity according to the following equation:

$$ECD(n) = C_0 + C_1L_1(n) + C_2L_2(n) + C_3L_3(n) + C_4L_4(n) + C_5L_5(n) + C_6L_6(n) + C_7L_7(n) + e\text{ , where}$$

C_0 = a constant

$C_{1\text{-}7}$ = rate of change of ECD for each of seven values of conductivity (µs/nautical mile)

$L_{1\text{-}7}$ = path length which ECD has traveled for each conductivity (nautical mile)

n = number of each point collected

e = vector of errors

The vector of C values which minimize the length of the error vector (e) is given by:

$$C = (A^TA)^{-1}(A^TY),\text{ where}$$

$$A = \begin{matrix} 1 & L_1(1) & L_2(1) & L_3(1) & L_4(1) & L_5(1) & L_6(1) & L_7(1) \\ 1 & L_1(2) & L_2(2) & L_3(2) & L_4(2) & L_5(2) & L_6(2) & L_7(2) \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ 1 & L_1(n) & L_2(n) & L_3(n) & L_4(n) & L_5(n) & L_6(n) & L_7(n) \end{matrix}$$

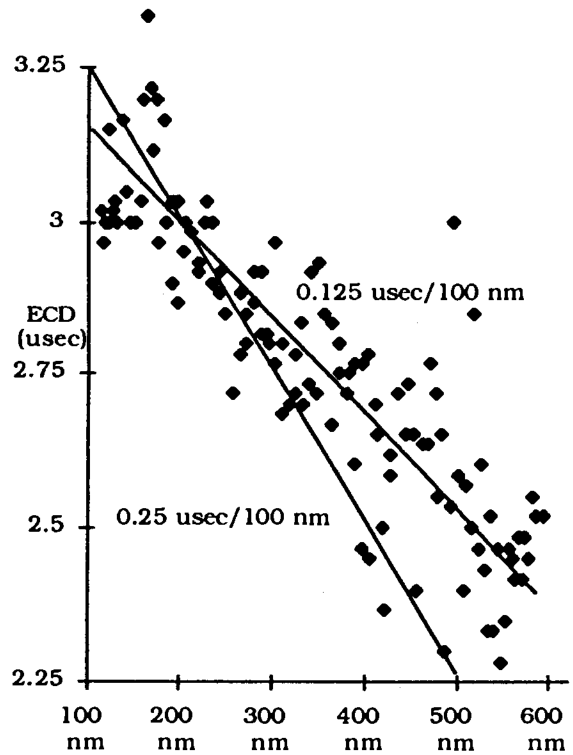

Figure 3. ECD in μsec vs distance for Baudette on flight from Kansas City to Great Falls

and Y is matrix of ECD's at each point, i.e

$$Y = \begin{matrix} ECD(1) \\ ECD(2) \\ ECD(3) \\ \cdots \\ ECD(n) \end{matrix}$$

Data was collected by BENDIX KING every 20 sec. We processed the data in groups of 9 samples to give us data every 3 min. The individual samples were checked for receiver warnings. Of the valid data, the largest and smallest were discarded and the mean of the rest calculated. The conductivity data base was divided into cells of 0.2° of latitude and 0.25° of longitude, or about 12 nm on each side. A plane travelling at 240 knots would travel 12 nm in 3 minutes. We discarded data beyond 600 nm where significant skywave interference could be present. We averaged approximately 25,000 samples to get our results. The program accesses a point in the pre-processed flight data and its averaged ECD, calculates the conductivity values along the path from the transmitter and stores the information in the appropriate matrix. Using data collected across the United States we can solve for the vector C, the rate of change of ECD for the various conductivities. With these values we have created a new model of the effects of ground conductivity on the rate of change of ECD. Figure 4 compares our model with same data as in Figure 1 above. Using these coefficients to predict ECD we obtained an rms error of 0.72 μsec compared to our raw data.

Several comments about our model must be made. The steep slope which occurs at conductivity of

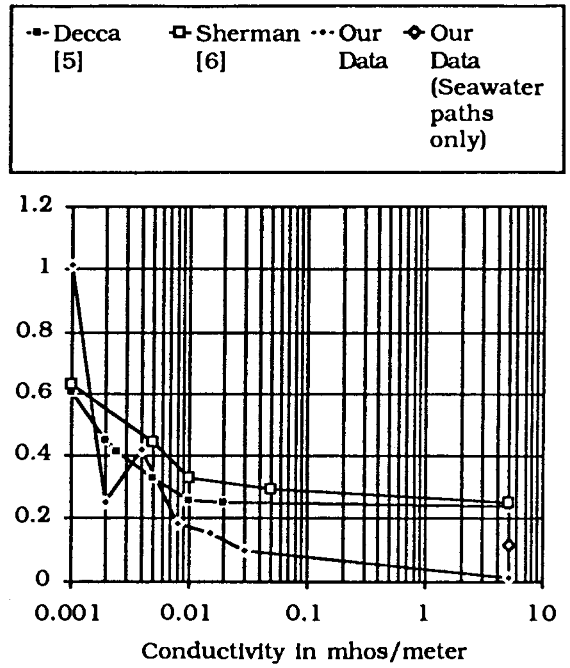

Figure 4. Change in ECD in μsec/100 nm vs ground conductivity.

.001 mho/m may have some degree of error because we had limited data at that that conductivity. We also are at a loss to explain the results at seawater conductivity data of 5 mho/m which suggested virtually no change with distance. We went back and looked at all of the graphs of ECD vs distance for those paths over all or mostly seawater and they indicated there was change with distance. We combined these into a single graph (Figure 5) and calculated the slope in a least squares sense. The result is the single point in Figure 4 (0.12 μsec/100 nm) and the straight line in Figure 5.

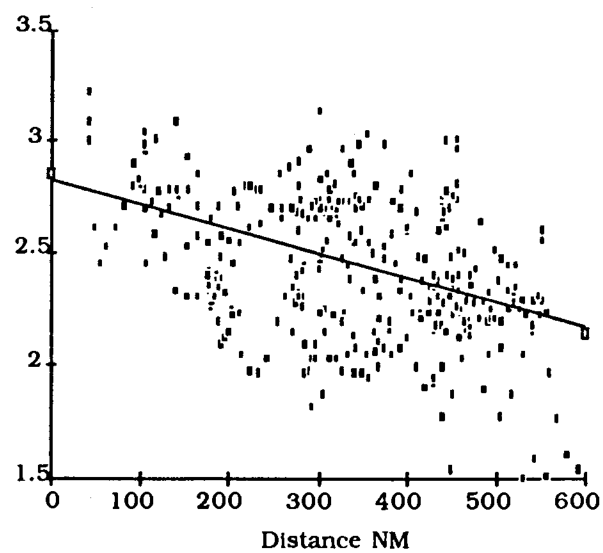

Figure 5. ECD vs distance for all seawater paths.

The model also appears to have an inconsistent spike at the conductivity of .004 mho/m. This spike may be best explained by terrestrial rather than conductivity effects. Much of the conductivity in the US of .004 mho/m is found in the mountainous regions of the United States. In these regions ECD changes more quickly with respect to distance. Figure 6 is an example of data collected over the Rockies. This data is consistent with Walter Dean's observations in [8]. The signal strength plots for propagation over mountains also showed drops in strength not predicted by Millington's method for the charted conductivity (also consistent with the plots in [8].) We feel the technology may be quickly advancing to the point where numerical integration of Maxwell's equations will be feasible to explain such phenomena.

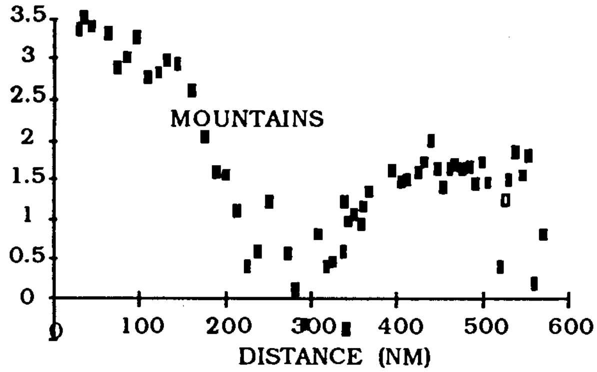

Figure 6. ECD of George in a flight across the Rocky Mountains.

We also attempted to determine if altitude has an affect on either ECD or signal strength. Most of the BENDIX KING data was collected at altitudes between 25,000 and 28,000 feet. We were provided with time tagged text files containing comments such as "takeoff", "landing", "10k and climbing", "level at 26k", etc. By doing linear interpolation between these points we were able to do crude estimates of altitude vs time and thus ECD vs altitude. There appeared to be a slight tendency for ECD to decease about 0.5 μsec. from ground to 10,000 feet, but the variations in the data were much greater than any trends. Because the BENDIX KING flights would cover as much as 100 nm between take off and level flight, we collected our own data under more controlled conditions. LCDR Dick Hartnett of the Academy engineering faculty flew his own private aircraft. From ground level to his 11,500 foot limit, we saw no variation with altitude in either the ECD or signal strength data. For plots of both the BENDIX KING and our own altitude data see [4].

SKYWAVE ANALYSIS

With increased usage of LORAN with overland propagation paths, groundwaves are more highly attenuated resulting in larger skywave to groundwave ratios when compared to propagation over seawater. David Last and others [2], suggested that skywave interference may in many cases be the limiting factor in a receiver's ability to select the proper zero crossing for tracking. At the 1987 WGA Symposium, [3] we had suggested methodology for systematically studying skywaves but had only collected a small amount of data. The method below is a modification of that in [3], and was used to collect more extensive data. The microprocessors in LORAN transmitters do better maintaining pulse shapes than earlier transmitters; as a result, the groundwaves are easier to model. In order to separate the two, the groundwave must be modeled and subtracted from the skywave. We modeled the groundwave based on the ideal equation for a pulse, differentiated from antenna current to near far field, ECD shifted by propagation, and the transfer functions of our pre-amp and filter. The LORAN waveforms were digitized at 2.5 MHz and 8 bits. Averages of 2048 negative phase coded pulses were subtracted from averages of 2048 positive pulses. Data was collected on the Malone and Carolina Beach signals from New London, CT at 12 minute intervals from February 24th to March 24th (1992). Figure 7 illustrates a typical pulse and the basic method of processing the data.

The first 40 μsec of the raw data is used to estimate the TOA, amplitude, and ECD of the groundwave and these parameters are used to generate a groundwave model. This groundwave model is subtracted from the raw data and the same algorithm is used on the remainder to estimate the same parameters on the first hop skywave.

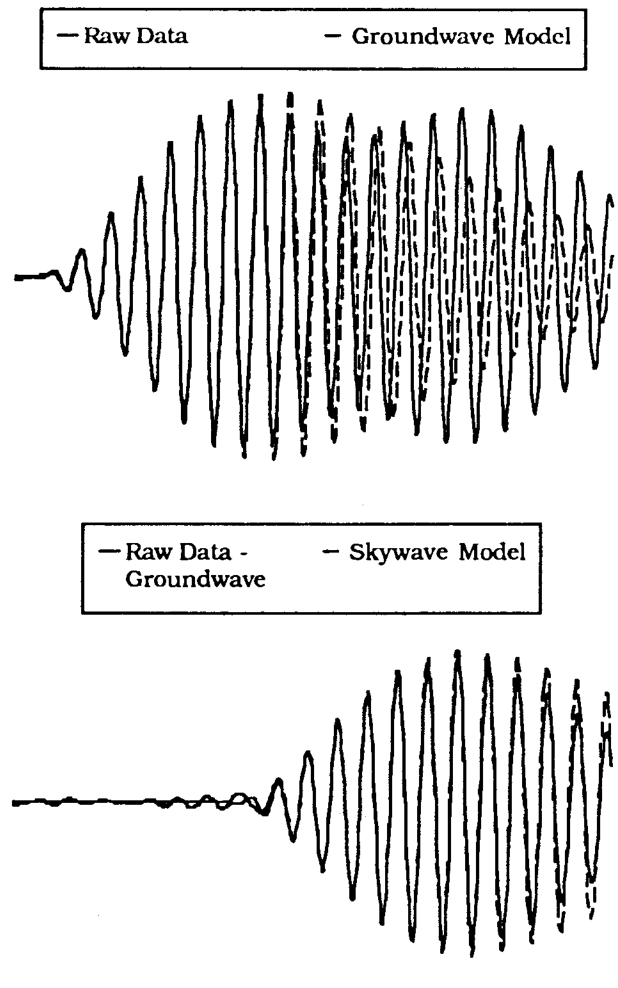

Figure 7. Processing Carolina Beach data for 0027 EST, 25 FEB 92.

In examining the data we noticed frequent cycle slips in our estimates of the TOA of the skywave. Figure 8 is an illustration of this in the Carolina Beach data. These cycle slips were usually reflected in a substantial ECD shift, (i.e. TOA would shift approximately 10 μsec but the sum of TOA and ECD was approximately constant.) In Figures 9 and 10 we used the sum of TOA and ECD (i.e. the TOA of the envelope) to estimate skywave delay. This results in much more random fluctuation, but we feel the data is more reliable. Table 1 summarizes our data on the typical delays and ratios for Carolina Beach and Malone for pulses which reach New London. We separated the data into nighttime and daytime intervals, and found the mean and standard deviation on a spreadsheet. We discarded any (delay) data where the skywave to groundwave ratio was less than 0.7 since our ability to measure the parameters of relatively weak skywaves is

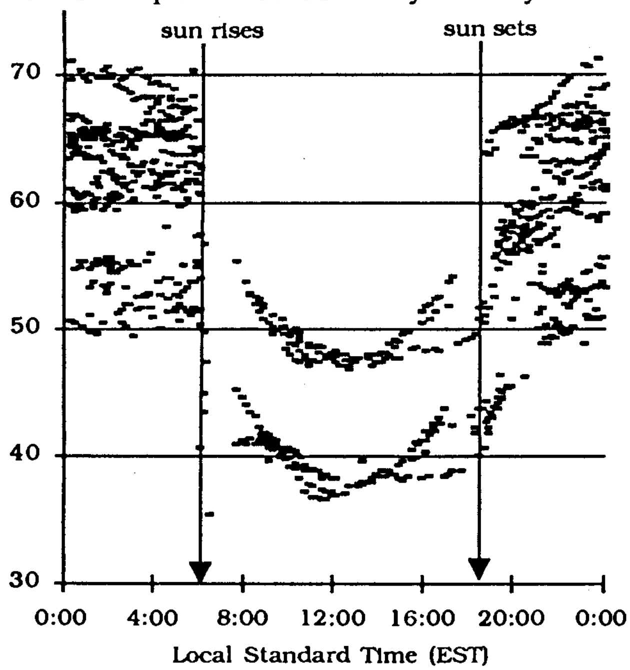

Figure 8. Skywave delay of tracked zero crossing (in μsec) for Carolina Beach (517 nm).

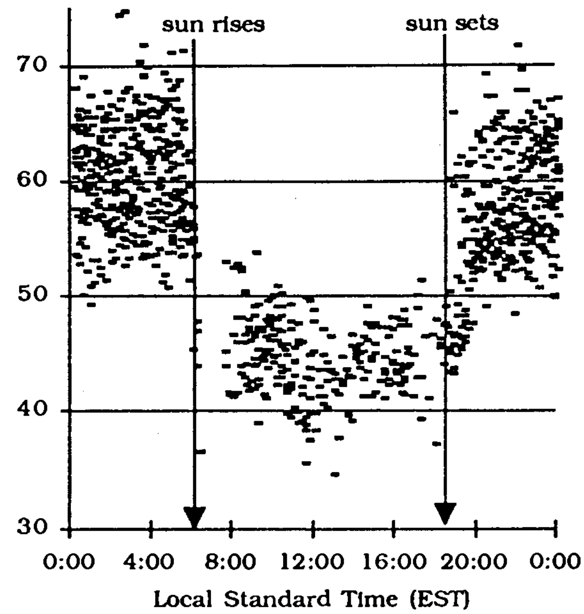

Figure 9. Skywave delay of envelope (in μsec) for Carolina Beach.

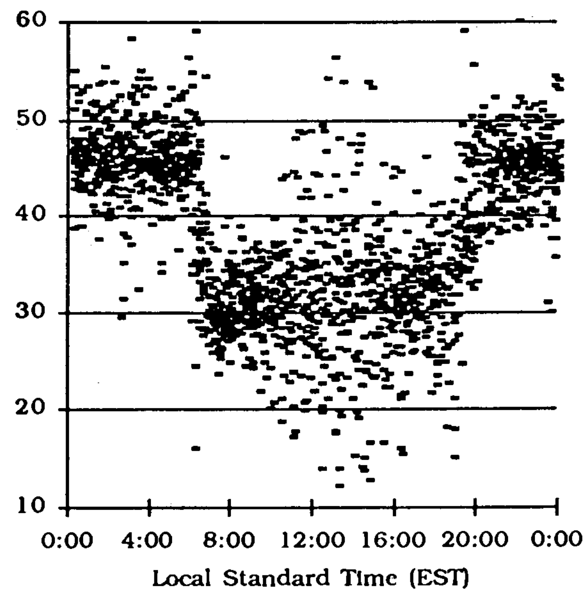

Figure 10. Skywave delay of envelope (in μsec) for Malone (886 nm).

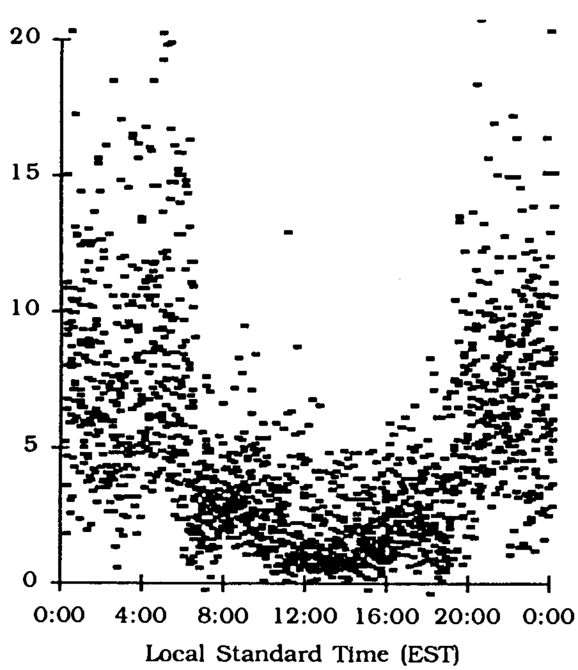

Figure 11. Skywave to groundwave ratio for Malone.

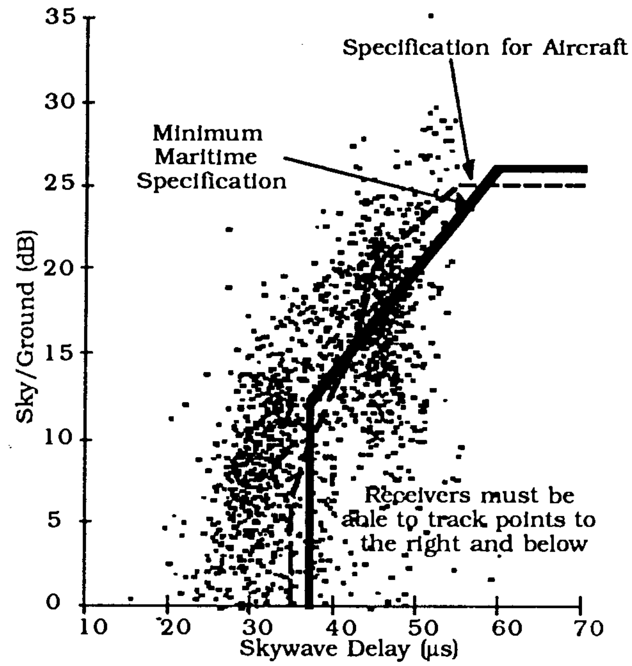

Figure 12. Comparison of Malone data to minimum performance specifications.

limited by the accuracy of our groundwave model. In this case we used 56% and 95% of the Carolina Beach and Malone data respectively. To obtain a more accurate groundwave model or to perform similar analysis for tube type transmitters it would be necessary to simultaneously record waveform data either in the near far field or at the transmitter. We expect to use near far field data in future studies. We are also developing a much more portable and less expensive system so that simultaneous data collection at multiple remote sites will be feasible.

	Night			
station	mean sky. delay	stdev sky. delay	mean sky/gnd	stdev sky/gnd
Malone	44.7	4.8	7.6	4.7
C. Beach	58.9	5.2	1.2	0.5

	Day			
	mean sky. delay	stdev sky. delay	mean sky/gnd	stdev sky/gnd
Malone	32.1	5.5	2.6	1.8
C. Beach	44.5	4.1	0.5	0.3

Table 1.

With this information and some simple trigonometry we can estimate typical nighttime and daytime layer heights. These estimates are summarized in Table 2.

Station	Delay (day)	Delay (night)	Layer ht. (day)	Layer ht. (night)
Malone	32.1 µsec	44.7 µsec	63.5 km	77 km
Carolina Beach	44.5 µsec	58.9 µsec	67 km	79 km

Table 2.

Figure 12 compares the minimum performance specifications for maritime, [2] and airborne [9], receivers with respect to skywave delay and skywave to groundwave ratio for our Malone data. For similar plots of Carolina Beach data see [4]. Notice that a significant drop in the skywave delay occurs during the daytime. During the day the layer height lowers and it takes less time for the skywaves to arrive at the receiver. As a result, we would expect skywaves to arrive earlier in the groundwave pulse during the day and cause more cycle slip errors. There is also more variance in the data during the day. This variance occurs because the skywave signals are not as clear during the day and since they arrive earlier they become more difficult to model.

Pulses from Malone to New London travel over an all land path of distance 886 nm. According to Figure 12, receivers just meeting the minimum would not be able to track this station as many of the points lie outside the minimum specification lines. It should be pointed out that for reliable LORAN navigation in New London, tracking the Malone station is not necessary.

CONCLUSIONS

By using extensive flight data provided by BENDIX KING we have presented a revised model of change in ECD as a function of ground conductivity. We found that for reasonable conductivities (8 mmho/meter or more) and smooth earth the (negative) change is about 0.1 to 0.2 µsec/100 nm and substantially lees than previously thought. Reflecting on the data after this paper is past due, there is the possibility that ECD is like magnitude in that earth curvature has much more affect at longer ranges. For example over seawater, the ECD may change from +2.5 µsec to 0 from 0 to 1000 nm, but it may be still +2.0 µsec at 500 nm. Perhaps the data should be divided into 0-400 and 400-600 nm ranges and a separate set of coefficients determined for each set of data.

We did find substantial shifts in ECD caused by terrain and hope that future efforts in numerical modeling can provide some insight into the problem. We found no substantial evidence of variation of ECD with altitude.

We presented a method of isolating skywaves from groundwaves and obtained statistically significant amounts of data on skywave delay and skywave to groundwave ratios. Future efforts will focus on development of a much more portable data acquisition system allowing studies at multiple remote sites and on signals from tube transmitters.

ACKNOWLEDGEMENTS

This study was funded by the Radionavigation Division of U. S. Coast Guard Headquarters [COMDT(G-NRN)] and indirectly by the U. S. Federal Aviation Administration [via COMDT(G-NRN).] We also sincerely appreciate the help of LCDR Dick Hartnett for flying his own aircraft to collect data, BENDIX KING for allowing us to use their flight data, and Alf Ramsay of RACAL-DECCA for providing the DECCA data. Particular thanks to Bruce Hensel of JET for a wide variety of help including technical assistance in interfacing and using JET receivers and obtaining permission to use the BENDIX KING data.

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SESSION E, F, G, H

Tutorials

TYPICAL LORAN-C HIGH POWER TRANSMITTER STATION

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July 1992

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1.0 INTRODUCTION

This paper describes a typical high-power Loran-C transmitter station, and establishes site and building requirements.

Companion papers are:

- Loran-C Site Survey and Selection Guide
- Loran-C Solid-State Transmitter Operation
- Loran-C Chain Annual Running and Maintenance Costs
- Loran-C Chain Control

A typical high-power solid state Loran-C transmitter station generating between 250 kW and 1 M watt peak power is shown in the photo in Figure 1 and in the layout drawing in Figure 2. It consists of a top loaded vertical antenna with a height of up to 220 meters, a Loran-C transmitter with between 16 and 64 power modules (Half Cycle Generators), prime and backup power units, monitor receivers and inter-site communications. In the usual hyperbolic mode, three to five of these stations operate together in a chain. A typical station is unmanned, except for a caretaker or security guard, and may be controlled from a remote "Chain Control Center". For convenience, the Chain Control Center may be colocated with one of the transmitter sites. These components will be described in the sections below, and building requirements will also be discussed.

2.0 ANTENNA

The Loran-C transmitting antenna is a "top loaded" vertical tower or "mast" with a height of up to 220 meters. A typical Loran tower configuration is shown in Figure 3. The tower is insulated from the earth by a base insulator which supports the weight of the tower. Guy cables are attached every 120° at several heights to support the tower. Additional cables are

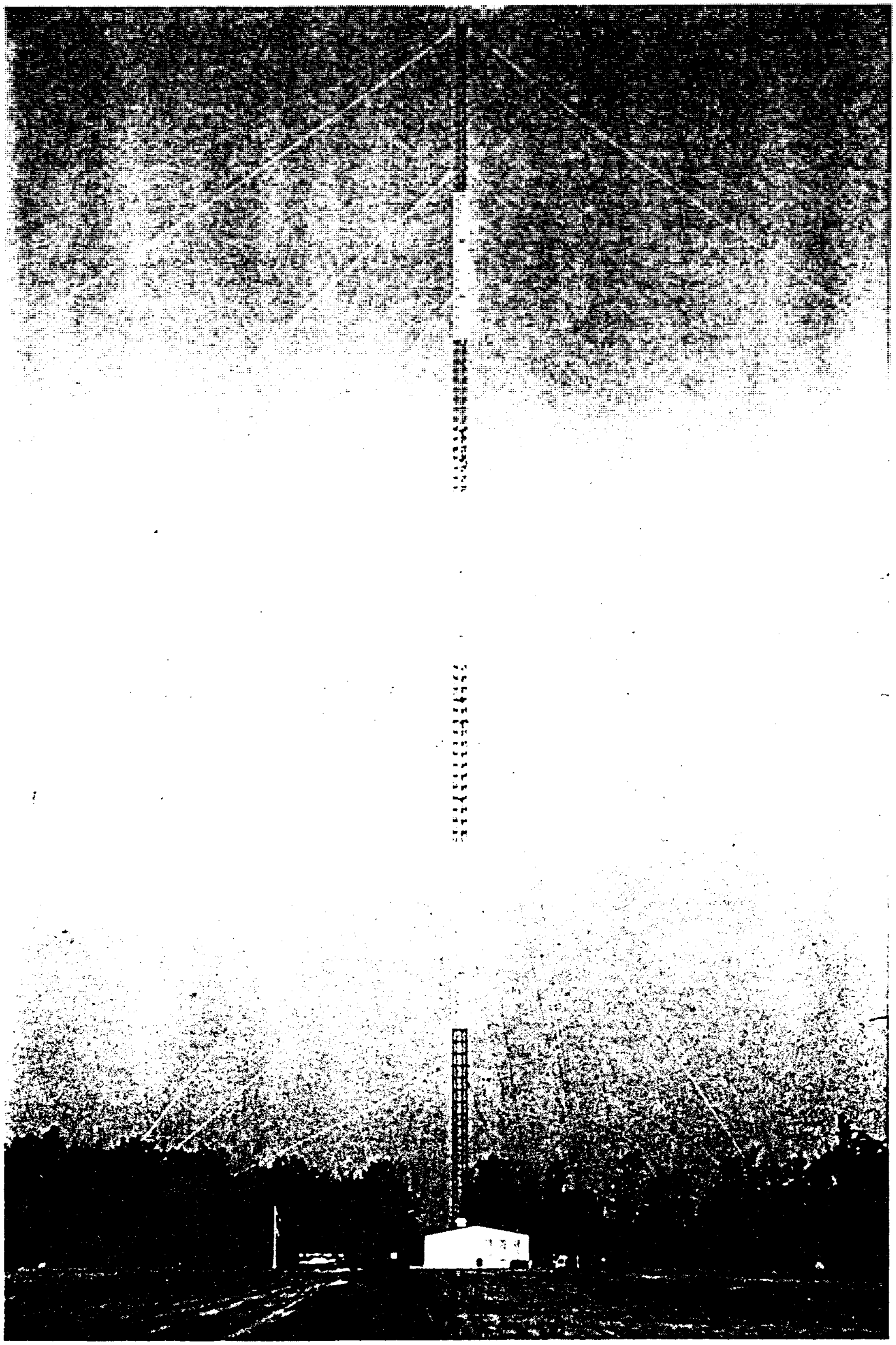

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Figure 1. Typical High Power Loran-C Station

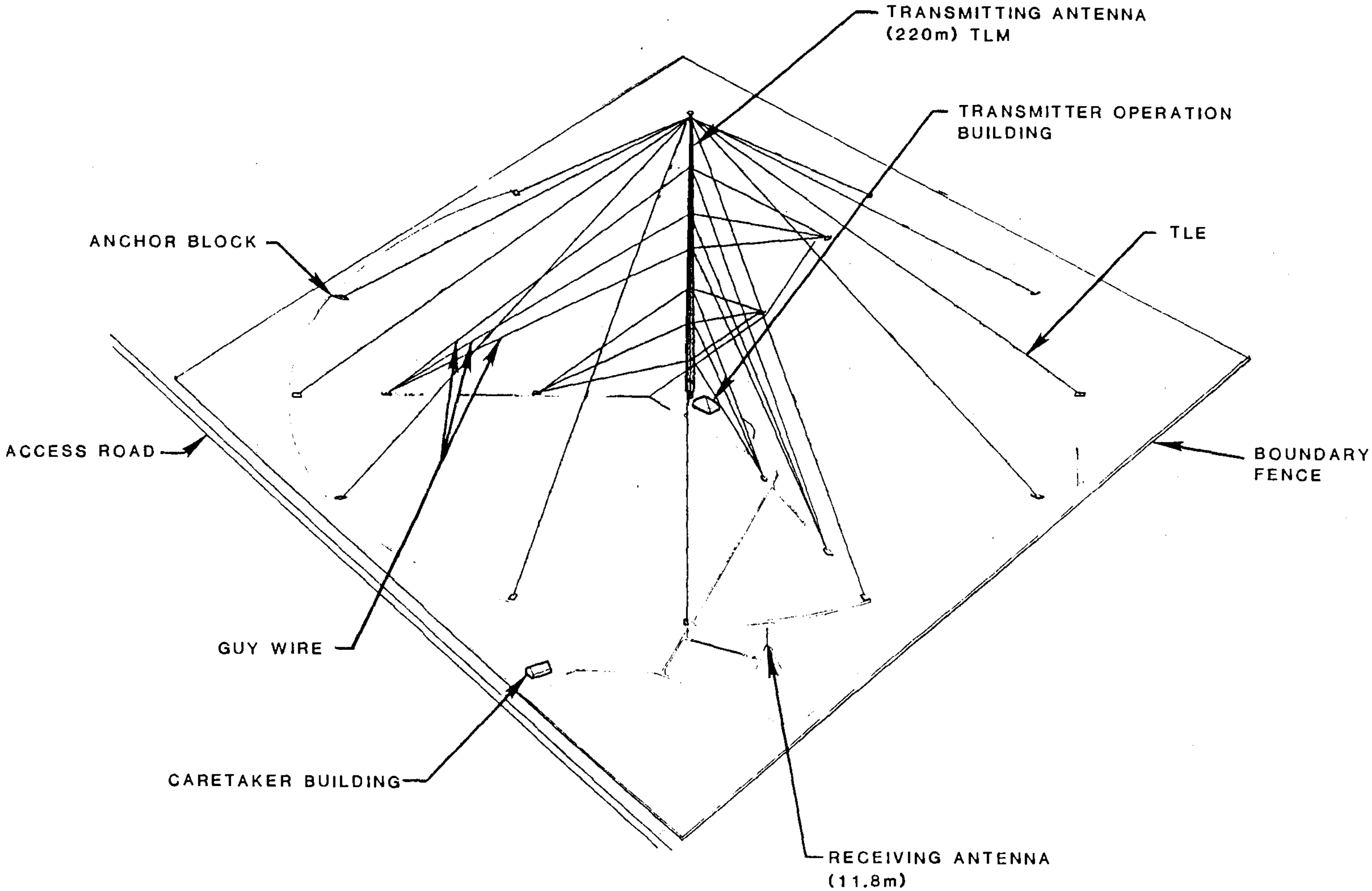

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Figure 2. Typical Site Layout

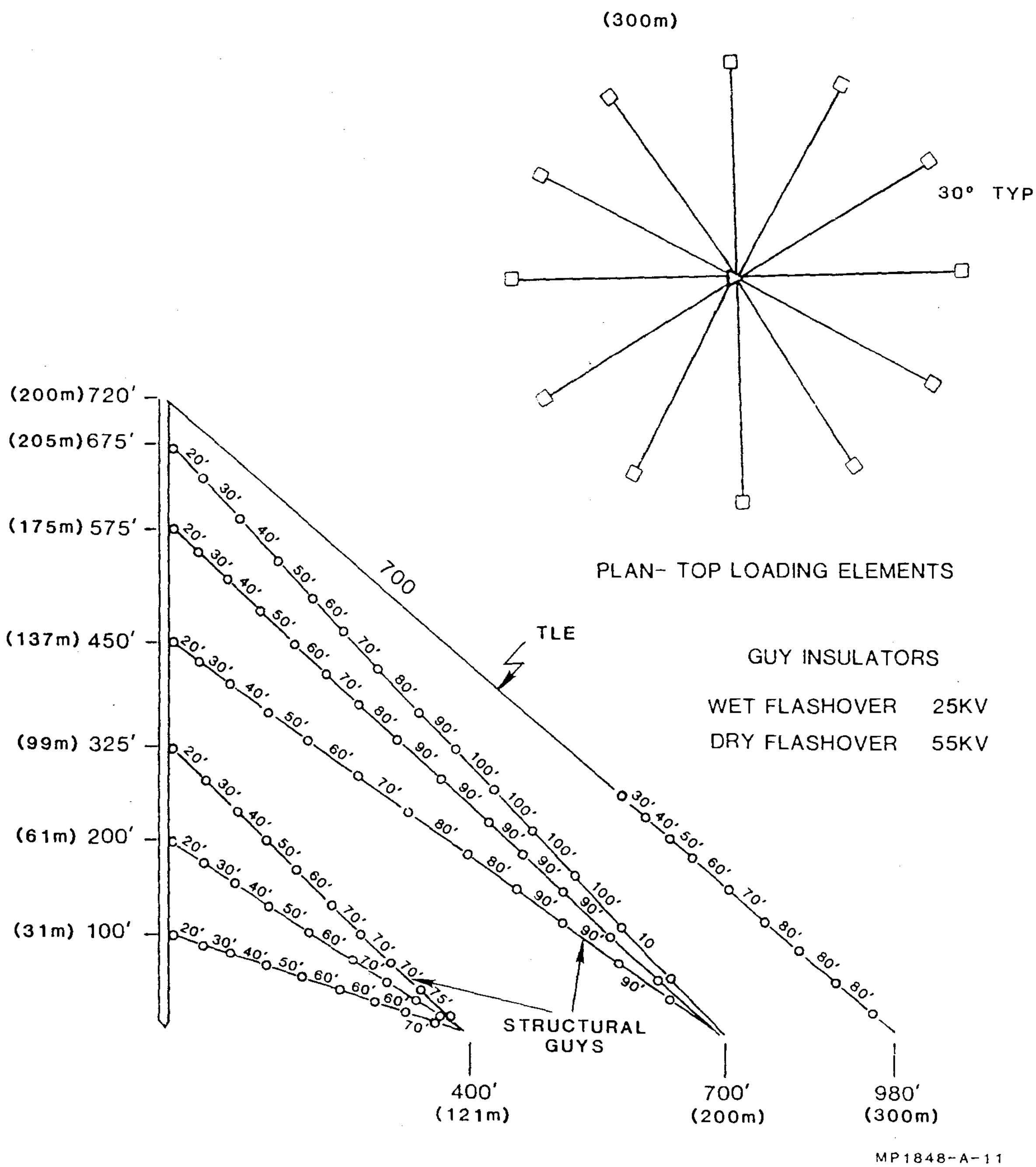

Figure 3. Top Loaded Monopole Tower Configuration

attached both mechanically and electrically to the top of the tower to give the system additional capacitance. These additional cables are the "top loading elements" (TLE) and the entire Loran-C antenna system is called a Top Loaded Monopole (TLM) antenna.

Reinforced concrete blocks are required to provide a base for the antenna tower and anchors for the cables. The size of these blocks depends on environmental factors at the site, particularly on wind and ice loading conditions and on the type and condition of the soil. Such factors are determined as part of the site survey process (described in a companion paper). In normal soil a tower base of approximately 15 cubic meters of reinforced concrete is required to support the dynamic load of 250 tons of a 220 meter tower. Six blocks between 10 and 77 cubic meters each are required to anchor the supporting guy wires, and twelve blocks between 5 and 18 cubic meters are required to anchor the top loading elements.

2.1 ANTENNA GROUND PLANE

The ground plane consists of up to 120 bare copper wires joined at the antenna base insulator and extending radially from the base to a distance somewhat longer than the antenna height, buried to a depth of 10 to 50 centimeters. The outer ends of the radials are usually connected to each other with a perimeter wire. The purpose of the ground plane is to improve the radiation efficiency of the antenna by providing a low loss return path for the antenna base current.

2.2 SITE REQUIREMENTS

A site is selected on the criteria set forth in the companion paper "Loran-C Site Survey and Selection Guide". Approximately 350,000 square meters of reasonably flat land is required for a typical 220 meter high Loran-C antenna.

The site must be sufficiently clear and graded to permit construction of buildings and installation of antenna supporting anchor blocks and the antenna ground plane. Access paths must be provided to permit inspections of major structures throughout the site.

Fencing should be included for both security and safety. It is not necessary to fence the entire area; fencing can be limited to the antenna base and anchors.

3.0 TRANSMITTER EQUIPMENT

The Megapulse solid-state transmitter forms Loran-C pulses by exciting a pulse-shaping circuit with a sequence of Drive Half Cycles (DHC) of RF energy. These half cycles are produced in modules called Half Cycle Generators, or "HCGs". The HCGs operate in sets to produce the component half cycles of the pulse waveform. The HCG is the basic building block of the transmitter; it is the focus of operational control, pulse shaping, antenna tuning, and many other functions. A transmitter is rated by the number of HCGs it contains: the usual range for high power stations is between 16 and 64 HCGs. The relationship between number of HCGs and the radiated power level for a given antenna height is shown in Table 1. The RF assemblies of a 32 HCG Transmitter are shown in Figure 4.

The Half Cycle Generators are controlled by the Pulse Amplitude and Timing Control Unit (PATCO). The PATCO controls the amplitude and timing of the individual HCG outputs to form extremely stable shaped pulses which conform at the antenna to the Loran-C specification. The PATCO is the uppermost unit in the Control Console's left and right cabinets (See Figure 5). The Remote Control Unit (RCU), located below the PATCO, allows the transmitter to be

TABLE 1. PRIME POWER INPUT REQUIREMENT AND RADIATED POWER
(Typical Soil Conditions)

Use	No. of HCGs	Prime Power Input		APPROXIMATE RADIATED POWER kw	
		0 PPS (kW)	300 PPS (kW)	625 Ft. TLM	720 Ft. TLM
Transmitter	16	6.0	38	225	260
	32	11.5	70	450	530
	56	20.5	121	780	925
	64	23.0	139	900	1060
Control Center	10 kW				
Maintenance Center	12 kW				

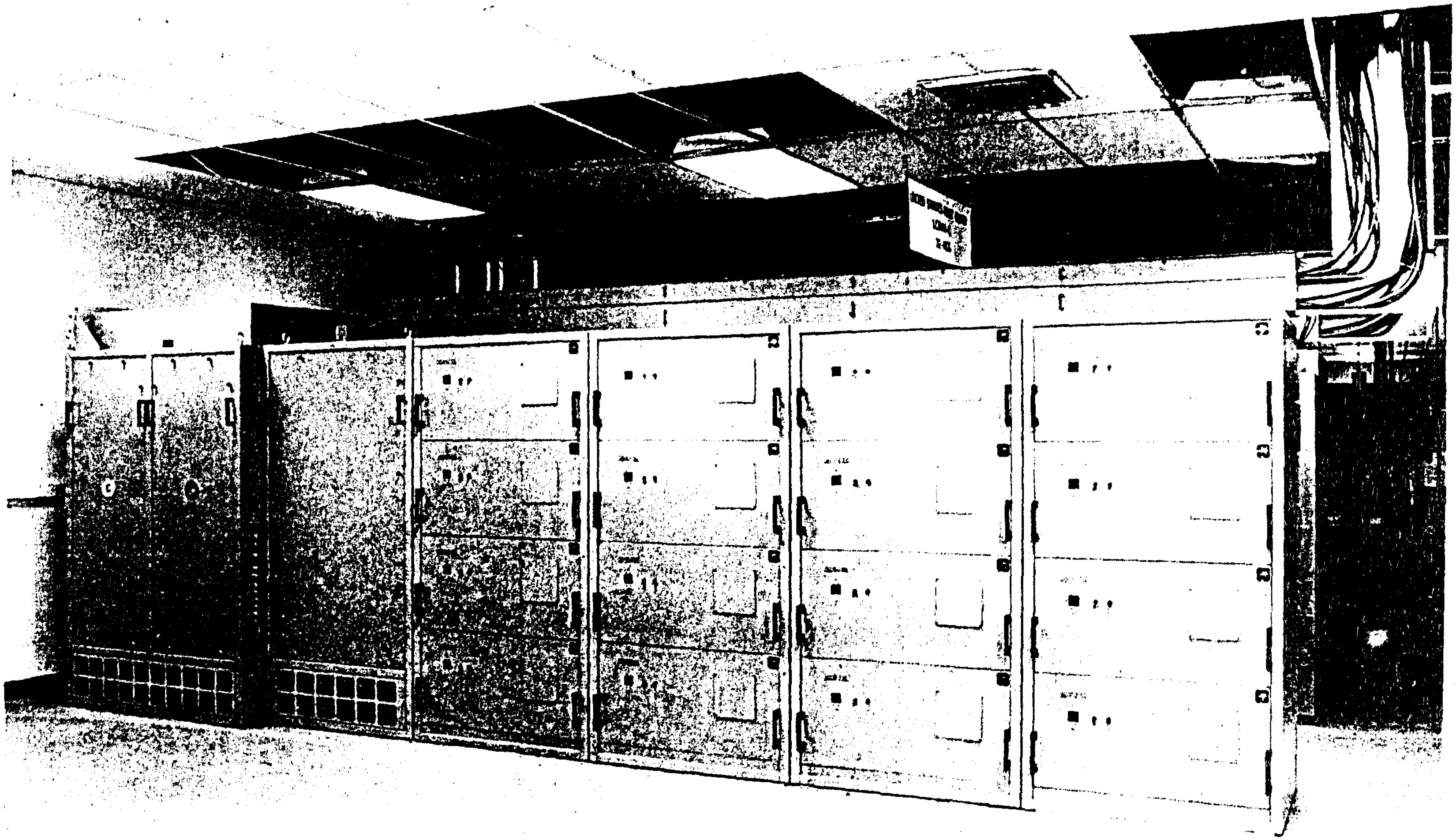

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Figure 4. RF Section of a 32 HCG Transmitter

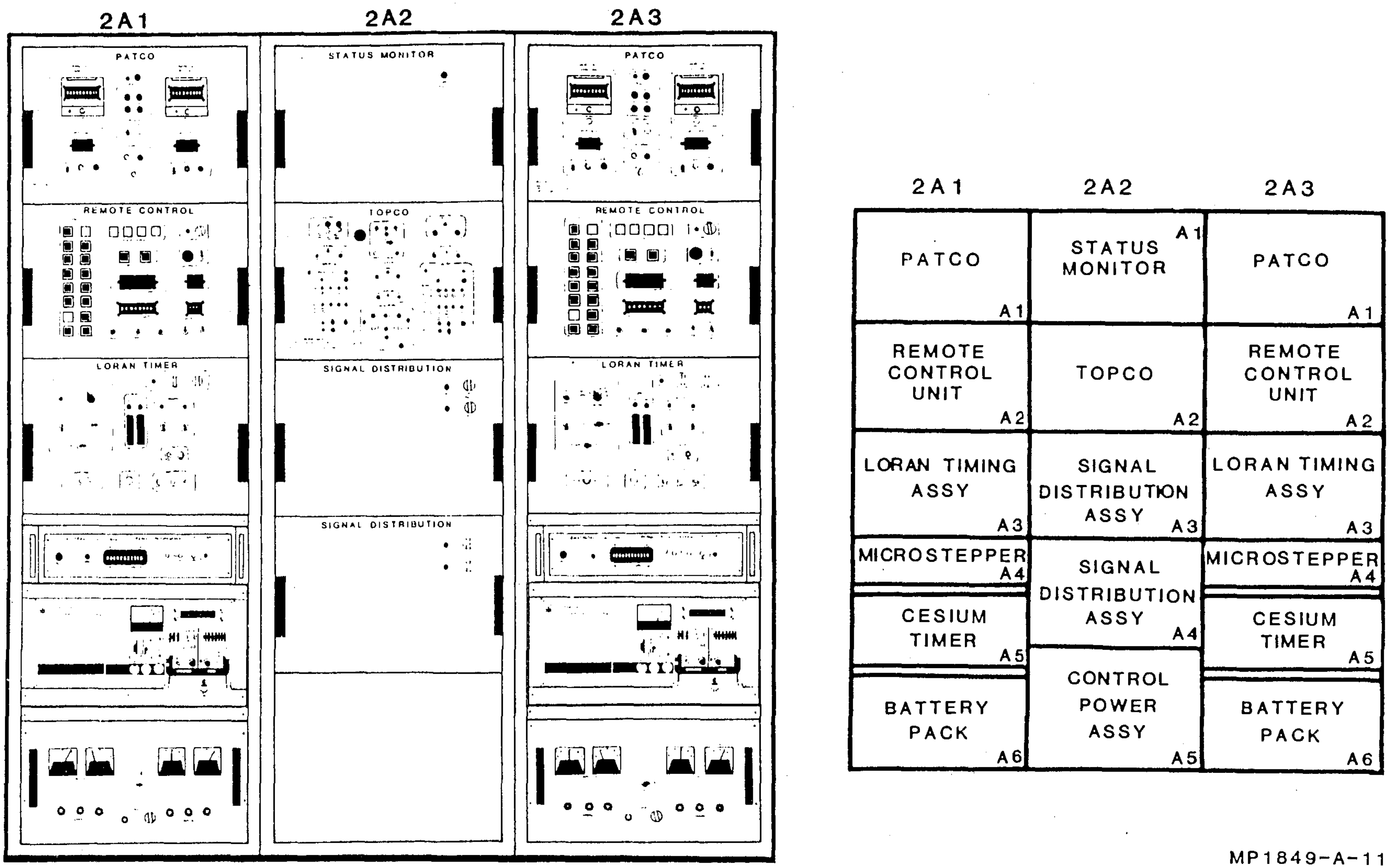

Figure 5. Control Console

controlled either locally or remotely. It also monitors the operation of the transmitter and provides switchover commands in case of a transmitter fault.

Loran pulses are transmitted in groups of eight (nine for the Master station) with a particular phase code to eliminate the effects of delayed skywave.

The precise time of transmission for these groups is controlled by the Loran Timer Unit (LTU) which in turn receives precise time information from the cesium standard (atomic clock) and microstepper. These two units are protected from power failures by the battery pack. The entire control system, including clocks, is redundant so that in the event of a fault in the on-line unit the standby unit can take over control.

The center cabinet of the control console, Figure 5, contains the Transmitter Operation and Control (TOPCO) unit which monitors the entire transmitter, and the Signal Distribution Assemblies (SDAs) which send control information to the individual HCGs.

The individual HCGs are connected in parallel to a Coupling Network which converts the half cycles into 100 kHz pulses. The detailed shape of the transmitted RF pulse is controlled by the Output Network which consists of an Output transformer and an Antenna Tuner. These elements are housed in a Coupling Cabinet and an Output Network Cabinet. The Coupling Cabinet also contains a "Tailbiter" which damps off the pulse after its useful portion to prevent prolonged "ringing". The Output and Coupling Networks are redundant, the on line units being connected to the HCG bus and the antenna via the Switch Cabinet.

A typical 64 HCG transmitter layout is shown in Figure 6.

The transmitter is powered by the Prime Power Distribution Unit (PPU) which controls main power distribution to all the units of the transmitter.

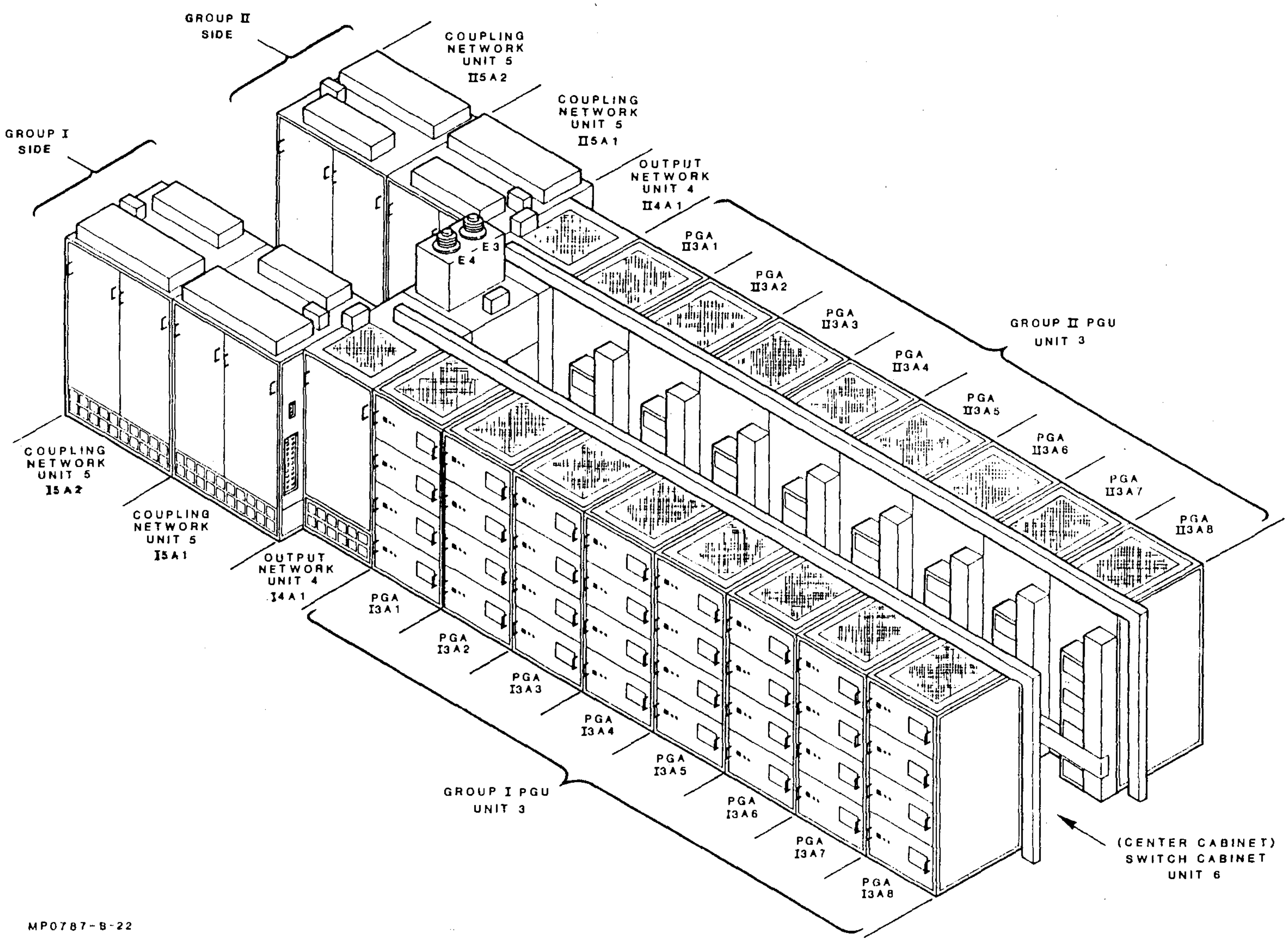

Figure 6. Typical 64 HCG Layout

It contains circuit breakers and a switch which determines whether the PGA will receive power under manual or automatic (TOPCO) control.

Table 1 shows the transmitter prime power requirements for various configurations and also for a Control Center and Maintenance Center which are often colocated with a transmitter. Table 2 also shows the cooling air requirements. Up to 400 kVA prime power may be required.

Prime power is usually furnished by local utility companies and backed up by redundant diesel generator units located on or near the transmitter site.

The transmitter is housed in a building requiring a floor area from 130 to 224 square meters depending on the size of the transmitter. A typical floor plan for a 16 HCG transmitter is shown in Figure 7. Separate rooms are provided for Control Console, transmitter, and prime power. An optional unit level Fire Protection system is available. Storage and instrument areas and sanitary facilities are required. An unmanned station usually would provide a Caretaker house on site or quarters within the building. Utility power, water, telephone, sewage facilities and access roads are required.

Civil works and construction requirements are supplied in an Interface Control Document (ICD) that is prepared for each site. The Interface Control Document identifies, defines and specifies the mechanical and electrical interfaces needed between the transmitter equipment and the buildings and civil works and between the transmitter equipment and subcontractor-supplied equipments. The document includes plans and engineering drawings sufficiently detailed to permit a contractor to prepare drawings for the construction of the building. A transmitter Installation Manual which gives detailed unpacking and installation instructions is supplied prior to shipment of the transmitter.

TABLE 2. TRANSMITTER HEAT DISSIPATION

Use	No. of HCGs	Total Airflow (Ft^3/Min)	Heat Dissipation (kW)	
			625 Ft. TLM	700 Ft. TLM
Transmitter	16	6,365	32	30
	24	8,365	47	43
	32	10,365	62	57
	40	13,915	78	73
	48	15,915	93	87
	56	17,915	108	100
	64	19,915	123	114
Control* Center		4,800	28	
Maintenance* Center		3,150	23	

* This Facility can be colocated at a transmitter site.

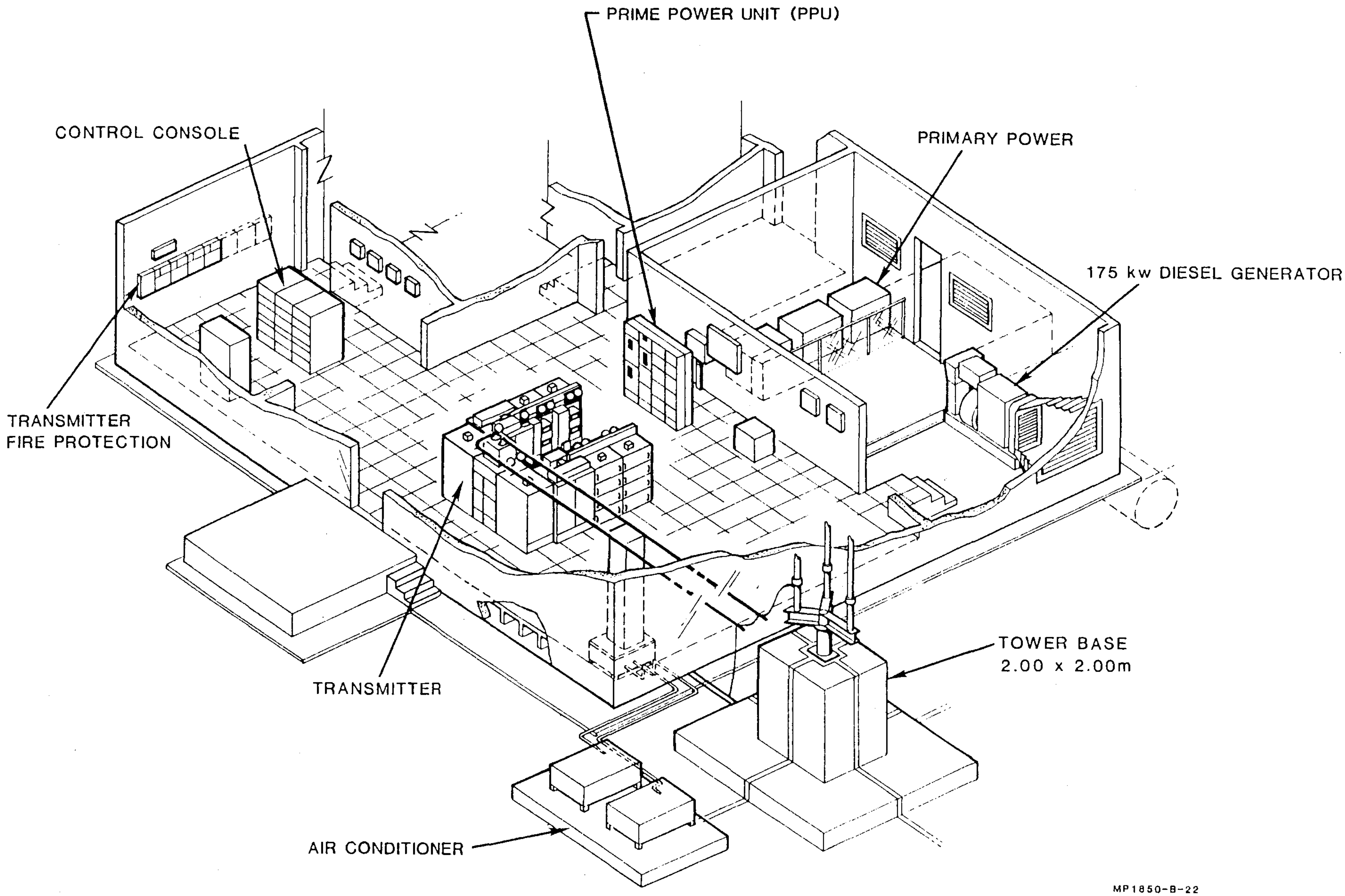

Figure 7. Typical Building Floor Plan for 16 HCG Transmitter

4.0 CHAIN CONTROL CENTER

The Chain Control Center is the "headquarters" of a Loran-C chain. It provides centralized monitoring and control of the transmitters in the chain and provides record keeping of chain performance. It also processes data from the System Area Monitor Unit (SAM) to determine whether each transmitter is operating within specification and whether all transmitters are precisely synchronous with each other. Although the Control Center may be at any location, it is often convenient to colocate it with the Master transmitter.

The system hardware of a Chain Control Center is designed on a modular plan which provides reliability, ease of operation, simple sparing, and convenient expansion. Functionally, the Control Center can be designed with greater or lesser degrees of automation. A representative automated Control Center is shown in Figure 8. For each transmitter in the chain, the Control Center has a dedicated microprocessor linked with the transmitter's pair of Remote Control Units (RCUs). The RCUs send status information about the transmitter--including fault and fault correction indications--to the processor where it is graphically displayed on a color monitor and stored for future use and for hardcopy output. Other information from the transmitter site may also be displayed and stored, including the status of each diesel generator unit, and the occurance of alarms for air conditioning, unauthorized entry, and diesel fuel level.

Each dedicated processor is also linked to a (redundant) common processor and printer. This main processor contains the chain synchronization algorithm. It receives data from the System Area Monitors as well as from the dedicated processors. Based on the data it receives, this processor constantly computes the micro adjustments needed to maintain the timing synchronization of the chain and sends adjustment commands ("Local Phase Adjustments" or "LPAs") to

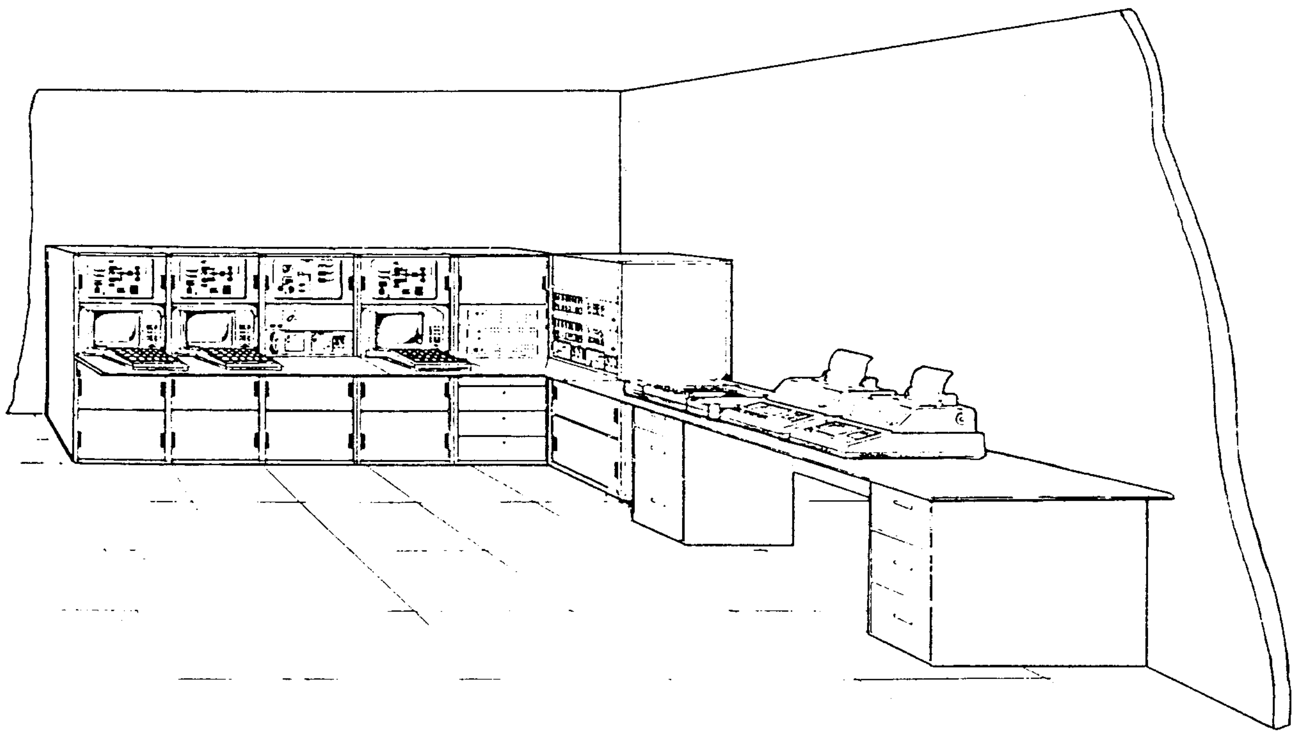

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Figure 8. Chain Control Center

the transmitters through the dedicated processors. The main processor also provides hardcopy logs and records of chain operation.

A Control Center may also utilize strip chart recorders for maintaining visual records of chain timing.

The Chain Control Center requires about 40 square meters of floor space. Since it is manned 24 hours per day, a day room and kitchen facilities are usually provided , requiring about 400 square meters of floor space. An advantage of locating the Control Center at a transmitter site is that no Caretaker facilities for the transmitter are then required.

Low speed data communication between the Control Center and the transmitter and SAM sites is required. Alternate voice channels or "data over voice" functions are desirable but not essential. Although communication is usually provided through commercial wire lines, HF radio or satellite links can be used if wire lines are not available.

LORAN-C SOLID STATE TRANSMITTER OPERATION

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July 1992

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LORAN SIGNAL GENERATION

1.0 INTRODUCTION

This paper describes the operation of the Megapulse 6500 solid state transmitter. The paper has three major sections: section 1 covers the required Loran-C antenna current signal, section 2 the transmitter equipment used to generate that signal, and section 3 system control operations. The descriptions offered here are relatively brief; they provide the reader an overview of Megapulse 6500 transmitting equipment, and can be used as a basis for further, more detailed study.

Companion papers are:

- Loran-C Site Survey and Selection Guide
- Typical High Power Loran-C Transmitter Station
- Annual Running and Maintenance Cost for a Loran-C Chain
- Loran-C Chain Control

1.1 TRANSMITTED SIGNAL DESCRIPTION

Every Loran-C transmitting station emits precisely timed pulses of 100 kHz carrier frequency. Each pulse has an envelope which increases in magnitude to a maximum and then decays again to zero. The peak of the envelope is reached about 65 μsec after the start of the pulse. A single Loran-C pulse is shown in Figure 1-1 and is thoroughly described in USCG COMDTINST M16562.4 "Specification of the Transmitted Loran-C Signal".

Every transmitting station emits these pulses periodically in groups. Each group contains eight pulses spaced 1 msec apart in time, as shown in Figure 1-2. Certain transmitting stations, called Master stations, transmit a ninth pulse 2 msec after the eighth pulse in each group. Transmitting stations which transmit eight pulses per group are called Secondary stations. Each

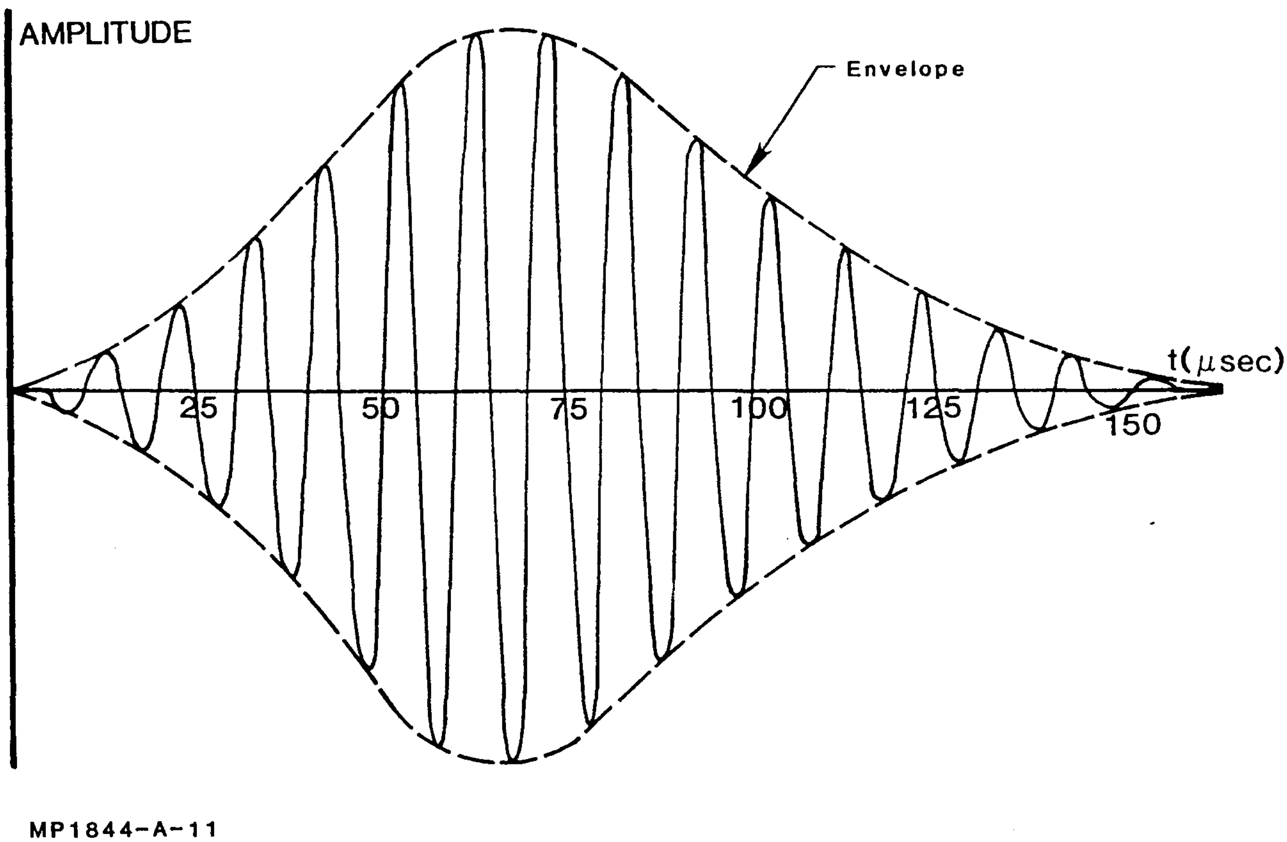

Figure 1-1. Loran-C Pulse

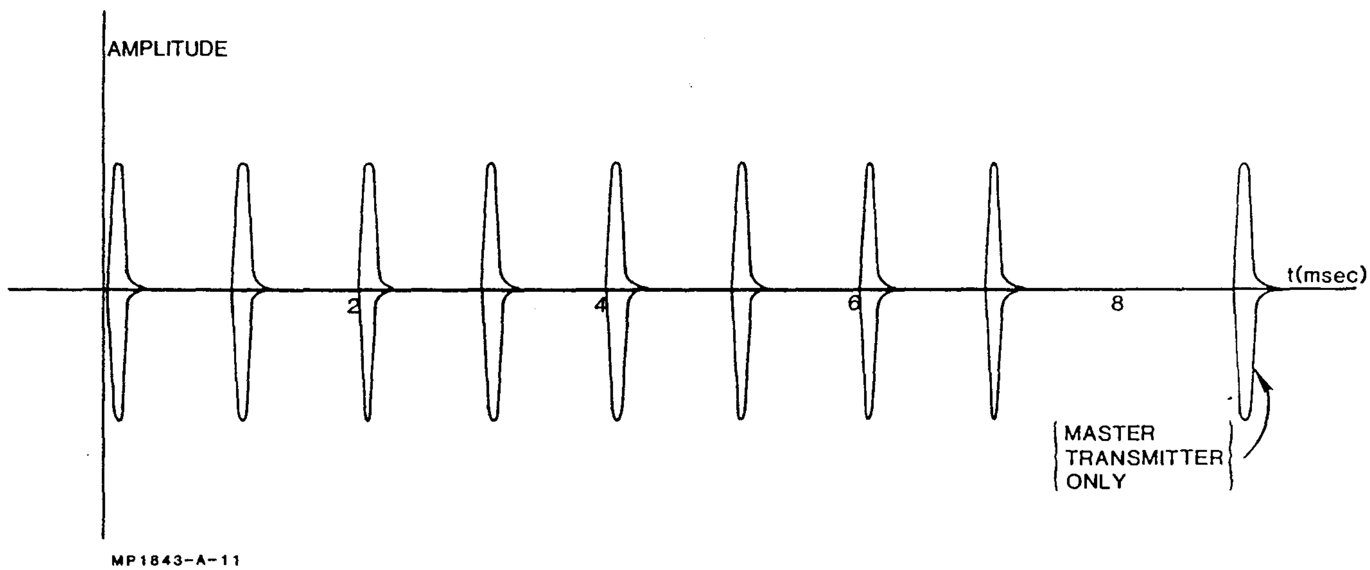

Figure 1-2. Loran-C Pulse Group Timing

pulse in a Loran-C pulse group may be transmitted with a carrier phase of either 0 or 180°, referred to respectively as positive (+) or negative (-) phase code. Standard Loran-C signals are transmitted with a fixed phase code sequence which extends over two successive groups of pulses and then repeats. Master stations use one phase code sequence, Secondary stations use another. Phase coding serves two purposes. First, it makes the Master station's transmission distinguishable from Secondary station transmissions; this facilitates the signal search and acquisition process of the Loran-C receiver. Second, it reduces the effect on system accuracy of the unstable skywaves which under certain conditions interfere with the groundwave.

The period of time between the emission of successive groups of pulses from a particular transmitting station is called the group repetition interval (GRI). The normal range of this interval is from 30 to 100 msec. Two or more Loran-C transmitting stations which are intended to provide navigation signals over a particular geographic area are called a chain. In every such Loran-C chain all transmitters emit groups of pulses with the same GRI. Only one transmitter in each chain emits Master (nine pulse) groups. All Loran-C chains transmit at the same 100 kHz frequency; they are distinguished by the use of different GRIs.

Consider that each GRI begins with the first pulse of the Master group. Then, relative to this start time, the emission of each Secondary transmitter is delayed by a time called the Emission Delay (ED) for that Secondary. The ED for each Secondary in a chain is unique and is coordinated with the other EDs to ensure that the pulse groups from the various transmitters of the chain will not overlap with each other anywhere within the area of Loran-C coverage. Typical timing of the pulse groups of a three-transmitter Loran-C chain is shown in Figure 1-3.

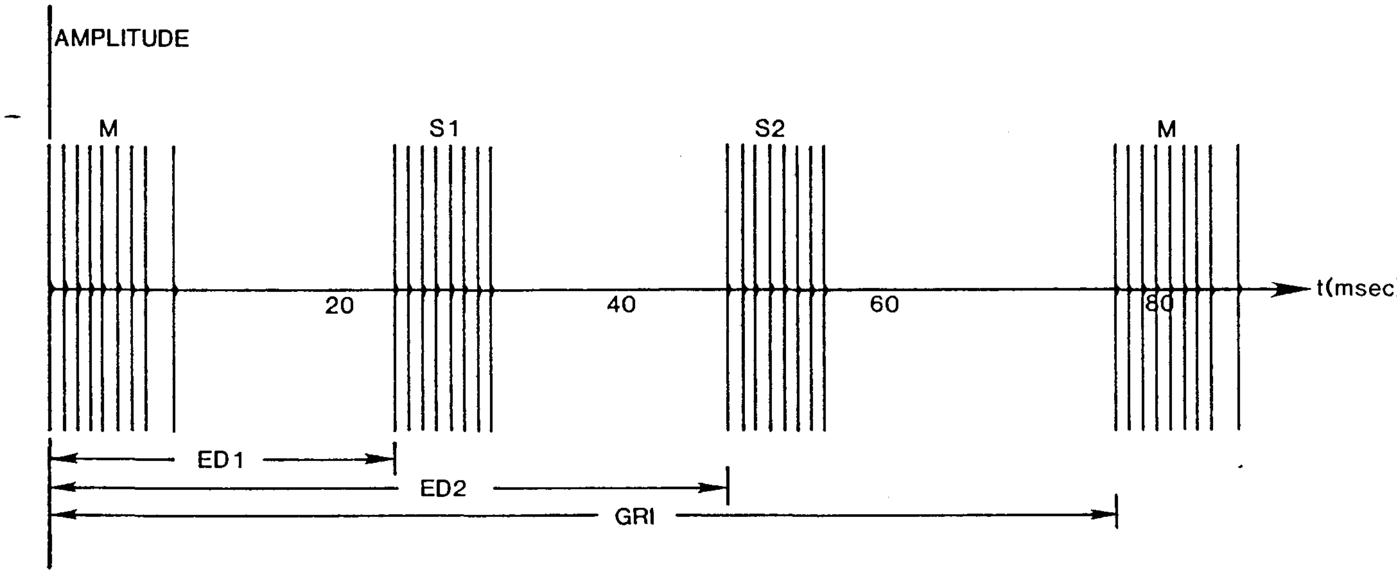

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Figure 1-3. Loran-C Chain Timing

2.0 LORAN-C TRANSMITTER

This section describes the assemblies in the Loran-C transmitter which generate Loran-C antenna current and discusses the functions fulfilled by each major unit of the transmitter. The equipment falls into two overall groups:

1) the RF Transmitter Group (radio frequency pulse generation)

2) the Control Console (transmitter timing and control functions)

2.1 RF TRANSMITTER GROUP

The RF Transmitter Group consists of the Pulse Generator Unit (composed of a number of Pulse Generator Cabinets containing four Half Cycle Generators each), redundant Coupling and Output Networks, and a Switch Network. These major elements of the RF transmitter group are shown in the block diagram of Figure 2-1.

The output waveform at the antenna is not derived from a conventional amplifier, but is synthesized by "impulse exciting" a double resonant network whose second resonant circuit includes the antenna itself. The "impulses" which drive the first resonant circuit in the Coupling Network are called "Drive Half Cycles" and are actually 5 μsec half sinewave pulses generated by the half cycle generators (HCGs). The outputs of up to 64 Half Cycle Generators (HCGs) are combined on the RF Buss. (The output of a single HCG is a current pulse of about 250 amps. This 5 μsec pulse is shaped approximately like a half cycle of 100 kHz sinewave. The time of its occurrence is determined by the timing of an input signal, and its peak amplitude is dependent on an amplitude reference input signal. These two inputs are generated by the Control Console's PATCO and the Signal Distribution Assembly.) Four adjacent firing times are used, thus providing 20 μsec of excitation to the tank circuits in the Coupling Network. Because this excitation is relatively short

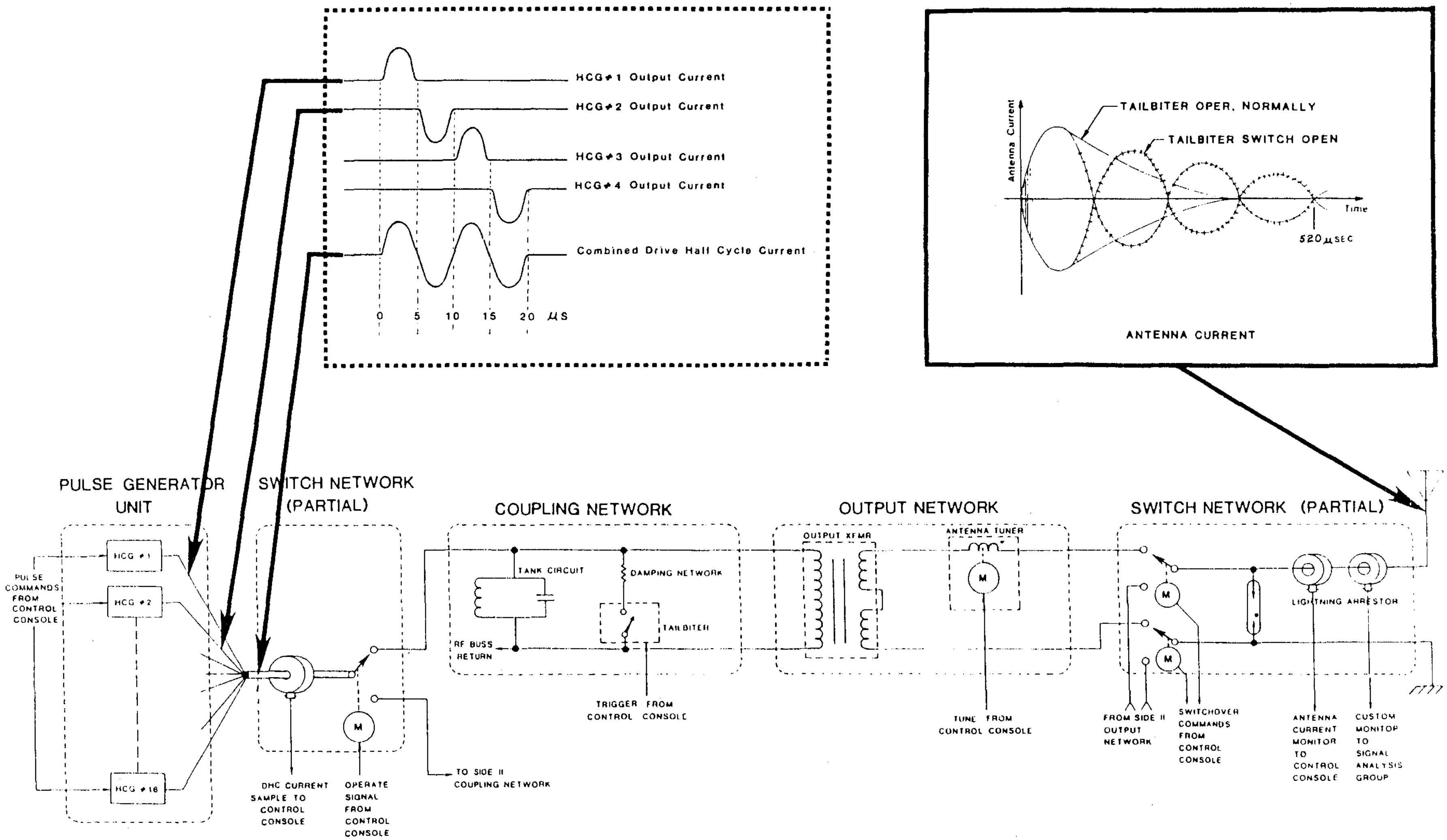

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Figure 2-1 RF Transmitter Group Block Diagram compared to the total antenna current duration, the shape of the output envelope is determined principally by the passive parameters of the double tuned networks and the result is a peak output current amplitude at 65 μsec.

Functional descriptions of each major element are presented below.

2.1.1 Pulse Generator Unit

A Pulse Generator Unit may consist of from four to sixteen Pulse Generator Assembly (PGA) cabinets, each containing four Half Cycle Generators. The number of PGAs provided at a particular installation determines the transmitter output power.

2.1.2 Half Cycle Generator (HCG)

The transmitter uses the HCGs as the basic power-generating subassemblies.

The HCG comprises five modules:

- Power Supply
- Megatron Charger
- Megatron
- Chassis
- Power Transformer

The main flow of power in the HCG is indicated by the striped arrows on Figure 2-2. Prime power from the AC power line is fed to the main transformer. The transformed AC is rectified and smoothed by the Power Supply module, and the resultant regulated DC is fed to the Megatron Charger module. The Megatron Charger under the control of PATCO transfers a precisely controlled quantity of energy from the Power Supply to a capacitor bank located on the Megatron Charger module. This transfer of energy is effected by turning on a Silicon Controlled Rectifier (SCR) charging switch located in the Megatron Charger.

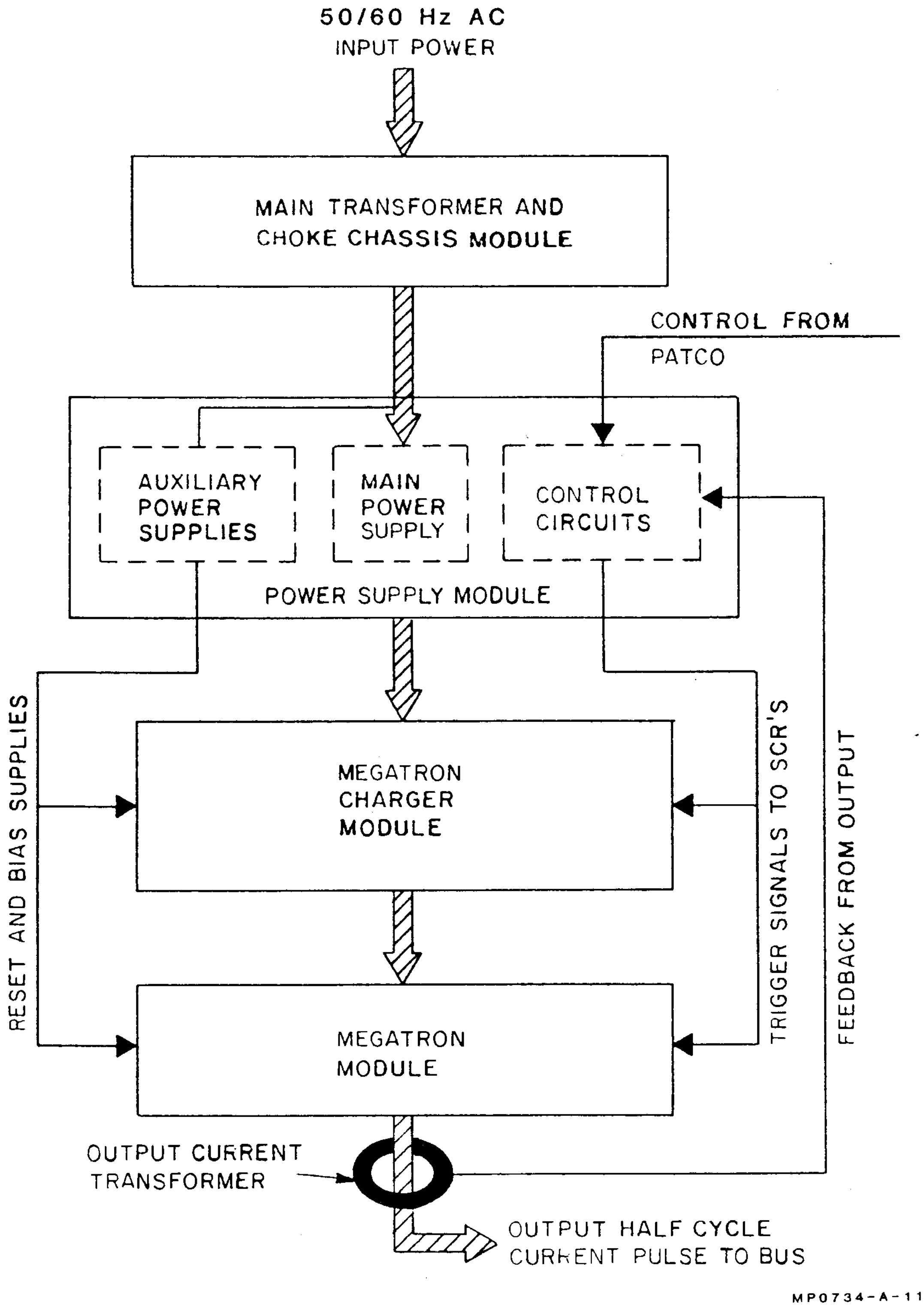

Figure 2-2 HCG Module Main Power Flow

When the desired amount of charge has been transferred to the capacitor bank, the charging switch is turned off. Then, again under control of the PATCO, the energy in this first capacitor bank is transferred into the Megatron module where it is stored briefly in a second capacitor bank. This transfer is effected by another SCR switch located on the Megatron Charger module. The final switching is accomplished by a magnetic pulse compression switch located in the Megatron module. Closing of this magnetic switch delivers the energy stored in the second capacitor bank to the output circuit in the approximate form of a 5 microsecond wide half sinusoidal current pulse.

2.1.3 Positive and Negative Pulse Generation

Half of the HCGs in the transmitter are connected to generate positive outputs and half to generate negative outputs. Phase coding is accomplished by reversing the triggering sequence of HCGs assigned to the four DHCs. Figure 2-3 shows generation of a Loran-C pulse with positive phase code by triggering positive groups of HCGs in the first and third DHCs. The second and fourth DHCs are negative and generated by firing the group of negatively connected HCGs five and fifteen microseconds later.

Similarly, a Loran-C pulse with negative phase code is generated by firing the groups in reverse order, the positive/negative order being replaced by negative/positive as shown in Figure 2-4.

2.1.4 RF Networks

Drive half cycle currents are delivered to the RF Networks which provide the energy storage, coupling, and tuning necessary to create the desired Loran-C antenna current pulse. These networks are contained in 3 types of cabinet: the Coupling Network, the Output Network and the Switch Network.

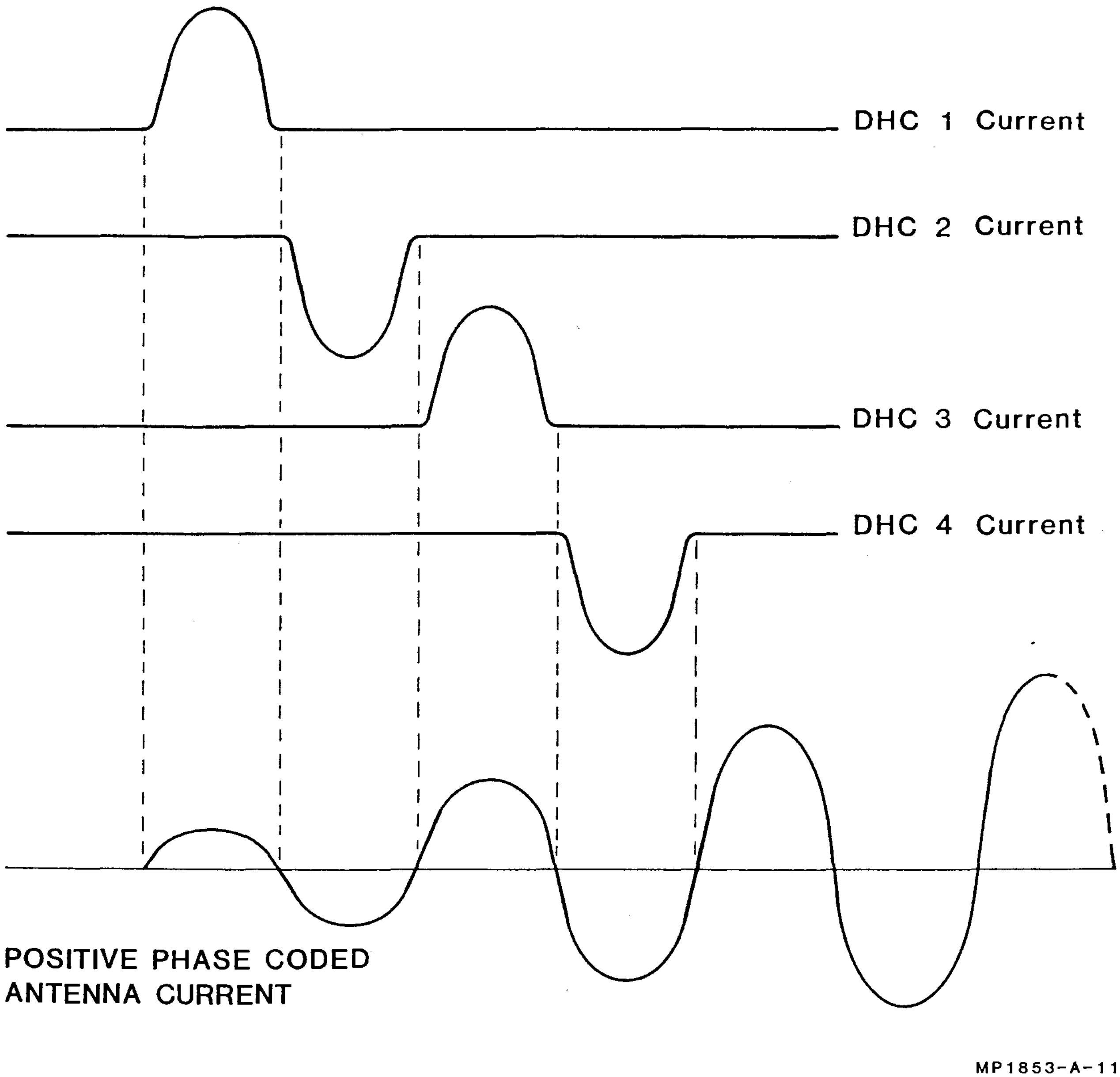

Figure 2-3. Generation of a Positive Phase Coded Pulse

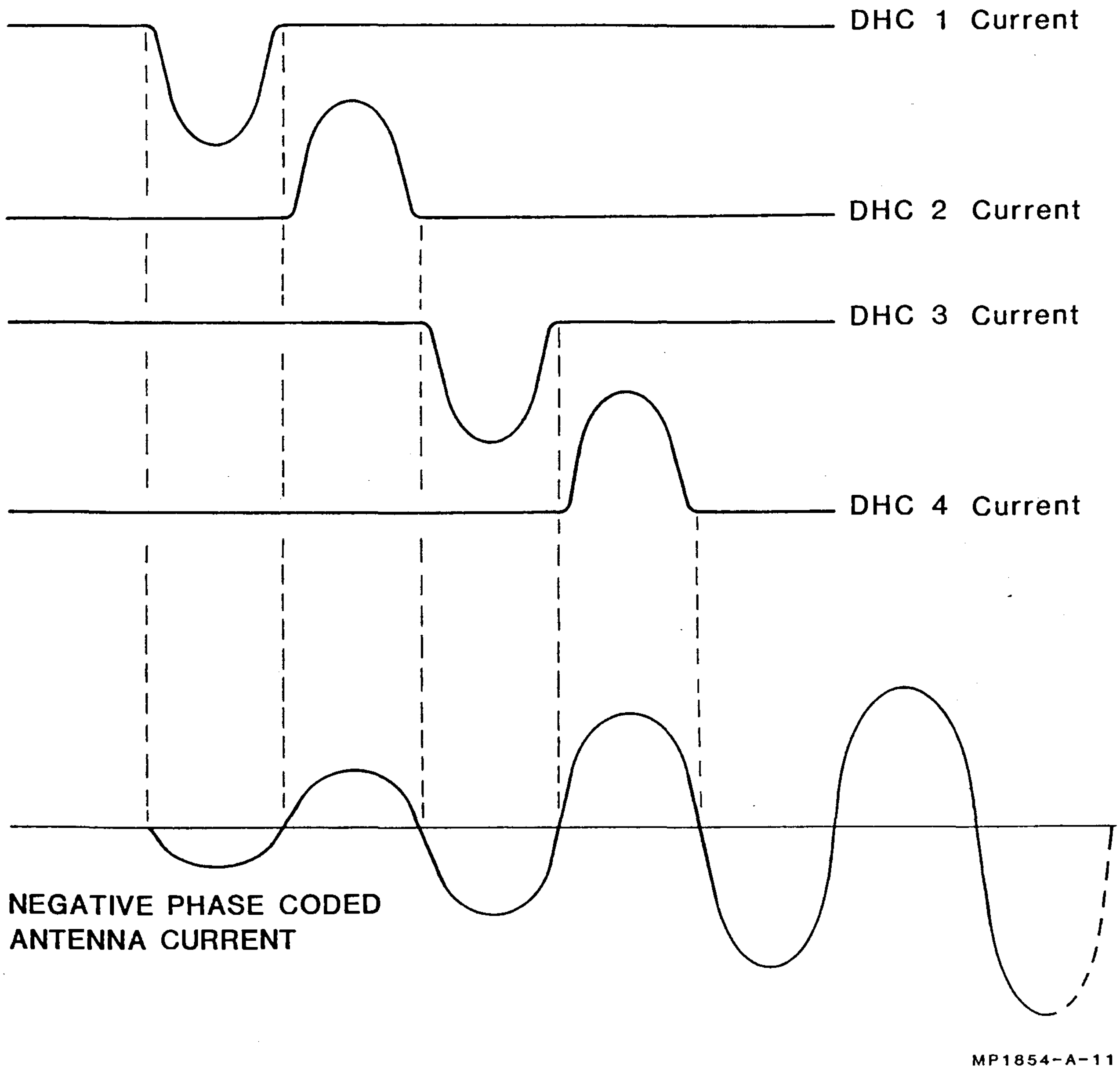

Figure 2-4. Generation of a Negative Phase Coded Pulse

2.1.4.1 Coupling Network

The principle function of the Coupling Networks is to shape the pulse generator output into a standard Loran-C pulse. This is accomplished by the following means.

The Coupling Network consists of a parallel LC tank circuit tuned to 100 kHz and "Tailbiter" circuits. The input to the Coupling Network is the Drive Half Cycle current from the HCGs. The Coupling Network output goes to the transmitting antenna via the Output Network. The antenna equivalent circuit is a series RLC network also tuned to 100 kHz. The Coupling Network and the antenna equivalent circuits are shown in Figure 2-5.

The energy in the DHC current is stored temporarily in the Coupling Tank circuit. This energy then transfers resonantly to the Antenna circuit. The antenna current, which is sinusoidal at the 100 kHz resonant frequency, initially builds up in amplitude and then decays. The values of the Coupling Network Tank L and C are chosen so that the amplitude of the antenna current reaches a peak at 65 microseconds. If no additional losses were present, an oscillatory exchange of energy between tank and antenna circuits would take place. But this would extend beyond 1 ms and interfere with the next pulse. Therefore, near the peak amplitude, the Tailbiter switch is closed connecting the Tailbiter resistance in the circuit and this causes the antenna current amplitude to decay rapidly and monotonically. This circuit operates without auxiliary power supplies and will provide a tail 60 dB down at 900 microseconds so that another pulse of this group may be generated at 1000 microseconds.

2.1.4.2 Output Network

The Output Network consists of a matching transformer and variable inductor. The function of the transformer is to perform an impedance transformation

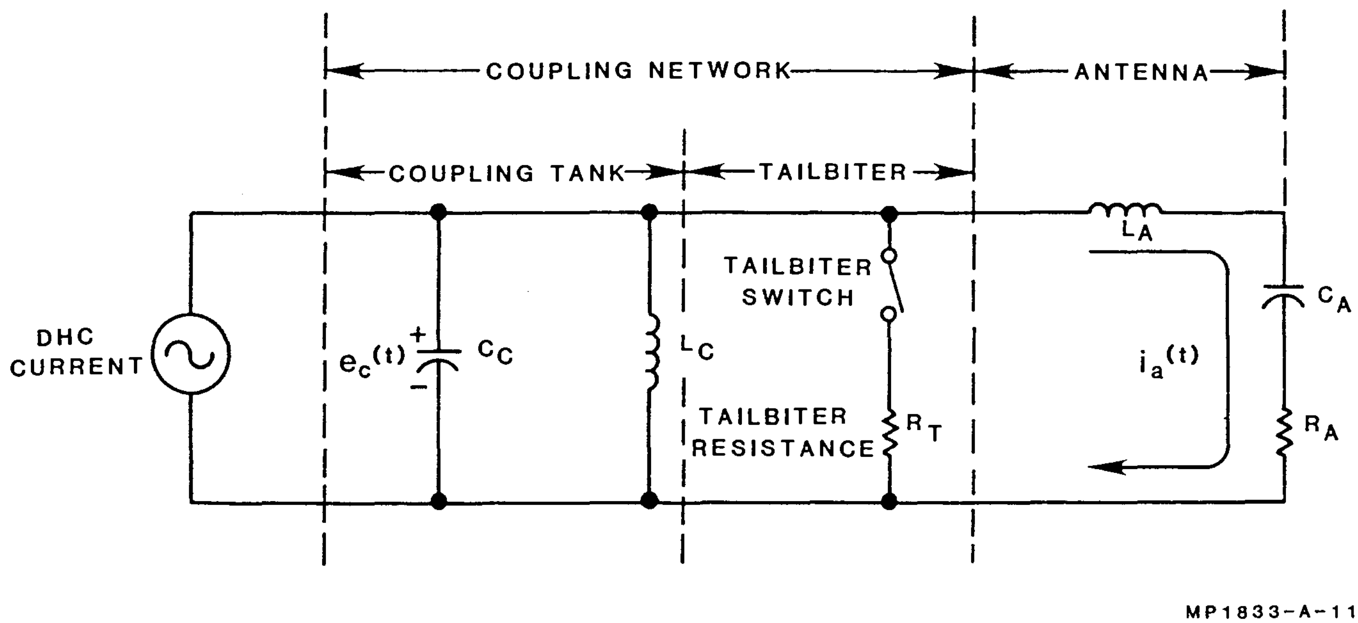

Figure 2-5. Equivalent Circuit of Coupling Network and Antenna

between the Coupling Network tank circuit and the antenna circuit. The function of the variable inductor is to tune the antenna circuit to resonate at 100 kHz. The inductance is controlled automatically by the PATCO to maintain the antenna circuit resonance.

2.1.4.3 Switch Network

The Switch Network contains motor driven switches which permit connection of either of the redundant coupling and output networks between the pulse generators and the transmitting antenna. Coupling and Output Network switchover may be commanded manually by an operator from either the transmitter site or the Chain Control Station, or automatically by the TOPCO when a fault is detected in the on-line Coupling or Output Networks.

2.2 THE CONTROL CONSOLE

Figure 2-6 shows a Control Console pictorial. The left and right cabinets contain the two redundant timing groups. The basic function of a timing group is to supply the proper timing and amplitude signals to the RF portion of the transmitter where the Loran-C pulses are actually generated. Only one timing group is on-line (i.e., controlling the transmitter) at any given time. The standby timing group, however, is always operating and is kept in synchronism with the on-line unit. The center cabinet contains the Signal Distribution Assembly (SDA), which determines which timing group is on-line by selecting the timing signals from either the left or the right PATCO. Within a timing group, the modules principally involved in generating the pulse triggers are the cesium frequency standard, the Loran Timing Unit (LTU) and the PATCO.

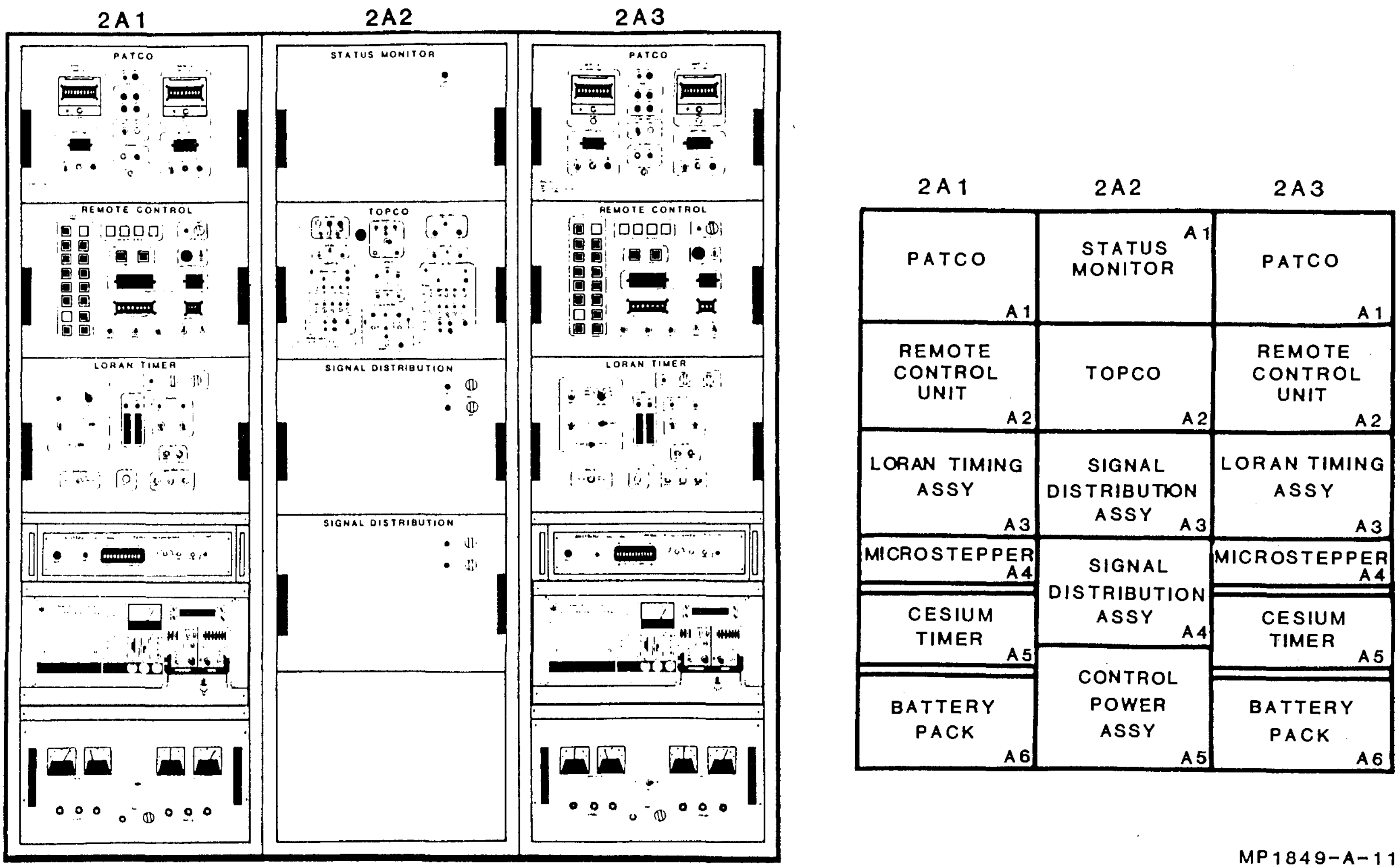

Figure 2-6. Control Console Pictorial

2.2.1 Frequency Reference

A cesium beam frequency standard and a phase microstepper provide a 5 MHz reference to the Loran Timer Unit. The cesium beam frequency standard is the source of an extremely precise and stable 5 MHz reference signal. This signal is obtained from a well defined quantum transition of the cesium atom. The cesium's frequency is very accurate but not perfect and a means of minor adjustment is needed. The phase microstepper within the cesium standard provides a means for fine tuning the 5 MHz reference frequency by inserting a constant phase change per unit time into the cesium output.

The output of the cesium standard provides the basic reference from which the times of transmission of the Loran-C pulses are derived. The time differences between Master and a Secondary are measured by the chain control system and compared with the desired time differences. Any errors are corrected by adjusting the actual times of transmission. The times of transmission may be adjusted in the Loran Timer Unit in discrete steps of as little as ten nanoseconds. These latter adjustments are called Local Phase Adjustments (LPAs).

2.2.2 Loran Timing Unit (Timer or LTU)

The timer accepts the 5 MHz reference frequency from the cesium standard and generates an output trigger for each Loran pulse to be generated. The sequence of triggers needed to make groups is called multipulse trigger (or MPT). The timer thus determines the desired start time for each Loran-C pulse. The principle inputs to the timer are listed below:

Input	Source
Group Repetitiion Interval (GRI)	Internal Switches
Phase Code	Internal PROM
Master or Secondary	Internal Switches
5 MHz Reference	Phase Microstepper/Cesium
Blink Condition	Front Panel or RCU
Local Phase Adjustments (LPAs)	Front Panel or RCU
Triggers On or Off	Front Panel or RCU
Single or Dual Rate	Internal Switches

Based on these input conditions, the timer determines the proper times at which pulses must be generated. As mentioned in the previous section, step adjustments to the times of transmission of the transmitter are made by inserting Local Phase Adjustments into the timer, either from its front panel or remotely via the Remote Control Unit (RCU). Phase code and group repetition intervals are also controlled by the timer.

2.2.3 Pulse Amplitude and Timing Controller (PATCO)

The PATCO controls three parameters of the Loran-C pulses: their timing, amplitude, and shape.

Pulse shape and amplitude are determined by reading front panel controls and generating a reference voltage for each Drive Half Cycle (DHC). Pulse shape is controlled by changing the relative amplitudes of each of the active DHCs.

Each Loran pulse is initiated by a trigger pulse sent to the PATCO from the LTU. When a trigger pulse is received, the PATCO delays it and encodes it into a Serial Data Stream (SDS) which is sent to each Half Cycle Generator. Each SDS includes a start pulse, a digital number proportional to the desired amplitude, a second digital number for Amplitude Compensation Delay (ACD), a TRIG pulse, and REF pulse.

A voltage waveform proportional to the current in each DHC is fed back to the PATCO. To control pulse amplitude the PATCO compares the DHC feedback with the reference voltage for that DHC and thus derives a HI/LO indication. The results of this comparision are then used to adjust the amplitude number sent to the HCGs in that DHC.

Timing is controlled by measuring the time of occurrence of the DHC feedback pulses and comparing this time with a REF timing pulse derived from the MPT. An early/late signal is then used to adjust the amount of delay inserted in TRIG and REF pulses by PATCO before they are sent to the HCGs.

Amplitude Compensation Delay is a digital number (in tenth microseconds) which is a function of the DHC amplitude reference level. It is used by each HCG to normalize its firing time and helps the HCG maintain its timing control.

Other functions which the PATCO performs are automatic antenna tuning and fault detection.

2.2.4 Signal Distribution Assembly (SDA)

The Signal Distribution Assembly (SDA) contains separate and identical distributing circuit cards for each Half Cycle Generator. A single SDA can accommodate up to 32 of these cards. Two SDAs are required when more than 32 HCGs are to be driven. Input signals to these circuit cards come from both PATCOs, although only the signals from the on-line PATCO are used. A signal from the TOPCO to the SDA determines which PATCO signals are used at any given time. This signal controls which of the two redundant PATCOs is on line.

2.2.5 Transmitter Operation and Control (TOPCO)

The Transmitter OPerational COntrol is an assembly capable of monitoring many transmitter signals for Fault Detection and Control (FD&C) and has several basic control switches for the RF power generator such as AC power on-off, RF Switch Armed/Disarmed, and Side Select.

2.2.6 Status Monitor Unit (SMU)

The SMU and TOPCO provide the bulk of the FD&C in the transmitter. The System Monitor Unit is primarily responsible for scanning the HCGs for faults and breaker alarms.

Internally, the SMU is a microprocessor controlled scanner capable of monitoring up to 64 HCGs, of passing signals from RCU to RCU, and of controlling an optional printer as a station log.

2.2.7 Remote Control Unit (RCU)

The RCU is a Remote Control Unit whose primary purpose is to interface the transmitter to remote data links via an RS232 interface.

The RCU is also able to locally initiate all remotely generated commands. Its front panel is shown in Figure 2-7.

The left column of lamps display faults and alarms of the transmitter. The next column displays various statuses of the transmitter. The top row of lamps display remote message activity and the bottom digiswitches provide, primarily, a means of inputting local commands and requests.

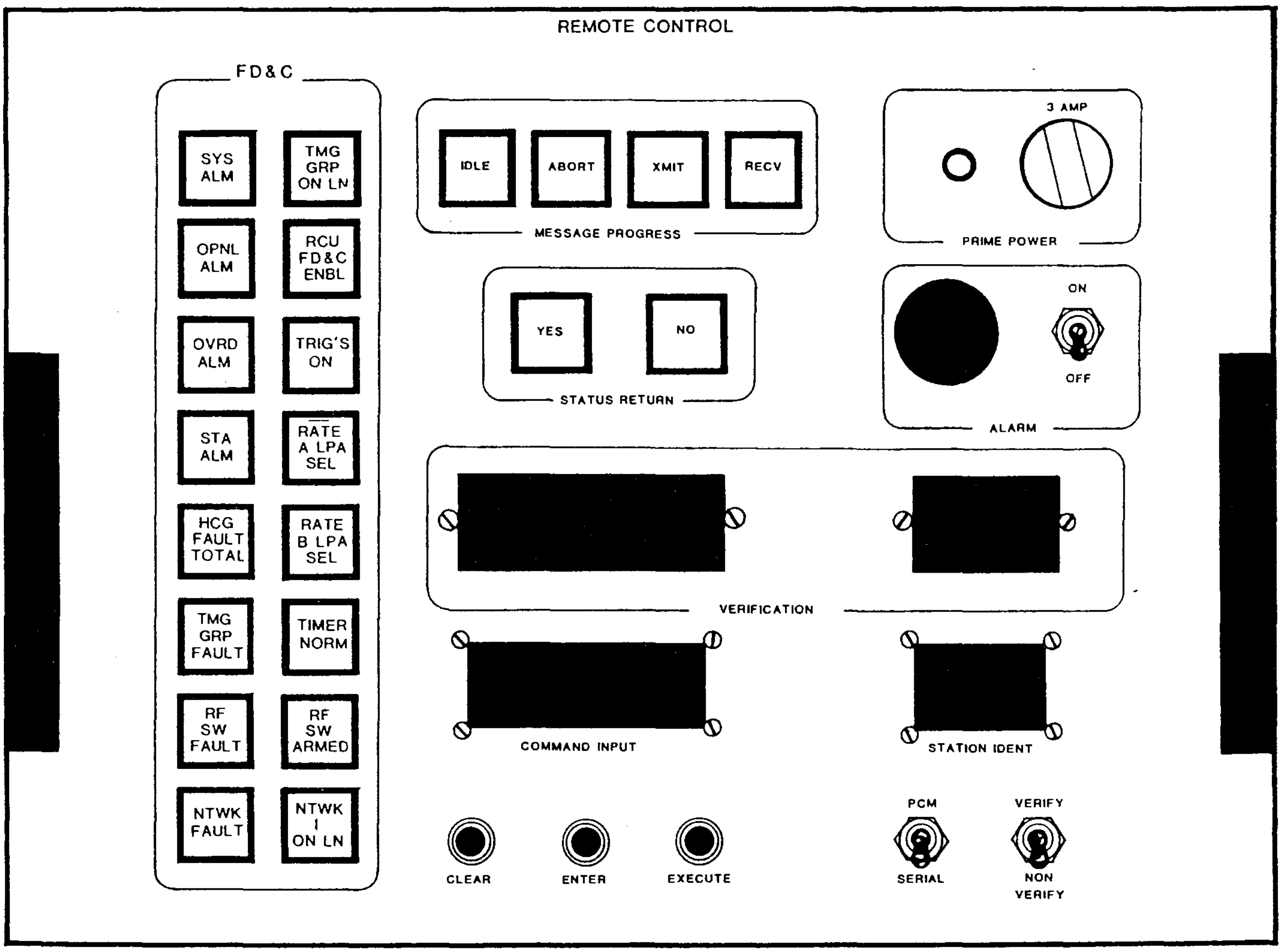

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Figure 2-7. RCU Front Panel

3.1 CONTROL FUNCTIONS

System controls can be grouped into two categories, presettable and operational. Presettable controls are set at installation and rarely changed. These include GRI, pulses per group, single or dual rate and ECD. These controls are located either inside or on the front panel of individual units. The principal presettable controls and their locations are listed as 1 through 8 in Table 3-1.

Operational controls are those which are likely to be utilized in everyday operation. There are several ways by which the operational controls can be initiated. Some can be initiated by using front panel controls on individual units (9 through 13 in Table 3-1). All operational controls can be initiated either locally by inserting an RCU command or remotely from the chain control station which sends a message to the RCU to initiate the command. The RCU then either executes the command itself or actuates the appropriate control lines to the individual unit which in turn executes the command.

3.2 FAILURE RECOVERY

Failures in the control system and the output and coupling networks are survived by switching to the redundant units. The Accufix 6500 transmitters also use a "fail soft" mode in which only minor output current changes will result from an HCG failure.

Failure of an HCG in a 64 HCG transmitter will cause only 1/4 μsec or less shift in ECD. This minor change is of no consequence to the system. A loss in output current (about 3% or .2dB) will also take place. Again this is negligible and will last only until a replacement action is taken.

In short, failures are very seldom, and they normally do not cause long interruptions in transmitter service since they are easily remedied by simple substitutions.

TABLE 3-1

TRANSMITTER CONTROL FUNCTIONS

FUNCTION OR NAME	CONTROLLED BY: CHAIN CONTROL	CONTROLLED BY: RCU at TRANSMITTER	CONTROLLED BY: UNIT FRONT PANEL	CONTROLLED BY: INTERNAL TO UNIT	REMARKS
1. Group Repetition Interval (GRI)	No	No	No	Switches in Timer	30,000 μs to 99,990μs A or B Rate
2. Phase Code	No	No	No	Timer PROMS	Loran-C Master or Sec.
3. Pulse per Group	No	No	No	Switches in Timer	9 (Master), 8 (Secondary A or B Rate
4. Blanking Priority	No	No	No	Switches in Timer	A Rate priority or alternating A, B
5. Power Level	No	No	PATCO	--	Set percent normal output current A or B Rate
6. Envelope to Cycle Difference (ECD)	No	No	PATCO	--	Under windows on PATCO A or B
7. Adjust REF	No	No	Cesium	--	Adjust REF frequency
8. Local Phase Adjust (LPA)	Yes	Yes	Timer	--	10 nanoseconds to 1 millisecond A or B Rate
9. Group Phase Interval Change	Yes	Yes	Timer	--	Delay 1 group interval A or B Rate
10. Blink	Yes	Yes	Timer	--	Master, 9th pulse, secondary, 1st and 2nd pulse; W, X, Y, Z; A or B Rate
11. Select Output Network I or II	Yes	Yes	TOPCO	--	RF Switch must be disarmed

TABLE 3-1
(Continued)

TRANSMITTER CONTROL FUNCTIONS

FUNCTION OR NAME	CONTROLLED BY				REMARKS
	CHAIN CONTROL	RCU at TRANSMITTER	UNIT FRONT PANEL	INTERNAL TO UNIT	
12. RF Switch Arm or Disarm	Yes	Yes	TOPCO	--	Enables/Disables RF Switching
13. Timer Synchronization	Yes	Yes	Timer	--	Synchronizes off-line timer to on-line timer
14. Timer Track Inhibit	Yes	Yes	No	--	Stops off-line timer from following on-line timer
15. Select Left/Right Timing Group	Yes	Yes	TOPCO	--	
16. SMU Reset	Yes	Yes	--	SMU	Restart SMU
17. PATCO Reset	Yes	Yes	--	PATCO	Restart PATCO
18. RCU Reset	Yes	Yes	--	RCU	Restart other RCU
19. Clear Faults	Yes	Yes	--	--	Clear RCU & SMU Fault Table
20. Report Faults	Yes	Yes	--	--	Send fault summary to chain control
21. Report Status	Yes	Yes	--	--	Send status summary to chain control
22. Operator Alarm	Yes	Yes	--	--	Turn on system alarm

LORAN-C RECEIVER SYSTEM TECHNOLOGY AND PHASE CODING

Walter N. Dean and Robert L. Frank

Consultants

Abstract

A Loran-C receiver is inherently a relatively simple device, but a number of special considerations inherent in the system call for some design considerations which may not be readily apparent. This paper discusses many of these special features. The multiple pulsing and phase coding developed for this system is described and its characteristics analyzed.

1. Introduction

This is an introduction to the essentials of Loran-C receivers, covering many, but by no means all, of the considerations which make the design of a loran receiver different from of other navigation or communication devices. Fundamentally, a Loran-C receiver is a very simple device - a broadband, fixed-tuned 100 kHz amplifier with an output which can be sampled digitally to produce time difference numbers representing the position of the receiver relative to the transmitters. In order to achieve the best accuracy of the system, it is necessary to make phase measurements on the 100 kHz pulses, to an accuracy of 0.1 microsecond or better. But a "coarse" measurement is also required, to assure that the measurements are being made on the same part of the pulses from each of the stations.

The basic receiver then can be represented by the block diagram in figure 1-1. The antenna is almost always a short vertical antenna, "short" meaning relative to a wavelength which is 3000 meters. The short antenna presents a high capacitive reactance at its base, so an impedance transformation is usually required to match it to a cable to bring the signals to the receiver itself. It is usual practice to employ an active coupler, with sufficient gain to overcome any noise picked up in the cable or generated in later amplifier stages.

After amplification, the signals are split into two channels, "phase" and "envelope", each with its tracking servo loop. These servo loops are combined with the signals from the timer to produce a time of arrival (TOA) number for the signals from each of the stations. The process of converting those TOAs to position information is not a part of this discussion.

2. Loran Signals

The generation of the loran signals has already been discussed in considerable detail in a previous session. The transmitted pulses are maintained in a precise envelope shape at each station, so that the only differences the receiver should see are those produced during the propagation of the signals over the earth. There are a couple of possible explanations for this pulse distortion. First, it must be recognized that, although 99% of the

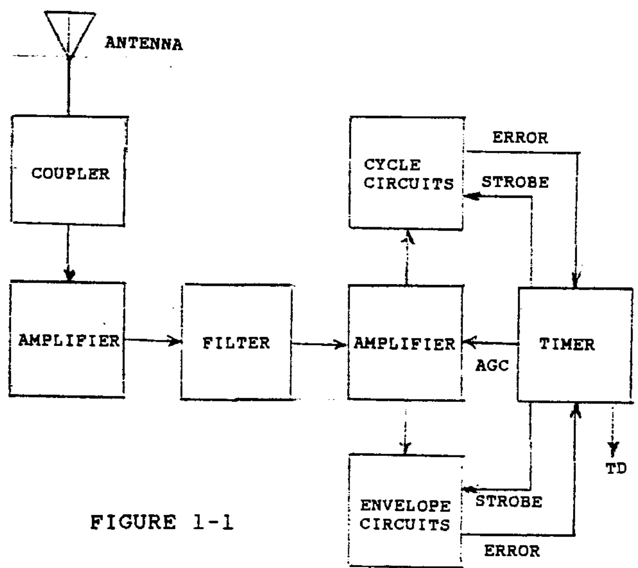


FIGURE 1-1

LORAN RECEIVER BLOCK DIAGRAM

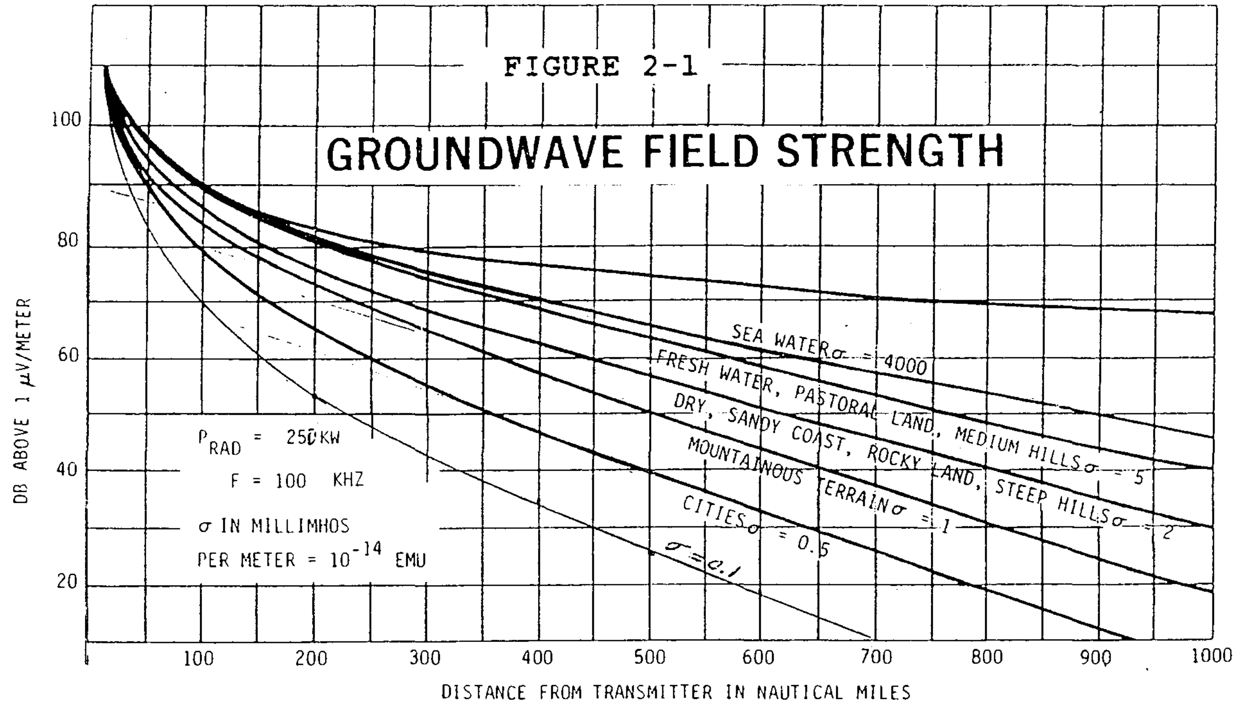
energy of the loran pulse is contained in the band 90-110 kHz, that 1% outside the band affects the pulse shape, particularly the rising edge. Over land of poor conductivity, the upper sidebands, above 110 kHz, will be attenuated more than the lower sidebands, below 90 kHz, resulting in a change in pulse shape.

Rapid (spatial) changes in pulse shape have also been observed over rough mountainous terrain, leading to the possible conclusion that the roughness, comparable to a wavelength, produces multipath effects which distort the pulses.

Signal field strength is another matter. Close to a transmitter, the loran signal field strength can be several volts per meter, equivalent to about 130 dB above one microvolt per meter. At the other end of the scale, the minimum signal strength is determined by transmitter power, the distance from the transmitter and the characteristics of the terrain over which the signal propagates. Figure 2-1 shows how the groundwave field strength varies with distance when propagated over earth of varying conductivities. The curves represent field strength for a transmitted signal power of 250kw, which is representative of a transmitter with a peak power of 1000kw.

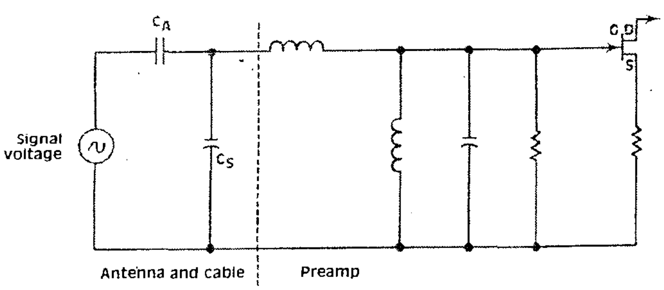
3. Receiving Antennas

The useful part of the loran signal propagates as a groundwave, as a vertically polarized electric wave. The simplest and most obvious type of receiving antenna is the vertical electric dipole, which in nearly all applications is replaced by a vertical



monopole. In either case, the "effective height" of the antenna is one-half the physical height, which means that a two meter vertical monopole in a field of one millivolt per meter would produce a signal of one millivolt between the base of the antenna and ground. A 17 inch whip, typical for a low performance aircraft, has an effective height of about 0.2 meters.

No matter how long it is, the antenna is electrically "short", that is, short with respect to a wavelength at 100 kHz. The 17 inch antenna measures 0.000067 wavelengths, so that it appears to the receiver as a very small capacitor. Since it may be necessary to locate the loran receiver some distance from the antenna, some method of matching the antenna impedance to that of a length of cable is required. This usually consists of a coupling device, with active elements to provide amplification and impedance transformation. Figure 3-1 shows the elements of such a coupler. In the diagram, the capacitive reactance of the antenna is shown shunted by the stray capacitance in the antenna base, as the coupler is usually built into the antenna base. Since this acts as a voltage divider on the signal, it is desirable to minimize C_s. The first inductor is selected for series resonance at 100 kHz, with relatively low Q, and the other elements provide additional bandpass filtering. It is desirable to have the coupler broadly tuned at the input to reject strong signals out of band which could overload subsequent active elements in the coupler.



Antenna Preamp Schematic FIGURE 3-1

It is common practice to provide power to the active elements on the center conductor of the coaxial cable used to carry the signals from coupler to receiver, thereby eliminating the need for a separate power cable. Amplification in the coupler needs to be sufficient so that the signal is not degraded by power supply noise or other signals picked up by the interconnecting cable.

4. Receiver Amplifier

The cable between the antenna coupler and the receiver proper is typically 50-ohm coax. A transformer coupling to the first amplifier stage is an easy way to get gain and also provide convenient coupling of the dc power to the coupler. The first amplifier has several design considerations. It should be low noise, to avoid adding noise to weak signals, and it must be able to handle the very strong signals received when close to a transmitter. This latter is a tradeoff for the designer. If there will be no great need for the receiver to work close to a transmitter, then the maximum signal handling requirement can be reduced. Close to a transmitter, signal voltage is inversely proportional to distance, making calculations quite simple. If it is necessary to handle strong signals, the gain of the first stage can be controlled, either by signal-activated AGC circuits, or by switched gain based on knowledge of the receiver's position.

5. Bandpass Filter

The function of the bandpass filter is to reduce out-of-band noise and interference, thereby improving the signal-to-noise ratio of the received loran signals. Especially in Europe, there are many interfering sources close to the 90-110 kHz loran band and it would be desirable to eliminate them with a filter which would then pass only the loran signals. Unfortunately, even though 99% of the loran pulse energy lies in the 90-110 kHz band, that remaining one percent is vital to the operation of the system. The problem is skywaves, which will be discussed later in more detail. At long ranges, over 1000 miles, and particularly at higher latitudes, the daytime skywave delay can be quite short, in the order of 35 microseconds. The FAA in the U.S. has prescribed tests calling for skywave delay of 35 microseconds and amplitude +6dB.

To determine the performance of the receiver with different bandpass characteristics, a graphical technique can be employed. It assumes that the loran pulse can be measured after being passed through the desired bandpass, either actually or by computer simulation. The following is an example.

To compare the performance of two filters, each with 20kHz bandwidth, one a 4-pole Butterworth and the other a 5-pole Butterworth, first the attenuation-frequency characteristics are plotted as in figure 5-1. This shows a significant difference in rejection at frequencies more than 20 kHz away from the loran band. The next step is to pass a standard loran pulse through each of the filters, and plot the output pulse shape on semi-log paper. Figure 5-2 shows a plot of the leading edge of the loran pulse from the 4-pole filter, and figure 5-3 shows the same from the 5-pole filter.

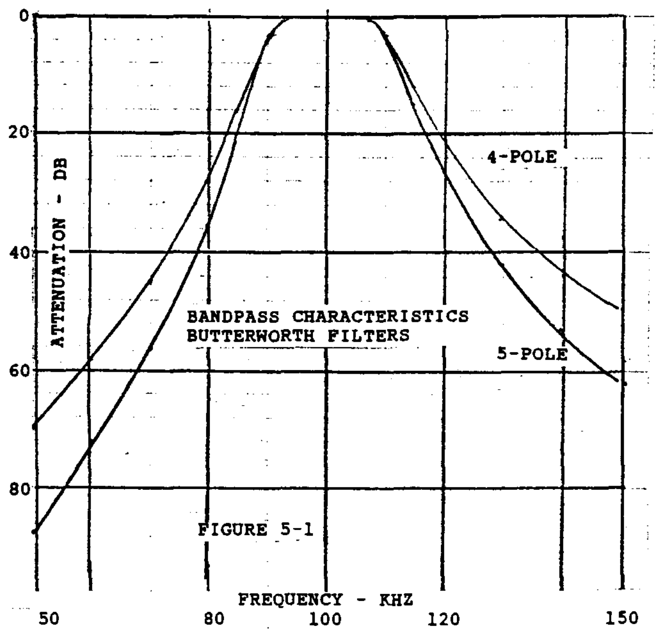


FIGURE 5-1

The factor which determines how high on the pulse the loran signal can be safely sampled is the presence of the skywave. In this instance, the worst case skywave is assumed to have a delay of 35 microseconds and amplitude relative to the groundwave of +10dB. In order to make this comparison, the leading edge of a skywave pulse is formed on the semilog plot by copying the groundwave pulse shape, delayed 35 microseconds and raised by a factor of 3.16.

The latest point on the loran pulse which can be used for tracking is that point at which the skywave is just small enough that its effect is negligible. For most practical purposes, that relative amplitude is 0.1, or -20dB. To determine when that occurs, one searches the graph to find the time that the groundwave and skywave curves are a factor of 10 apart. Any time later, the skywave is relatively greater amplitude, and bad things can happen. These points are shown on the two figures, indicating that with the 4-pole filter, the pulse can be sampled at 27% of peak amplitude, while with the 5-pole filter, it must be sampled at 25% or less to avoid skywave contamination. The difference in sampling point is trivial, indicating that the 5-pole filter would be the better choice.

On figure 5-2 the skywave is also shown with a relative amplitude of +6 dB, a figure used in some specifications. This allows the pulse to be sampled at 35% instead of 27%, which would make about 1.2 dB improvement in SNR.

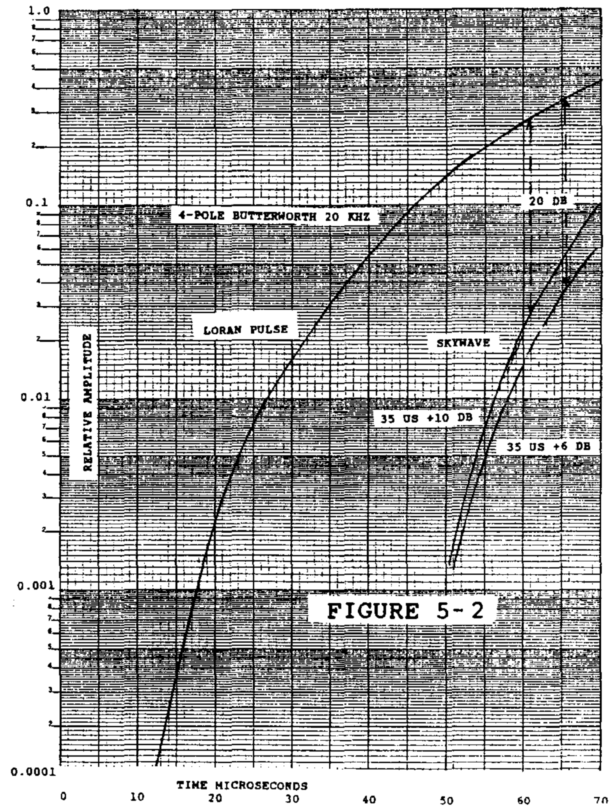


FIGURE 5-2

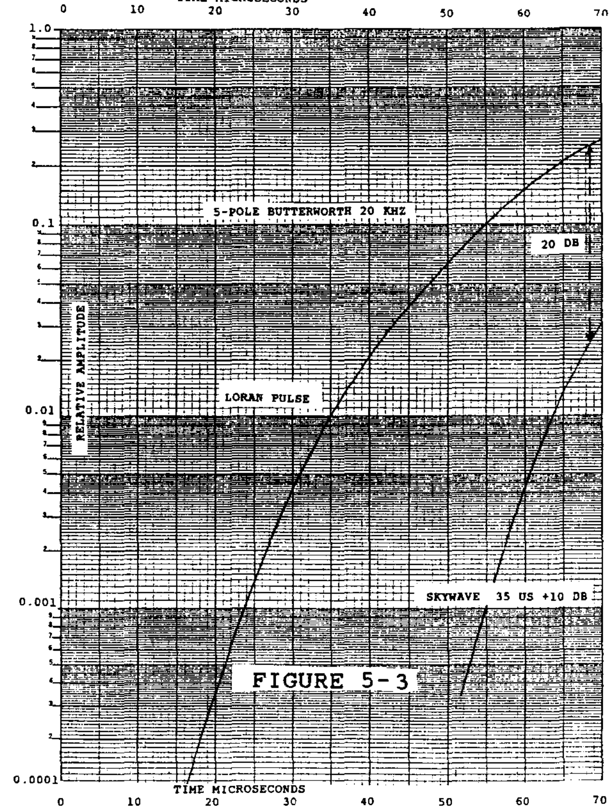


FIGURE 5-3

6. Interference Rejection

There are a number of techniques available for reduction of the effects of interfering signals. This will be discussed in detail in a later paper, so just a brief summary will be made here.

The simplest and possibly most reliable rejection circuit, generally called "notch filter" is the tuned L-C circuit, tuned to the frequency to be rejected. In the U.S.A., the relatively small number of interferers allows receiver designers to use a number of fixed-tuned notches. Complications arise when one tries to change the tuning to respond to a dynamic environment which changes with both position and time. Some receivers use the computing capacity of the set to combine knowledge of the locations of troublesome emitters with knowledge of the receiver's position to control the frequency of several notch filters. Other sets have used special detectors to determine the frequency and amplitude of signals being received, adjusting signal-rejection circuits to reduce the most troublesome.

7. Signal Tracking

Basic to the loran receiver, but not detailed here, is a timing function, part of the computing part of the receiver, which produces sampling strobes timed to 100 nanoseconds or better, and has the ability to use the error signals from the sampling process to position the strobes. The timing of the strobes then becomes the timing information which is used by the computer to calculate position and other derivative information.

The block diagram of a loran receiver shown in figure 1-1 shows the essentials of two servo loops, "cycle" and "envelope. During the process of signal acquisition, a pattern of strobes is set up in the Group Repetition Interval (GRI) by the timer, which is driven by a reasonably precise oscillator. Once a loran station (usually the Master) is detected, the timer is phase-locked to the Master signals by the cycle tracking servo loop, so that all timing measurements are made relative to the Master station. Once phase lock is achieved, all the stations in the chain can normally be acquired. The cycle tracking is done by sampling a zero-crossing of one of the 100 kHz cycles of the loran pulse. This is frequently done by hard-limiting the loran signal, and tracking the +/- transition. This has the advantage of being simple, independent of signal amplitude and resistant to impulsive noise. A linear tracking loop is more complex, but has some better interference rejection characteristics.

Cycle tracking is obviously only one step in the process of timing the loran signal. The "envelope" circuits are there to produce a signal to cause the envelope strobes to be positioned on the proper point on the leading edge of the loran pulse. The function is to step the pattern of sampling strobes in units or multiples of 10 microseconds along the pulse until the proper point on the pulse envelope is found. The means of determining which point is the correct one is the subject of the following section.

The precise timing of all the tracking strobes is controlled by the cycle tracking servo loop. This is typically a second-order servo loop, so that it tracks with zero error at constant velocity. The servo gains are determined by the dynamics of the application in which the receiver is to be used. Inertial or other rate-sensitive inputs have been used to permit use of longer averaging times in a maneuvering environment. The envelope tracking can use a long time-constant first order filter, since it is not affected by system dynamics.

8. Pulse Envelope Analysis

The problem stated above is essentially to be able to select a particular point on the leading edge of a loran pulse, independent of the amplitude of the pulse. The first requirement, then is for an AGC circuit which will keep the important parts of the loran pulses within the linear range of the tracking circuits.

One of the first envelope detection techniques developed was the "derived envelope". In this the received loran pulse is actually detected in a synchronous detector, then passed through circuits which produce the derivative of the pulse function, as shown in figure 8-1. Subtracting the derivative from the original pulse produces a waveform with a zero crossing whose timing does not vary with signal amplitude, but which can be adjusted by varying the relative amplitude of the derivative function.

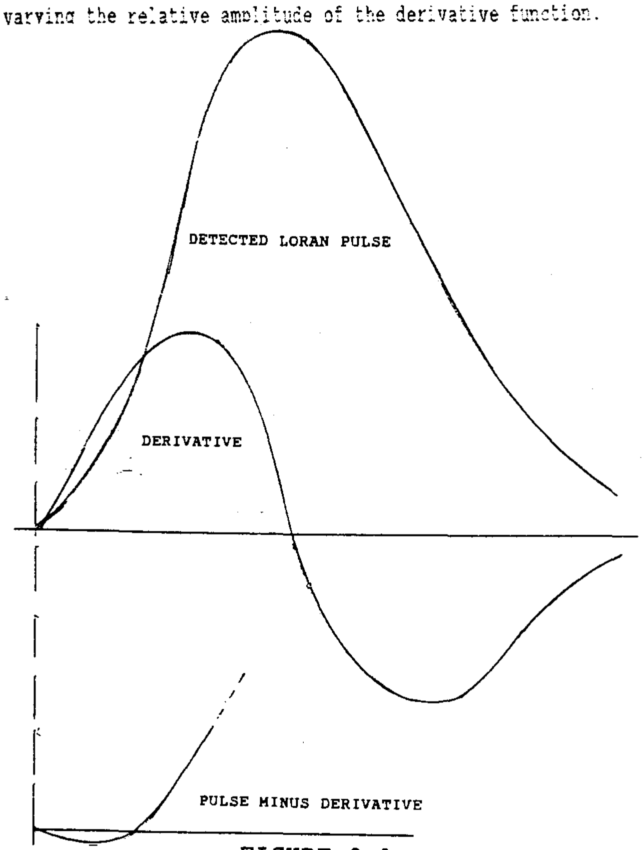


FIGURE 8-1

DERIVED ENVELOPE TECHNIQUE

A simpler and less expensive technique is the "delay and add", which uses the pulse directly, and adds to it a 5 microsecond delayed (and inverted) pulse of adjustable amplitude. The result is illustrated in figure 8-2, where the combining ratio is varied from 1.0 to 1.5. The desired result is the moving of the point of phase reversal from 80 to 20 microseconds from the start of the pulse. The detection of the phase reversal is simple in theory but a little tricky in practice in a noisy environment. One possible problem is the precision required of the 5 microsecond delay, as shown in figure 8-3, which shows that a variation of a few percent can have a serious effect on the precision of the phase reversal.

In the AN/BRN-5, the slope of the leading edge of the pulse was measured by taking the ratio of successive half cycles of the pulse. Figure 8-4 shows how this ratio varied for the first 70 microseconds of the pulse. In the case of the BRN-5, the receiver bandwidth was 70 kHz, and tracking on the pulse was at the 40 microsecond point. The figure also illustrates how the receiver bandpass determines the pulse shape, as input pulses with rise times of 60 and 75 microseconds have almost identical output shapes, even with this very wide bandwidth. Narrower band filters will be more inclined to mold pulses to their own character.

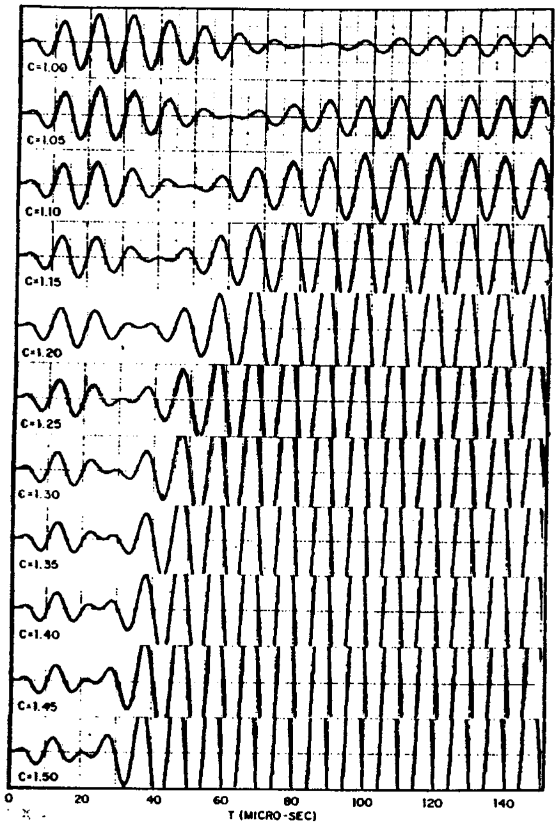


FIGURE 8-2 VARIATION OF "DERIVED" POINT vs. CHANGE IN COMBINING RATIO

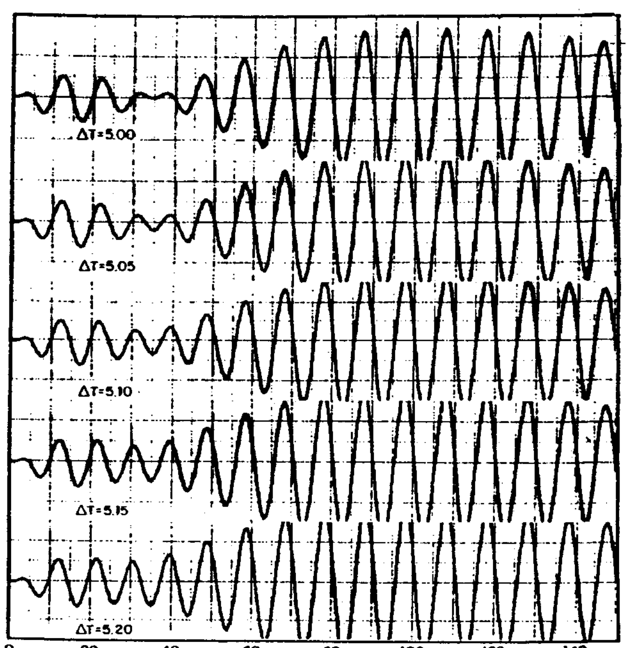


FIGURE 8-3. EFFECT OF CHANGE IN DELAY ON DERIVED WAVEFORM

9. "Third Cycle" Tracking

The myth of using the third cycle of the loran pulse for tracking has been around for a long time, apparently based on the assumption that the received pulse is the same as the transmitted pulse. The reality is shown in the semi-log plot of the pulse

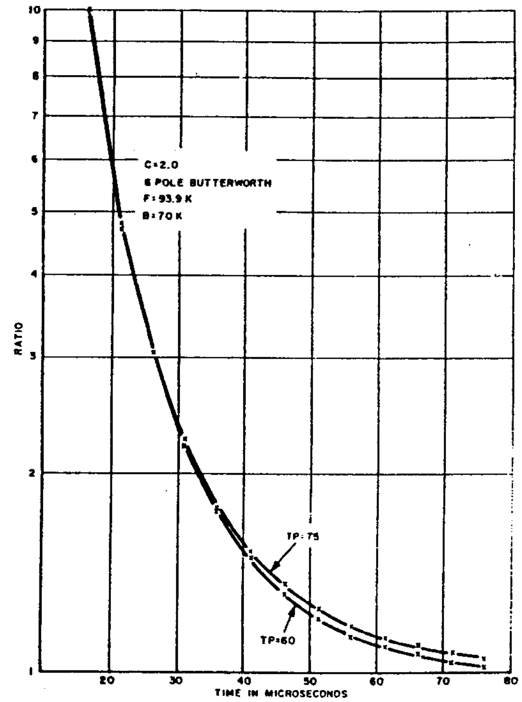


FIGURE 8-4. RATIO E_2/E_1 FOR DIFFERENT T_p

envelope, figure 5-2. The tracking point selected is actually 60 microseconds after the start of the input pulse. Thirty microseconds before that point, the pulse amplitude is only 0.016 of peak, which could be considered the start of the pulse by a less critical observer.

10. Displays

Very little need be mentioned about displays for loran receivers. Two general types are used, LED and LCD, and each have their advantages and disadvantages. For aircraft installations, the high-intensity LED display is most popular, although most expensive. It is the most readable under most conditions, but all will "wash out" and be unreadable in direct sunlight. The liquid crystal displays are best in bright light, but are harder to read in dim light, and tend to be temperature sensitive.

MULTIPLE PULSING AND PHASE CODING

The original Low-Frequency Loran system, which operated at 180 kHz, transmitted single pulses from each of the slave stations and a pair of pulses from the master, as a means of visual identification on an oscilloscope. For the CYTAC system in the early 1950's, multiple pulsing was used to raise the average transmitted power without losing the advantages of pulse transmission and time sharing. It was thus possible to increase the effective range of the system without increasing the peak transmitter power. Phase coding was introduced as a means of identification and interference reduction.

In a phase-coherent, or synchronous-detection type system, it is possible to modulate the signals by shifting the phase of the r-f carrier within the pulse envelope. In its simplest form, this "phase code" modulation takes the form of phase reversal in some of the pulse carriers. The multiple pulsing and phase coding used in the Loran-C system is shown in figure C-1. The symbols + and - represent in-phase and 180 degree out-of-phase pulses.

	MASTER	SECONDARIES
A GRI	+ + - - + - + -	+ + + + + - - +
B GRI	+ - - + + + + -	+ - + - + + - -

Figure C-1 Loran-C Phase Codes

Phase coding serves a number of purposes. solving some of the problems introduced by multiple pulsing. 1) It provides a method of identification of signals for automatic equipment. 2) It expedites the automatic search process and simplifies the automatic search apparatus. 3) It solves a problem of multihop skywave interference. as will be discussed later. 4) It provides for communication between stations.

The problems of automatic search and their solution by phase coding can be best understood by considering in simplified form the signal detection system used in the Loran-C receiver shown in figure C-2. The r-f signal is received and fed to two balanced modulators. A 100 kHz reference signal generated in the receiver is fed in quadrature to the two modulators. The output of the balanced modulator represents the detected pulse envelope multiplied by the cosine of the angle between the reference and the signal. When the reference and signal are in phase. a positive pulse output is obtained. and when they are out of phase. a negative pulse results. The outputs of the balanced modulator "detectors" are sampled in gates controlled by triggers generated in the receiver. These samples are passed through low-pass filters so that only the very low frequency components get through. Typical bandwidths are in the order of 1 hz for search and 0.1 to 0.03 hz during tracking.

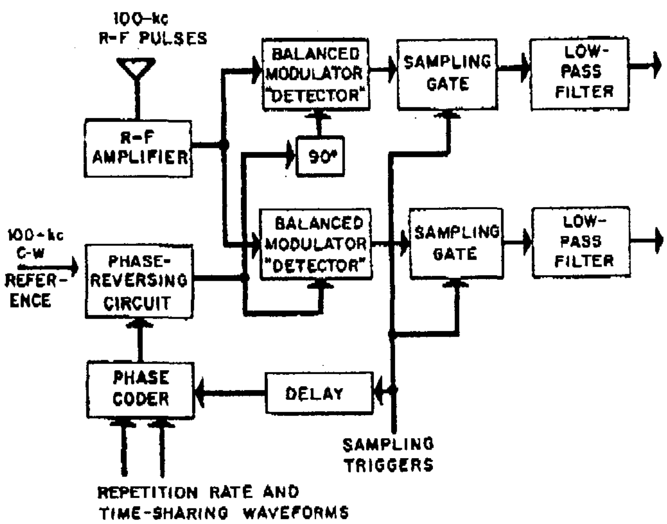


Figure C-2—Loran-C detection system.

Multiple-Pulse Coding

The Loran-C transmissions consist of groups of eight pulses from each transmitter. spaced 1000 microseconds apart. with the Master transmitting a ninth pulse delayed 2000 microseconds from the eighth. This ninth pulse was originally added for master station identification on manually operated receivers using an oscilloscope for pulse matching. It is not used by automatic receivers. but is used in some locations as a means of interstation communication. It is not being considered in this discussion.

The function of the phase coding in eliminating multi-hop skywave interference can be understood by reference to figure C-3(a). which shows the signal out of a balanced modulator when the

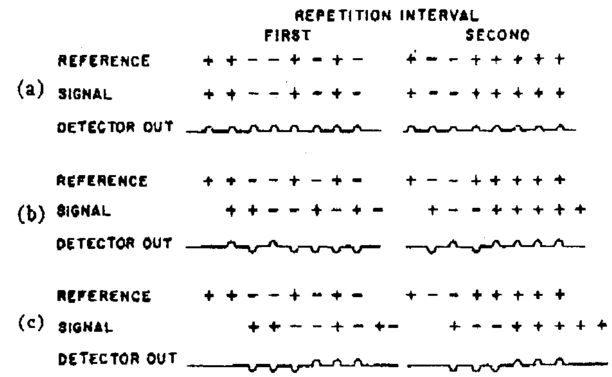


Figure C-3 - Multihop Skywave Rejection

reference and signals are aligned: all the detected pulse envelopes are the same polarity. and when sampled will produce a net dc output. Figure C-3(b) shows the condition that exists when the signal is delayed one pulse with respect to the reference. in other words. the condition resulting from a multihop skywave delayed 1000 microseconds. In this case. the output pulses are both negative and positive and averaged over the two repetition intervals sum to zero. Figure C-3(c) shows that zero summation exists similarly for a delay of 2000 microseconds. and further analysis will show that the same cancellation exists for all possible misalignments or all amounts of skywave delay. The Master ninth pulse is not shown. since it is not sampled by the automatic receivers.

For one method of automatic search with multiple pulsing and the existing phase code. it is necessary that the master pulses be divided into two parts. Sampling corresponding to the first four pulses is designated M1. and the second four M2. M1 and M2 samples are filtered separately. and the product M1*M2 operates a threshold device responsive only to positive polarity. During initial Master search. there are four possible conditions: the coder in the receiver may be either in step or out of step by one repetition interval. and the master identification circuits may be sampling either master or secondary pulses. It is desired that the master search circuit stop the automatic search only when the eight master pulses are being sampled. and when the receiver and transmitter coders are in step.

In the master and secondary phase codes shown in figure C-1. each odd-numbered pulse has a fixed polarity during successive repetition intervals. but even numbered pulses have alternating polarities during succeeding intervals. Thus. for all cases where odd-numbered pulses are aligned with the reference for even-numbered pulses. the detector output will have an equal number of plus and minus outputs during two repetition intervals. the net output will be zero: it is thus necessary to consider further only even-numbered pulse misalignments.

The results of such an analysis are summarized in Table 1. The action is such that a positive M1*M2 search threshold signal is obtained only for the unique condition of alignment of the eight master sampling gates with the eight master pulses. and with the reference coder in step with the transmitter. It should be noted that the M1 and M2 are only relative. until a phaselock is obtained by the receiver on the master signals. But since the product is used as the search threshold device. the analysis is valid for all polarities.

For time difference measurement. the whole master group is used. as indicated in the column "Track Signal (M1+M2)". The zeroes for all pulse samples ahead of the correct alignment again indicate no response to delayed skywave signals. The spurious responses when the coders are out of step show why the total response is insufficient for initial alignment.

TABLE II

ANALYSIS OF SEARCH AND TRACKING (EIGHT MASTER PULSES)

	Pulses Sampled (by Master Sampler)		Net Sampled Voltage* M1	Net Sampled Voltage* M2	Search Threshold Signal (M1×M2)	Track Signal (M1+M2)
Transmitter and Receiver Coders in Step (Normal Track Condition)	Master	#1–2	0	0	0	0
		1–4	0	0	0	0
		1–6	−4	+4	−16	0
		1–8	+8	+8	+64 (Correct Alignment)	16
		3–8	−4	+4	−16	0
		5–8	0	0	0	0
		7–8	0	0	0	0
	Secondary	#1–2	0	0	0	0
		1–4	0	0	0	0
		1–6	−4	+4	−16	0
		1–8	0	0	0	0
		3–8	+4	−4	−16	0
		5–8	0	0	0	0
		7–8	0	0	0	0
Coders Out of Step by One Repetition Interval	Master	#1–2	0	+4	0	+4
		1–4	0	0	0	0
		1–6	0	−4	0	−4
		1–8	0	0	0	0
		3–8	−4	0	0	−4
		5–8	0	0	0	0
		7–8	+4	0	0	+4
	Secondary	#1–2	0	+4	0	−4
		1–4	0	+8	0	+8
		1–6	0	+4	0	+4
		1–8	0	0	0	0
		3–8	−4	0	0	−4
		5–8	+8	0	0	+8
		7–8	−4	0	0	−4

* Summed over two repetition intervals, each unit represents one pulse.

Once the coder in the receiver is in step with the master. search for the secondary signals may be initiated using a single quadrature set of sampling gates and low-pass filters without a breakup corresponding to M1 and M2. since getting the coder in step with the master aligns the secondary intervals. The analysis of the response with improper pulse alignment for the master applies equally to the secondaries. so that a net output occurs only when all eight sampling gates are aligned with corresponding pulses. This property also provides for rejection of multihop skywaves in the secondary signals.

Interference Reduction

Pulse systems basically have sideband frequencies separated from the carrier frequency by multiples of the pulse repetition rate. When the pulses are processed by sampling. any c-w interference which has the same phase as the pulses when sampling occurs acts just like interfering pulses. Reduction of interference was the initial incentive toward development of phase coding. With the 8-phase CYTAC coding, each pulse of the group had effectively a different carrier frequency. Any single c-w interference can be synchronous with one pulse out of eight. therefore there is an 8 to 1 or 18 dB reduction in degradation compared to an uncoded system.

In going from the 8-pulse 8-phase 8-group CYTAC code to the 8-pulse 2-phase 2-group Loran-C code. the inherent c-w rejection was reduced from 18 dB to 12 dB (4 to 1). Six of the 12 dB comes from the existence of two effective frequency families: one is 100 kHz +/- S*(GRR) where S is any integer and GRR is the Group Repetition Rate in Hertz. This is for the pulses that have the same phase from one group to the next. The other is 100 kHz +/- (T/2)*(GRR) where T is an odd integer.for pulses which reverse phase from one group to the next. The other 6 dB comes from the phase reversal pattern within the group. The total 12 dB improvement can be seen in figure C-4. where the Master code is compared with two c-w interferences - phases shown at the times of sampling.

```
  M    + + - - + - + -           same or opposite
       + - - + + + + +           with respect to M

100kHz + + + + + + + +    s s o o s o s o
       + + + + + + + +    s o o s s s s s  Net = 4 same

100kHz + + + + + + + +    s s o o s o s o
  +    - - - - - - - -    o s s o o o o o  Net = 4 opposite
1/2GRR
```

Figure C-4 Interference Reduction

In the case of either interference. 3/4 of the samples balance out between same and opposite phases compared to the loran code. leaving a voltage residual of 1/4. -12 dB.

Schemes have been developed which can eliminate the effects of any one synchronous interfering signal by automatically detecting the presence of the interference. and then eliminating the samples of the pulses adversely affected. Such a system was invented by Meranda and Phillips and used in the AN/ARN-78 and -85 loran receivers built in the middle 1960's.

History of Operational Use

Loran-C is a derivative of low frequency loran first developed in the late 1940's. A rough chronology of the developments culminating in the present system is as follows:

(1) Low Frequency Loran - 1946-1948 180 kHz narrow-band. single pulsed. no phase coding. no combined envelope/phase tracking.

(2) CYCLAN - 1948-1950 160/180 kHz dual frequency narrow-band. single pulsed. no phase coding. envelope/phase tracking.

(3) CYTAC - 1951-1955 100 kHz wide band. eight pulses 1280 microsecond spaced per group. Envelope/phase tracking. 8-phase coding used only for short test Aug.-Oct. 1955.

(4) Loran-C 1957-present 100 kHz wide band. eight pulses 1000 microseconds spaced per group. bi-phase coding.

(5) Loran-D Military Experimental 100 kHz wide band. 16 pulses 500 microseconds spaced per group. bi-phase coding.

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Atmospheric noise, EM propagation, skywaves, coverage, GDOP and interference - A tutorial paper

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1 Introduction

This set of three tutorials on Loran-C has been cunningly designed and by now you will have grasped the master plan. Simply think about the signal. Ed McGann and Bill Roland described how it is generated and the tricks which must be played upon it to persuade it to leave the comfort of the transmitting station and set off on its journey. Walt Dean and Bob Frank told you more about its properties and explained how the receiver deals with it when it arrives and how it outputs the position.

My job is to tell you about the part in between the transmitter and receiver: the propagation of the signal. In an ideal world the signal would travel directly from transmitter to receiver, suffering only the delay which the receiver will seek to measure and, no doubt, a modest degree of attenuation due to the spreading out of the wavefronts. The Loran-C pulses reaching the receiver from the various transmitters would be of the text-book shape. The receiver would merely amplify them, identify the correct cycle and measure the time-of-arrival (TOA) of the appropriate zero crossings. That is not the way it is!

The signal from each transmitter is attenuated, sometimes severely, by travelling over land. Land paths, and sea paths too, change the shape of the pulses and cause the envelope to be delayed by a different amount from the cycles it contains. Noise and interference are received along with the signal. The noise may originate in the atmosphere or it may be man-made. In Europe especially, the Loran-C signals are obliged to share their frequency band with large numbers of other transmissions. These so-called *carrier-wave interferers* may reach the receiver with much greater strength than the Loran signals. And the Loran pulses themselves will travel from transmitter to receiver not only via the direct path along the surface of the earth but also via multiple reflections, predominantly by the ionosphere.

So the task of the receiver may be a very difficult one. To amplify the weak, attenuated signal; to extract it from the atmospheric noise; to reject the strong carrier-wave interference; to distinguish the wanted signal which travelled via the groundwave path from the unwanted skywave reflections and to establish the correct cycle and zero-crossing when the envelope and cycles are out of alignment. In this presentation I will talk about the causes of all these propagation-related effects and their magnitudes. I will tell you about their very fascinating properties: for instance, how they vary with time or in space. But at the end of the day, it is their effects on the position measurements made by the receivers which matter, the seriousness of any position errors they may cause. It is impossible, and pointless, to try to isolate these propagation phenomena from the performance of the Loran receivers. So as I talk about propagation, which is my task, I will constantly return to the performance of the receiver, for example, by linking the strength of the skywave interference to the ability of the receiver to reject it.

I see, too, that I am to talk about *Geometrical Dilution of Precision*. I'm going to take that as a shorthand way of describing the bunch of factors which link the result (how accurately and reliably the receiver measures position - which is all we are really interested in) to the cause of those errors, the propagation of the signal. That gives me licence to mention not only Geometrical Dilution of Precision, which we'll shorten to *GDOP*, and other related geometrical factors, but also the way in which receivers group stations, their *operating modes*, hyperbolic, cross-chain and so on. And finally, I would be neglecting my duty as the Propagation Man in this grand design if I didn't talk at least briefly about the other effect of land paths on Loran signals: the way they delay them and the 'additional secondary factors' or 'fixed errors' which result.

2 Signal attenuation

The way in which groundwave signals, such as those of Loran-C, are attenuated as they travel over land and sea paths is very well understood. Bremmer and Norton have published families of curves which relate their attenuation to the conductivity of the ground. Put simply, the lower the ground conductivity, the more rapidly the signals are attenuated because the energy losses in the ground are greater. Sea water is the best. Poor land has much lower conductivity; it may be dry desert, or rocky mountains with negligible soil cover, or it may, surprisingly, be ice. Broadly, what's good farming land is also good Loran land.

Many paths from transmitters to receivers pass over terrain of different values of conductivity: so-called *mixed* or *inhomogeneous* paths. There is a technique for combining the effects of the different sections of path (unfortunately, this is more complicated than simply adding them up) called *Millington's method*. You'll hear people talk about the whole business of field-strength prediction as 'Millington's method'. It isn't, Millington (an Englishman) just worked out how to deal with mixed paths.

The problem in predicting Loran-C field strengths is predominantly that we have only a limited knowledge of ground conductivity values. In some countries these are well mapped and the results are published in the CCIR Atlas of Ground Conductivities. In others they appear to be a state secret! It is possible to gather information from a variety of sources and where necessary even to estimate the ground conductivity from geological maps. Then, knowing the power of the Loran transmitters and examining the paths to the receiver, we can calculate the strengths of the signals.

That gives us one of the key elements of the propagation picture.But the receiver is concerned about the signal-to-noise ratio of the Loran transmissions. So now we must look at the question of noise - and the answer is very complicated!

3 Atmospheric noise

Atmospheric noise is caused by thunderstorm and other electrical discharge activity in the atmosphere. At any time there are many hundreds of active storm cells around the world and, because low-frequency signals propagate long distances, a receiver is subject to the combined effects of large numbers of atmospheric noise sources. The closer they are, the stronger the interference so, not surprisingly, the strength of atmospheric noise varies substantially with the time of day and season of the year. The nature of these variations is quite well understood but, of course, we are dealing here with a random, stochastic process, so we have to approach it probabilistically.

The CCIR publish maps which plot contours of the median value of atmospheric noise. They divide the day into six 4-hour blocks, and the year into four, 3-month seasons and there is a map for each of these 24 time periods. The variations of atmospheric noise in time and space range over many tens of dBs. The patterns are complex but, broadly, the median value is greater in summer than in winter and it is higher near the equator than in polar regions.

The CCIR maps show median values at the frequency of 1 MHz. The 100 kHz values needed for Loran-C may be calculated from the 1 MHz value, but the relationship between them is also time and season-dependent. The question then arises as to what probability level to take. This is arbitrary, but the US Coast Guard have established a commonly-used reference. They calculate the 95-percentile value for each of the 24 time periods throughout the year and then average the results. The USCG document which defines the Loran-C signal pulse also describes clearly how to derive this value from the raw CCIR figures.

Although we use the language of statistics to describe and quantify atmospheric noise, it is not truly random in character. Noise from nearby thunderstorms is caused by specific discharges. Such noise contains spikes which greatly exceed the median value - and they are more frequent than would be the case if the distribution were normal. Commonly Loran-C receivers contain limiter circuits which remove these spikes and return the distribution of noise to something closer to Gaussian. The receivers then minimise the effects of the noise by integrating the measurements they make over periods which are very long compared with the duration of a Loran-C pulse, or pulse group.

For a long time, atmospheric noise was regarded as the principal, in fact as the only, source of noise to affect Loran-C reception. It is the signal-to-*atmospheric*-noise ratio which the US Coast Guard have traditionally calculated when estimating the coverage of individual transmitting stations. The Coast Guard lower SNR limit is -10 dB (that is, the signal is 10 dB below the noise) and it is assumed that Loran-C receivers integrate zero-crossing measurements over a sufficiently-long period that this limiting SNR value results in a one-sigma uncertainty of 100 ns in the resulting time-difference measurements.

This approach served us well until it became desirable to design systems to operate here in Europe. Then it was discovered that there was a source of noise which was not only stronger, but also more insidious, than atmospheric noise: carrier-wave interference.

4 Carrier-wave interference

Carrier-wave interference (CWI) is due to communications signals transmitted at frequencies within, or close to, the Loran-C frequency band. Now, strictly, Loran-C doesn't have a *frequency band*, not one that it can call its own! In general it operates subject to a requirement that it must constrain its transmitted spectrum so that less than 1% of the energy lies outside the range 90-110 kHz, and it is that range which is popularly called *the Loran-C band*.

This bandwidth limitation forces the Loran-C system into a series of compromises which are most easily understood by considering the constraints on the bandwidths of receivers. Ideally, receivers would have a sufficient bandwidth to preserve the Loran-C pulses undistorted; that would require them to recover *all* the energy of the signal, both within and outside the 90-110 kHz band. But then they would also receive other interferering signals. In the US, where Loran-C has long been a major navigation aid, the 90-110 kHz band has been protected. Other potentially-interfering transmissions have been kept away. And, fortunately, even the adjacent frequency bands, from say 50 to 150 kHz, are little used. What interfering signals there are can generally be suppressed by the use of narrow-band notch filters, with only minor degradation of the shape of the Loran pulses.

The situation in Europe is profoundly different: up to a thousand stations are licensed to transmit in the 50-150 kHz band! Not all of them actually do so, not all the active ones are on the air at any time, many are of low power and the stations are distributed over a wide geographical area. And, even in Europe, all significant interferers have been driven out of Loran's 90-110 kHz band. Even so, the result is that, almost without exception, anywhere in the European region, carrier-wave interference is stronger than atmospheric noise.

Now it is important at this stage not to lose heart! Keep a cool head and remember that Loran-C does work, and work well, in Europe; but co-existence between Loran and these other services has required detailed study of the problem leading to careful design of the system. The motto has been: *know your enemy*! And we also have a number of powerful defensive tools, some which have long been known and others which have emerged more recently.

The traditional first line of defence employed by Loran receiver manufacturers has been to increase the number of notch filters fitted to the European models of their products; six or eight filters are not uncommon. Recognising that identifying the frequencies to which these filters should be tuned, and setting them up, may be a substantial task and that the filters should ideally be retuned as the receiver moves through a changing distribution of interfering signals, some manufactureres have equipped their receivers with automatically-tuned notch filters. These receivers identify the strongest interfering signals and direct notches to zap them. They do this continuously and adaptively, always minimising the level of interference. Unfortunately, as we will see, it isn't simply the strength of the interference which matters.

It has long been recognised that the effect of any individual carrier-wave interferer on Loran-C reception depends profoundly on its precise frequency. Here's why: because receivers operate by sampling the pulses of the signal. So, in accordance with classical sampling theory, they behave like comb filters, responding to a series of closely-spaced frequencies, which exactly correspond to the spectral lines of the transmitted Loran signals. If an interfering signal falls right on one of these frequencies, the receiver will obtain a consistent error from sampling it. There can be an offset in the readings which will result in an error in the measurement of the zero-crossing times of the Loran-C pulses and, hence, in the measured position of the receiver. And it doesn't matter over how long the receiver averages those readings, if the interference is *synchronous* with a spectral line of the Loran signal, they will all be wrong; averaging won't help.

On the other hand, if the interference falls, say, mid-way between two spectral lines, the signal is not synchronous with the sampling process. Each sample has a different error, and averaging a large number of them allows the true reading to emerge. Loran-C receivers are extremely effective in attenuating *non-synchronous* interference in this way. And the longer their averaging time, the narrower the frequency band around each spectral line within which they are sensitive to interference. This is the comb filter in action. You will understand then that both the strength and the frequency of each interferer determine the error it can cause in the measured position. Unfortunately, receivers with automatically-tuned notches at present have no way of dealing with this complexity and aim simply for the strongest interferers. There's a big push on at the moment to design more sophisticated automatic notch-tuning systems. It's difficult, and interesting, and it has some of our more mathematically-inclined colleagues in quite a frenzy of excitement!

Now, what about using bandpass filters to pass the 90-110 kHz Loran signals and attenuate carrier-wave interference? Certainly we can do that to a considerable degree, provided we are willing to pay the price. The narrower the filter, the more the risetime of the Loran-C pulses passing through it will be stretched. We will see when we come to look at skywave effects that extending the risetime makes the receiver less able to identify the wanted groundwave signal and reject the interfering skywaves. And there is another problem: the slower the rate of change of the envelope of the pulse, the more difficult it becomes for the receiver to identify the cycle which contains the correct zero crossing. So cycle uncertainty may also become a problem.

However, this is all a matter of compromise: if we are prepared to allow some extension of the risetimes of the pulses, we can certainly introduce a relatively-narrow and steep-sided bandpass filter at the input to the receiver. Such a filter can provide substantial rejection of interference at frequencies well below 90 kHz or well above 110 kHz. This is an approach used very successfully by some receiver manufacturers and it greatly reduces the number of strong interfering signals, essentially to those close to the Loran band. Filtering mustn't be overdone, but it is yet another weapon in our armoury to use against the dragon CWI.

All these techniques have been known for a long time. In designing the Loran-C systems for North-West Europe, a novel approach has recently been adopted which can have a profound effect on the ability of receivers to tolerate interference. The idea is simple: you choose the *Group Repetition Interval (GRI)*, carefully so as to minimise the effects of the actual interferers operating in the area to be covered by each chain. This is a technique which has been pioneered at Delft University of Technology in the Netherlands in conjunction with our group at Bangor. Given that there's a bunch of academics involved, you won't be too surprised that the next bit gets a bit technical!

To implement the technique you start with a list of all the interfering stations which can affect the coverage region, containing the location, the power and the frequency of each station. Then you adopt a standard design of receiver, specifying its bandpass filter characteristic and the width of the comb responses around each spectral line. The strength of each interferer is calculated at each of an array of geographical points covering the region of interest. The field strength is estimated from the transmitter power and location, taking groundwave attenuation into account and also estimating the strength of the skywave. Then, having regard to the frequency of the interferer, the attenuation provided by the bandpass and comb filters of the receiver are calculated. In this way we compute the strength of the interference and the position error it can cause. This complicated process is repeated for every interferer at every point; not surprisingly, it uses a lot of computer time!

The result is a measure of the uncertainty with which the receiver can expect to make Loran time-of-arrival measurements at each point in the coverage area. Now we look at the GRI. The key to understanding this approach to minimising interference is to recognise that it is the choice of *GRI* which determines the frequencies of the spectral lines of the Loran transmission and of course, the corresponding frequencies to which the comb filter lets the receiver respond - the frequencies of the synchronous interference. So, all we have to do is to repeat our large calculation using each feasible GRI and then choose the GRI which gives the smallest errors!

The results are dramatic: receiversare seen to suffer tens of times more interference when the worst GRI is employed than with the best. Selecting the most suitable GRI for use in the area tunes the comb filters of all receivers and greatly reduces the effects of the carrier-wave interference.

The method described has the additional benefit that it identifies the most serious remaining interferers to which the notch filters of the receivers should be tuned. If we specify a minimum number of notch filters of a certain performance we can finally calculate the additional reduction of interference which they will afford.

There is one other way in which receivers reject CWI. A Loran-C receiver applies a pattern of phase reversals to the signals it receives so as to cancel their ***phase-coding***. These receiver phase reversals also affect each interfering carrier, reducing its effect by some 8-16 dB.

Carrier-wave interference is a potentially serious problem, especially in Europe. But by a combination of narrower receiver bandpass filters, judicious use of notch filters and careful choice of GRI it can be overcome. The result is that the coverage of well-designed Loran-C chains should extend out to limits set by atmospheric noise and not carrier-wave interference.

5 Skywave interference

Terrestrial radio-navigation systems such as Loran-C work on the assumption that the signals travel from the transmitters to the receiver in a sensible fashion - via the shortest paths! Perversely, some signals choose to take longer paths, especially via refraction in the lower layers of the ionosphere. With increasing range from the transmitting station the groundwave signal is attenuated.

The strength of these skywave components, in contrast, changes little with range at distances between 100 and 2000 km from the station. Thus the *skywave-to-groundwave ratio (SGR)* increases with increasing range. A long way from the station, Loran-C receivers are faced with the task of identifying groundwave signals in the presence of skywave components which may be substantially stronger. It is traditionally assumed that they do so by identifying and tracking a point 30 µs into he Loran pulses, which are assumed to be of the standard shape. They take advantage of the fact that the delay of the skywaves with respect to the groundwave always exceeds 30 µs.

However, we have seen that, because most receivers employ bandpass filters which are narrower than ideal, the risetimes of the received pulses are extended. This allow later strong skywave components to interfere with earlier weaker groundwaves. Skywave components which arrive with short delays are more serious than long delay ones. Clearly, it is necessary to take into account both the strength (the SGR) and the delay of the skywaves with respect to the groundwaves. The Minimum Performance Specifications for Loran-C receivers published by the RTCM and the IEC lay down limiting combinations of SGR and delay which receivers should meet.

Both the delay and the strength of the skywave signals received over a path vary with the time of day and the season of the year, in sympathy with changing ionospheric conditions. Skywave strength depends with the intensity of ionisation in the D layer. Skywaves are normally stronger at night than by day and stronger in winter than in summer. The delay varies with the effective height of the ionosphere, considered as a reflecting surface. This is typically 73 km by day andVhigher by night, 91 km. So on average day-time skywaves are weaker, but earlier, than nighttime ones.

Skywave propagation at frequencies in the region of 100 kHz has been carefully observed and recorded over many years, not least by the Decca Navigator Company. Decca operates in the same frequency area as Loran-C and is very susceptible to skywave interference. As a result of these studies we understand how skywave paths behave, at least in statistical terms. At any season of the year and time of the day in any specific region it is possible to state approximately the rms strength of skywave field strength to be expected over a path of given length from a transmitter of known power. Skywave intensity is, however, subject to short-term random variations but the probability of its exceeding any particular value with respect to the rms can also be stated. In addition, because of Loran-C research we know the average delay values by day and night.

This understanding enables us to design Loran-C chains in such a way as to minimise skywave interference. At any location we can estimate the field strength of the groundwave signal, taking path attenuation into account. We can also estimate the delay of the skywave signal and the maximum field strength which it will not exceed for more than a specified percentage of the time during the worst time and season of the year. We can thus ensure that skywave conditions remain within the limits specified in the receiver Minimum Performance Specifications and so are acceptable to all receivers which meet those specifications. This is what has been done in planning the North-West European Loran-C chains. It has meant that the transmitter stations are a little closer together than is necessary simply to overcome atmospheric noise. But, since there is a carrier-wave interference problem as well, that's no bad thing. The result is quite a conservative design.

6 Envelope-cycle difference (ECD)

As Loran-C signals propagate, especially over land paths, an interesting effect occurs; the envelope apparently travels at a slightly different speed from the cycles. As a result, the ECD changes, in a negative direction. The reason for the change of ECD is that the velocity of propagation of groundwave signals in the region of 100 kHz is a weakly non-linear function of frequency. The velocities of the spectral components of the Loran-C signal thus vary non-linearly across the band from 90 to 110 kHz. As a result, the Group Velocity of the signal, which affects the propagation of the envelope, is slightly different from the Phase velocity, which affects the cycles. Thus the ECD changes.

The rate of change of ECD with distance is such that, over an all-seawater path, the shift builds up to approximately -2.5 µs by the edge of the coverage area. Receivers are most tolerant of noise when the ECD of the received signal is close to its ideal value of zero. Thus it is customary to transmit a signal which has an ECD of +2.5 µs (near to the station in the *near far-field*) so that the ECD falls so as to reach zero at the edge of coverage.

Over land paths the rate of change of ECD with distance is greater than over seawater, but by an amount which is rather poorly understood. Observations are not helped by the localised changes of ECD which are sometimes observed close to steps in ground conductivity. Sherman has fitted an empirical curve to a large body of measurements and his work gives the best known relationship between the rate of change of ECD and the ground conductivity. Using Sherman's curve it is possible to estimate ECD changes over specific paths or to map ECD contours around transmitting stations. Fortunately, it has been found that, since rate of change of ECD and rate of signal attenuation both increase with falling ground conductivity, the ECD value is always acceptable within the coverage area of a station, as determined by SNR considerations.

It is important to understand and estimate these variations of ECD with range since doing so allows the ECD settings at transmitting stations to be set for optimum conditions in the limiting areas of coverage. This process has been carried out for all the stations of the planned North-West European Loran system.

7 Coverage of individual stations

The techniques described so far allow us to predict the coverage of individual Loran-C transmitting stations. Traditionally, the USCG have done this by estimating the field strength, using ground conductivity data and Millington's method, and the atmospheric noise in the region to be served. The coverage boundary is the contour at which the field strength of the signal has fallen to 10 dB below the noise.

It is now considered desirable, at least in Europe, to include consideration of carrier-wave interference, skywave interference and ECD in this process. The levels of carrier-wave interference are estimated using the same approach as for GRI selection: the list of interfering stations, the effects of groundwave and skywave propagation paths and attenuation by the receiver bandpass, notch and comb filters and phase decoding effects. The remaining interference can affect the receiver in two undesirable ways: by causing uncertainty in time-of-arrival measurements and by reducing the reliability of cycle selection. It is possible to show that a signal-to-interference (SIR) ratio of approximately 14 dB results in a TOA uncertainty equal to that caused by the USCG's limiting value of atmospheric SNR. The way interference affects cycle selection also depends on frequency in a complex way. But generally we believe that cycle selection is not the limiting factor; if you look after the TOA uncertainty, cycle selection will look after itself. So we can use the signal-to-interference ratio to set a coverage limit equivalent to the -10 dB signal-to-atmospheric noise ratio.

We've seen how to check that skywave interference is acceptable and to ensure that the change of ECD with range doesn't get out of hand. So we can predict the coverage of a transmitter by computing each of these factors at every point in a large geographical array of points covering the area of interest. Then, we check each of them against the limits we've set. If all of them are within limits, the point lies within the coverage of the station. If not, then not.

The final stage in any coverage-prediction process is to compute the coverage not of a single transmitting station, but of an entire chain of stations or even of a system comprising several chains. In order to do this we have to take into account both geometrical considerations and the way the receiver uses groups of stations.

8 GDOP and geometrical considerations

As you know, the Loran receiver makes time-difference (TD) measurements between the signals arriving from pairs of stations. Each TD defines a line of position, *an LOP*. The receiver uses a minimum of two LOPs, normally derived from three stations, to give a position fix. Thus the receiver obtains a fix from a *triad* of stations. All the propagation effects I've been talking about conspire to cause uncertainty in the timing measurements the receiver makes, the fundamental components of the fix. These give rise to uncertainties in the LOPs and so in the fix itself. The greater the signal-to-noise ratio, signal-to-interference ratio and so on, the more precise the fix. The factor which determines what fix accuracy results from a given accuracy in TOA measurements is the GDOP, the Geometrical Dilution of Precision.

It is well-known that on the baseline between two transmitters a given uncertainty in the time-difference measurement gives the least uncertainty in the position of the LOP. Further from the stations or behind one of them, in a baseline extension area, the GDOP becomes greater. Also, the closer to a right angle the LOPs cross one another, the smaller is the area of uncertainty and the greater the precision of the fix.

A set of equations relate the fix repeatable accuracy to the precision of the time-of-arrival measurements. They incorporate these two factors, the *lane expansion factors* of the two LOPs and the their *angle of cut*.

The simplest way to deal with this relationship is probably the one traditionally adopted by the US Coast Guard. They assume that each of the three signals which contribute to the fix has the minimum allowed signal-to-noise ratio, -10 dB. As a result, the timing uncertainty in each time-difference measurement has a standard deviation of 100 ns. Geometrical considerations are now taken into account to calculate the fix repeatability at each point in the coverage area. The boundary of the coverage of the triad of stations is arbitrarily taken to be that contour at which the $2d_{rms}$ (or 95% probability) uncertainty of position reaches 0.25 nm (463m).

A more sophisticated approach, adopted recently in North-West Europe, is to take account of the *actual* SNR and SIR of each signal independently and so calculate the resulting uncertainty in its time-of-arrival measurement. The uncertainties of the resulting TDs are then calculated and, finally, the fix uncertainty, taking geometrical factors into account. This allows contours of repeatable accuracy to be drawn, which can include the 463m limit.

9 Receiver operating modes

Traditionally, the triad of stations which contribute to a Loran-C position fix are the master and two of the secondaries of a single chain. The master station is the common element in the two lines of position. This way of working, if it is given a name at all, is designated the *hyperbolic mode*.

It is sometimes advantageous to be more adventurous, for example, by constructing a triad using stations from more than one chain or by omitting the master station and using three secondaries. The result may be a more favourable geometry or improved SNR than can be achieved in the hyperbolic mode.

Receivers are already on the market which operate in the so-called *semi-circular mode*, employing the master and a secondary station from one chain together with a secondary from another chain. Also feasible, at least in principle, is the *cross-chain mode* in which each LOP is generated bytaking a master-secondary pair from each of two chains. The most advanced option is the *master-independent mode*; in this there are no restrictions, the LOPs can be derived from any two pairs of stations, even taken from four chains, if required.

Hyperbolic operation is the norm because synchronisation of the stations within a chain can be controlled very precisely. All other modes additionally require precise synchronisation between chains. Until recently this has not been achieved. Now it is possible and new systems of chains, in particular the North-West European system, are likely to embody sufficiently accurate inter-chain synchronisation to enable receivers to operate in these advanced modes.

10 Additional secondary factors

When Loran-C signals propagate over paths of different values of conductivity, not only are the signals attenuated by different amounts, but their velocities of propagation differ also. The lower the conductivity, the greater the attenuation and the lower the velocity of propagation, except under certain unusual circumstances in the near field region very close to the transmitter. These phase-velocity effects are well understood and the time delay of the signals travelling over a path of known conductivity can be accurately predicted. The effects of the various sections of a path of mixed, or inhomogeneous conductivity, can be combined using an extension of Millington's method: the *Millington-Pressey method.*

A Loran-C receiver, having made time-difference measurements, is faced with the problem of calculating the corresponding distance-difference values. A very common simplifying assumption is that all signals travel over sea-water paths. The additional propagation times occasioned by the land paths are called *additional secondary factors (ASFs).* If ASFs are simply ignored, Loran-C positions may be in error by hundreds of metres. However, ASFs can be estimated theoretically, or measured. A common practice of Loran users is to measure the 'Loran' position of a prominent land-mark or sea-mark and then use any error in the measured position to give an adjustment which is applied to all fixes in the region. This is a legitimate practice since normally ASFs change only gradually over an area. In many areas the ASFs have been extensively surveyed and tables of values published.

An alternative technique which has been developed recently is to compute a map, or table, of ASF values using a ground conductivity map. The resulting data may contain errors due to imperfections in the conductivity data which are consistent over substantial areas. A limited surveying operation is then carried out which generates a sparse data set of corrections and the computed data *force-fitted* to match the measurements. In that way the detail in the results provided by the computer model are preserved while the underlying wide-area discrepancies are removed. The technique is the most economical way to obtain high-quality ASF data.

SESSION I

Receiver Technology

DIGITAL INTERFACE STANDARDS FOR NAVIGATIONAL EQUIPMENT NMEA 0183 AND IEC 1162

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Abstract

This paper describes the work of the National Marine Electronics Association (NMEA) and the International Electrotechnical Commission (IEC) in developing a common standard for use in interfacing electronic navigation and sensing equipment. NMEA Standards were originally developed for interconnecting Loran-C receivers to other shipboard equipment and NMEA Standard 0183 is currently in wide use throughout the world for interconnecting various sensors, with many applications involving Loran-C and GPS. The Draft IEC Standard 1162 arose from the requirement generated at the International Maritime Organization (IMO) in the 1980's for a system to interface the various navigation equipment required by the Safety Of Life At Sea Conference (SOLAS) for the new Global Maritime Distress and Safety System (GMDSS). Providing vessel position data to the safety system is of particular interest.

Originally intended for marine applications, these standards are becoming increasingly used in airborne, terrestrial and industrial applications - wherever navigation and communications are involved.

Digital Interface Standards

NMEA and IEC Interface Standards are intended to serve the public interest and add to safety at sea by facilitating interconnection and interchangeability of equipment, minimizing misunderstanding and confusion between manufacturers, and assisting purchasers in selecting compatible equipment. The interconnection of radio navigation equipment, originally Loran-C, and now Omega, Decca, Transit and GPS, was the first and is still the most frequent use for these standards. In addition to interfacing Loran-C and GPS to autopilots, electronic chart displays, RADAR/ARPA displays and data collecting equipment, the Digital Interface Standard is used with a variety of communications, meteorological and vessel instrumentation equipment.

These standards define electrical signal requirements, data transmission protocol and timing, and specific sentence formats for a 4800 baud serial data bus. This data is in printable ASCII form and may include information such as position, speed, water depth, frequency allocation, etc. Each bus may have only a single talker but may have multiple listeners. Future standards will address multiple talker networked applications as well as high speed applications for file transfer and video data.

NMEA Standards

NMEA standards activities were initiated by autopilot manufacturers who were anxious to make use of real-time 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). NMEA 0180 data is a single asynchronous serial character at 1200 Baud representing cross-track-error left or right of the course line in offset binary. 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 follow.

By 1981 manufacturers were using more sophisticated autopilot algorithms and proposed additional "complex" characters that would provide XTE, 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.

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. This new standard "NMEA 0183 - Standard For Interfacing Marine Electronic Navigational Devices" used the same hardware specification but at a 4800 Baud rate. Various data field types are identified and fields are separated by "," (comma) 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 and Version 2.00 in January 1992.

IEC Standards

An early input (1981) to IMO from Inmarsat identified the future need for a standardized data interface for use between navigational and communication equipment on the ship's bridge, and which could be used to provide current position information to relevant equipment. In particular the proposed FGMDSS (Future Global Maritime Distress and Safety System - now GMDSS) would require information for distress alerting, either directly via radio or indirectly via an EPIRB which would automatically float free, loaded with position and other relevant data.

A particular problem existed with ship's heading data where conventional gyro compass output signals were in "incremental" and not "absolute" units, requiring an initial synchronization of any compass repeater units, complicating the generation of heading data for a multi-purpose transmission system. Ship's position would have to be obtained from a world-wide positioning aid, and there was no agreement on what this standard should be.

For such applications it was clearly apparent that several types of equipment would be involved and the adoption of a standard data interface would be advantageous.

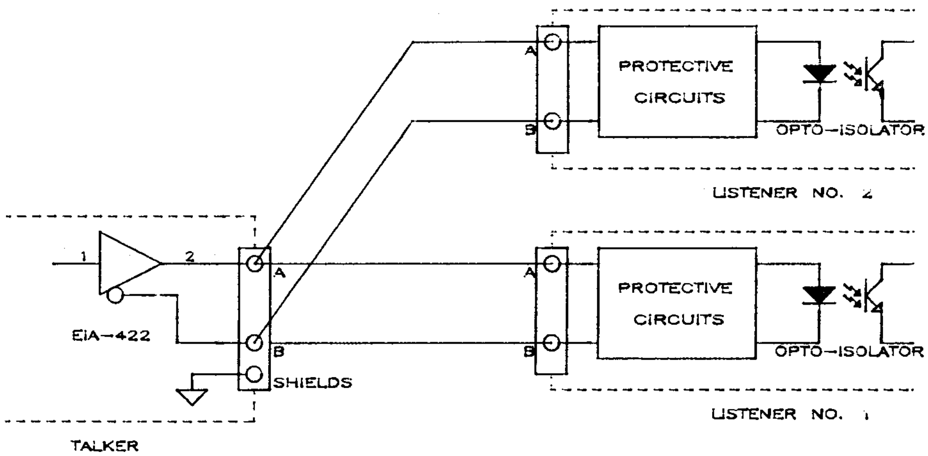
At a subsequent meeting of the IMO sub-committee on Radio Communications (COM 25) the seven key parameters for an interface were identified, and simultaneously CIRM established one interface group to give more detailed consideration to the problems and work involved. In the meantime IEC has generated standards for Omega, Loran-C and Decca Navigation, and is currently working on the standards for maritime GPS, with GLONASS to follow.

Since these early discussions the IEC established Technical Committee 80 (Navigational Instruments)-Working Group 6 (Digital Interfaces). The first meeting of TC80-WG6 was held in London in 1988, followed by a second in July 1989. These early meetings identified the main elements of this data system, and even at this early stage the equivalent of the Voyage Data Recorder was included.

At subsequent meetings it became very clear that the work undertaken by the NMEA in the USA to generate data interface standards was very close to that of WG6. Accordingly close attention was paid to adopting common technical standards where possible and finally, in mid-1991 the two were aligned.

From the IEC side consideration was given to the needs of the imminent GMDSS, due to be implemented from February 1992, and the equipment list and related sentences were added to include these requirements.

Currently the work of WG6 is to convert all text in the NMEA 0183 Standard to the IEC format, without disturbing the technical alignment with NMEA 0183, and gaining the approval of the national committees. It should be noted that the systems developed so far cover single-talker/multi-listener systems, and the task of including multi-talker/multi-listener systems has yet to be tackled, and pressure is mounting for this to be covered.



NMEA 0183 Interface Standard hardware requirements for a single-talker/multi-listener ground-isolated serial data interface

FIGURE 1

<u>NMEA 0183/IEC 1162</u>

The standard can be thought of as consisting of three components:

- Hardware
- Data Format
- Data Content

The following sections describe these three parts of the Standard.

<u>Hardware</u>

The hardware requirement specifies a single transmitter, or talker, connected to one or more receiver, or listener, using shielded twisted-pair cable as shown in Figure 1 above. There is no standard connector specified and this will vary from equipment to equipment. For noise suppression, and to avoid ground loops, it is recommended that the shield be connected at the talker but unconnected at each listener.

Data signals exist between the two wires of the twisted-pair and ground isolation is required for each of the two wires at the listener. The current version of the standard specifies that the driver at the talker meet the requirements of EIA-422 (positive voltage signals with a differential of 2 to 6 Volts between the wires, the direction of the differential changes for "1" and "0"). Early equipment commonly used EIA-232 drivers (negative and positive voltage signals of 6 to 12 volts on one wire with respect to the other representing "1" and "0") or TTL voltage levels (0 and + 5 Volts representing "1" and "0").

Each of these transmitter schemes will work when connected to a differential input listener that uses an opto-isolated receiver. The current version of the standard allows for the use of a differential-amplifier receiver meeting the requirements of EIA-422 for IEC applications that have talkers that use the matching EIA-422 driver. The NMEA still requires the use of an opto-isolated receiver for more general use in order to maintain compatibility with existing equipment. An EIA-422 differential-amplifier receiver will not respond to single polarity 0 and +5 Volt signals.

The electrical signals transmitted are serial asynchronous ASCII characters in accordance with ANSI standards. Each character contains 8-data bits and no parity and is transmitted at 4800 Baud.

Data Format

The data format, from the simplest element upward, is composed of:

- ASCII characters
- Fields made of characters
- Sentences made of fields

Each sentence, which may contain no more than 82 characters, always starts with "$" and ends with <CR><LF>. Between these characters lie fields. The first field is always the address field, subsequent fields are data fields including an optional checksum field. Fields are separated by delimiters which are "," except that "*" is used before the checksum field as shown below.

"$"	HEX 24 - Start of sentence
<address field>	Talker ID and sentence formatter
[","<data field>]	Zero or more data fields
.	
[","<data field>]	
["*"<checksum field>]	Optional checksum field
<CR><LF>	Hex 0D 0A - End of sentence

Two types of sentences are allowed: Approved Sentences where the meaning of each field is defined and Proprietary Sentences where the content of fields is determined by each manufacturer. The sentence type is determined in the first (Address) field following the "$". Proprietary sentences always start as "$Pxxx", where xxx represents a 3-character manufacturers code assigned uniquely to each manufacturer, with the remainder of the sentence defined by the manufacturer. Approved sentences never start with "$P" but rather with "$xx" where xx is the talker Identifier, LC for Loran-C, GP for GPS, etc. Three more characters, the Sentence Formatter, complete the Approved Sentence address field and serve to uniquely define the data content of the sentence. "$LCXTE" for example is the start of sentence and address field for Cross-Track-Error data from a Loran-C receiver.

A special case of the Approved Sentence is the Query Sentence where the Address Field is "xxyyQ" following the "$". Talker xx is requesting data from listener yy. The first and only data field provides the approved 3-character Sentence Formatter of the data being requested. The listener will reply to the talker on a separate output port since the standard provides for a single talker only.

Data fields may be numeric or alpha-numeric. Certain data fields may be defined to be a fixed number of characters, this is true for both alpha-numeric and numeric fields, while others are identified as variable length fields. In the case of variable length numeric fields, a decimal point may be included as well as leading or trailing zeros. The number of decimal places may also be variable. A field were data is either temporarily or permanently not available is left empty and appears as ",,". This is classified as a "null" field but it is important to note that the ASCII NULL character is not used.

Data Content

The current version of the standard provides for transfer of a variety of data types between a wide range of equipment. Tables 1 and 2 list the talker IDs and the Sentence Formatters for the existing Approved sentences. Entries with an "*" are designated by IEC for use with IMO marine electronic devices. This is the minimum requirement for equipment that is specified by IMO to meet SOLAS regulations. An example of a typical sentence structure and its content is shown in Figure 2 below.

```
XTE - Cross-Track Error, Measured
      Magnitude of the position error perpendicular to the intended
      track line and the direction to steer to reduce the error.

      $--XTE,A,A,x.x,a,N*hh<CR><LF>
             | |  |  | └ Units, nautical miles
             | |  |  └ Direction to steer, L/R
             | |  └ Magnitude of Cross-Track-Error
             | └ Status: V = Loran-C Cycle Lock warning flag
             |              A = OK or not used
             └ Status: V = Loran-C Blink or SNR warning
                        V = general warning flag for other navigation
                              systems when a fix is not available
```

Figure 2 - Typical NMEA 0183 sentence definition

TABLE 1 - TALKER IDENTIFIERS

AUTOPILOT:	
General	AG*
Magnetic	AP
COMMUNICATIONS:	
Digital Selective Calling	CD*
Satellite	CS*
Radio-Telephone (MF/HF)	CT*
Radio-Telephone (VHF)	CV*
Scanning Receiver	CX*
DECCA Navigation	DE
Direction Finder	DF*
Electronic Chart (ECDIS)	EC
Emergency Position Indicating Beacon (EPIRB)	EP*
Engineroom Monitoring Systems	ER
Global Positioning System (GPS)	GP
HEADING SENSORS:	
Compass, Magnetic	HC*
Gyro, North Seeking	HE*
Gyro, Non-North Seeking	HN
Integrated Instrumentation	II
Integrated Navigation	IN
LORAN:	
Loran A	LA
Loran C	LC
OMEGA Navigation System	OM
Proprietary Code	P
Radar and/or ARPA	RA*
Sounder, depth	SD*
Electronic positioning - other	SN
Sounder, scanning	SS
Turn Rate Indicator	TI*
TRANSIT Navigation System	TR
VELOCITY SENSORS:	
Doppler, other/general	VD*
Speed Log, Water, Magnetic	VM
Speed Log, Water, Mechanical	VW
TRANSDUCER	YX
TIMEKEEPERS, TIME/DATE:	
Atomic Clock	ZA
Chronometer	ZC
Quartz	ZQ
Radio Update, WWV or WWVH	ZV
Weather Instruments	WI

TABLE 2 - SENTENCE FORMATTERS

AAM - Waypoint Arrival Alarm
ALM - GPS Almanac Data
APB - Autopilot Sentence "B"
*ASD - Autopilot System Data
BEC - Brg. & Dist to Wpt, Dead Reckoning
BOD - Bearing, Origin to Destination
BWC - Bearing & Distance to Waypoint
BWR - Brg. & Dist. to Wpt, Rhumb Line
BWW - Bearing, Waypoint to Waypoint
DBT - Depth Below Transducer
DCN - Decca Position
*DPT - Depth
*FSI - Frequency Set Information
GGA - Global Positioning System Fix Data
GLC - Geographic Position, Loran-C
GLL - Geographic Position, Latitude/Longitude
GSA - GPS DOP and Active Satellites
GSV - GPS Satellites in View
GXA - TRANSIT Position
*HDG - Heading, Deviation & Variation
*HDT - Heading, True
HSC - Heading Steering Command
LCD - Loran-C Signal Data
MTW - Water Temperature
*MWV - Wind Speed and Angle
OLN - Omega Lane Numbers
*OSD - Own Ship Data
RMA - Minimum Specific Loran-C Data
RMB - Minimum Navigation Information
RMC - Minimum Specific GPS/TRANSIT Data
*ROT - Rate Of Turn
*RPM - Revolutions
*RSA - Rudder Sensor Angle
*RSD - RADAR System Data
RTE - Routes
*SFI - Scanning Frequency Information
STN - Multiple Data ID
TRF - TRANSIT Fix Data
*TTM - Tracked Target Message
*VBW - Dual Ground/Water Speed
VDR - Set and Drift
VHW - Water Speed and Heading
VLW - Distance Traveled through the Water
VPW - Speed, Measured Parallel to Wind
VTG - Track Made Good and Ground Speed
WCV - Waypoint Closure Velocity
WNC - Distance, Waypoint to Waypoint
WPL - Waypoint Location
XDR - Transducer Measurements
XTE - Cross-Track Error, Measured
XTR - Cross-Track Error, Dead Reckoning
ZDA - Time & Date
ZFO - UTC & Time from Origin Waypoint
ZTG - UTC & Time to Destination Waypoint

Conclusion

This paper provides background and an introduction to the NMEA 0183 Standard For Interfacing Marine Electronic Devices and the Draft IEC 1162 Standard. The standards are the same in technical content and are meant to be interchangeable.

The NMEA 0183 Standard has been in wide use for nearly a decade. The latest version 2.00 expands the base of applications and takes into consideration new equipment and requirements of equipment to be used in GMDSS. The Draft IEC 1162 Standard is presently under review by member organizations with comments expected to be complete by the Fall of 1992. At that time minor revisions will be made to produce NMEA 0183 Version 2.01 to keep the two documents aligned.

Follow-on work of the two Standards Committees will be the development of a multi-talker/multi-listener network.

When implementing the standard it is necessary to consult the official text of the respective NMEA or IEC document. Information and updates on the standards may be obtained from:

National Marine Electronics Association
P.O. Box 50040
Mobile, AL 36605
USA

International Electrotechnical Commission
3, rue de Varembe
P.O. Box 131
1211 Geneva 20
Switzerland

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AMERICAN NATIONAL STANDARDS INSTITUTE,
ANSI X 3.15, 1976
ANSI X 3.16, 1976
ANSI X 3.4, 1977

Biographies

Mike Fox

M.P. (Mike) Fox is the Secretary-General of CIRM, London and chairs IEC/TC80/WG6 on digital interfaces.

He also acts as the secretary of WG6, WG8 (GMDSS equipment), and SWG4a (GPS). Formerly with Sperry for over seventeen years, he has participated in maritime standards work for many years. He is a strong advocate of having uniform international standards which preclude the development of unnecessary regional and national maritime equipment standards.

CIRM (Comite International Radio Maritime) is the long established international association of marine electronic companies which has sponsored the work of IEC - TC80 - navigational instruments for the past five years, and is very active in presenting the industry viewpoint at international fora.

Frank Cassidy

Frank is Chairman of the NMEA Standards Committee and a Director of the Wild Goose Association.

He received his B.S.E.E. from Northeastern University and the S.M. in Engineering and Applied Physics from Harvard University. From 1968 to 1971 at the GTE Applied Research Laboratory he designed oceanographic research instruments for the Woods Hole Oceanographic Institution. At Megapulse from 1971 to 1981 his work involved the design of solid-state Loran-C transmitters and systems, serving as the Technical Manager for the Suez Canal Vessel Traffic Management System. At Datamarine Frank is involved in the design and development of Loran-C and GPS receivers and Electronic Chart Systems.

Detection of Automatic Blinking beyond FAA limits

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Abstract— **To ensure integrity of the Loran-C system during non-precision approaches, an automatic blinking system should notify the user if the system is not functioning properly. To be certain that timely detection of this blinking can be guaranteed, one of the requirements on an airborne Loran-C receiver is that it should flag an alert if the signal to noise ratio drops below -6 dB [1]. This paper addresses some simple methods of blinking detection, that will ensure safe operation beyond this -6 dB limit.**

1 Introduction

If the Loran–C system is used to support IFR non-precision approaches, the user would like to be sure that the chain timing is within its specification. Therefore, Loran–C transmitters broadcast the pulses with a certain on–off ratio (blinking) if their baseline timing is out of tolerance. This means that the first two pulses of the involved secondary and the ninth pulse (if any) from the master is turned on and off with a certain ratio [2, 3].

The airborne Loran–C receiver should detect this on–off behavior of a part of the Loran–C signal and flag an alarm within an integrity limit of 10 seconds [4]. If the receiver is unable to notify the user within the integrity limit, a warning should be flagged to indicate that the integrity of the data cannot be guaranteed. To be certain that Loran–C receivers are able to detect blinking and loss of signal within those 10 seconds, a -6 dB signal to noise ratio (SNR) limit is used as an integrity threshold [1, 5, 4]. Presumably, this limit corresponds with a decision threshold or a false alarm rate of a detection probability distribution when the Loran–C pulse is sampled around the standard sampling point (half-peakvalue). As soon as the SNR, defined according to [3], drops below this -6 dB the receiver should flag a warning.

As Carroll [1] already mentioned, using this -6 dB threshold is not really an unambiguous limit, because different receivers are known to compute different SNR readings. The reason for these different readings could be caused by the different signal processing schemes. If a Loran–C receiver computes a lower SNR value than it should according to [3], than this receiver might perform better under these signal conditions due to better signal processing. This means, that in fact using the SNR value computed by the receiver could provide a better limit than using an SNR value computed according [3].

The key issue is that the certification requirement should not be an SNR limit, but that receiver is able to detect blinking within the integrity margin of 10 seconds, and is capable of flagging a warning if this is not possible. In this way, more elaborate receivers are no longer discriminated, because now they could be certified for blinking detection under lower SNR conditions than other receivers.

To show that it is possible to detect blinking under lower SNR conditions than -6 dB, this paper will discuss a few methods, and compare them to obtain their relative performance.

2 Standard blinking detection

In this paper, standard blinking detection means that the Loran–C pulse is only sampled around the standard sampling point (SSP), and that these samples are used for detection of blinking. The amplitude of the envelope at this $25\mu s$ point determines by definition the power of the Loran–C pulse. Normally, the half cycles in the neighborhood of this point are used for cycle identification, thus using cycles with an amplitude approximately half of the Loran–C pulse peak amplitude [3]. For simple comparison with the other blinking detection methods, the amplitude of the envelope at the SSP is defined as unity (0 dB), and thus the Loran–C peakvalue will be equal to 2 (6 dB).

Although the signal used for blinking detection is a filtered signal, taking filtering into account is not really necessary in this case. This approach will slightly favor the standard detection method, since nonlinear phase filtering causes the rising edge of the Loran–C pulse to become less steep and more straight, thus the amplitude of the pulse at the place where the skywave will start will be lower in reality. Another reason for not using filtered signals is that the amount of noise and distortion depends on the filter used. Since there are many different filters to choose from, it would be wiser to concentrate on the input signals. Regardless of the type of filter used, all receivers apply their processing to the same input signals. This strategy will be sufficiently simple and useful for the relative comparison to be made.

3 Groundwave peak blinking detection

Although only the carefully controlled beginning of the pulse is normally used to obtain reliable timing data, there is no real reason to use only this part of the Loran–C pulse for the detection of blinking. Blinking detection does *not* require a very precise defined and controlled part of the Loran–C pulse. It is sufficient if a decision can be made about the *presence* of a pulse with a certain reliability.
The best way to make this decision is to observe the Loran–C signal at the place where it is the strongest, thus at the top of the pulse. Because the envelope at the SSP was defined as 1 (0 dB), the peakvalue of the Loran–C pulse will be equal to 2 (6 dB). This results immediately in an increase in SNR of 6 dB, thus instead of detecting blinking upto a limit of -6 dB, the receiver will be able to detect blinking upto a limt of -12 dB with exactly the same reliability. Unfortunately, skywaves present in the real world can interfere with the groundwave, althus reducing the available signal power if they have the opposite phase. To find the worst case skywave interference, the skywaves should be subtracted in-phase from the groundwave. According to the IEC specifications [6], a receiver must be able to function properly with 12 dB stronger skywaves arriving 37.5 μs after the beginning of the groundwave, upto 26 dB stronger skywaves arriving 60 μs later. All the specifications are quite silent about resistance against long delayed skywaves [3, 7, 6]. Another problem is that there are no minimum and maximum skywave levels specified, only levels which the receiver should be able to sustain. Therefore it will be impossible to define real worst-case skywave interference, since more powerfull (or earlier arriving) skywaves might exist.
To show the benefit by using peakvalues, the peakvalue of the groundwave Loran–C pulse is computed after in-phase subtraction of worst case skywaves. The resulting peakvalue is plotted in dB's relative to the undisturbed halfpeak amplitude for different skywave arrival times figure 1. It is clearly shown that even under the worst case skywave interference the peakvalue is still 3 dB larger than the half peak value. Although skywave strength increases by increasing arrivaltime, the influence of skywaves decrease due to the greater time delay betwee ground- and skywave. One should remember that skywave delay decreases, if the distance to the transmitter increases. The small steps in the curve are not caused by the finite changes of the arrivaltime, but are a result of the detection algorithm. The detection algorithm looks for the maximum peakvalue, not for the maximum envelope value in the groundwave dominated part of the composite signal. The jumps in the curve are thus the amplitude differences of succesive halfcycles.

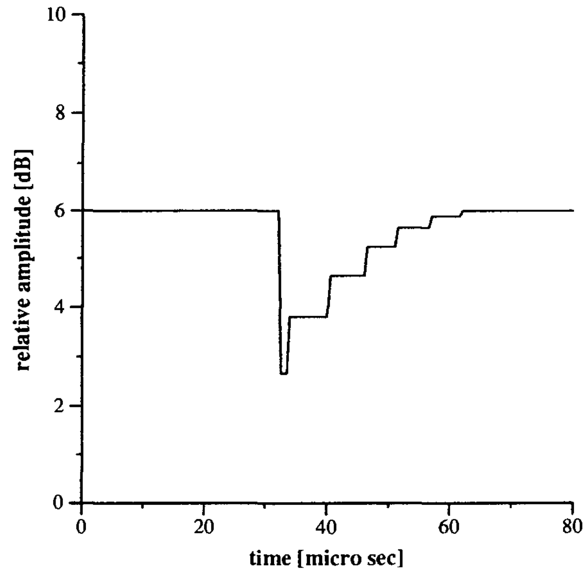

Figure 1: Groundwave peakvalue versus skywave arrivaltime

4 Skywave peak blinking detection

As shown in the previous paragraph, extra signal power can be obtained by sampling in the top of the Loran–C pulse. By this method, skywave interference can cause a peformance degradation of 50 % compared to the maximal possible value. The reason for sampling at the top was that only the presence of a pulse had to be detected. Since the skywave can be much stronger than the groundwave, using the skywave for blinking detection can give even better performance. The skywave is nothing more than a delayed replica of the groundwave, thus as a groundwave-pulse blinks the skywave-pulse will blink too. Since there are no mimum or maximum skywave levels specified, the strongest skywaves receivers have to cope with succesfully as specified in [6] are used.
Although the result might be rather optimistic, it will show clearly the capabilities of this method. One should notice that using worst-case skywave intensities according to [6], wil mean in this case using best-case signal strengths. Since even best case skywave

signals can suffer from groundwave interference, the groundwave is subtracted in-phase from the skywave. Figure 2 shows the obtainable improvement relative to the half peak value of the standard Loran–C pulse. For comparison, the obtainable result by using the groundwave peak is plotted as the dotted line in the same figure.

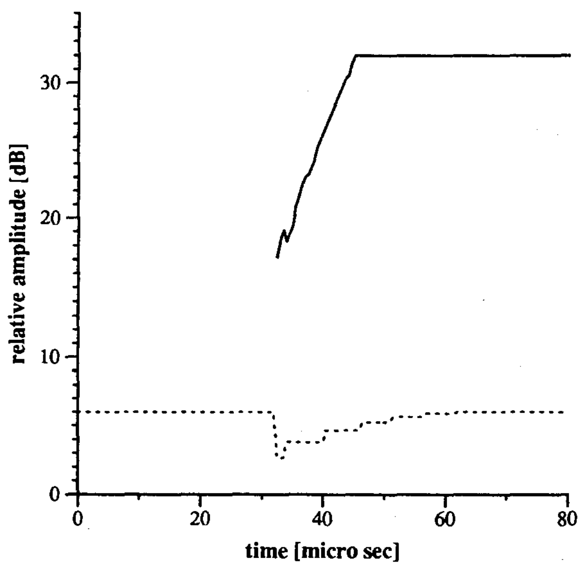

Figure 2: "Best case" skywave peakvalues with worst case groundwave interference

Groundwave signal levels will normally decrease with increasing distance to the transmitter due to the limited conductivity of the earth and spacial expansion. Skywaves do not suffer from the limited conductivity of the earth, and the amplitude of skywaves might increase relative to the groundwave over distance [8]. That means that in fact the real power of the skywave increases with decreasing arrivaltime! The nice aspect of this behaviour is that not to far from a transmitter one has strong groundwave signals and thus an high SNR. At larger distances where one could suffer from the poor SNR, the skywave intensity is relatively strong and using the skywave for detection of automatic blinking can really improve the receivers blinking capabilities. Something not discussed in this article, is the use of more than one sample per Loran–C burst. Increasing the amount of (uncorrelated) samples will even further improve the capabilities of blinking detection. More over taking multiple samples per Loran–C burst can be found in [9].

5 Conclusions

It has been shown that there are different ways of detecting automatic (aviation) blinking beyond the -6 dB limit. Therefore, it would be better and more fair to require only timely detection of blinking and flagging of a warning as soon as the receiver isn't capable of detecting blinking within the integrity limit of 10 seconds. The result of this more fair and flexible requirement is that some airborne Loran–C receivers could be certified for non-precision approaches to operate under conditions where other receivers would fail. The disadvantage of this more fair and flexible certification requirement is that the certification procedure itself becomes more complex. Instead of applying a signal 6 dB below the noise level and a simple check if a warning is flagged, testing should be based now on a wide range of signals and more statistical methods. For certification of non-precision approaches at airports however, this method wouldn't be very practical, since a SNR threshold cannot be used at all. The most important item for certification of non precision approaches should be the reachable accuracy due to intersection of the lines of position (HDOP) of the Loran–C stations and possible propagation disturbances due to conducting structures in the area of operation. If the signal to noise ratio should be taken into account somehow, than it might best be done by classification of the Loran–C receivers according to their performance, and certfy the approaches for those specific classes. Allthough the -6 dB limit is not very useful for receiver certification, such a limit might be useful for Loran–C system design. If most of todays airborne Loran–C receivers function properly up to this threshold, then a requirement in case of designing or expanding a Loran–C system could be that at (specific) airports at least an SNR of e.g. -6 dB [5] should be provided.

Acknowledgements

The author would like to thank the Electronic Engineering group in which this research has been conducted, in particular Mr. H.J. Lincklaen Arriëns for his support by the realization of this paper. Also, he would like to thank Prof.dr.ir. D. van Willigen for convincing him to publish the ideas presented in this paper.

Biography

André Nieuwland was born in the Netherlands in 1968 and started to study electrical engineering at the Delft University of Technology in 1986. He concluded this study with the presentation of his master's thesis "Weighted Spectrum Analysis in Loran-C" in 1991. In January 1992, he started a PhD. study at the Electronic Engineering Group, to develop and implement a Loran-C receiver based on digital signal processing techniques. Furthermore, he will be actively involved in future GRI calculations for the North-Western European Loran-C chains.

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AN ADVANCED LORAN-C RECEIVER STRUCTURE

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ABSTRACT

In this paper, a new LORAN-C receiver structure is proposed that is capable of reducing the influence of multipath and interference. Additional, it has the advantage of fast acquisition, since all the estimation processes are performed simultaneously instead of sequentially. A brief explanation is given of the theory behind the new structure, followed by a discussion how to implement it. Finally, some simulation results demonstrate the considerable improvements that can be obtained.

1 INTRODUCTION

One of the main tasks of any navigation receiver is to measure propagation delays of received signals. In order to estimate these delays, receivers employ several tracking loops, which synchronize locally generated signals to the received signals. The structures of these tracking loops is often derived from maximum likelihood equations [1]. However, a number of assumptions and simplifications in the derivation results in a certain performance degradation.

Digital signal processors make it possible to avoid some simplifications by a direct calculation of the maximum likelihood equations. However, they can do more than just replace the conventional tracking loops; digital signal processors open the way to new techniques to combat all kinds of disturbances like multipath, interference and dispersion. If a certain model of these disturbances is available, it is possible to design a receiver that estimates the unknown parameters of the model, thereby eliminating its deterious effects on the estimates of the wanted signal parameters like the propagation delay.

2 LORAN-C MAXIMUM LIKELIHOOD ESTIMATES

The received LORAN-C signal can be written as:

$$r(t) = \sum_{i=o}^{M} \sum_{c=-\infty}^{\infty} \sum_{j=o}^{7} a_i p_{cj} l(t-\tau_i-jT_o-cGRI)\cos(\omega_o t+\theta_i) + \sum_{k=1}^{K} b_k \cos(\omega_k t+\phi_k) + n(t)$$

$$= s(t) + n(t) \ , \ T_o = 1 \text{ ms} \qquad (1)$$

$$l(t) = (t/t_p)^2 \exp(2-2t/t_p) \qquad t \geq 0$$

$$l(t) = 0 \qquad t < 0 \ , \ t_p = 65 \ \mu s$$

where M is the number of skywaves, each with a different amplitude a_i, delay τ_i and phase θ_i, respectively. The LORAN-C signals consist of a puls train with puls shape l(t). These pulses are multiplied by a phase code p_{cj}, which can take values of {+1,-1}, and repeats itself every 2 Group Repetition Intervals. Further, the presence of K carrier wave interference (CWI) signals is assumed, together with a noise signal n(t).

Out of the received signal r(t), a receiver has to estimate the delay τ_o and phase θ_o of the LORAN-C groundwaves. Usually, these estimates are provided by tracking loops, which consist of a certain detector that measures the difference between the desired parameter of the input signal and that of a locally generated signal. A loop filter is used to filter the measured differences and control the local signal in such a way that the difference is driven to zero.

2.1 OPTIMUM ESTIMATES

The maximum likelihood estimates of τ_o and θ_o are those values that maximize the logarithm of the conditional probability density function (pdf) $p(r(t)|s(t))$. Under the assumption that n(t) is white Gaussian noise, and that the desired parameters can be regarded as constants during a measurement time T, the equation that has to be maximized can be written as [1]:

$$L[r(t)] = -\int_o^T [r(t) - s(t)]^2 \, dt \qquad (2)$$

where s(t) is the deterministic part of the input signal of equation (1). So for Gaussian noise, the maximum likelihood method is equal to the least squares method; both minimize the mean square error of an input signal r(t) minus an estimated signal s(t). In reality, however, the noise is not completely Gaussian, causing a certain degradation in the estimation errors. This degradation can be minimized by introducing a certain nonlinear operation on the input signal r(t), like explained in [2].

The estimates that maximize L[r(t)] are those for which all partial derivatives are zero. By writing out these derivatives, one can find the expressions for the desired estimates. The delay estimates τ_n of the groundwave (n=0) and skywaves, for instance, are given by:

$$\hat{\tau}_n = \max_{\tau} \int_o^T [r(t) - \sum_{\substack{i=o \\ i\neq n}}^{M} \sum_{c=o}^{C} \sum_{j=o}^{7} \hat{a}_i \, p_{cj} \, l(t-\hat{\tau}_i-jT_o-cGRI) \cos(\omega_o t+\hat{\theta}_i)$$
$$- \sum_{k=1}^{K} \hat{b}_k \cos(\hat{\omega}_k t+\hat{\phi}_k)] \sum_{c=o}^{C} \sum_{j=o}^{7} p_{cj} \, l(t-\tau-jT_o-cGRI) \cos(\omega_o t+\hat{\theta}_n) \, dt \qquad (3)$$

where C is the number of GRIs within the observation interval T.

In words, to get the maximum likelihood estimate of for instance the groundwave delay τ_o, first the estimated interfering signals -all skywaves plus CWI signals- have to be subtracted from the input signal. Then, the resulting signal has to be correlated with a locally generated groundwave signal. The delay $\hat{\tau}_o$ that maximizes this correlation is the desired estimate.

Looking at equation (3), it is clear that the calculation of the optimum estimates gets quite complicated. In a practical implementation, the input signal should be sampled and stored for a period of T seconds. Then from these samples all unknowns - a total of (M+K+1)·3 - have to be calculated by solving the same number of equations. The time T should be large enough to get an acceptable error due to noise in τ_o and θ_o, the delay and phase of the Loran-C groundwave. On the other hand, T has to be small enough to assure the parameters stay approximately constant, in order to track receiver movements. Therefore, T should be equal to practical Loran-C loop bandwidth values, ranging from about one to tens of seconds. For a practically achievable sampling rate of 50 kHz, this gives an amount of samples of $50 \cdot 10^3$ up to 10^6.

Concluding, the optimum estimator is difficult to realize in practice. Therefore, it is desired to make some simplifications that ease the realization, while the major advantages are maintained. The derivation of such a suboptimum estimator is the subject of the next section.

2.2 SUBOPTIMUM ESTIMATES

In order to simplify the estimation procedure, two steps can be taken. First, the correlation with the local Loran-C signal can be performed prior to all other operations. In this way, the correlation function becomes a new input signal from which all desired parameters can be extracted. The major advantage of this step is the elimination of all asynchronous CWI signals, since the correlation acts like a comb filter, greatly reducing signals that have a frequency spacing of more than 1/T Hertz with a Loran-C spectral line. An additional advantage is that the correlation function repeats itself every 2 GRI. Therefore, it is necessary to store only 2 GRI of data instead of T seconds, by simply adding all samples that have a relative delay of a number of 2 GRI.

Secondly, it is not necessary to correlate with an exact replica of the Loran-C signal. Such a correlation is equal to using a very narrowband filter, with the result that the Ground-to-Skywave Ratio (GSR) in the leading edges of the Loran-C pulses worsens. Instead, a more wideband filter may be used, in order to profit from the improved GSR which allows a much more simpler way to estimate the groundwave parameters; Instead of searching for the maximum of the pulse, one can search for a certain point on the leading edge which is free from skywaves. Most Loran-C receivers use this technique [3], at the cost of a decreased Signal-to-Noise Ratio (SNR) in exchange of a greatly simplified estimation technique as compared to the maximum likelihood solution of equation (3). However, CWI signals are more difficult to combat. Till now, receivers only use notch filters for these kind of disturbances. Unfortunately, notch filters distort the shape of the Loran-C pulses, thereby introducing an extra source of errors. Further, receivers normally do not have the possibility to check if disturbances are properly eliminated; They simply assume that the signal after filtering is clean, with the consequence that certain errors due to residual

CWI signals or skywaves may not be detected, or only after a very long time. Therefore, in the following description of an advanced receiver structure, the emphasis is on the elimination of CWI signals, together with a detection criterion to see if the residual powers of skywaves, noise and CWI signals has an acceptable level.

So the first step of the suboptimum estimator is a bandpass filtering of the input signal r(t). To reduce the sampling rate, it is desirable, though not necessary, to perform an in-phase and quadrature downconversion. After this, the signal can be sampled and averaged over 2 GRI, so samples with a relative delay of 2i GRI (i=1,2,..) are accumulated and stored in memory. This means that for a sampling rate of 50 kHz and a GRI of 100 ms, only 10^4 (complex) samples have to be stored, independent of the total averaging time T. Note that the same concept of averaging over 2 GRI is used in [4]. where the main goals were a fast acquisition time and an extended tracking range by using skywave correction (without explaining what kind of correction).

In figure 1, an example of the averaged signal is drawn. For clearness' sake, only 4 Loran-C pulses are shown. Before downconversion, the signal is bandpass filtered by a third order Butterworth filter with a bandwidth of 30 kHz.

The next step is to add all individual Loran-C pulses within the averaged 2 GRI interval by correlating the averaged signal with

$$\sum_{c=o}^{1} \sum_{j=o}^{7} p_{cj}\ \delta(t-\hat{\tau}_n-jT_o-cGRI) \tag{4}$$

where L is $2GRI/T_o$, i.e. the number of milliseconds within 2 GRI. $\delta(t)$ is the Dirac function. In a sampled system, the Kronecker delta function would be used, but for simplicity of notation, time continuous signals will be assumed in the rest of the paper.

The correlation is easy to perform, since the signal of (4) only has 16 nonzero values. The resulting correlation function $x(\tau)$ can be described as:

$$x(\tau) = \sum_{i=o}^{M} a_i\ l_f(\tau-\tau_i)\ \exp(j\theta_i) + \sum_{k=1}^{K} b_k\ \exp[j((\omega_k-\omega_o)\tau+\phi_k)] + n_f(\tau) \tag{5}$$

Note that the parameters b_k and ϕ_k in general will be different from the original parameters in (1), because of the filtering and correlation operations.

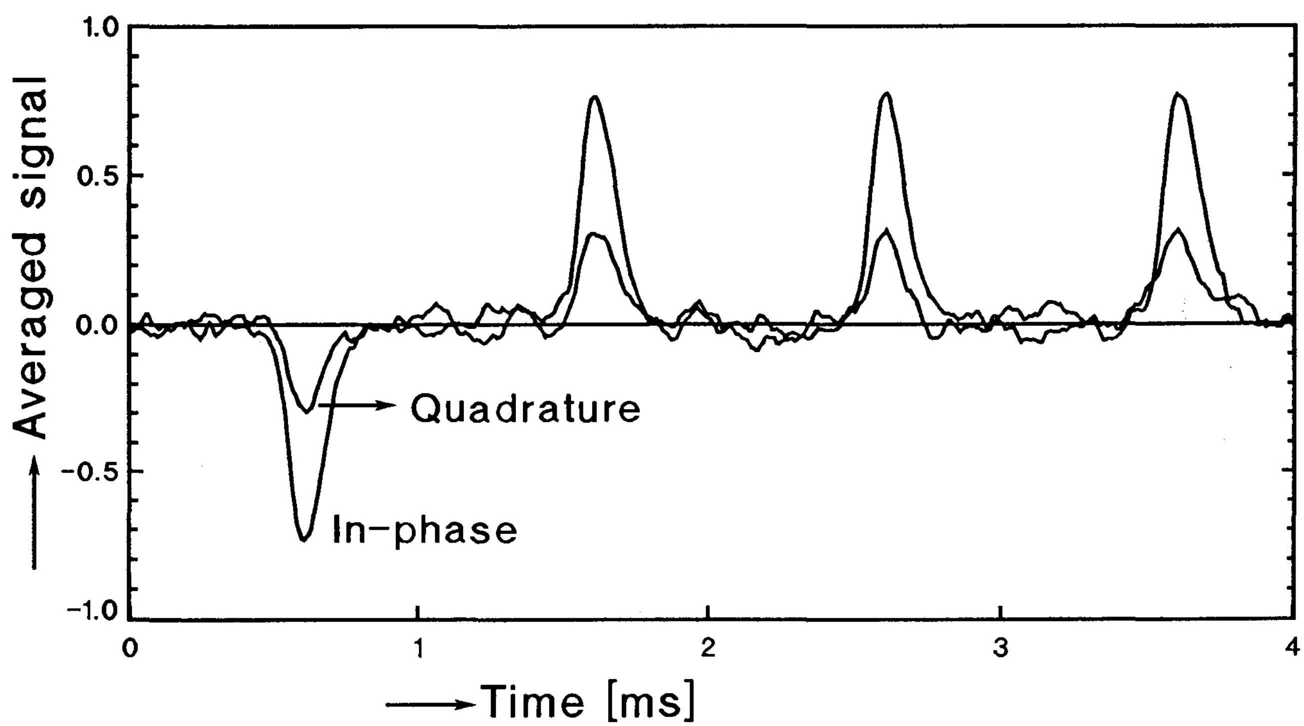

Figure 1: Loran-C signal after filtering, downconversion and averaging

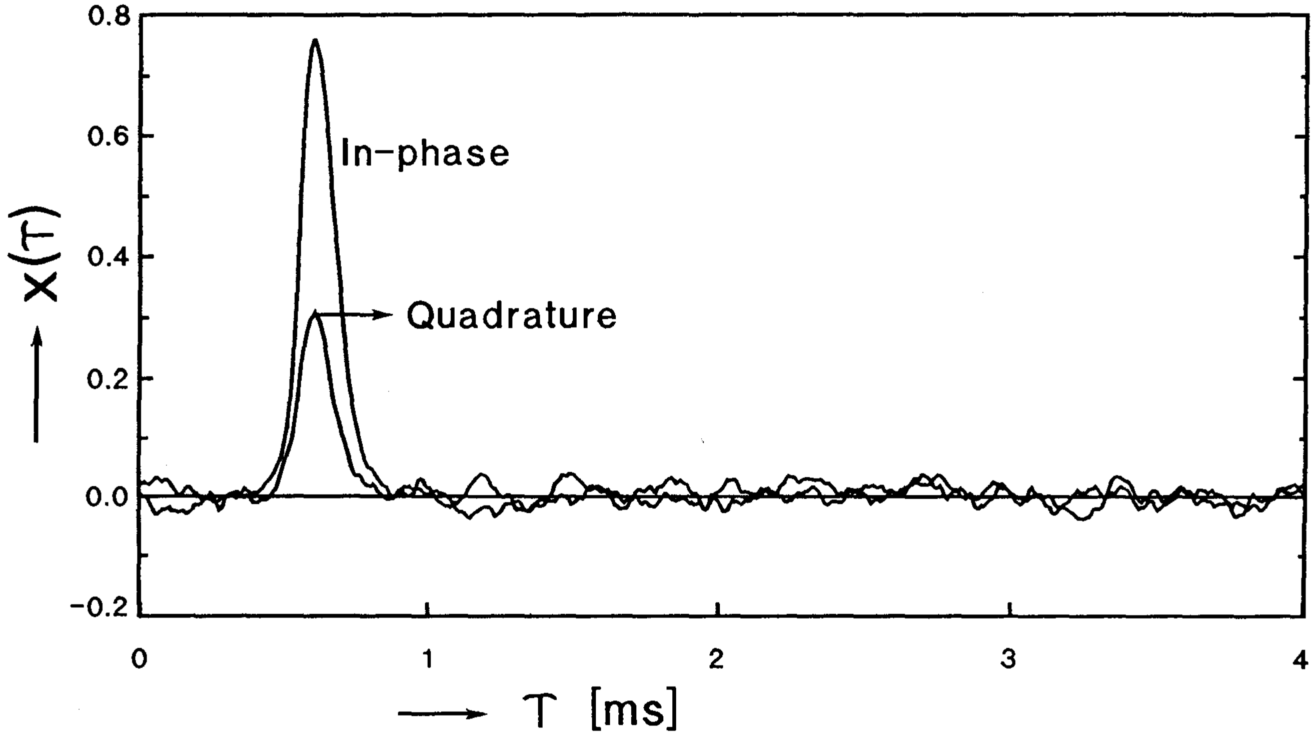

Figure 2: Signal of figure 1 after correlation

As an example of the resulting signal $x(\tau)$, the signal of figure 1 is shown after the correlation operation in figure 2.

Now, the maximum likelihood estimates of the unknown parameters of equation (5) are:

It is assumed that the CWI angular frequencies ω_i are known, or estimated by calculating the FFT of the averaged signal $x(\tau)$, or by a more sophisticated method like described in [5,6]. These spectrum methods are also useful to estimate the number of CWI signals K.

$$\hat{\tau}_o = \max_{\tau} \mathrm{Re}\{\ x(\tau)\ -\ \sum_{k=1}^{K} \hat{b}_k \exp[j((\hat{\omega}_k-\omega_o)\tau+\hat{\phi}_k)]\ \exp(-j\hat{\theta}_o)\ \}$$

$$\hat{\theta}_o = \arg\{\ x(\hat{\tau}_o)\ -\sum_{k=1}^{K} \hat{b}_k \exp[j((\hat{\omega}_k-\omega_o)\hat{\tau}_o+\hat{\phi}_k)]\ \}$$

$$\hat{a}_o = \mathrm{Re}\{\ (\ x(\hat{\tau}_o)\ -\ \sum_{k=1}^{K} \hat{b}_k \exp[j((\hat{\omega}_k-\omega_o)\hat{\tau}_o+\hat{\phi}_k)]\ )\ \exp(-j\theta_o)\ \}$$

$$\hat{b}_i = \mathrm{Re}\{\ \frac{1}{T_1-T_o}\int_{T_o}^{T_1} \{\ x(\tau)\ -\ \hat{a}_o\ l_f(\tau-\tau_o)\exp(j\theta_o)\ -\sum_{\substack{k=1\\k\neq i}}^{K} \hat{b}_k \exp[j((\hat{\omega}_k-\omega_o)\tau+\hat{\phi}_k)]\ \}$$

$$\cdot\ \exp[-j((\hat{\omega}_i-\omega_o)\tau+\hat{\phi}_i)]\ d\tau\ \}$$

$$\hat{\phi}_i = \arg\{\int_{T_o}^{T_1} \{\ x(\tau)\ -\ \hat{a}_o\ l_f(\tau-\tau_o)\exp(j\theta_o)\ -\sum_{\substack{k=1\\k\neq i}}^{K} \hat{b}_k \exp[j((\hat{\omega}_k-\omega_o)\tau+\hat{\phi}_k)]\ \}$$

$$\cdot\ \exp[-j(\hat{\omega}_i-\omega_o)\tau]\ d\tau\ \} \qquad (6)$$

In equation (6), T_0 and T_1 define a certain window, which includes at least the leading edge of the Loran-C pulse, but excludes skywaves and Loran-C pulses from other transmitters. To demonstrate especially the CWI insensitivity of the algorithm, skywaves are left out in the following examples. In this specific case, the interval can be chosen such that it contains the major part of the Loran-C pulse.

Because of the nonlinearities in the equations of (6), they have to be solved iteratively. To check if the calculation was successful, the Signal-to-Residual Ratio (SRR) can be calculated according to equation (7). If the SRR is significantly smaller than the expected SNR of the averaged signal, then the errors of the estimates will also be larger than expected. So by calculating the SRR, a receiver can immediately detect the occurrence of large errors, thereby greatly enhancing the integrity. In words, the SRR is the estimated signal power of the Loran-C groundwave at the standard sampling point, divided by the power of the residuals which remain if the estimated Loran-C signal plus CWI signals are subtracted from the averaged signal $x(\tau)$.

Figure 3 focusses on one millisecond out of the total of 2 GRI. For simplicity, only the in-phase part of the signal is drawn. In this millisecond, there is one Loran-C pulse present. Its top has a delay of about 0.2 ms. Also present are two CWI signals, which result in a Signal-to-Interference Ratio (SIR) after the whole averaging process of 0 dB. Further, noise is present with a Signal-to-Noise Ratio (SNR) of 30 dB after averaging. This means that for an input SNR of 0 dB, 1000 Loran-C pulses have to be averaged to reach an SNR of 30 dB. For a GRI of 100 ms, this corresponds to an averaging time T of 12.5 seconds. Both SNR and SIR values are using the Loran-C power at the standard sampling point, as defined in [7].

Figure 3 is an example of extreme synchronous CWI, since the correlation with the phase code attenuates synchronous CWI signals by about 12 dB [5]. Thus the input SIR in the case of figure 3 is -12 dB, far worse than specified in the Minimum Performance Standards [7]. When a conventional algorithm is used to estimate the delay and phase of the Loran-C pulse -equal to solving equation (6) with K set to zero- a phase error of -230

$$SRR = \frac{(\hat{a}_0/2)^2}{\frac{2}{T_1-T_0}\,\mathrm{Re}\left\{\int_{T_0}^{T_1}\left\{x(\tau)-\hat{a}_0\ \mathrm{lf}(\tau-\tau_0)\exp(j\theta_0)-\sum_{k=1}^{K}\hat{b}_k\ \exp[j((\hat{\omega}_k-\omega_0)\tau+\hat{\phi}_k)]\right\}^2 d\tau\right\}} \tag{7}$$

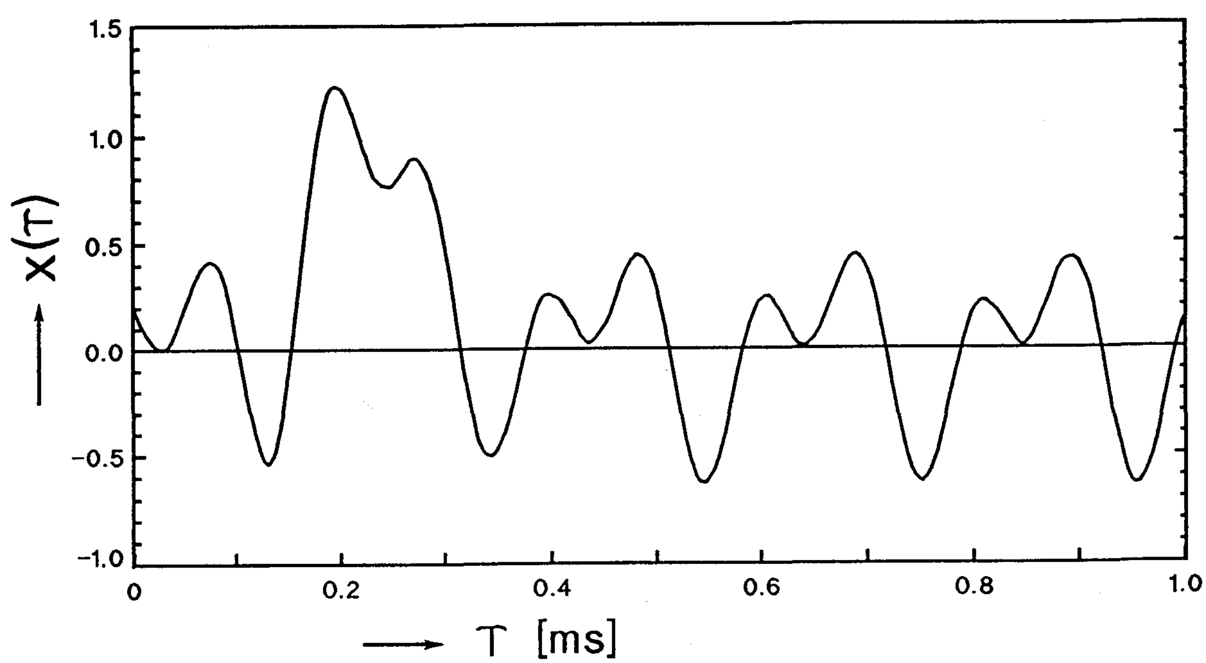

Figure 3: Averaged Loran-C signal plus CWI signals

meters and a delay error of 20 km occur in this case, so it is impossible to identify the correct cycle. When the maximum likelihood estimates are calculated according to equation (6) for K=2, phase and delay errors of 8 m and -293 m are achieved, respectively. The SRR for this case is 29.7 dB, which is nearly the same as the SNR, meaning that all signals were properly reconstructed. This specific example shows the advantage of using a certain knowledge of disturbing effects in order to minimize their influence. For Loran-C, this means that in principle it is possible to estimate the errors caused by all kind of interferences like skywaves and CWI signals, and even propagation effects -ECD and ASF [8]- as long as a general model of the disturbances is available with some unknown parameters that have to be estimated.

By estimating interfering signals, like the previous example of figure 3, it is possible to achieve nearly the same variance in the delay and phase estimates as in the case of noise only; the SNR determines the absolute lower bound of the resulting error variances. As a result, Monte Carlo simulations with similar signals as in figure 3 gave standard deviations in the phase measurements in the order of ten meters for SNR = 30 dB (after averaging) and tens of meters for SNR = 20 dB, corresponding to practically achievable error levels in the absence of strong interference.

3 Positioning aspects

In the previous analysis, the main parameters of interest were the delay τ_o and phase θ_o of the Loran-C groundwave. Because of the downconversion of the input signal, the zero crossings one is used to are no longer visible, however, the principles remain the same; the delay estimate τ_o should have an error less than 1.5 km in order to resolve the phase ambiguity correctly. If one wants to perform a hyperbolic position fix, the desired time differences between two different transmitters a and b are given by:

$$T_d = \left[\mathrm{Int}\left\{\left(\hat{\tau}_a - \hat{\tau}_b - \frac{\hat{\theta}_a - \hat{\theta}_b}{2\pi f_o}\right) f_o\right\} + \frac{\hat{\theta}_a - \hat{\theta}_b}{2\pi} \right] / f_o \quad [s] \quad (8)$$

In equation (8), f_o denotes the Loran-C carrier frequency (f_o=100 kHz) and Int{·} means rounding to the nearest integer. So the first term of (8) gives the time difference between a and b in whole cycles, while the second part adds a fractional part of a cycle. Note that if ECD and/or ASF correction values are known, they can be subtracted from the measured delays and phases prior to the calculation of (8).

CONCLUSIONS

An advanced Loran-C receiver structure was proposed, especially focussing on the elimination of CWI signals, although skywaves and even propagation errors like the ECD and ASF could also be included.

By calculating the Signal-to-Residual Ratio, a receiver can detect unacceptable errors in real time, e.g. cycle identification errors, thereby greatly enhancing its integrity. This detection method can also be used if only the Loran-C groundwave parameters are estimated.

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SESSION J

Signal Characteristics and Simulation

An Improved Cycle Identification Algorithm

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Abstract— In the presence of synchronous interference, cycle identification is the most critical part of the Loran–C receiver since cycle slips may easily occur and immediately result in range errors of multiples of 3 km. This paper will discuss a pulse matching cycle identification technique, and compare this technique with a conventional method.

Introduction

One of the major problems in Loran–C operation in Western Europe is the presence of interference. Especially synchronous interference, that is when the frequency of an interference signal coincides with a Loran–C spectral line [1], is utmost annoying because it produces an offset in range measurement and might even lead to cycle slips.

Since the phase of a synchronous interference signal is the same on sample moments spaced 2 Group Repetition Intervals (GRI) apart, the distortion of the Loran–C pulse will be exactly the same as the pulse transmitted 2 GRIs before. Therefore, the long integration times (multiple GRIs) of cycle identification loops, although increasing the signal-to-noise-ratio (SNR), will not increase the signal-to-synchronous-interference-ratio (SSIR). The only reduction of these unwanted signals is caused by averaging over the (different phase coded) pulses within 2 GRI. This suppression will be generally somewhere between 9 and 24 dB [2], dependent on the frequency of the interference and the phasecode used as is pointed out in figure 1.

For simplicity, phase coding and pulse repetition will not be dealt with any further, since the major topic is the basic comparison between two cycle identification techniques. Phase coding only reduces the level of synchronous interference, it does not change the way of interaction significantly.

With a conventional cycle identification algorithm, only a small part of the Loran–C pulse is used. Thus only a part of the information available is used. With the proposed pulse matching technique, more of the available information is used, resulting in an improved performance with respect to (synchronous) interference. In section 1 will be explained in more detail how conventional cycle identification algorithms are affected by synchronous interference. Section 2 will present an improved cycle identification algorithm with respect to interference, based on a pulse matching technique. Section 3 will discuss how properties of the input signals influences the proposed cycle identification technique.

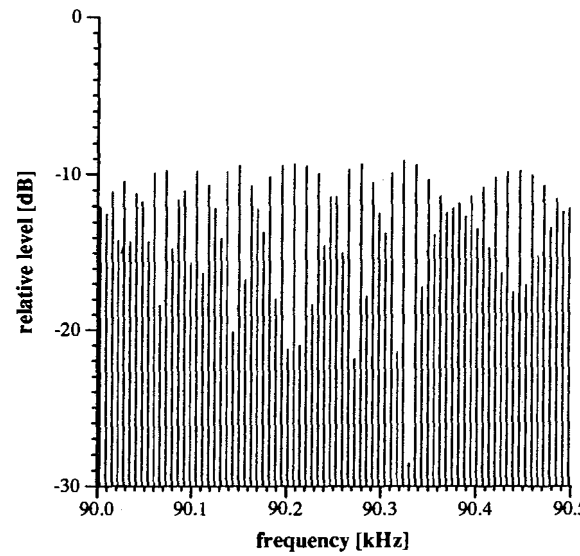

Figure 1: Part of the line spectrum, resulting from the Master phasecode pattern for a GRI of 7777 and a frequency span from 90.0 to 90.5 kHz

1 Conventional cycle identification

There are two common cycle identification algorithms which are basically the same [3]. One is based on determining the ratio of successive half cycles, the other one is known under the name delay-and-add. In the first case, the sampling clock is in lock and samples the Loran–C pulse on the peaks of the half cycles. Then, the ratios of successive halfcycles are calculated and the ratio closest to the expected ratio at the standard sampling point (SSP) [1] determines the cycle to be selected. By the second method, a $5\mu s$ delayed version of the received pulse is added to the attenuated

received pulse. If the attenuation factor is equal to the ratio of the successive half cycles around the SSP, the proper cycle can be identified by locating the zero crossing of this composite signal. Since the attenuation factor is linear dependent on the half cycle ratio, the latter method is in fact the same as the first one. Due to the distorted envelope of the Loran–C pulse, the zero crossing identifying the SSP after the delayed pulse is added, will be shifted in time. As soon as this zero crossing is shifted more than $5\mu s$, the proper cycle can no longer be identified and the wrong cycle will be selected for tracking.
Computer simulations have been carried out, performing a conventional cycle identification on a single Loran–C pulse in the presence of interference. The simulated interference signals are sine-waves with a frequency varying between 75 and 100 kHz. At each frequency, the initial phase of the interference is rotated over π radians to find the ultimate worst case interference, and the amplitude is increased in small steps until the detection algorithm failed. The level of interference the receiver was just not able to deal with successfully, is plotted against the interference frequency in figure 2.

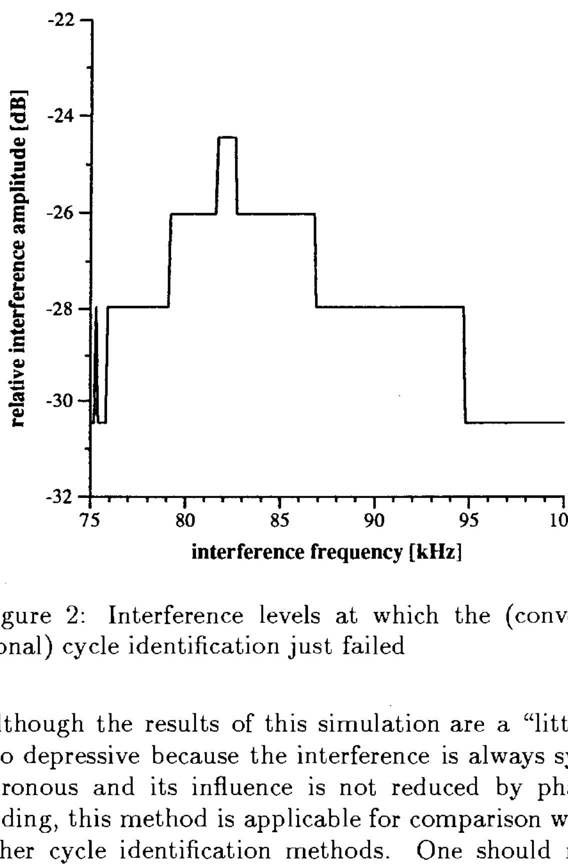

Figure 2: Interference levels at which the (conventional) cycle identification just failed

Although the results of this simulation are a "little" too depressive because the interference is always synchronous and its influence is not reduced by phase coding, this method is applicable for comparison with other cycle identification methods. One should notice that the presence of envelop-to-cycle discrepancy (ECD) can even reduce the maximum level of successful sustainable interference.

2 Pulse matching cycle identification

As already mentioned in the introduction, the performance of the cycle identification algorithm can be improved, by using more of the already available information. Thus instead of matching two successive half cycles, a larger part of the received Loran-C pulse should be matched with a reference pulse to estimate the time of arrival (TOA) within $\pm 5\mu s$. This matching can be done by locking the sampling clock to the Loran–C signal, and sampling the incoming signal at the same positions as the samples of a reference pulse. Ideally, if the reference pulse is subtracted from the incoming Loran–C pulse, the sum of all the squared errors (SSE) will be zero. As soon as the mismatch between the reference pulse and the incoming pulse increases, the sum of the squared errors will increase. The only thing the receiver has to do is to sample the input Loran-C signal at the predefined sampling positions, subtract the reference pulse form the received pulse, and compute the sum of the squared errors. This process is repeated for every sample within a certain window, limiting the possible TOAs. The most likely TOA can be obtained from the position of the minimum of the SSE-curve.
The remaining question is which part of the Loran–C pulse can be used for the estimation of the TOA. One restriction is that the first two half cycles are small compared to the other halfcycles at the front of the pulse (respectively 1% and 8% of the pulse peakvalue), and probably buried in the noise. Therefore, the choice has been made to start the reference interval at the top of the third half cycle, where the signal value is already 19% of the peak value. Long integration times might be useful to extract these small half-cycles out of the noise, but the integration time is limited by performance requirements as response time and receiver dynamics. Using these small cycles will therefore not be considered in the rest of this paper.
A second restriction on the usable part of the pulse is the presence of skywaves. According to [4], skywaves can arrive with a minimum delay of $37.5\mu s$. Thus at first glance, the usable part of the Loran-C pulse is limited to the $25\mu s$ starting at $12.5\mu s$. The IEC-specifications [4] however, specify the skywaves the receiver should be able to cope with successfully. It does not specify the skywaves a receiver normally encounters during operation. If one examines the graphs of the skywave delay versus distance, one should notice that there is a large part in the coverage area where the skywave arrives later than the $37.5\mu s$ [5]. The receiver should thus be able to estimate the TOA of the skywave, to determine the maximum usable interval for pulse matching and reach optimal performance. Although a little skywave influence is not immediately destructive, it will limit the usable signal

interval. Compensation of the skywave might reduce this limit and will improve the performance.

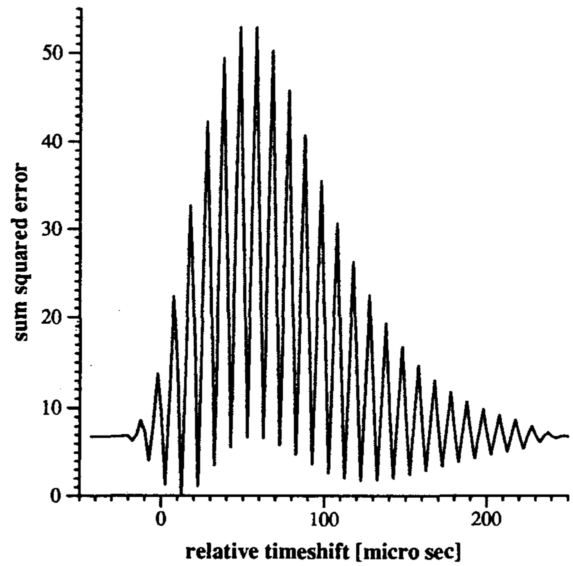

Figure 3: Sum squared error versus relative timeshift

Figure 3 presents the SSE versus time shift of the input signal relative to the reference pulse. The real arrival time of the pulse is zero. Because the part of the pulse used for matching stretches from $12.5\mu s$ to $42.5\mu s$, the minmum SSE will occur at $12.5\mu s$. The samples are taken synchronous with the Loran–C signal at a rate of 400 kHz for reasons explained in [6] and [7].

To show the improvement possible relative to the conventional algorithm, simulations have been carried out to obtain the interference levels the pulse matching cycle identification algorithm is just not able to deal with successfully. The interference amplitude limiting the cycle identification is really worst case interference: At each amplitude level at each frequency the phase is altered to apply an interference signal with a worst case phase. Since the simulations are performed using only one pulse, all frequencies are very synchronous. The obtained interference levels are plotted in figure 4 against the interference frequency for several lengths of the reference pulse interval. All reference pulse parts start at $12.5\mu s$. For comparison, the result of the earlier used conventional cycle identification method is plotted in the same graph. The improvement is clearly shown, especially with regard to interference frequencies further away from the Loran-C band and increasing reference pulse length. The smaller differences inside of and at the edge of the Loran-C band are caused by the high correlation between the interference and the Loran-C signal.

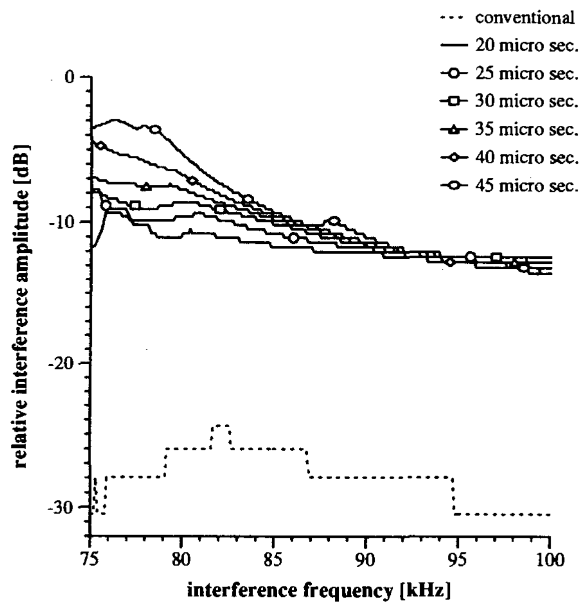

Figure 4: Interference levels at which the cycle identification just failed

3 Correlation in input signals

As briefly mentioned in paragraph 2, correlation between the interference and the Loran–C signal limits the improvement of the pulse matching cycle identification algorithm. Correlation is not limited between interference and Loran–C signal only. If white gaussian noise is filtered, then successive noise samples will show correlation if the time between the samples is small. To get an impression of the time over which the correlation of the noise extends, one can regard the rise time of a filter, that is the time a filter needs to rise from 10% to 90% of the final value. If a noise spike is applied to a filter, it will take about the rise time of the filter before the filter output of the filter is back to its original value. The rise time for a first order low-pass filter is given by formula 1 [8]. In our case, the input signal is bandfiltered with a 128 tabs finite impulse response (FIR) filter of about 20 kHz width, thus B should be equal to 10 kHz.

$$T_{step} = \frac{0.35}{B} \tag{1}$$

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

It will be clear that if a sample is taken every $2.5\mu s$ (400 kHz), the noise of two succesive samples will be correlated. Thus doubling the amount of samples will not improve the SNR with 3 dB as one might expect. The SNR can be increased however by averaging the samples of multiple pulses before the pulse matching

technique is applied. Since the influence of noise depends on the filter used and the major topic is the resistance against interference, all simulations are conducted with the absence of noise.
Except from correlated (colored) noise, there is another reason for not increasing the sampling frequency indefinitely. The interference is narrow banded, and sampled with a frequency far above the Nyquist rate. Ergo, increasing the sampling frequency will not yield extra information.
Figure 5 shows the performance of the pulse matching cycle identification for various sampling frequencies between 400 kHz and 2.5 MHz. The reference interval used stretches from $12.5\mu s$ to $52.5\mu s$. As is clearly shown, there is almost no extra gain in using very high sampling frequencies as long as one only considers the resolution of $\pm 5\mu s$ required for the cycle identification. If one would use this algorithm for phase tracking however, it might be useful to use asynchronous sampling and increase the sample frequency to obtain better time resolution.
If the input signal has an ECD shift, the pulse matching will result in a larger minimum error. This ECD will influence the performance of the cycle identification algorithm. If this ECD shift can be predicted however, the reference pulse can be adjusted to represent the *expected* received pulse. This will improve the matching to the level of the non-distorted pulse.

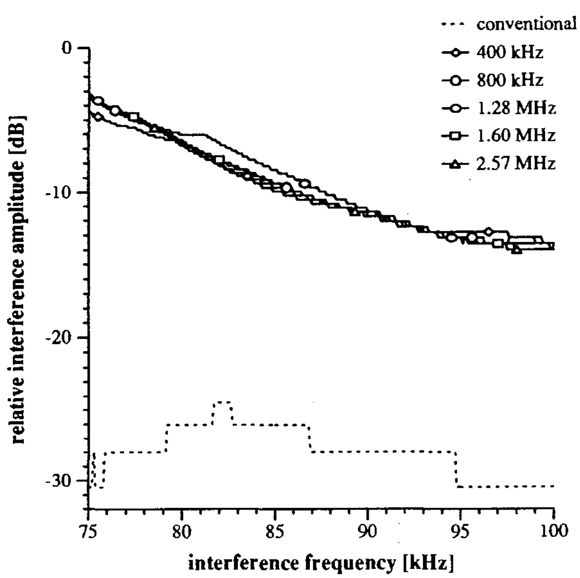

Figure 5: Interference level at which the pulse matching cycle identification just failed for various sampling frequencies

4 Concluding remarks

Loran-C pulse matching will provide a better cycle identification than the conventional delay-and-add technique with respect to interference. One can expect that the pulse matching algorithm leads to a (slightly) different shaped line spectrum, representing the receivers sensitivity for signals with those frequencies. With respect to noise, the improvement possible with the pulse matching technique will be limited, since the noise after filtering is correlated.
The same algorithm can be used for tracking too, if the sampling speed is high enough to obtain the required time resolution.
The presence of skywaves will limit the part of the pulse suitable for pulse matching. If the skywave delay is rather constant, then one might use the TOA of the skywave to support the cycle identification. The estimation of skywave delay can be done by applying the same pulse matching technique to the skywaves. The major advantage is that now a signal can be used for cycle identification that is generally much stronger than the groundwave, hence reducing the influence of interference and increasing the SNR significantly. If necessary the groundwave groundwave can be subtracted first to reduce the influence of groundwave interference. The resolution required for this compensation should be better than the $\pm 5\mu s$ of course.
Searching for the minimum value of the sum squared errors for every sample within a certain window is of course a processing power consuming job. A less processing power consuming implementation might be based on correlation, which is basically the same as searching for the minimum sum squarred error [9].

Acknowledgements

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Biography

André Nieuwland was born in the Netherlands in 1968 and started to study electrical engineering at the Delft University of Technology in 1986. He concluded this study with the presentation of his master's thesis "Weighted Spectrum Analysis in Loran-C" in 1991. In January 1992, he started a PhD. study at the Electronic Engineering Group, to develop and implement a Loran-C receiver based on digital signal processing techniques. Furthermore, he will be actively involved in future GRI calculations for the North-Western European Loran-C chains.

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LORAN-C SIGNAL ANALYSIS TEST DATA AND SIMULATION

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Abstract

This paper provides an in-depth review of the rapidly expanding Loran-C high-technology, nanosecond accuracy system that is being used for aircraft navigation, HHE, restricted waterway navigation, and numerous overland navigation applications. Significant technological and operational changes and improvements that have occurred in the past 15 years are highlighted. Temporal and spatial errors are presented in quantitative terms. Most important, existing and proven compensation techniques for Loran-C sources of error are defined that causes the system to be a high accuracy nanosecond precision system. Models and test data are presented to illustrate Loran-C performance and prediction.

Introduction

The objective of this paper is to define the maximum potential accuracy and resolution achievable with the Loran-C radionavigation system and describe techniques for achieving this capability in a harbor navigation environment.

Over the last several years, the FAA, U.S. Coast Guard, and the marine community have been investigating techniques for using Loran-C for precise navigation. These investigations include analytical studies supplemented by field tests in selected ports, overland, and the airspace to develop performance and operational data. The FAA and USCG desires to assimilate the base of knowledge on Loran-C precision navigation and present this information in a form that will encourage and stimulate the industry to exploit the full capability of the Loran-C system.

This paper includes a compilation of research information on Loran-C performance and operational capabilities from Government and industry studies, analyses, tests, and experiments to characterize the maximum potential accuracy and resolution achievable with the Loran-C system used by marine vessels in a typical harbor environment. Specific attention has been given to:

1. Description of the Loran-C error sources and means to compensate.
2. Description of geographically dependent effects, especially the land/sea interface.
3. Definition of Loran-C coverage contours.
4. Definition of various differential Loran-C concept alternatives, including: automatic corrections, manual corrections, initiate and go, and on-the-fly corrections.
5. Definition of receiver performance specifications and iimitations, with particular attention to resolution and accuracy.
6. Provides necessary data for Loran-C simulation.

A definition of the Loran-C navigation system is provided. The literature includes numerous Loran-C navigation descriptions; also highlighted are significant technological and operational changes and improvements that have occurred in the past 15 years. These new Loran-C system features are summarized in Table 1.

Table 1. Loran-C System Features.

Improvement	Technological	Operational	Impact
Loran-C Pulse Control	X	X	Textbook shape pulse (leading edge)
Solid State Transmitters	X	X	99.9 percent time availabilities
Improved Chain Control Equipment (positioning, processing, and communications)	X	X	Increased chain stability, reliability
Improved Chain Control Procedures		X	Increased chain stability (better compensation for temporal fluctuations)
Increased Automation	X	X	Reduced labor and increased reliability
Improved Loran-C Survey Methods	X		Improved compensation for land-sea boundary changes (CCZ) and spatial effects (bridges, islands, etc. within harbors)
Improved Planning (GDOP considerations)		X	Improved accuracy
User Equipment	X	X	Improved resolution, automation, and reliability

Summary

We also define, in quantitative terms, the source and magnitude of Loran-C temporal and spatial errors. Transmitter timing fluctuations, propagation (temporal and spatial), noise (atmospheric), and frequency interference are presented in quantitative terms. Descriptions of the compensation techniques that can be used to minimize Loran-C errors are provided. Compensation techniques for temporal and spatial fluctuations are presented. Since noise, frequency interference, receiver error, and cycle selection problems are reduced or eliminated by good receiver design practices mitigation techniques for these are presented.

The error sources, causes, and proven compensation techniques that are dealt with herein are summarized in Table 2. A few important observations referring to items listed in Table 2 should be made.

1. (Items 1,2,3) Data includes examples of very large errors caused by both temporal and spatial errors. We no longer care how large these errors are since there is a proven compensation technique for each error source. Of course, knowing the origin of these errors is a requirement.

2. (Items 4,5,6) Limitations may actually be associated with the user equipment. Two differential Loran-C tests have shown 25- to 50-foot accuracy is achievable. When examining the raw test data it is obvious these values are in the receiver noise. This is a definite challenge for the Loran-C manufacturers.

3. (Items 2,3) A compendium of test data has been collected over the past 15 to 20 years and presented. A clear distinction has been drawn between spatial and temporal effects (terrain elevation, effects of structures, time varying effects such as surface impedance, refractive index changes, etc.). This distinction is of great importance when recognizing the limitations of techniques such as PLAD or positioning reference systems used for Loran-C surveys. These techniques strictly provide a calibration of spatial effects. Differential Loran-C methods or variations thereof are required to compensate for temporal fluctuations.

4. (Item 2) Automatic differential systems appear more practical than manual due to the frequency update (correction interval) requirements for most harbor and river areas.

5. To compensate for spatial changes requires a Loran-C grid survey. Both the visual aid and position reference systems are defined. Issues associated with grid survey standardization are summarized.

Functions and requirements for radionavigation aids vary depending on harbor, river, seaway dimensions (depth and width of the channel), vessel type and size (cargo, pleasure craft, and several other categories), and equipment performance characteristics associated directly with the electronic navigation system being used. Similar considerations are true for airspace applications. The remainder of this paper focuses on the Loran-C electronic navigation system--a proven system for Coastal Confluence Zone, restricted (harbors, rivers, and seaways) waterway navigation, and airspace applications.

Loran-C Navigation System Definition

Loran-C is a low-frequency, radionavigation aid operating in the radio spectrum of 90 to 110 kHz. Although primarily employed for navigation, transmissions are used for time dissemination, frequency reference, and communications.

Table 2. Loran-C Error Sources and Compensation Techniques.

Error Source	Cause	Compensation Technique
1. Transmitter timing	Cesium, timer, and transmitter variations	Accurate and stable time base frequency, phase fluctuations adjustments on short- and long-term basic, cycle compensation loop
2. Temporal fluctuations	Refractive index changes along propagation path. Surface impedance variation along propagation path	Differential Loran-C and variations of this method
3. Spatial effects	Bridges (such as Golden Gate); buildings; terrain elevation (islands, peninsulas in vicinity of harbor, river, etc.)	Conduct grid survey. Reflect warpage in grid. This is a one-time fix. Use position reference system or visual grid survey methods
4. Noise (atmospheric and man-made)	Electrical discharges in the atmosphere and power generation equipment	Band limiting and switched O in the receiver. Linear: filtering done at low level ahead of amplifier and clipped linear amplifier. Hard limiter: all linear processing at low-level output has square wave shape. Signal processing filters to minimize effects of interference and noise, shape the envelope, and minimize unwanted distortions. Narrow-band switching of the filters is provided to gain SNR.
5. Frequency Interference	In-band 90-100 kHz Near-band 70-90 kHz Out of band 70 & 130 kHz	Band limiting. Interference filters (notch filters) number depends on operational area. Filter the analog signal or change cross-correlation process to eliminate synchronous interference
6. Receiver	Error measurement technique	Linear and hard limiter amplifiers have wide-band amplifier with low internal noise

These other applications of Loran-C do not affect the navigation accuracy. The Loran-C system consists of transmitting stations in groups forming chains--a coverage area specific to each chain, receiving equipment, a propagation medium between transmitters and receiver, and methods of application. At least three transmitter stations make up a chain. One station is designated master while others are called secondaries. Chain coverage area is determined by the transmitted power from each station, the geometry of the stations, including the distance between them and their orientation. Within the coverage area propagation of the Loran-C signal is affected by physical conditions of the earth's surface and atmosphere which must be considered when using the system. Natural and manmade noise is added to the signal and must be taken into account. These physical conditions and noise effects can be troublesome and impact Loran-C signals. However, as will be demonstrated later, all known error sources can be minimized by using existing error compensation techniques and good receiver design practices. Receivers determine the applied coverage area by their signal processing techniques and can derive position velocity and time information from the transmission. Methods of application provide for conversion of basic signal time of arrival to geographic coordinates, bearing and distance, along track distance and cross error, velocity vectors, and time and frequency reference.

All transmitters in the Loran-C system share the same radio frequency spectrum by sending out a burst of short pulses and then remaining silent for a predetermined period. Each chain within the system has a characteristic repetition interval between the pulse bursts that enables receiving equipment to be uniquely synchronized thereby identifying the chain and stations within the chain being employed.

Over the past 15 years, the U.S. Coast Guard has introduced present day technology into the Loran-C system as follows:

1. Use of solid-state transmitters.

2. Better chain control procedures.
- Improved algorithms to provide corrections
- Automated unmanned control monitors
- Increased number of monitors and strategically locating the control monitors
- Use of microcomputers

3. Using present day grid calibration techniques (position reference systems) for Loran-C surveys. Charts are now eflecting real-world data rather than pure predictions.

4. Increased redundancy and back-up procedures to provide continuous service.

5. Good chain planning is now resulting in shorter base lines and higher signal-to-noise ratios.

6. Transmitting antenna improvements.

7. Improved communications control between stations.

Results of the above can be stated quantitatively in terms of the traditional gauge of performance (i.e., the percentage of usable time the service is available each month). The availability and reliability of Loran-C systems throughout the world continues to improve [1].

The worldwide Loran-C chains have provided 99.9-percent service (less scheduled outages). Periods of scheduled off-air are linked to the same deficiencies which that plagued Loran-C chains for years (i.e., maintenance of the towers, transmitters, and couplers that are part of third- and fourth-generation equipment). The new chains are displaying a significant decrease in off air time due to the installation of solid state transmitters and dual antenna couplers.

Coverage Area. The coverage area of a chain is usually defined in terms of signal strength and geometry of the transmitting stations with respect to each other, as they will support a specified position accuracy from a Loran-C receiver having certain minimum performance characteristics. Coverage area as defined herein is the term applied on charts prepared by the U.S. National Ocean Survey and the U.S. Defense Mapping Agency and in the Loran-C implementation plan by the Coast Guard.

Loran-C coverage now encompasses over 20-million square miles around the U.S. (including Hawaii and Alaska), Japan, Canada, Pacific Ocean, Atlantic Ocean, Mediterranean Sea, and the Norwegian Sea. Loran-C interest is growing rapidly in Europe. The Commonwealth of Independent States has used Loran-C for years.

New chains are being designed to provide high accuracy (well below 500 feet). Privately-owned Loran-C chains are being considered in the Arctic (northern frontiers of Canada) and other areas. The applications are requiring accuracies better than advertised for the Coastal Confluence Zone (CCZ), particularly in the national airspace (NAS). NAS considerations will greatly enhance CCZ and restricted waterway navigation accuracy. To achieve higher accuracies for harbor, restricted waterway navigation, offshore applications, etc. augmentation techniques (such as differential Loran-C) and Loran-C mini-chains have been demonstrated.

Loran-C Error Sources

The U.S. Coast Guard has conducted numerous efforts to determine the source, magnitude, and statistics of Loran-C error sources. These error sources are significant in terms of magnitude and frequency of occurrence; however, in each case there is a compensation technique. Fortunately the Loran-C system has matured over the years and proven compensation techniques have been developed. Additionally, Loran-C today includes the use of high technology and good design practices developed from many years of experience for both Loran-C transmission and user equipment. Estimates for each category of error source will be provided based on a review of tests conducted over the past 15 to 20 years. A description of compensation techniques and good receiver design practices will follow.

Sources of Fluctuations in Transmitted Signals. Predicted transmitted error in terms of timing synchronization, pulse shape control, phase control, and parameter drift will now be estimated.

Timing Synchronization. The time when each pulse is transmitted is controlled by a cesium beam frequency standard that provides stable and accurate time base frequency of 5 MHz and 1 MHz which are used as inputs to the Loran-C timer set. Together these two equipments form a "Loran-C clock." Synchronization of the clocks at all the stations in a chain is accomplished by LPAs (Local Phase Adjustments) on a short-term basis and frequency and phase adjustments on a long-term basis.

The frequency standard used at Loran-C stations is a Hewlett-Packard Model 5061A Cesium Beam Atomic Frequency Standard. The setability of these standards is $\pm 10^{-13}$. In other words, the fractional frequency offset between two 5061A standards cannot be reliably reduced below this level. A fractional frequency offset of 7×10^{-13} corresponds to 60-nanosecond gain or loss of time per day between the two clocks. If the frequency of the two clocks remained constant after being set then three 20-ns LPAs per day would correct for this drift and the maximum error during one day would be ± 10 ns. However, the frequency of cesium beam oscillators changes with time in an unpredictable manner. In addition there is phase noise and the timer certainly adds some additional phase noise or jitter and the information used to derive LPAs is corrupted by all the other temporal fluctuations.

In the short term, most of the fluctuations due to frequency standard instability are due to phase noise since the longer term frequency effects are removed by LPAs. Thus we estimate that the short-term variations are about 5-ns rms. Due to the fact that the timer has a quantization level of 6 ns, we roughly estimate an rms error of about 10 ns due to the Loran-C timer set.

Not all of the fluctuations in the transmitted signal are due to cesium standard instability. The transmitter itself is also a source of signal fluctuation. However, the transmitter is maintained in phase lock with the 5-MHz output of the cesium standard to within ±20 ns by the cycle compensation loop. Plots produced at Loran-C transmitting station Middletown, CA (the X-secondary on the West Coast USA Loran-C chain), have been examined that show these slight adjustments [2]. The cycle compensation loop function is recorded continuously and the records are saved. This loop compensates for changing bias levels within the transmitter and changing delay times. It is estimated that because of the fact that the cycle compensation loop only makes 20-ns corrections, fluctuations in the signal due to the transmitter are roughly estimated to be 6 ns.

The rss of the cesium variations, the timer variations, and the transmitter variations yield an equipment error of

$$[(10)^2 + (5)^2 + (10)^2]^{1/2} = 15 \text{ ns} .$$

Loran-C Temporal Timing Fluctuations

There are three categories of important error sources that can cause time differences (TD) Loran-C timing fluctuations. These are: receiver-induced, transmitting equipment, and propagation fluctuations. To determine the magnitude and source of Loran-C transmitting induced timing fluctuations it would be necessary to locate receivers near (50 to 70 km) two or more transmitters in a service area. Through simple addition and subtraction of TDs significant propagation and equipment fluctuations could be separated as long as the fluctuations are larger than receiver error (typically 25 ns). Specifically, this measurement configuration requires the following assumptions:

1. The propagation fluctuations in a signal traveling in one direction over a given baseline are equal to the propagation fluctuations in a signal traveling in the opposite direction.

2. Propagation fluctuations over the short paths are small compared to other timing fluctuations.

3. Receiver-induced fluctuations are small compared to chain and propagation fluctuations.

4. Chain fluctuations are the same for all receivers in the service area of interest (i.e., chain fluctuations are not spatially dependent).

We have been able to separate equipment and propagation induced fluctuations.

TD and TOA measurements have been conducted over a large area in the Southern Triad of the West Coast, USA [3]. One of the West Coast experiments was aimed at determining the stability of Loran-C signals. No Loran-C timing fluctuations could be attributed to large atmospheric changes even though numerous cold and warm weather fronts (parallel and perpendicular to the propagation paths) passed over the various propagation paths. The timing fluctuations were typically below 35 ns (rms, standard deviation) each week for 12 weeks. Propagation fluctuations (rms, standard deviations) were below 20 ns and masked by receiver noise. Additionally, two receivers (LC204 and BRN-5 linear) were colocated at Ft. Cronkhite (near San Francisco) monitoring TDX and TDY for ten continuous months. The propagation paths ranged between 50 nmi and about 475 nmi. The mean values over the entire 10 months (that included winter--the most severe fronts cross the paths) did not change more than 60 ns and standard deviations were <35 ns. The Ft. Cronkhite measurement site is only 100 miles north of the control monitor (located at Point Pinos, CA). This shows good control when the receiver (user) is near the monitor.

The West Coast results show a very stable (Southern Triad) Loran-C system that was not significantly affected by frontal systems passing over the propagation paths. Additionally, the results at Ft. Cronkhite show good control when the user is in the vicinity of the control monitor.

Previous Experiments on the East Coast. The expectations, based on earlier East Coast data collections, that weather phenomena might change the groundwave phase by as much as 0.5 to 1 ms or more were not borne out in any of the data collected on the West Coast (USA) and more recently in the Canadian Great Lakes region.

Diurnal fluctuations measured over a propagation path (753 nmi) between Carolina Beach and Dana have revealed 1-ms changes in the winter and 0.5-ms changes in the summer [4]. The propagation paths in the Great Lakes experiment are as long as the Carolina Beach-Dana path (in both cases typically 550 to 650 nmi). There is a difference in conductivity of about a factor of 2 which should not have significant impact. These large timing fluctuations have been attributed to the passage of frontal systems. Attempts to explain the above changes in Loran-C TDs based on meteorological (i.e., changes in temperature occurs the same time as the change in TD) explanations have been attempted by several researchers [5,6,7]. Even though the Loran-C data compares well with a specific weather parameter (temp.), the fact remains that diurnal TD timing fluctua-tions are about 4 to 5 times as great as can be explained by simple calculations using expected changes in the index of refraction.

Temporal Fluctuations Summary. Tables 3 and 4 show Loran-C temporal timing fluctuations measured over the past 10 to 15 years. Several observations can be made about this tabulation:

1. The largest peak-to-peak temporal fluctuations have occurred in the winter season.

2. These effects in the Northern areas may be related to surface impedance changes (snow, ice, and freezing conditions).

3. These fluctuations are all smaller than reported before approximately 1973 (perhaps improved chain control, better geometry, shorter baselines, higher SNR, and careful placement of control monitors are impacting these new results).

4. Reports produced by the sponsoring/performing organizations have explained these computations reasonable well and have demonstrated the means to compensate for temporal errors.

Spatial Error. The time-of-arrival of a Loran pulse depends on the electrical properties of the earth's surface over which these signals propagate. These electrical properties include the impedance or conductivity of the ground, the roughness or terrain variations of the surface, the refractive index of the atmosphere at the surface, and the lapse rate or rate of change of

Table 3. Test Results Showing Temporal Fluctuations.

Sponsoring Organization	Results
Canadian Hydrographic Service	TD fluctuations vary from 0.05 to 0.3 µs peak-to-peak over two to three days depending on location with regard to control monitor. Weather fronts produce 0.05 µs TD change
U.S. Coast Guard	Seasonal TD variations 0.06 µs at ft. Communication weekly TD variations are typically 0.035 µs
U.S. Coast Guard	Weekly TD variations are 0.3 µs
U.S. Navy highly	Seasonal TD variations are correlated with refractivity.
Systems Management	Weather fronts reported to induce large TD variations
FAA/TSC	Seasonal variations in Vermont at 0.8 µs peak-to-leak (largest in winter)
U.S. Coast Guard	Seasonal TD variations in St. Marys River Chain are 0.4 µs peak-to-peak and largest in winter. Diurnal TD variations are 0.04 µs peak-to-peak
U.S. Coast Guard	Differential Loran-C errors of 1 µs reduced using Differential Loran-C. 50-foot accuracy demonstrated

refractive index with altitude above the surface. Spatial variations of the transmitted Loran signal are primarily influenced by the nonhomogeneous surface impedance and by variations in terrain elevation.

Temporal Effects. Temporal effects may be produced by time changes on these spatial features but are more easily influenced by the surface refractive index and the lapse rate of the refractive index of the earth's atmosphere, which are known to change diurnally and with changing weather conditions as discussed earlier.

Spatial Effects Testing. One of the objectives of the Loran-C Signal Analysis Harbor Navigation project conducted by the U.S. Coast Guard was to improve the accuracy and control of Loran-C through a better understanding of Loran-C signal characteristics. An important step in achieving this objective was to better define the predictability of the Loran-C signal phase and amplitude characteristics and to explain differences between observed TDs and predicted TDs using current prediction and calibration techniques with emphasis on terrain and surface impedance behavior.

Four groundwave propagation prediction models or techniques have been reviewed and tested against each other and against a carefully controlled experimental database [8]. This work has been instrumental in understanding the behavior or spatial effects on Loran-C. Therefore, the prediction models used to explain the experimental results will be discussed. The four techniques are:

1. *Homogeneous Spherical Earth*--A well researched technique that includes comprehensive published literature.

2. *Millington's*--A semi-empirical technique currently used for system calibration.

3. *Wait's Multisegment Spherical Earth*--A theoretical model to account for inhomogeneous earth.

4. *Integral Equation Solution*--A computer program to calculate signals over irregular inhomogeneous terrain.

The following paragraphs include comparison between Millington and integral equation predictions, and the measured database to better explain the significance of spatial and surface impedance effects on Loran-C signals. Comparisons have also been conducted using the flat-earth homogeneous spherical earth, and Wait's multiple segment techniques in [8] will not be shown here.

Experimental Configuration. Measurements of phase time difference and signal arrival times (TOA) were taken at eight sites over a period of 60 days, as nearly as possible along the Yankee to San Francisco Harbor path, between Searchlight, NV, and Ft. Cronkhite, CA. The main reason for these measurements was to compile a comprehensive experimental database for comparison with predicted results from prediction techniques previously mentioned. Analysis and interpretation of the differences between measured and predicted data were to lead to a better understanding of Loran-C signal characteristics.

The Searchlight/Ft. Cronkhite path was selected for the experiment because of its *extremely variable terrain* and demonstrable history of *short-term weather fluctuations.* The assumption was that irregular terrain and variable surface impedance along the path would produce experimental results that differed significantly from simple model predictions and therefore would provide a database for thoroughly testing models that account for *irregular terrain* and *impedance.*

It was also expected that weather variations typical of the time of year might occur during data collection periods along the path. If large variations in measured data occurred concurrently with significant weather phenomena, then the data could provide additional guidance to improve models of weather produced variations in the prediction codes.

Before proceeding with the experimental results a discussion of modeling techniques used to analyze the test data is in order.

Model Intercomparison. *Classical Techniques.* This idealized technique will not produce phase delay estimates with useful accuracy for irregular paths (such as defined in [8]). However, because the classical technique is embedded in other techniques, the numerical procedures should be considered.

The general classical theory solution results in an infinite series representation for the complex groundwave loss function. The series converges rapidly for long paths but requires many terms for paths less than 100 km in length. Two short-path approximations are available, one for high surface impedance and the other for low surface impedance.

The evaluation of the classical theory determined the required number of terms in the series for a specified path length and level-of-accuracy, and also defined appropriate distances to switch from the accurate series solution to the short-distance approximations [8].

Millington's Technique Compared to Wait's Multiple Segment Technique (MULSEG). Both these techniques account for inhomogeneous impedance along the path. The results produced by these two techniques have been compared for

Table 4. Test Information.

Sponsoring/Performing Organizations	Completion Data	Loran-C Chain	# of Sites	Test Duration	Measurements	Location	Data Interval	Data Sample Size (Approx)	Application	Data Quality (μsec)	Motivation
Canadian Hydrographic Service	1978	Northeast US	3	3 wk	TDW,TDX	Great Lakes Region	100 sec	Oct 80 to Nov 80	Great Lakes Navigation	0.02	Temporal effects and relation to chain control
US Coast Guard	1978	U.S. West Coast	18	10 mo	TDX,TDY	West Coast (Southern Triad)	100 sec	Aug 77 to May 78	Harbor Navigation	0.02	Temporal fluctuation evaluation and means to compensate
US Coast Guard/Magnavox	1977	U.S. East Coast	3	3 mo	TOAN	Fort Wayne, IN Newark, NJ Washington DC	15 min	Feb 77 to April 77	Loran-C System Support	0.02	Cause of Diurnal TD variations
US Coast Guard/Internav	1973	U.S. East Coast	8	2 mo	TDY,TDZ	Delaware River	100 sec	Jul 73 to Aug 73	Harbor Navigation	0.02	Differential Loran-C evaluation
US Navy/Sperry Systems Management	1971	U.S. East Coast	3	1 yr	TDM,TDY	Nantucket, MA Carolina Beach Jupiter, FL	15 min	Oct 65 to Sep 68	Strategic Submarine Navigation	0.01	Potential improvement afforded by propagation corrections
FAA/TSC	1980	Northeast U.S.	3	14 mo	TDW,TDY,TDX	Burlington, Newport, and Rutland, VT	3 hrs	Aug 79 to Oct 80	Civil A/C Navigation	0.1	Seasonal, diurnal variations in TD grid bias
US Coast Guard/TASC	1980	St. Marys River	3	1 yr	TDX,TDY,TDZ	Northern Michigan	15 min	May 79 to May 80	Ore carrier navigation of St. Marys	0.02	Month-to-month TD variations

several hypothetical cases. One example is shown in Figure 1 for a five-segment path. The results are typical of results obtained for a number of other cases [8]. As a result of this comparison, we concluded that the prediction differences are small compared to errors caused by the neglect of terrain variations.

Millington's Technique Compared to the Integral Equation Solution. Results from Millington's technique and the integral equation technique have been compared for two cases: one where terrain effects are important, and one where terrain effects are suppressed. These comparisons were made during the process of comparing experimental and predicted results and are discussed later.

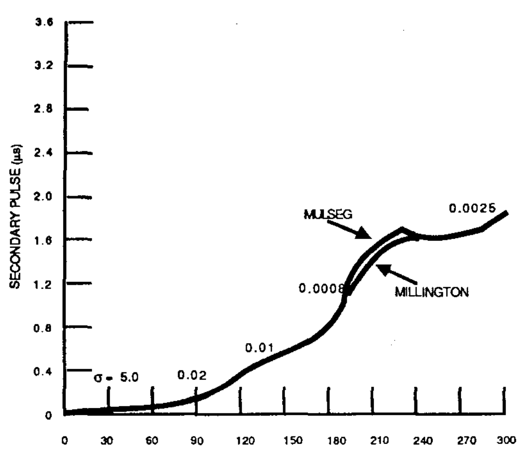

Figure 1. Comparison of MULSEG and Millington for a Five-Segment Path (Sea to Land).

Data Preparation. All methods considered require an accurate definition of geodetic path length as input. Also, all methods currently use a single value for the effective earth radius along the path. The classical approach requires a single value of surface impedance for the entire path. Millington's technique and MULSEG require surface impedance data for as many segments as are required to account for inhomogeneity along the path. The integral equation requires inhomogeneous impedance data for segments along the path and terrain variations relative to a smooth spherical reference.

Path Length. For accurate prediction, path length needs to be determined within a few tens of meters. Phase prediction errors resulting from path length error are approximately 3.3 ns per meter. Accurate size position surveys and geodetic distance calculations using Sodano's technique provided path length accuracy that should limit the phase error to less than 10 ns in this experiment.

Effective Earth Radius. An effective earth radius, a_e (usually larger than the earth's actual radius, a), is used to approximately account for the refractive effects of the lower atmosphere. Approximate relationships defining the effective radius in terms of surface refractive index are provided in [9] and elsewhere. A ratio of a to a_e of 0.85 was used in the calculations reported here.

Surface Impedance. Crude estimates of surface impedance can be obtained from existing surface conductivity maps or from maps providing general surface and topographic features. These estimates are usually adequate for Millington's technique, where the typical application is to adjust original estimates of surface impedance to match selected experimental data before using the surface impedance values to make predictions.

To make more accurate predictions, surface impedance is estimated using best available data defining geophysical and electrical properties of surface and subsurface layers. The availability and detail of these data depend strongly on location.

Figure 2 shows (thin lines) the best estimate of the surface impedance along the propagation path, using geophysical data from the U.S. Geological Service and the California and Nevada Bureaus of Mines. Data were obtained at various locations for one, two, three, or four layers and processed using a multilayer surface impedance model. The details of the data and processing are provided in [9]. Figure 2 shows amplitude data only. the surface impedance phase in all cases was very close to 45 degrees.

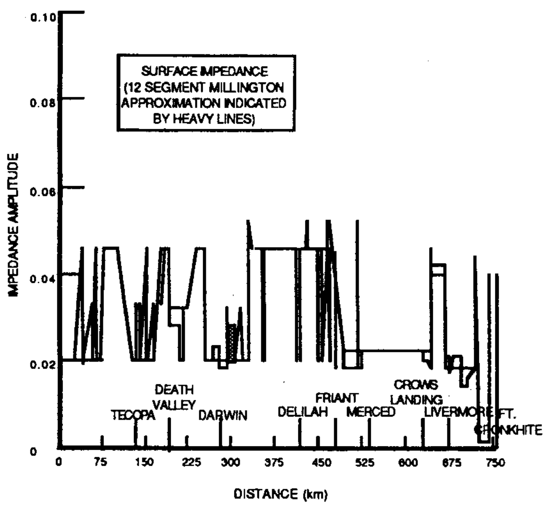

Figure 2. Approximation to the Surface Impedance for a Millington Calculation.

Also shown on Figure 2 (heavy lines) is a twelve-segment approximation that was used later in comparing Millington's technique calculations to the integral equation results.

Terrain Data. Terrain data are required only for the integral equation approach. For many areas of the world, digitized data are available that provide more detailed definition of terrain variation than can be used in the computations. Proper automation of data search and smoothing routines can reduce this data preparation task to a reasonable computer effort.

In the experiment described here, digitized data were not available over the entire path and terrain variations were obtained from the most detailed topographic maps available. Digitizing the data from the maps and subsequent verification of the data took 2 to 3 manweeks. Data preparation for the integral equation technique can be a formidable task unless a digitized database and associated software to scan and select appropriate data are available.

The original data defining terrain along the propagation path are plotted in Figure 3. The detail shown in the figure is more than is required in the integration equation and some data smoothing was applied. Phase predictions shown later used terrain data that were smoothed by averaging data over a 3-km interval.

Comparison Between Predictions and Experimental Data. One primary goal of this effort was to compare pure predictions (i.e., no tuning of input data using measured signal phase or amplitude data) with measured data. Figure 3 shows the predicted secondary phase (signal phase lag in excess of the free space phase lag) for the integral equation results and Millington's technique results. The integral equation results were obtained using the detailed impedance estimates shown in Figure 2 and the terrain variations shown in Figure 3 (after smoothing). The Millington results were obtained using the twelve-segment approximation to the detailed impedance estimates shown on Figure 2.

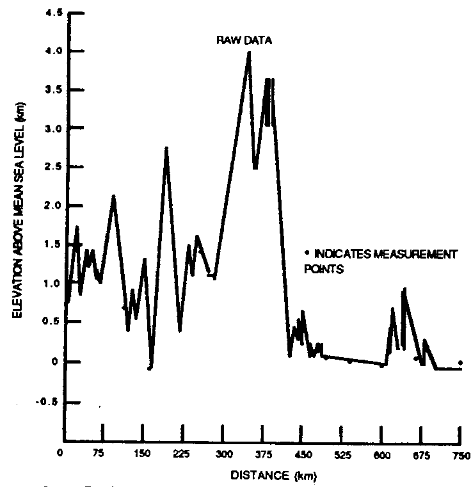

Figure 3. Original Worst Case Path Terrain Data.

The experimental results are shown on Figure 4 by the bars above the measurement sites. The length of the bar indicates approximate bounds on experimental error as defined earlier. Since only relative (not absolute) secondary phase measurements were obtained, a reference point for the data must be selected. In this comparison we chose to equate predicted and measured secondary phase at Tecopa, the site nearest Searchlight. The origin could also be selected to minimize mean rms difference between measured and predicted values. However, it can be observed from Figure 4 that no origin selection can be made that will remove all large prediction and measurement differences. The maximum difference as shown on the figure between integral equation predictions and measurements is about 0.5 μs.

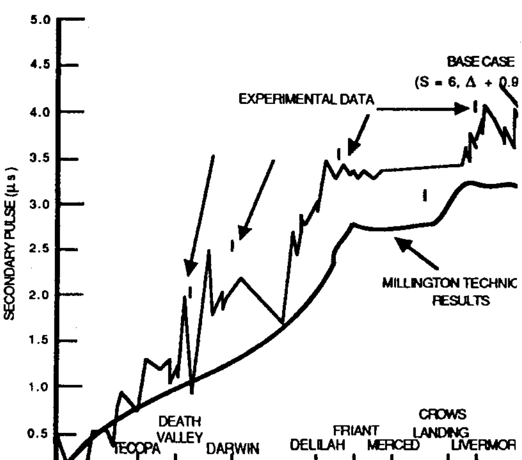

Figure 4. Comparison between the integral equation and Millington's technique results.

It can also be noted from Figure 4 that the integral equation results produce better agreement with the measured data than Millington's results (i.e., inclusion of the terrain effects provides an apparent improvement).

To verify that the differences between the Millington and integral equation predictions are due to terrain effects, a second calculation was performed with the integral equation, but with terrain effects suppressed. These results, with Millington's technique results repeated, are shown in Figure 5. The agreement between predictions is very good and provides confidence in the computational models. The results provide further verification that Millington's technique is useful when terrain effects are minimal.

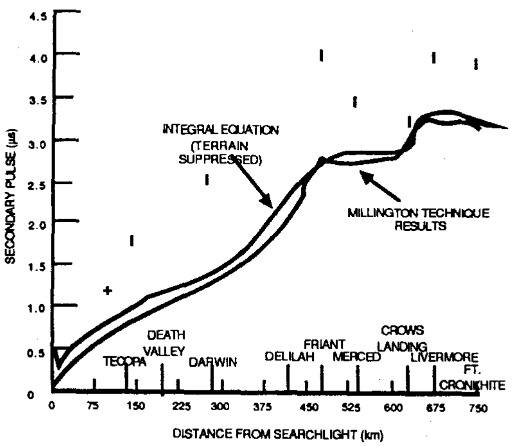

Figure 5. Comparison of Millington's Technique with the Integral Equation Technique (with Terrain Variations Suppressed).

Additional Comparison. Two additional sets of calculations were performed to provide a crude measure of sensitivity of predicted versus measurement difference to input parameters. We believe that terrain data is adequately defined and input value errors would most likely be the surface impedance definition. Figure 6 shows the original integral equation predictions, the measurements, and a new integral equation prediction made with the conductivity of all segments along the path decreased by a factor of 2 (this increases the surface impedance by approximately a factor of 2). Note that the two predictions now almost bracket the measured data. It is clear that selective adjustment of the conductivity of different segments by a factor of approximately 2 could produce good agreement between measured and predicted values. These adjustments were not performed because of the computer costs for repetitive calculations with the integral equation program.

Also shown on Figure 6 by the filled-in circles are results obtained with Millington's technique with the impedance of the twelve-segment approximation adjusted to approximately minimize the rms difference between Millington's predictions and measurements. Impedance values had to be generally increased to compensate for terrain effects and/or errors in the original impedance values. The results obtained by varying the impedance values indicate that the impedance values need to be known much better than a factor of 2 for accurate (100 ns) predictions over long overland paths.

Clearly it has been demonstrated that deterministic prediction techniques alone are not adequate for precise navigation. However, a careful balance between predictions and measured data (empirical models) may have some merit.

Predicted Weather Effects. Except for one isolated incident, no significant weather-produced fluctuations were observed during the West Coast experiments. As a result, little emphasis was placed on prediction of weather effects. One example of predicted weather-produced fluctuations was produced using surface weather data from a station (Reno, NV) near the Master transmitter. The atmospheric pressure in millibars, the temperature and dew point temperature were taken at Reno. These values were used to compute the surface refractive index and a corresponding value of effective earth radius. Phase fluctuations, which are the sum of the primary and secondary phase fluctuations, were computed for path lengths of 100, 300, 500, and 700 km.

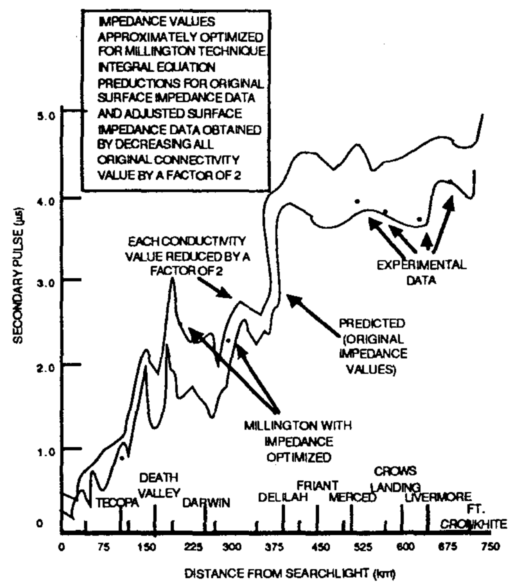

Figure 6. Comparison of Measurement of Millington and Integral Equation Predictions After Surface Impedance Adjustment.

The predicted phase fluctuations were small, showing a maximum value of 15 ns. These values agree in order of magnitude with the experimental observations during the Loran-C Signal Analysis West Coast Experiment with one exception, where it is postulated that a larger change was produced as a result of precipitation-induced surface impedance changes. A discussion of this exceptional case was provided in [10].

Conclusions

Detailed conclusions and recommendations are provided in [8]. A summary of the discussion in [8] is provided below.

1. For a smooth, inhomogeneous earth, Millington's technique and Wait's multiple segment technique produce nearly identical results. Therefore, Millington's technique should be used in preference to Wait's because of its greater simplicity and shorter running time.

2. Millington's technique and the integral equation technique give nearly identical results for a path with highly inhomogeneous impedance when the terrain variations are suppressed for the integral equation calculations.

3. The integral equation calculations show that both terrain and surface impedance variations are important in predicting

secondary phase. Our numerical computations indicated that the terrain can be defined with sufficient accuracy with data points spaced at approximately an integration step size of 1 km. Our experimental observations and predictions indicate that to obtain prediction accuracy on the order of 100 ns or better, the surface impedance uncertainty must be much less than a factor of 2 for overland paths.

4. The effect of terrain variations (in this case elevations greater than one wavelength above the mean geoid) was to increase the secondary phase. Thus, matching calibration data with impedance variations alone requires higher than actual impedance values to compensate for the terrain effects.

5. Data preparation for the integral equation method is a formidable task. The hand preparation of the data for the worst-case path required an effort of about 1 man month. Digital terrain data tapes for the path were not available. Hand preparation of data for a coverage area would not be practical.

6. The highly variable terrain and surface impedance along the worst-case path and the differences between predicted and measured values indicate the need for more closely spaced measurement points to adequately calibrate phase change along the overland portion of the path from an experimental standpoint. On the other hand, measurements made beyond the region of major terrain variations can be used to compensate for the integrated effects of terrain-induced fluctuations. A good example is the match between measurements and predictions at Ft. Cronkhite shown in Figure 4. Ft. Cronkhite is the last measurement point along the path and is located in San Francisco Harbor.

7. Compensation techniques exist for each type (temporal and/or spatial) of error causing Loran-C to be a ns precision system.

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Use of Simulated Atmospheric Noise in the Calibration and Characterization of LORAN-C Receivers

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Abstract

The LF band used for LORAN-C navigation is susceptible to the effects of atmospheric noise. The two main components are background Gaussian noise and impulsive lightning noise. As the FAA continues in its efforts to incorporate LORAN-C into the National Airspace System for use as a supplementary navigation aid for nonprecision approaches it is necessary to develop a better understanding of the effect of atmospheric noise on the accuracy, availability, and integrity of LORAN-C. A simulation facility including the capability to create three different noise models, has been developed which provides a controlled, repeatable and realistic noise environment for the calibration and testing of LORAN receivers. This paper describes the noise models, how they are created, calibrated and used in the evaluation of LORAN receivers. In addition, the Center has analyzed how current calibration methods and performance requirements influence the design of receivers.

1. Introduction

Natural noise in the LF band at approximately 100 kHz consists of two components: 1) a low level white Gaussian component attributable to the background continuum of signals and 2) a high dynamic range non-stationary impulsive component due to the noise from individual lightning strokes which are capable of propagating great distances. One of the main works in characterizing atmospheric noise at LF was the 1972 doctoral dissertation of Donald Feldman at MIT [1]. Feldman described the design of an instrumentation system to measure the key statistics of the VLF and LF noise process at several frequencies. Data were collected during the summer of 1971. Three noise scenarios were considered in the analysis: 1) quiet conditions, in which the impulsive component due to individual lightning events was relatively low, 2) tropical noise conditions typical of those in the summer at middle latitudes in which impulsive lightning noise from numerous thunderstorms is propagating over long distances, but without local activity, and 3) frontal conditions in which lightning is occurring at close range associated with a squall line or local thunderstorm.

Measurements were made at 14, 65, and 80 kHz. These measurements provided the basis for the comparison between noise models and data. Feldman characterized the noise not only in terms of first order statistics and probability density functions but in terms of temporal correlation and frequency correlation properties. Feldman then searched for a mathematical structure which provided the best match to the observed data over the three scenarios. His analysis of the data indicated that the basic mathematical structure first discussed by Kapp and Kurz [3], which consisted of two components, one multiplicative to simulate the lightning, and an additive background component, provided a good starting point for a canonical atmospheric noise model. The general form of the Kapp and Kurz model is given by

$$y(t) = n_1(t) + A(t)n_2(t) \tag{1}$$

where $n_1(t)$ represents the Gaussian background component, $A(t)$ is a time varying multiplicative intensity function, and $n_2(t)$ is a second independent Gaussian noise source which is modulated by the intensity function. The multiplicative form for the impulsive noise component was first described by Hall [2] and is referred to as the "Hall Component". Hall proposed to generate the multiplicative noise component $A(t)$ from the inverse of a Chi process with m degrees of freedom given in equation (2) as

$$A(t) = \left[\sum_{i=1}^{m} b_i^2\right]^{-0.5} \tag{2}$$

where $b_i(t)$ are samples from statistically independent Gaussian low pass processes.

Feldman showed that a noise model based solely on the Hall model without the additive Gaussian component provided a relatively good representation of the observed noise probability density function when there is significant local lightning activity (frontal scenario); however, it tended to lose accuracy as the level of local lightning activity decreased. When the level of activity was low, the background Gaussian noise process became more significant. While the model suggested by equation (1) did match the probability density of the noise observed by Feldman, there was a significant difference in the time correlation properties of the channel between the measured and modeled noise processes.

To improve accuracy of the time structure of the new model, Feldman proposed that the "Hall" component of the noise should be randomly switched on and off to simulate the impulsive nature of lightning induced noise. The improved channel noise model attributed to Feldman consists of three independent components, the $X(t)$ switching function, the $A(t)n_2(t)$ "Hall" component, and the background additive white Gaussian noise term $n_1(t)$. The form of the combined Feldman/Hall/Kapp noise model implemented is given by equation (3) as

$$y(t) = n_1(t) + X(t)A(t)n_2(t) \tag{3}$$

where X(t) is a two state [0,1] random process whose purpose is to switch on the "Hall component" for short periods of time to simulate the impulsive nature of lightning noise. The processes X(t) combined with A(t) provides additional degrees of freedom to synthesize the complicated time structure of lightning-induced noise. The times of occurrence, duration, and intensity of noise bursts are random and non-stationary. The $n_1(t)$ and $n_2(t)$ are conventional normal $N(0,\sigma)$ random noise processes. A model of this form lends itself readily to both computer and real time hardware implementations using conventional uniform and normal random variables as the basis.

The Feldman/Kapp/Hall model (3) generates the switching function X(t) from a Markov-Markov process. The process X(t) is a two-state function with states "0" corresponding to off and "1" corresponding to on. Two transitions are associated with this Markov process: the transition from the "0" ->"1" and the transition from the "1" ->"0". For a generalized Markov process, the times for the transitions 0->1 and 1->0 are generated from independent Poisson processes (exponentially distributed transition times). Let λ_{01} and λ_{10} be the Poisson parameters for the 0->1 and 1->0 transitions respectively. For a Poisson random variable, the probability that the transition time T exceeds t_{next} is given by

$$P(T>t_{next}) = e^{-\lambda t_{next}} u(t_{next}) \qquad (4)$$

where λ is the Poisson parameter associated with the process and u(t) is the well known unit step function. For a first order Markov process, the transition parameters would be constant. For the double Markov process used in the Feldman noise model, the transition parameter λ_{01} is drawn from an independent Poisson random process. The parameter λ_{10} is constant. The random nature of the first parameter provides the non-stationary time structure of the impulsive noise. Figure 1 redrawn from Feldman shows how the model in equation (3) can be synthesized.

The first step in the synthesis of atmospheric noise is to generate the X(t) switching function. This function is double Markov with transition parameters λ_{01} and λ_{10}. X(t) in the "1" state takes on value 1 while in the "0" state it is 0 indicating that the impulsive component is off. The parameter λ_{10} is a constant and is chosen to synthesize the short term time correlation of A(t). A simple transformation given in equation (5) is used to map a uniform U[0,1] random variable into an exponentially distributed Poisson random variable. Feldman observed that λ_{10}=850 Hz provides good correlation to experimental data.

The parameter λ_{01} which drives the 0->1 state transition is itself stochastic and is used to control the time intensity of the non-Gaussian excursions of A(t). In the Feldman model, the parameter λ_{01} is generated from a second independent two-state Markov process W(t) in which the "1" state corresponds to the parameter $P=p_x^f$ and the "0" state corresponds to the parameter $P= p_x^s$ in the Feldman thesis. The two-state Markov process W(t) has two transition parameters μ_{01} and μ_{10}. The μ_{10} rate is constant and is chosen to provide long time correlation associated with multiple lightning discharges. The μ_{01} rate is constant and is chosen to simulate the intensity of the noise switching function. Thus the Markov process W(t) drives a second Markov process X(t) leading to the nomenclature Markov-Markov process. The transition times $t_{next_{10}}$ and $t_{next_{01}}$ for the W(t) process are generated by independent Poisson processes. The mathematics of Markov processes, though complicated, are well developed. Feldman presents an analysis of the probability density function $f_y(y)$ based on the X(t), W(t), and A(t) processes.

Having generated the random numbers for the W(t) random process which creates the λ_{01} transition parameter, X(t) is generated. The binary Markov process X(t) is used to multiply (or switch on and off) the impulsive Gaussian noise component $A(t)n_2(t)$. Both the occurrence and duration of X(t) are independent Poisson random processes. Each time X(t) switches from the 0->1, a new multiplicative noise term A(t) is generated. The A(t) process is synthesized according to inverse Chi statistics shown in equation (2) by taking m independent N(0,1) Gaussian random variables, squaring the output, and summing. We then take the square root and the inverse to produce the A(t) scale factor. The function is scaled by an intensity parameter to complete the calculation. The process A(t) is used to scale an independent Gaussian noise source to form the "Hall" component. The "Hall" component is summed with an independent Gaussian noise source $n_1(t)$ to form the composite atmospheric noise output y(t). The percentage of power which resides in the Hall and background noise components can be adjusted parametrically.

The C60b Atmospheric Noise Model

The current standard "atmospheric noise" model used for testing LORAN-C receivers is described in FAA Technical Standard Order TSO-C60b. It can be viewed as a distant cousin of the more realistic and complicated Feldman/Hall/Kapp model. Like the Feldman noise model, the C60b "atmospheric noise" model consists of two independent components, one designed to simulate the background noise and one designed to represent the effect of impulsive lightning bursts in a narrow band system. The form of the noise model is given by equation (5) as

$$y_{C60b}(t) = P(t)\sin(2\pi 100\text{kHz}\, t + \phi) + n(t) \qquad (5)$$

where n(t) is a low level bandpass Gaussian noise component. P(t) is a fixed amplitude train of 30 msec pulses which occur randomly according to first order Poisson statistics with an average rate of 50 pulses per second, and $\sin(2\pi 100\text{kHz}\ t + \phi)$ represents the carrier frequency of the LORAN-C signal. The random variable ϕ is uniform over $[0,2\pi]$ and randomizes the phase of the pulses. Thus after complex baseband demodulation, the component looks like a complex fixed amplitude pulse train. According to the specifications, 15.85 percent of the noise power is in a Gaussian component which has been filtered by a simple LC filter with 30 kHz 3 dB bandwidth and 100 kHz center frequency. The remaining 84.15 percent of the total noise power resides in the impulsive component. The ratio of the total power in the signal to that in the Gaussian component is

8 dB. The rms amplitude of the sine wave is 59.5 times that of the rms Gaussian noise component. The ratio of the power in the impulsive to Gaussian components is about 5 dB. The significance of these numbers will be discussed subsequently

The C60b atmospheric noise model does not simulate the variations of the amplitude structure of the impulsive component or its time structure which are characteristic of real atmospheric noise. But it is one step more sophisticated than a simple additive Gaussian noise process in that it does have a random impulse-like component. Because the amplitudes of the pulses are fixed, the probability density function of the C60b "atmospheric noise" does not match the atmospheric noise data collected by Feldman.

2 Hardware Implementations of Noise Models

The first step in developing a more realistic technique for calibrating, characterizing, and evaluating LORAN receiver performance is to create real time implementations of the different noise models: 1) simple Gaussian noise, 2) the atmospheric noise model described in TSO-C60b and finally 3) an advanced noise model synthesized from the Feldman thesis. These become external noise inputs to a LORAN-C simulator which resides at the Volpe Center. Performance of LORAN receivers at constant signal-to-noise ratio using the various noise models can be evaluated and the difference between the way they perform in the presence of different noise conditions can be observed.

The basic approach used for implementing the noise models was to build the noise simulator from off-the-shelf equipment which could be controlled by computer to minimize both total cost and implementation time. The key element of the noise simulator is an HP-8904 waveform synthesizer which consists of four internal waveform synthesizers along with internal multipliers and summers. The instrument has the capability to synthesize Gaussian noise in addition to classic waveforms such as sinusoid, triangle, square, and pulses, and can be controlled via the IEEE-488 bus, keyboard, or a special external bus. Figure 2 shows the basic architecture of the LORAN-C evaluation system.

To simplify the design of the software for the control computer, a technique known as stored channel simulation was used for generation of the switching times for X(t), and for A(t). Using this technique, all times and coefficients are generated in advance and stored on disk prior to commencing the simulation. This has two advantages: 1) the exact conditions of the simulation are repeatable and 2) the real time tasks of the computer are limited to reading from memory the transition parameters and accurately controlling the times of the transitions. A totally real time simulation would have required a sophisticated multi-tasking, multi-layer operating system and would have significantly added to the cost and development time of the model with little additional benefit.

Synthesizing the Feldman/Hall/Kapp noise model in the waveform generator required all 16 of the fast hop addresses to represent the A(t) values. This becomes the amplitude scaling factor of one Gaussian noise source. Fifteen of the 16 waveform channels are programmed to Gaussian noise with different values while the 0 address is reserved for the off state. A second Gaussian noise source provides the background component. While only 4-bit quantization of the A(t) values is provided, increased dynamic range is provided by using logarithmic quantization. Using this technique a 40 dB dynamic range on A(t) is provided. The maximum dynamic range is limited by that of the synthesizer. Memory (16 MBytes) was added to the high performance 33 MHz 80486-based computer to allow simulations of 1 hour duration without repetition of the sequence.

The Feldman thesis calculates parameters used for creating the various noise scenarios including quiet, tropical, and frontal conditions. Parameters used in the simulating the various conditions are presented in Table 1.

Calibration of the model consisted of calibration of timing loops within the control computer and of measuring the total RMS power within the 30 kHz standard filter using a true rms meter. For the Feldman noise models, the ratio of the power in the Gaussian component to the impulsive component varied from scenario to scenario. Using the tropical noise parameters from Table 1, the ratio was measured at approximately -17 dB so that a greater portion of the total power resides within the impulsive component than for the C60b noise model. For the frontal noise parameters the ratio (magnitude) was on the order of 20-23 dB. When evaluating noise one must keep in mind both the total absolute noise power and the ratio of the noise in the two components. For each of the noise scenarios and different noise models, calibrations to absolute rms signal amplitude (dBμv) within the filter bandwidth at the output of the LORAN simulator were developed. These are being used in the evaluation of different receivers.

Table 1. Parameters used in Different Noise Scenarios

Condition	σ	M	$p_{x}f$	$p_{x}s$	Pw	μ_{10}	λ_{10}
Tropical	1.26	1	0.99	0.27	0.66	0.6	850
Frontal	3.50	1	0.99	0.15	0.89	0.2	850
Quiet-night	1.34	2	0.75	0.25	0.50	1.0	850
Quiet	2.22	2	0.11	0.11	xxx	xxx	850

Figure 4 shows in the time domain typical plots of the noise waveform for the different noise models. In each of the figures, the amplitudes and time scales of the digital oscilloscope were set constant and the rms noise power in the 30 kHz filter bandwidth was also set constant. Figure 4a plots a bandpass Gaussian component, Figure 4b plots a TSO C-60b atmospheric noise output in which the very narrow pulses of carrier are observed and Figure 4c plots a typical Feldman atmospheric noise waveform in which different amplitude and time duration bursts of lightning noise are observed. Note in the figure that some of the noise bursts are very short duration while others are relatively long duration.

3 Calibrating and Measuring Signal-to-Noise Ratio

Definition of Signal-to-Noise Ratio

TSO-C60b, which is the standard for certifying LORAN-C receivers for nonprecision approach, describes the precise procedure for measuring signal-to-noise ratio (SNR). Noise power is calculated from the true rms voltage measured at the output of the 30 kHz bandpass filter. Signal power is determined by 1) determining the amplitude at the standard sampling point or 2) adjusting a sinusoid until it has the same amplitude as the peak of the LORAN signal and then scaling by 0.506 and measuring the rms value.

LORAN manufacturers calculate SNR in a variety of different ways and for this reason in this and all subsequent analysis, we refer back to this technique as establishing the true SNR for comparison to that calculated by different receivers.

The "Infamous" 8 dB Noise Scaling Factor

Feldman showed that depending on the noise scenario (*i.e.,* tropical, frontal, quiet, etc.) the ratio of the noise power in the impulsive component to that in the background Gaussian component could range from 5-20 dB or more. Designers of LORAN-C navigation receivers have incorporated sophisticated nonlinear signal processing to mitigate primarily impulsive noise. A number of nonlinear signal processing techniques are used including clipping, noise blanking or hole punching, hard limiting, and other proprietary techniques: Kalman filtering is also used.

Feldman showed that in a theoretical sense, either hard limiting or idealized nonlinear filtering could eliminate most of the effect of impulsive noise. It was shown that the improvement due to the nonlinear processing could range from 5 to 20 dB over ordinary Gaussian noise with the same power. Looking at the figures in his thesis, 8 dB appears to be a median value. This 8 dB scaling factor has taken on almost mythical proportions. Recall that the ratio of the total noise power to the background component in the C60b atmospheric noise model is also 8 dB.

The certification procedure which is based on being able to detect BLINK or signal outage within 10 seconds at a minimum SNR allows LORAN manufacturers to test their receivers using one of two different noise models 1) the TSO-60b atmospheric noise model, or 2) Gaussian noise in which they are allowed to add 8 dB to the measured SNR. The premise of the 8 dB scaling on the Gaussian noise is as follows: Assume that the C60b atmospheric noise is used with approximately 84% of the noise power in the impulsive component and 16% in the background Gaussian component. An ideal receiver is assumed capable of removing completely the effect of the spikes so that only the background component is there. Now in theory, this background Gaussian component, 8 dB below the true rms level of the noise, represents the effective noise power and manufacturers can use this value. Gaussian noise sources are inexpensive and readily available, unlike the more specialized atmospheric noise models.

Any receiver which does anything less than perfect removal of the spike noise benefits by using the second (Gaussian + 8 dB) noise technique rather than the atmospheric noise model. Advanced receiver techniques are designed to eliminate the high dynamic range excursions due to the impulsive lightning noise. Thus depending on the nature and percentage of noise power which is impulsive and its dynamic range, much of the noise power could be eliminated by the receiver processing. Some techniques come closer to removing 100% of the spike noise than others. The greater the percentage and the more dynamic the nature of the impulsive noise, the greater the benefit of the sophisticated signal processing.

4 Observations on LORAN Receiver Performance with Different Noise Models

Signal-to-noise ratio is a commonly used measure of LORAN performance, especially in the process of certification of aviation receivers. To illustrate how different noise models and different ways of computing SNR have different effects, in terms of the SNR presented to the user, two receivers were tested using different noise models. Brand A was designed specifically for aviation applications and computes the signal to noise quality measure at the output of its non-linear processing circuits which tends to greatly mitigate the effect of impulsive noise. Signal-to-noise ratio is calibrated using Gaussian noise at the output of the hard limiter. It is a true rms estimate only for Gaussian noise. Brand B is a modified marine receiver which computes signal-to-noise ratio (SNR) using a true rms noise estimate taken at times when the signal is not present and from the estimated signal strength in each of the channels. The SNR is therefore computed from the dB signal level minus the dB noise estimate and represents an estimate of the true rms SNR. This is a true estimate of the snr and does not take into consideration

Both receivers were connected to the LORAN simulator. Feldman atmospheric noise, TSO-C60b atmospheric noise, or Gaussian noise were input to the external noise channel of the simulator. Data logging devices were connected to both receivers to access signal strength in three channels M,W, and X, and a true rms noise estimate at the output of the antenna filter, and the receiver calculated SNR in each of the three channels.

Figure 5 compares measured signal-to-noise ratios for both Brands A and B for the three different noise models (Feldman, Gaussian, and TSO-C60b), at the output of the M channel. When the noise source is purely Gaussian, the SNR values presented by Brand B (true rms estimate) and Brand A (processed but calibrated using Gaussian noise) appear close to identical as expected. Signal level estimates from the receivers were within ±2 dB of the calibrated output of the LORAN simulator.

With the C60B noise, Brand A's processed SNR was approximately 4-5 dB greater than that computed using true rms SNR as measured by the Brand B. This indicated that Brand A was removing much but not all of the effect of the spike noise. The SNR improvement factor was on the order of 5 dB rather than 8 dB. Note that because of this it would be in the manufacturer's best interest to use Gaussian + 8 dB rather than the TSO-C60b atmospheric noise model.

With the Feldman type noise using the tropical scenario in Table 1, the ratio of the background noise to total noise power was on the order of -17 dB. The SNR improvement observed on the processed SNR of Brand A ranged from about 8-16 dB at high signal-to-noise ratios, indicating that the nonlinear processing was providing significant improvement.

In the next experiment, the scenario was changed from tropical to frontal in Table 1 and the SNR difference between the Brand B and Brand A was calculated. In this mode the improvement was greater by several dB since the ratio of the background noise to total noise power was reduced less than -20 dB.

The next experiment used the tropical scenario and gradually increased the background noise component. Since the Gaussian component was very small relative to the total noise power, small increases (6-12 dB) had little effect on the total noise power. The SNR measured in Brand B changed little. The SNR measured on Brand A degraded by approximately 6-8 dB and began to approach that of the Brand B as the Gaussian noise power was increased.

This raises an interesting question. Many manufacturers use Gaussian noise to evaluate their receivers since it is very simple to generate. Most read the C60b specification as allowing them to add 8 dB to the SNR based on the assumption that the impulsive component could be totally removed. While using the Gaussian noise might actually represent a worst case with the sophisticated non-linear signal processing, the changing of the processed SNR by 8 dB would only be valid if 1) their receiver were capable of removing the *entire* effect of spike noise and 2) the ratio of the power in the background noise to the total noise is 8 dB. If the mix is different, the results will be different. The more realistic atmospheric noise model would greatly benefit the more sophisticated receiver designs.

5 Conclusions

In this phase of the ongoing effort we were successful in implementing the Feldman noise model in real time, and in conducting realistic tests on selected LORAN receivers. This provides us a tool with which to characterize LORAN performance more accurately. Several recommendations become clear in light of the analysis to date.

1) The C60b specification should include effects of insertion loss in the description of the filter used for calibrating signal to noise ratio.

2). In all tests, signal-to-noise ratio should be calibrated carefully externally using the definition in TSO-C60b rather than internally using the estimates of the receivers.

3) With the current atmospheric noise model in C60b, there is no incentive for manufacturers to elect the atmospheric noise model. In fact, it tends to punish the more sophisticated algorithms by allowing manufacturers to assume 100% spike removal (this is what is done when Gaussian + 8 dB is used).

4) A more realistic noise model which provides both time- and amplitude-varying impulse noise would provide a more accurate assessment of LORAN performance and would tend to encourage manufacturers with novel advanced signal processing techniques which can remove a greater portion of the effects of impulsive noise. Use of a model of this type which can be synthesized with relative ease will show the sophistication of the different design.

5) The use of the Gaussian + 8 dB model should be reconsidered.

6) Depending on the robustness of the individual algorithms, receiver manufacturers should be able to set their thresholds at which they will flag results as not reliable.

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2. Hall, H.M., "A new model for Impulsive Phenomena: Application to Atmospheric-Noise Communication Channels", Stanford Electronics Laboratory Report SEL-66-052, AD-648-650, August 1966.

3. Kapp, J. and L. Kurz, "Performance of Two suboptimum detectors and signal selection in Gaussian and Impulsive Noise", Proc Seventh Allerton Conference on Circuits and System Theory, 459-465, IEEE, New York, 1969.

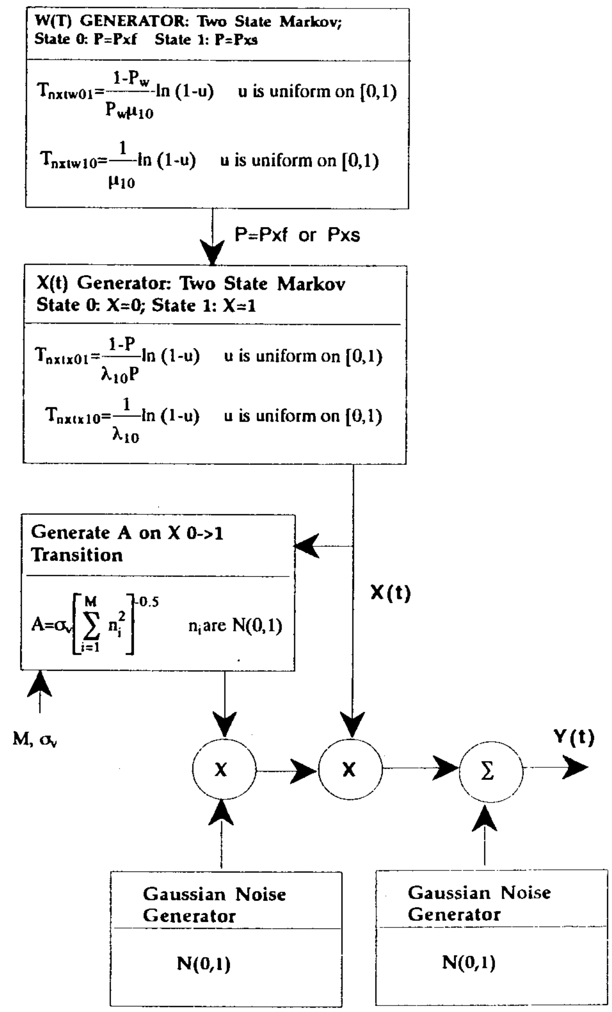

Figure 1. Generator for Feldman/Hall/Kapp Noise Model

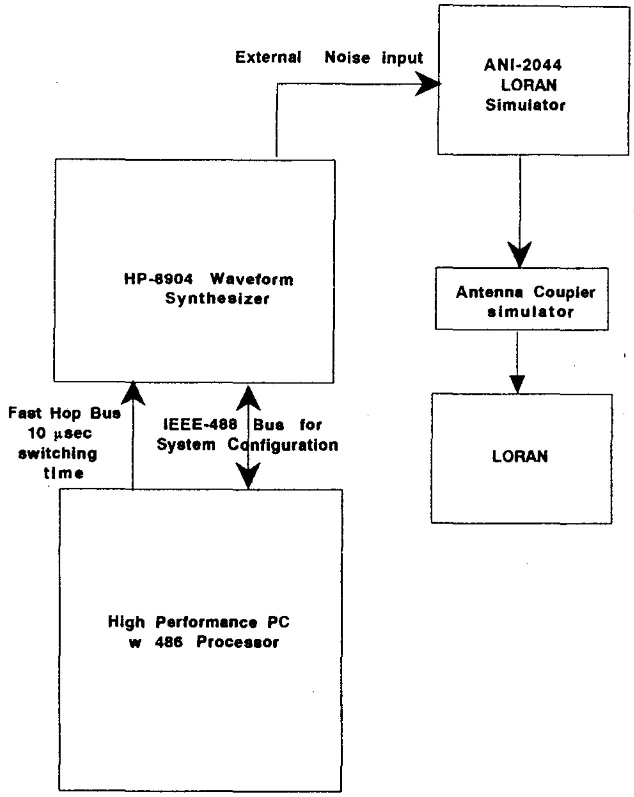

Figure 2. Top level diagram showing equipment used in noise simulator

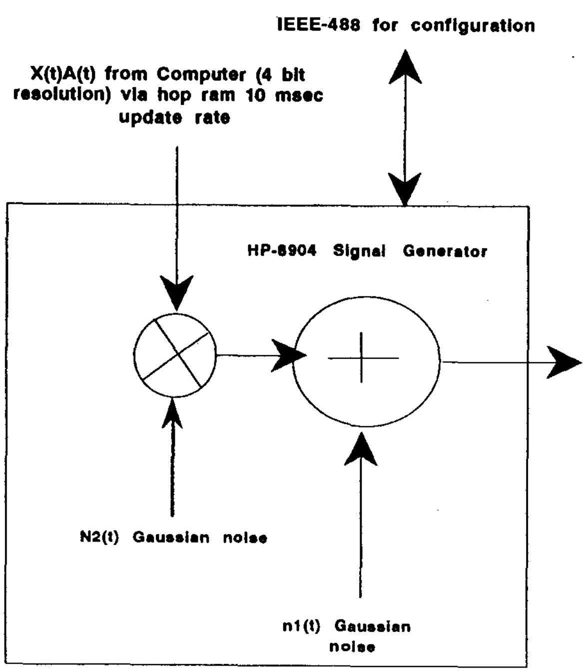

Figure 3. Use of the HP-8904 Waveform Synthesizer for generating both Feldman and C60b noise models

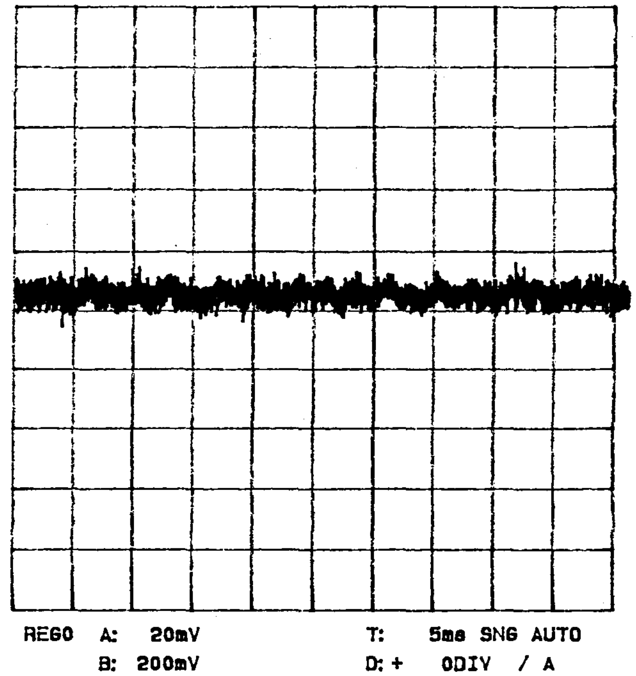

Figure 4a. Bandlimited Gaussian Noise

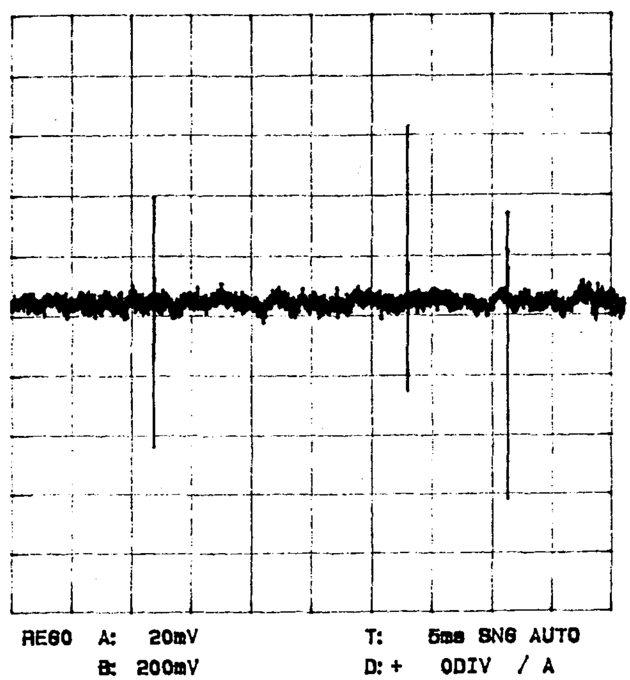

Figure 4b Bandlimited C60b Atmospheric Noise

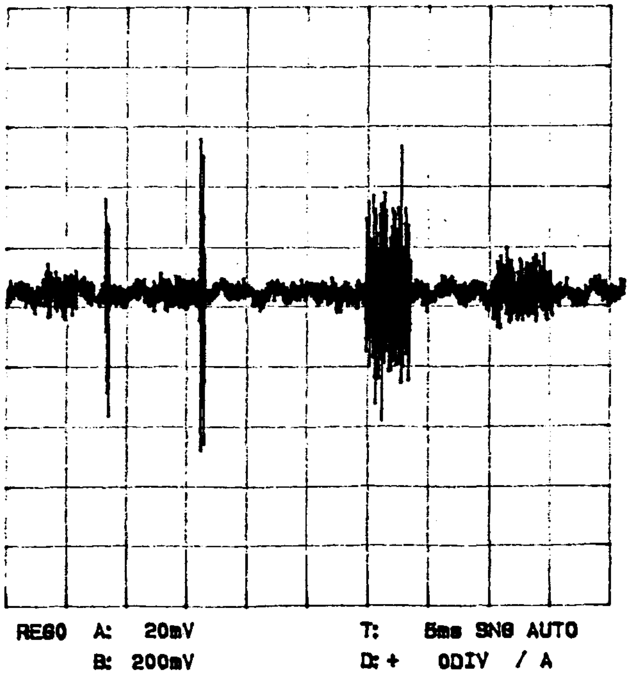

Figure 4c. Bandlimited Feldman Noise

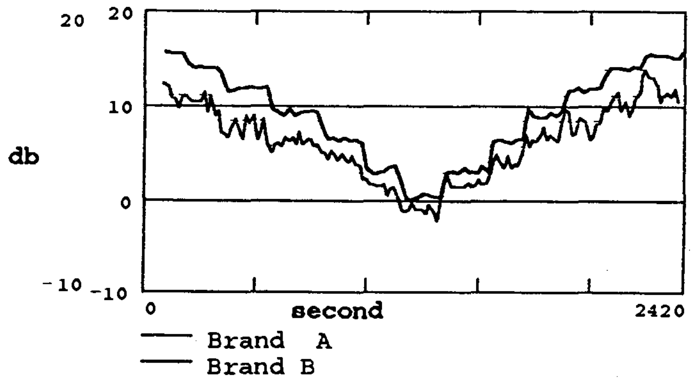

Figure 5b. SNR vs time for C60b Atmospheric Noise

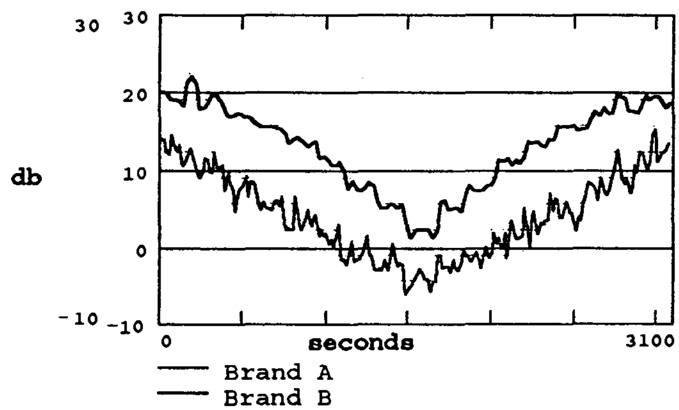

Figure 5c. SNR vs time for Feldman Noise

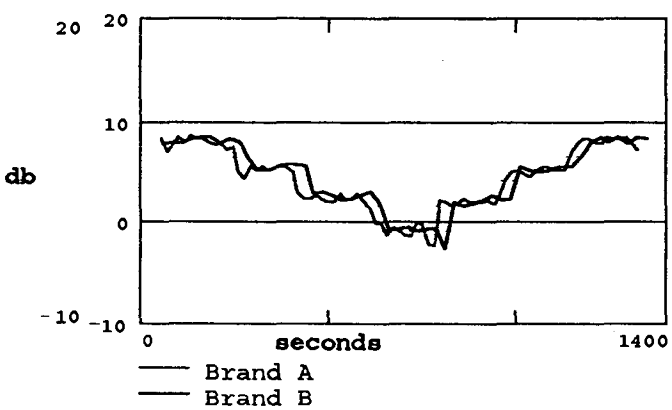

Figure 5a. SNR vs time for Gaussian Noise

SESSION K

Integrated Systems

AN ECONOMIC IMPLEMENTATION OF A COMBINED LORAN/GPS RECEIVER

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Abstract

Sharing a large part of the mechanical and electrical cost of the set allows a combined LORAN/GPS to cost little more than a GPS set. Additionally, the powerful CPU and accurate reference oscillator, needed for GPS, allow a very high performance LORAN function.

From the starting point of a very economical GPS design, the extensions for LORAN are outlined, being solely antenna, preamp and filter for the LORAN signal, and a switch to select GPS or LORAN signals in the baseband gain path.

The extended algorithms for noise reduction by long term correlation are discussed, made feasible by the accurate clocks and powerful CPU.

The main benefit of the combined set is to cover outages in each system, so the two functions must not be interdependent. However access to a single GPS satellite allows clock calibration for LORAN, and range/range working.

Introduction

The combined LORAN GPS set originates from three major requirements....lack of console space in the vessel, the requirement of fishermen to preserve LORAN derived positions, and a desire to move to the latest and greatest (GPS) while not entirely trusting its availability, so wishing to remain with the tried and tested LORAN.

The console space argu ment is a lot deeper than it appears, as it saves the need to learn another set of commands and buttons, and saves on installation costs

The economies

The economies are in a single case, display, controls, power supply, whatever the implementation. Additionally, where the GPS and LORAN implementations are sympathetic, part of the radio circuitry, the A/D converters, the reference oscillators and the processor can all be shared, completely if the system, is time multiplexed, or partially if LORAN and GPS run simultaneously.

The cross benefits

The cross-benefits of combined set are several. At the simplest, if either system is operating, the other can have a good estimation of initial position without searching. Additionally, the application of a 32-bit processor allows greatly enhanced LORAN performance, as does the accurate TCXO, and when the GPS is running, the 0.1ppm clock, and the 100ns absolute time. The benefits are discussed separately below. The security of being able to use either system, and to check one against the other, is a desirable feature, whilst the ability of LORAN signals to penetrate forest and city environments that GPS signals cannot is of great interest to land-mobile users. (beware of neon signs for city LORAN !!!)

GPS system outline

My GPS design was revolutionary when proposed in 1988, in that it used a very simple radio, as frequency stability and amplitude control were not a problem, and performed all the correlation and signal processing in software in the CPU. This meant that a very powerful CPU was used, and when not acquiring GPS satellites (the major load) this CPU can be applied to other tasks... like map handling, or LORAN processing. Thus the entire GPS system consists of an Antenna, Radio, CPU (with ROM and RAM), user interface, PSU and case.

The radio has to amplify the microwave signal, mix it down to a convenient frequency, and amplify it again, with filtering at both frequencies. The L-band filtering is easily done with ceramic filters. The baseband filters have been made very simple by converting directly to baseband, and using low pass filters on lowcost operational amplifiers. The total gain required is around 150dB, including LNA. By providing half of it at baseband, the system is greatly simplified.

The output of the op-amps is sampled at a 2MHz rate, and packed 8 samples to the byte, and passed up the transputer link into internal memory. This uses negligible CPU time as it cycle-steals on the 50nS internal bus every 16 microseconds.

When the input buffer is full, every millisecond, the input is diverted into a second buffer and the CPU works on the data in the first buffer. This switching repeats each millisecond.

The main signal processing task is the de-spreading of the spread-spectrum signal by mixing with a synchronised, locally generated copy of the spreading code used in the satellite.

The software then mixes the signal down to a few kilohertz from whatever the radio provided (up to 2 MHz), filters it through an 8 KHz wide filter (to allow for Doppler shift), then mixes it down in I and Q to less than 200 Hz, which is synchronously demodulated in a S/W phase-locked loop, and the satellite orbit data extracted.

When positioning, 4 satellites are tracked simultaneously, but the demodulation is no longer required, the data having already been received.

In volume, the radio can be built for under 50 dollars, and the CPU card for about the same, so a black box GPS can be built for around 100 dollars.

(for further detail see ref [1])

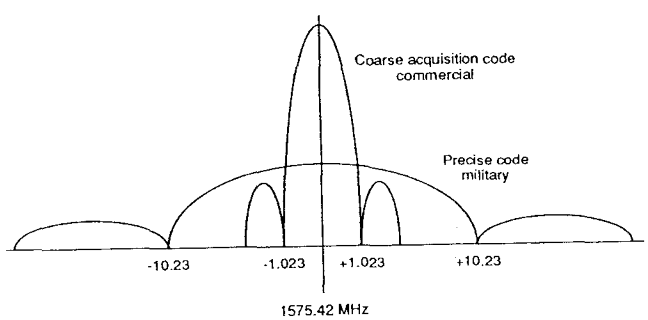
LORAN system outline

This paper is prepared for a LORAN conference, so the audience know better than I the internals of a LORAN receiver. The radio for a LORAN receiver must receive the 100KHz signal, in a wideband fashion as being a pulsed signal , its bandwidth is large. Conventionally many manual or automatic notch filters are provided to kill interfering transmitters, especially the Decca navigation transmissions found in Europe. Apart from these filters, the LORAN radio is not usually expensive.

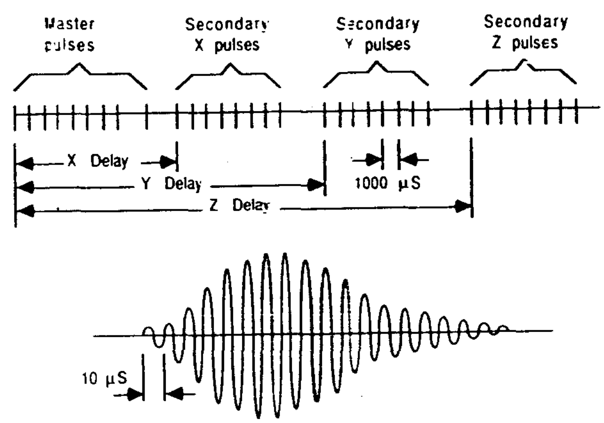
The particular cycle of the LORAN signal to be tracked is the third cycle of each pulse... any later and one risks pollution by sky-wave versions of the same signal. This is usually detected by ratioing the successive waves, until the ratios indicate that the correct cycle has been detected.

A LORAN receiver can be built with an 8085 or similar 8-bit processor.... it is not a major computational task. However, if a powerful processor is available, the hardware can be greatly simplified. This was demonstrated in 1987/8 (refs [2],[3]) in the USA, but was not wonderful in Europe for two reasons. Firstly although the system could pull out the first and second cycles from thermal noise, to identify the third, in Europe the predominant noise was man made, and thus not random, and tended to capture the limiter of the 1-bit A-D converter. Secondly, the accuracy of the reference clock was such that integration was limited to a group of eight pulses (ie 7 milliseconds), as to reach the next group, some 50-100ms later, was too inaccurate in phase.

(for further detail see ref [2] and [3])



Figure(1) GPS Signal (frequency domain)



Figure(2) LORAN Signal (time domain)

Conventional LORAN limitations

The accuracy of a LORAN system is largely limited by the signal to noise ratio, (atmospheric noise), and man made interferers. The interferers that cause most interference are those that are synchronous.(see ref (4)). This is because the interferer energy pulls the phase of the LORAN waveform in the same direction every cycle and every pulse, so even long integration cannot remove the effect. Long integration can of course pull the signal out from random noise.

Benefits of 10ppm clock and 20 MIPS 32 bit CPU

The 10 ppm clock allows the integration of consecutive pulse groups.

LORAN repetition rates are roughly 50 to 100ms, and with the different phase inversions in alternate frames, this is an effective 100-200ms. To integrate effectively over this period, means that the carrier must not have significant phase error after 200ms. 10ppm allows 2 micro-seconds drift, which is 72 degrees of phase at 100KHz, so even at worst case on the slowest chains, 3 pulse groups (2 intervals), and thus 24 pulses, can be successfully integrated.

The LORAN set described in ref (2) could only integrate over 8 pulses, as the intrinsic oscillator error defeated the 16 pulse version.

It should be noted that for slow (ie surface) platforms, a simple LORAN set can calibrate its clock from a single strong LORAN transmitter, and use that calibration to handle the weaker transmitters in the chain. This is often not done, however, as the CPU power of a low cost LORAN set is inadequate.

The powerful CPU provided for GPS reasons easily overcomes the processing limitations of the usually 8-bit LORAN sets. In addition, it can filter the signal, not just by integration, but also by notching out unwanted frequencies. With the same 2 MHz sampling frequency, or a lower sub-harmonic if required, the LORAN signal is greatly oversampled. After integration of several pulse groups, an FFT can be performed, certain output bins deleted, and then the reverse FFT performed prior to correlation with the desired envelope shape 100KHz synthetic carrier in the amplitude domain. A simpler version simply takes the amplitude and phase of the signal in the 100.000KHz bin.

Alternatively, the desired enveloped carrier can be stored in the frequency domain, and a sliding correlation done with it to find the best match.

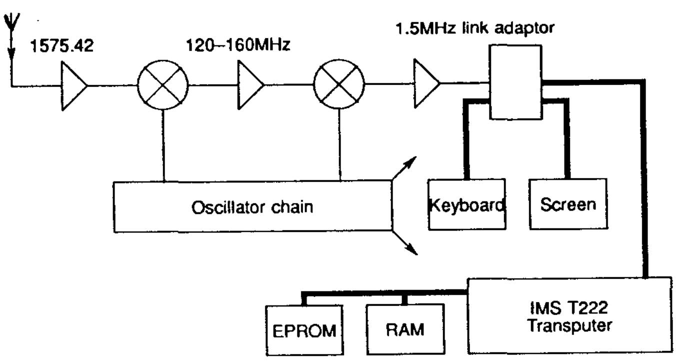


Figure (3) GPS Architecture

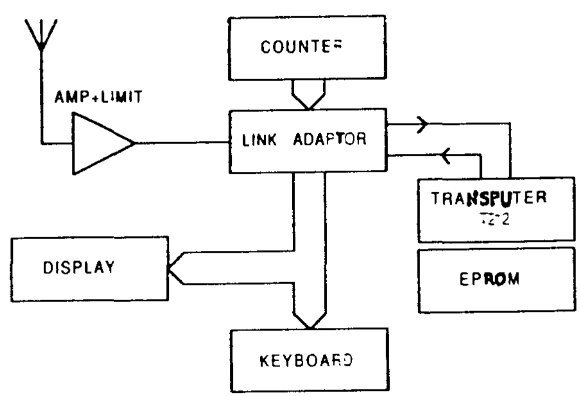


Figure (4) LORAN Architecture

These and many other processing options are open when one has a processor that can do a 1024 point complex FFT in 30ms. For example, even before acquiring LORAN transmitters, the hardware filters can be set up by monitoring the incoming spectrum, adjusting a filter to remove the nastiest spike, and repeating the operation.

Benefits of a 0.1ppm clock and 100ns absolute time

Once locked to a GPS satellite (even only one), with an approximate position, the user on a surface platform can integrate over 200 rather than 2 GRI's....ie 20 seconds, in acquiring even the first LORAN signal. The limitation is now user velocity, rather than clock error. This extra 10dB of margin (* 100, = 20dB, S=100s, N=n*SQRT(100)) allows acquisition on extremely weak signals.

Once the difference between UTC(GPS) and UTC(LORAN is established, the 100nS absolute time accuracy available from the GPS system allows LORAN positioning on only two transmitters, and these can even be from different chains.

Until the time errors are guaranteed, this facility is only likely to be used to continue positioning after a particular LORAN transmitter has been lost.

Another use for the accurate time is to resolve, when using very weak LORAN signals, whether one is using groundwave or skywave, to enable rejection if the latter is all that is found.

Implementation of a combined set.

As shown in Figure (5), the combined set has minimal duplication.... everything is shared except the two RF front-ends. Note that some hardware notch filters may still be required in the LORAN front end, because if a local interferer saturates the high-gain section of the radio, the desired signals cannot pass through, whatever the filtering capabilities of the software.

The signals from the two front ends are selected via an analogue multiplexer, then passed down the baseband gain chain to the sampler. As the 100KHz +/- 30 KHz LORAN signal is so much narrower than the GPS signal, any filters provided here for GPS can be left in circuit.

The processor then controls the multiplexer as required.... note that during GPS data-download, LORAN access is limited to during those frames whose information is not required (or is already held). During initial LORAN acquisition, continous access is not required, as integration is always performed on a GRI basis, so between the sliding GRI trial windows, plenty of time is available for GPS access to the signal path.

Care must be taken that there is not a DC offset between the two multiplexer inputs, as this would require a long settling time on the op-amps after each switching operation. This is achieved by DC blocking them, and coupling them together via two high value resistors whose centre point is decoupled to ground.

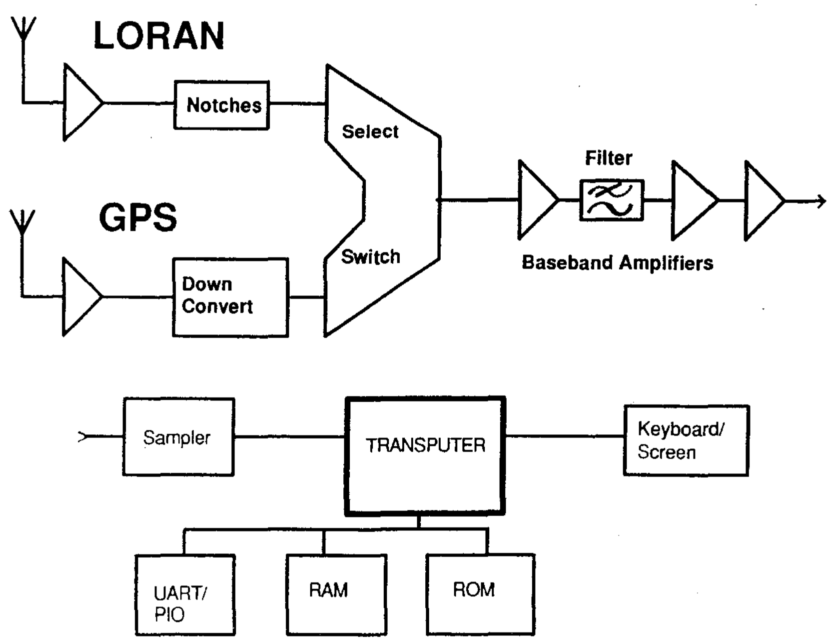


Figure (5) Combined Architecture

Conclusions

An economic means of providing both GPS and LORAN in the same equipment has been described, operating quasi-simultaneously, ie the user will not detect that the processor is being shared. Both functions are independent, allowing each to cover for the other in the event of a control/space segment failure of either system, but each system can benefit from the presence of the other in normal operation, the LORAN gaining the most.

With LORAN sets at a few hundred dollars, one would not expect GPS to be added. However the additional cost to add LORAN to the already low-cost GPS design is a very beneficial proposition, with major performance benefits for Land-Mobile use, when forests or high-rise city buildings cause masking of the GPS signal.

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The Gollum Integrated Navigation System

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Abstract— **Recently, integration of different radio navigation systems has become very popular, since it improves system integrity, availability, accuracy and reliability. This paper discusses a new, flexible and cost-effective approach to system integration, centered around a single-chip Application Specific Processor (ASP). An overview of *Gollum* is presented and the application of the ASP for the implementation of a six-channel GPS, OMEGA, Loran-C and MLS receiver is given. The ASP is currently being implemented on a 180,000 transistor 2 μm CMOS Sea of Gates chip, and is expected to run at 100 MHz clock speed.**

1 Introduction

This paper presents a description of the *Gollum* integrated navigation system. As opposed to conventional integrated air navigation systems, which consist of a number of separate sensors and a navigation computer, we integrate all essential functions into one concept, based on a single-chip high-performance digital processor.

The Gollum system covers all modes of air navigation. As stated in [1], hybrid GPS/Loran-C has the potential to serve as a sole means of navigation system non-precision approaches. It can also be used for area navigation. OMEGA can serve as a backup system for Loran-C in areas where Loran-C is not available. GPS/OMEGA could also provide data for en-route navigation. Including a receiver for the Microwave Landing System (MLS) in our system will also make precision approaches possible.

Our goal is to build a low-cost system for small aircraft. MLS normally needs a Precision Distance Measuring Equipment (DME/P) transceiver, which would significantly increase the cost of the total system. In our system we use the combined GPS/Loran-C position fixes to replace DME/P.

The central component of our system is an Application Specific Processor (ASP). The ASP performs signal processing tasks for a six-channel C/A code GPS receiver, OMEGA and Loran-C receiver, and an MLS receiver. To further reduce the number of external components, it also contains analog interface circuitry.

Combining the functionality of these navigation systems purely in hardware on a single chip results in a very complex design, which is difficult to debug and not very flexible. Therefore, wherever possible, signal demodulation tasks are implemented as software running on the ASP. These tasks include Loran-C input filtering and spectrum estimation, GPS signal acquisition and multipath detection/estimation, phase-lock tracking loops and Kalman filters.

In this paper we focus on the design of the ASP, its environment and some of the Digital Signal Processing (DSP) functions it performs. Section 2 describes our approach to partitioning. Section 3 introduces the ASP architecture and implementation. Sections 4 contains brief descriptions of the various systems to be implemented.

2 Design partitioning

Our design objective is to share hardware resources between receiver functions as much as possible. This means that similar signal processing functions of different systems should be performed by the same modules. This is especially true for the digital signal processing functions, which are performed by the ASP under complete software control. It is therefore important to convert the signals from all subsystems to a form in which they can be processed by the ASP in a uniform fashion. Other ASP tasks include position calculation overall system control.

The Gollum system contains receivers for GPS, OMEGA, Loran-C and MLS. Some signal characteristics of these navigation systems are summarized in Table 1. From this table it is clear that GPS and

MLS have similar characteristics, while Loran-C and OMEGA are also quite similar.

subsystem	transmission band
C/A code GPS	1,574.4 – 1,576.4 MHz
MLS	5,043.0 – 5,090.7 MHz
Loran-C	90 – 110 kHz
OMEGA	10.2 – 13.6 kHz

Table 1: Signal characteristics

Contrary to the conventional multi-sensor system of Figure 1, which consists of several physically separated modules, the Gollum system is partitioned across subsystem boundaries (see Figure 2).

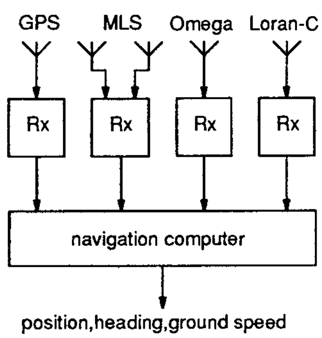

Figure 1: Conventional design partitioning of multi-sensor radio navigation systems

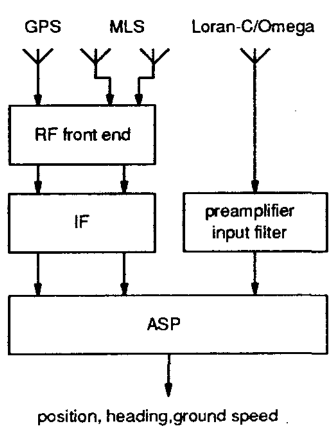

Figure 2: Design partitioning of the *Gollum* system

Partitioning decisions are made on the basis of centerfrequency and bandwidth. First, GPS and MLS signals are converted to baseband, after which they can be processed simultaneously by the same demodulation module (the ASP) as the Loran-C and OMEGA signals. Functions with similar properties can be identified and implemented on ASICs of appropriate technology.

Greater hardware utilization is achieved by time-sharing functional units of the ASP between different tasks under complete software control. These tasks are not limited to position calculation and system control, but also include real-time digital signal processing, for instance FIR filtering, spectrum analysis, signal acquisition, tracking and demodulation algorithms.

Peripheral analog circuits, like A/D converters, are included on the chip for further reduction of external components and interconnections. Only the external discrete RF circuitry is dedicated to specific subsystems.

3 A Navigation Specific Processor

Processor architecture

To process signal flows from all subsystems in real-time, the *Gollum* processor should have high throughput. The scalable *Move* architectural framework [2] is very suitable for embedded applications requiring high performance. Our navigation computer is based on this framework.

In conventional computer architectures operations are specified explicitly, and data transports result implicitly from these operations. Conversely, in a so-called move machine these data transports are specified, and operations are performed as their side-effects. This *transport-triggered* programming model allows a very simple and clean processor organization, which can easily be tailored to a particular application. The processor structure is shown in Figure 3.

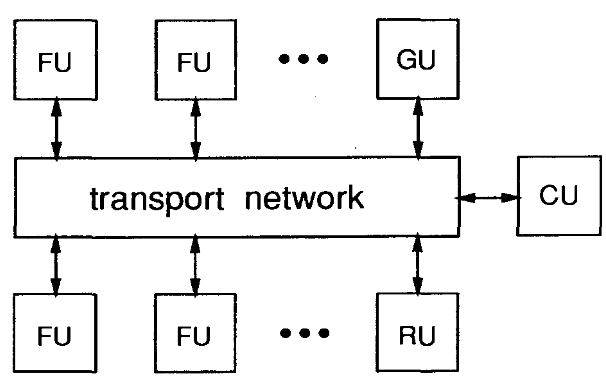

Figure 3: Structure of a move machine

A move machine consists of a number of functional units (FUs), a transport network connecting these

FUs, and a control unit (CU)[1] supervising data traffic through the transport network. The functionality and performance of a move machine can be adapted to the particular application by including the appropriate FUs and the proper connectivity in the transport network.

Functional units communicate with the transport network through a uniform interface, which is visible to the programmer as a number of dedicated registers. This separation of data transport and operations allows for individual optimization of the transport network and functional units, which improves hardware utilization and maximum attainable clock speed. Circuit simulations have shown that a clock frequency of 100 MHz is possible using conventional 2 μm CMOS technology.

Programming a Move machine

The performance of modern high performance computers depends highly on optimizing compilers capable of detecting and exploiting fine-grain parallelism in the application program [3]. Because of its programming model, a move machine has greater code scheduling freedom for such a compiler. Therefore, more FUs can be kept busy, which speeds up program execution.

An FU typically has three connections to the transport network: an operand input register, a trigger input register and an operation result output. To perform a binary operation, the first operand is moved to the FU operand register. The operation is then initiated by moving the other operand to the trigger register. Depending on the latency of the FU, the result of the operation is available at the result output after one or more clock cycles. This result can again be moved to the input of another FU or stored temporarily in the Register Unit (RU).

If one physical trigger register is mapped onto different register addresses, an FU can perform different types of operations, depending on the particular address through which the register is accessed. For instance, we can map the trigger register of an add/subtract unit onto addresses x and y. Writing an operand to address x initiates an add operation, while writing an operand to address y initiates a subtract operation.

The guard unit (GU) evaluates boolean expressions of one or more operands, the so-called guards. These guards allow conditional execution of individual move operations within an instruction.

Unconditional/conditional branches and jumps, that change the flow of control of a program, are performed through unconditional/conditional moves to the Program Counter (PC), which is just another register connected to the transport network.

ASP implementation

FUs are not part of the instruction execution pipeline. This pipeline consists of only three stages: Instruction Fetch (IF), Address Decode (AD) and Data Move (DM). The processor cycle time is limited by the slowest of these 3 stages. If code is properly scheduled, FU latency has little effect on performance. Therefore, to minimize cycle time FUs can have many pipeline stages.

The transport network of the ASP consists of four 32-bit move buses. There is a single 32-bit instruction format, which has a dedicated, fixed instruction field for every move bus, each consisting of a source address, a destination address, and a guard specifier (see Figure 4).

guard1	src1	dst1	•••	guardn	srcn	dstn

Figure 4: The ASP instruction format

For economical reasons the external memory bus, which is used for both data and instructions, has a width of 16 bit. This means that data and instructions, which are 32 bit, have to be fetched and stored in two memory cycles. If the fastest static RAMs currently available are being used, these cycles take at least 20 ns [4]. Consequently, the presence of a fast on-chip instruction cache is crucial to the performance of our ASP, especially where DSP code is concerned.

A new instruction can be issued every clock cycle, but only if this instruction is already present in the instruction cache. DSP algorithms, for instance digital filters, are usually tight loops, iterated many times. It is precisely this code, that needs to run at maximum speed. Therefore the instruction cache needs to be only large enough to contain the biggest DSP loop. A cache containing 16 instructions is sufficient for our DSP code.

4 The Gollum subsystems

4.1 GPS

GPS serves as Gollum's primary navigation aid. Therefore the GPS subsystem is crucial to overall system performance. This has led to the choice of a multichannel GPS quadrature receiver structure with fulltime early-late code tracking loops. Figure 5 shows a typical example of such a demodulator, which is usually replicated N times in an N-channel receiver.

Although it is possible to perform the necessary signal processing entirely in software [5], this option was

[1] also called the Instruction Fetch unit (Ifetch)

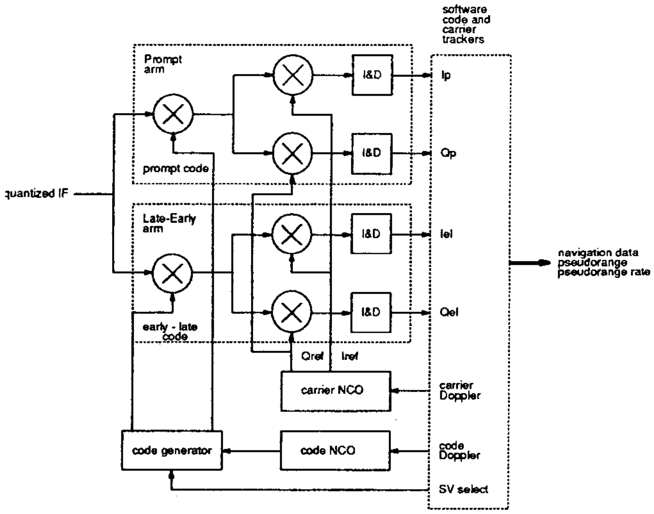

Figure 5: GPS demodulator structure

dismissed, because the computational burden (amount of data transports) is too high to allow time-sharing of the ASP with the other subsystems. Therefore, the ASP has a dedicated GPS FU, which can simultaneously process L1 C/A code signals of up to six satellites. The current version may be extended to eight-channel operation, once we have determined the full functionality of the ASP. Acquisition can be performed completely in software, but only for a limited number of satellites at a time. Software demodulation can also be used for detection and correction of multipath errors.

The GPS FU consists of a novel pipelined multiplex L1 C/A code correlator/demodulator [6]. It utilizes the excess speed of the ASP to increase the number of satellite signals that can be processed in parallel. It occupies the area of approximately two single channel demodulators, but it has performance comparable to a conventional six-channel system. In our application compactness is very important, because the chip on which the whole system must be realized, does not allow the use of much dedicated hardware.

A single signal sample is correlated sequentially with 6 different local codes and their respective derivatives (difference of early and late codes). The effective signal sampling rate is 100 MHz / (6 + 6) = 8.33 MHz, which is well beyond the minimum required sampling rate for a C/A code signal.

The necessary throughput can be achieved through the use of pipelined processing elements. For instance, the throughput of an N-bit ripple-carry adder can be improved by approximately a factor M, if the addition is divided in M-bit chunks and distributed along N/M pipeline stages. The adder can now perform N/M additions simultaneously, but still has almost the same latency as the original, non-pipelined adder.

By introducing these processing elements in a feedback loop, the desired multiplexing operation is introduced automatically, with dwell time equal to the pipeline latency. This principle is illustrated in Figure 6.

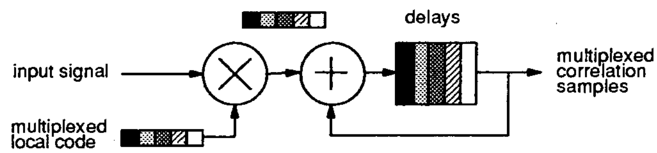

Figure 6: Pipelined multiplex correlator

Every pair of pipeline stages contains the current demodulator state for one satellite channel. The number of pipeline stages is twice the number of satellite channels. Therefore no intermediate results need to be saved and restored, while other satellite channels are being processed.

The GPS FU is easily integrated into the ASP framework. It processes the satellite signals without much interaction with the transport network. To reduce interrupt overhead, signals from all subsystems are decimated to a common sampling frequency of 50 kHz, where they are further processed in software. This uniform sampling rate simplifies interrupt handling in the software kernel controlling systems tasks.

4.2 OMEGA

OMEGA consists of eight ground-bases transmitting stations located throughout the world. Each of stations transmits a time-multiplexed signal of 10.2, 11.05, 11.33, 13.6 kHz and one additional frequency unique to each station [7].

Input signal filtering can be performed using analog or digital bandpass filters. In the case of analog filtering, there would be four n-th order bandpass filters, one for each OMEGA frequency. The output of each of these filters should then be converted to digital form for further digital processing. This means that four A/D converters are needed, but no processor cycles are consumed for signal filtering. On the other hand, silicon area is consumed for the filters, which are dedicated *only* to the OMEGA subsystem. This is not consistent with our design philosophy, so we do not favor this option.

In the case of digital input filtering, the raw input signal is first converted to digital form, and then filtered with IIR bandpass filters. We need only one A/D converter, which can be shared with the Loran-C subsystem. The filters can be run under software control. Therefore they can share hardware resources, like adders, multipliers and registers/memory, which is what we wanted to achieve. The main disadvantage is the existence of round-off errors, which complicates the design of stable recursive filter structures. Nevertheless, using digital input filters appears to be the best choice for our system.

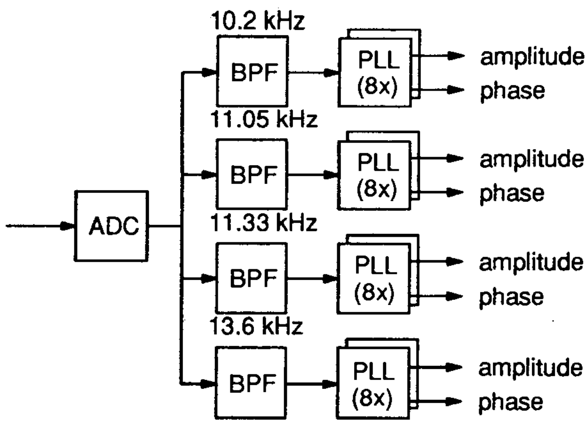

Figure 7: Block diagram of the OMEGA subsystem

The OMEGA receiver structure (Figure 7) is quite simple and can be implemented in our navigation system without much difficulty. The input signal from the on-chip A/D converter provides digitized signal samples at a rate of 50 kHz. These samples are filtered using digital bandpass filters centered at the four OMEGA frequencies. The outputs of these filters are used to drive 32 software quadrature phase-lock loops (PLLs), one for each combination of frequency (4) and transmitter (8). Such a PLL, including the input bandpass filter, is shown in Figure 8. These PLLs share hardware and code, but each of them has their own pool of data, such as input filter coefficients, carrier phase and frequency, state of the Integrate & Dump (I & D) filters, the loop filter, the Numerically Controlled Oscillator (NCO) and values of the signal envelope.

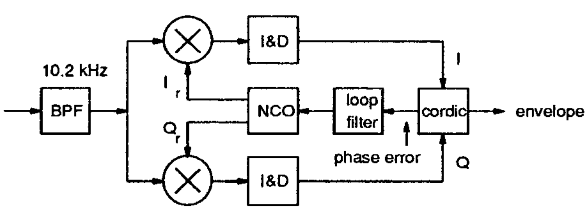

Figure 8: Block schematic of OMEGA PLL

4.3 Loran-C

The Loran-C receiver to be implemented should be resistant against high levels of (synchronous) interference as present in Western Europe. Recently, several techniques have been developed to meet this requirement. First of all, a sharp cut-off Finite Impulse Response (FIR) filter of 128 taps can be used to suppress as much of the interference as possible, without introducing too much pulse distortion [8]. Second, a weighted spectrum analysis [9] can be applied to estimate the frequencies of the more harmful interference signals, after which notch filters can be adjusted to suppress these signals. Third, a pulsematching cycle identification method can be used [10], which is less sensitive to (synchronous) interference than conventional cycle identification algorithms.

Too make all of this possible, the Loran-C signal is sampled at a rate of 400 kHz. This frequency is suitable for the pulsematching technique and high enough to prevent aliasing problems. Furthermore, the samples can be easily decimated to 50 kHz, decreasing the amount of samples processed during spectrum analysis [8, 9].

Considering the computationally intensive tasks, like spectrum analysis and FIR filtering, it is worthwhile to optimize the ASP for these tasks by providing special hardware support. The implementation of the algorithms will be discussed in more detail in [11].

We use a 128-taps direct form FIR filter, that consists of a tapped-delay line of which the weighted tap outputs are accumulated to form an output sample (see Figure 9). The tap weights (filter coefficients) correspond to the impulse response of the filter. This filter operation is the same as taking the inner product of a vector with input samples and a vector with filter coefficients. Therefore, hardware support exists of two vector registers of length 128.

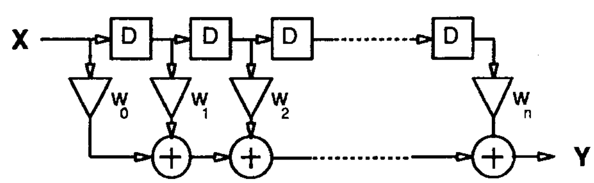

Figure 9: Direct form FIR filter implementation

The high resolution spectrum analysis, required for weighted detection of narrowband interference [9], also needs hardware support. The data could be processed by means of three Fast Fourier Transforms (FFT) on small segments of about (worst case) 10,000 points, but since the FFT does not access data points in a sequential order, the required memory bandwidth will be too high. Therefore, spectrum analysis is implemented with a single Discrete Fourier Transform (DFT) with a modified frequency step size. This DFT can be split in small loops, which can be programmed to use the vector registers.

4.4 MLS

The Microwave Landing System provides guidance signals by periodically transmitting horizontal and vertical scanning beams, which are detected and converted to azimuth/elevation information by an MLS receiver in the aircraft. There are 200 different MLS channels in the 5 GHz band, and the ground transmitting equipment is assigned one of these channels.

Gollum's MLS subsystem consists of a data processor and an angle processor. It selects the proper MLS channel by setting the frequency synthesizer to the channel frequency. The front end and IF sections then convert the received signal to baseband. The data processor demodulates and decodes the DPSK[2] data, and forwards this information to the angle processor. The angle processor interprets the data that indicates which information will be transmitted next by the ground equipment.

The angle processor and data processor each have different inputs. The former needs a compressed envelope signal, while the latter needs a limited carrier signal. A simplified block diagram of the MLS angle information and data receiver is given in Figure 10. Both functions are performed in software at a sampling rate of 50 kHz. After the angle signal is converted to digital form, the time delays between the TO and FROM scanning beams are calculated, from which azimuth and elevation data can be determined.

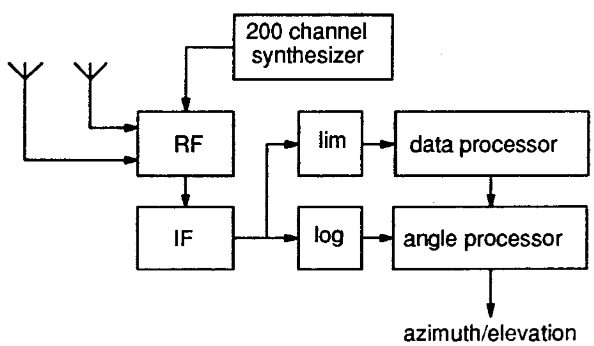

Figure 10: Simpified block diagram of MLS angle and data receiver

Precision DME (DME/P) is an integral part of MLS guidance equipment [12]. It provides a precision ranging function to complement the MLS azimuth and elevation guidance functions. The DME/P, however, contains a 1 GHz transmitter, which increases power consumption, cost and volume of the complete system. It can also interfere with other on-board receivers, and therefore complicate integration of the total system, for instance antenna placement.

For these reasons we chose not to implement DME/P in our system. Instead, we will use positioning information from GPS/Loran-C or GPS/OMEGA to replace the DME/P ranging function, similar to [13]. Differential positioning techniques could be used, with a reference station located in the vicinity of the runway. Differential positioning can be as accurate as DME/P, and MLS's auxiliary data channel could be used to transmit diffentential positioning data to all aircraft within the MLS coverage area.

[2]Differential Phase Shift Keying

5 Conclusions

This paper discussed some aspects of the design of the *Gollum* integrated navigation receiver. It is not partitioned by subsystem, as is normally the case in integrated radio-navigation systems, but by required functionality of the components within these subsystems. This approach results in a significant reduction of hardware volume and cost. The heart of the system consists of an Application Specific Processor (ASP) performing various tasks, ranging from realtime DSP to calculation of positions and general receiver control. Receiver functions for four navigation systems – GPS, OMEGA, Loran-C and MLS – were discussed, as well as ASP customization for some of these functions. Specifically, hardware support was described for a six-channel C/A code GPS receiver and a high-performance Loran-C receiver. The ASP is currently being implemented on a 180,000 transistor 2 μm CMOS Sea of Gates chip.

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Biography

Eric Aardoom was born on September 9, 1963, in Nieuwerkerk aan den IJssel, the Netherlands. In 1989 he received the Ir. degree in Electrical Engineering from Delft University of Technology, the Netherlands, where he is currently working towards the Ph.D. degree. His interests include spread-spectrum techniques, frequency synthesis, mixed analog-digital circuits and high-performance processor architectures for Digital Signal Processing.

André Nieuwland was born in the Netherlands in 1968 and started to study electrical engineering at the Delft University of Technology in 1986. He concluded this study with the presentation of his master's thesis "Weighted Spectrum Analysis in Loran-C" in 1991. In January 1992, he started a PhD. study at the Electronic Engineering Group, to develop and implement a Loran-C receiver based on digital signal processing techniques. Furthermore, he will be actively involved in future GRI calculations for the North-Western European Loran-C chains.

A High–End Gollum Loran–C implementation

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Abstract— This paper describes some of the design considerations for the Loran-C subsystem of the Gollum navigation receiver. The main component of the Gollum hardware platform is an application specific processor (ASP), which provides support for digital signal processing of GPS, Omega, Loran-C and MLS signals. Real-time digital signal processing functions are executed on the ASP in a time-shared fashion. We discuss how essential functions of a high-end Loran-C receiver can be implemented on this platform.

1 Introduction

With the advent of modern RISC processors and programmable Digital Signal Processors (DSPs), more computationally intensive DSP tasks can be performed at low cost. As described in [1], we use these developments in the design of an multi-system integrated navigation receiver. An Application Specific Processor (ASP), based on the transport-triggered *Move* architecture framework [2], is being designed for efficiently handling specific DSP tasks for four different radionavigation systems: GPS, Omega, Loran–C and MLS. The major distinction between the Gollum approach and conventional integration of navigation systems is that the different systems are integrated in a single piece of equipment, significantly decreasing weight, size and cost.

Navigation and signal processing tasks are performed mainly in software. Receiver characteristics, like e.g. filter coefficients and bandwidth of tracking loops, can be easily changed by altering some parameters in the software. An additional advantage is that the software for a specific navigation system need not be permanently resident in the high-speed memory of the processor. If one of the navigation systems is not used for some reason, the "software receiver" does not consume any CPU time. Furthermore, code for similar tasks of different systems can be shared (e.g. tracking loops for OMEGA and Loran-C), reducing the overall amount of software.

This paper will not focus on the final characteristics of the Loran-C receiver subsystem, but on the hardware support required to perform the basic operations on the Loran-C signals in real-time. Because this optimization of the processor for computationally intensive real-time processing tasks is independent from the higher level parameters (e.g. filter coefficients), there is no loss in flexibility.

The Loran-C receiver should be resistant against the high interference levels present in Western Europe. Therefore, a linear digital receiver structure, as described in [3, 4], was adopted (see figure 1).

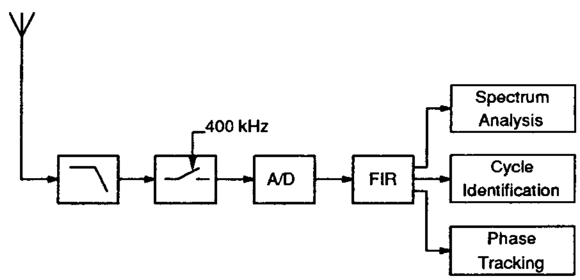

Figure 1: Block diagram of a digital Loran–C receiver

In a linear digital receiver the input signal should be quantized with an adequate number of bits to obtain sufficient resolution over the total dynamic range. A/D conversion, capable of handling the high dynamic range of the Loran-C signal, is discussed first in Section 2. Section 3 describes some design alternatives for implementation of a FIR bandpass filter, required for suppressing interference outside the Loran-C band. Further interference suppression is achieved through the use of notch filters. Strategies for realizing notch filters, analog and digital, are presented in Section 4. Finally, the implementation of high resolution spectrum analysis is discussed in section 5.

2 A/D Conversion

According to the RTCA Minimum Performance Standards [5], the airborne Loran-C receiver should be able to cope with signal strengths between 30 and 120 dB/μV/m and differential signal strengths of 80 dB or less. To handle signals with relative amplitude of 80 dB, at least 14 bits are required.

According to IEC performance standards [6], the difference between the smallest signal level (25 dB) and the minimum noise level (12 dB) is 13 dB. Although values specified for marine and airborne receivers differ, we use this value to estimate the number of of bits required to detect the weakest signal with sufficient resolution.

The Signal-to-Quantization-Noise-Ratio (SN_qR) of the weakest signal should be of the same order as the Signal-to-Noise-Ratio (SNR) of the input signal. For SN_qR's not too small, formula 1 can be used to estimate the number of bits (ν) required to reach an SN_qR of $\geq$ 13 dB [7]. It can be found that 2 bits are sufficient. The total number of bits required for sampling the input signal is thus 14 + 2 = 16 bits.

$$SN_qR = 4.8 + 6 \cdot \nu \qquad (1)$$

Several options are open to obtain the required dynamic range:

Logarithmic ADC

The first option is to use a logarithmic ADC. The problem lies in the fact that an anti-log operation is needed to make the front-end linear again before FIR filtering takes place.

Controlled-gain ADC

Another possibility is to use an amplifier with a gain adjustable in powers of 2. If the signal strength is determined at the output of the ADC, the amplifier can be adjusted such that the maximum range of the ADC is used. This configuration more or less the same as an Automatic Gain Control (AGC). In case that a weak signal follows a strong signal, the "AGC" should be adjusted from a low gain to a higher gain.
Because the transmitters of a Loran-C chain are broadcasting in a strict time scheme, it is predictable when the next strong or weak pulses will be received. Therefore, the AGC can be adjusted just before the Loran-C pulses arrive. If only the pulses are sampled and processed, the switching time can be as large as one millisecond, because the spacing between pulses from different transmitters is at least one millisecond or more. If samples are taken continuously however, the switching time should be less than the time between two samples. A negative aspect of this approach is that an accurate, adjustable, and fast-settling amplifier is required.

Floating-point ADC

The extreme case of this keyed AGC is a floating-point ADC. It is using non-linear quantization like is the case with the controllable amplifier. Only now, successive *samples* can have different scale factors instead of samples of successive *bursts*. The main disadvantage of this approach is that the ASP needs arithmetic operations supporting a peculiar floating-point format.

Linear ADC

The last option is to use a linear ADC with sufficient range. From a systems point of view, this option is preferable, since it provides the required resolution and dynamic range, without prior detailed knowledge of signal strength and reception pattern. Therefore this straightforward solution was selected.
The ADC should operate at 400 kHz, providing precise quadrature samples for spectrum analysis. If the receiver is not within the Loran-C coverage area, this ADC might even be used for conversion of OMEGA signals.

3 Input filter implementation

Choice of the input filter

A Finite Impulse Response (FIR) filter of 20 kHz bandwidth is used to limit the influence of noise and out-of-band interference. Unlike most other filters, a FIR filter can be designed to have a constant group delay (linear phase response) in the pass band. Therefore, the phase response does not cause pulse distortion, as is the case with a steep analog filter. The only distortion introduced is caused by the suppression of the small frequency components outside the 90 to 110 kHz band. To obtain a bandwidth of 20 kHz and 80 dB suppression for all frequencies outside the 75 to 125 kHz band, a 128 taps FIR filter is sufficient [3].
Figure 2 presents the direct form structure of a FIR filter. Every input sample is shifted through a delay line. The output of each delay is multiplied with a filter coefficient, after which the multiplied output is summed. The ASP architecture is extremely simple. Its only addressing mode is direct addressing. Consequently, any address calculation must be performed using the general-purpose arithmetic units. This overhead would make real-time FIR filtering of the Loran-C signals impossible. As discussed in [8], the FIR filter can be implemented efficiently using on-chip vector registers, since this eleminates the address calculations and the memory bottleneck.

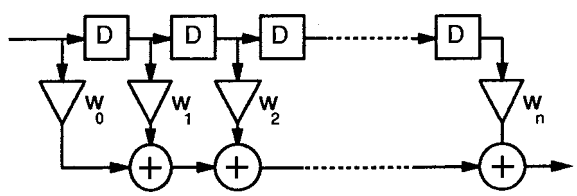

Figure 2: Direct form FIR filter

Vector registers

The vector registers consist of a FIFO queue with local feedback from the head to the tail through a 2-input multiplexer. The FIFO rotates one position when the head element is read, and the head element is written back into the FIFO at the tail position. The register does not rotate when the tail element is written directly from the system bus. The block diagram of the vector register is shown in Figure 3.

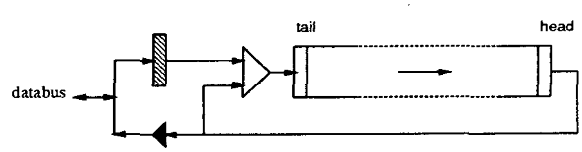

Figure 3: Vector register

FIR filter implementation alternatives

Straightforward direct form FIR filter

The FIR filter operation is identical to the calculation of an inner product of a vector of filter coefficients and a vector of signal samples (see figure 4). To store all filter coefficients and data samples these vector registers should have a length of 128 words.

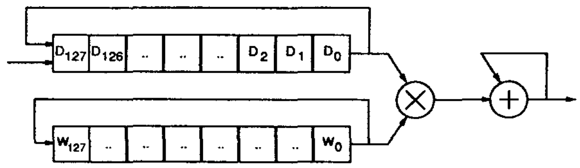

Figure 4: Direct form 128-tap FIR filter

The pseudo-code for the calculation of one output sample looks like:

```
OutSample = 0
for i = 0 to 127
    Outsample = Insample[j] * Weight[j] + Outsample
Shift new Insample in DataRegister
```

Because an instruction is issued every clock cycle, calculation of one output sample take at least 128 cycles, that is 1.28 μs with an 100 MHz clock. The output of the FIR filter can be decimated by a factor N by calculating only one output sample for each N input samples.

Linear phase FIR filters

Vector registers consume significant chip area. For a linear phase FIR filter this area can be reduced, due to the symmetry of the filter coefficients. This can be achieved if one of the registers can rotate in both directions (see figure5).

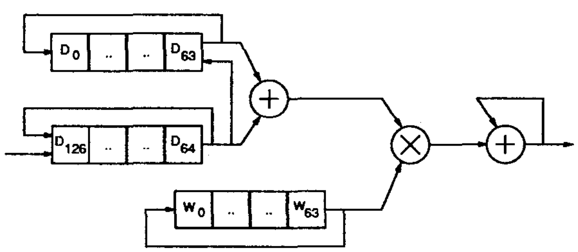

Figure 5: 128 taps FIR filter with reduced (vector) register length

In this case, the pseudo-code for calculating one output sample looks like:

```
OutSample = 0
for i = 63 to 0
    TempVal = InSample[i] + InSample[127-i]
    OutSample = TempVal * Weight[i] + OutSample
Shift Backward DataRegister_1
Write InSample[64] in DataRegister_1
Shift new InSample in DataRegister_2
```

Both registers are rotated, summing two data samples before multiplication with the filter coefficients. This will cost an extra addition, but it saves the extra multiplication otherwise needed (64 additions and 64 multiplications against 128 multiplications). If both registers are completely rotated, the last sample (D_{64}) is written in the upper register, discarding sample D_0. Unfortunately, we expect that altering the vector registers in such a way that they can rotate in two directions will consume even more silicon area than a full-size implementation. Writing the head value of the lower data register at the tail position of the upper data register is not a solution, because then the upper data register has to be rotated 63 times after every write.

To solve this problem, one vector register should run virtually backward, that is, after a complete rotation it needs an extra shift to be aligned again with the other register. Although there are in total 128 storage words in the registers, we effectively use only 127 of them, creating a 127-tap FIR filter.

As an example, figure 6 shows an implementation of a 127-tap FIR filter with 64-word vector registers. First, sample D_{63} is written at the tail of the upper register, and also multiplied with coefficient W_{63}. D_{62} and D_{64} are now at the head of the registers. They are read simultaneously, then summed and finally multiplied with W_{62} etc. The same goes for D_{61} and D_{65}, D_{60} and D_{66}, etc. These operations are repeated 63 times. D_{63} is now at the head of the upper register, followed by D_{62}, D_{61}, etc. This is exactly the order needed for the next filter iteration.

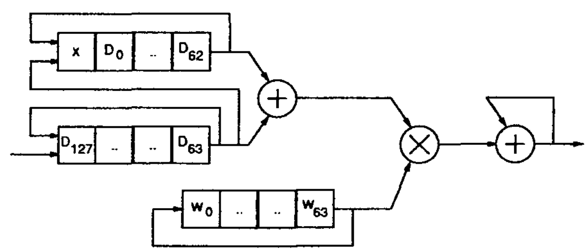

Figure 6: 127 taps FIR filter with reduced (vector) register length

Now, the code for calculating one output sample will look like:

```
OutSample = 0
TempVal = InSample[63]
OutSample = TempVal * Weight[63]
Write TempVal in DataRegister_1
for i = 62 to 0
    TempVal = InSample[i] + InSample[126-i]
Shift new InSample in DataRegister_2
```

In theory, two data samples are now processed per processor cycle, provided that the processor has enough arithmetic units and buses to transport these data samples, and a filter coefficient once per processor cycle. This means that the total execution time of the

filter can be 64 cycles instead of 128, excluding loop overhead.
One disadvantage of this method is that the initial fill of the registers will cost $63 \cdot 62 \ldots 2 \cdot 1 = 2016$ cycles, because the upper register has to be rotated 63 times before a new value can be written into the register. These extra cycles are inherent to the filter operation, and they are not necessary when the output samples are calculated continuously. Another disadvantage is the fact that the additional communication bandwidth and arithmetic capability of the ASP may eliminate the chip area advantage of the reduced vector register storage. However, This additional capability may also be used for the benifit of other processing tasks.
Our choice is to implement the FIR filter in the direct form because of its straightforward implementation. With the direct form a wide variety of processing schemes can be realized without the problems otherwise encountered. E.g. a decimating FIR filter can be realized easily, the filter can be "switched off" between the Loran-C bursts and the parameters can be changed to obtain an asymmetrical frequency response.

4 Notch filter implemention

There are several ways of implementing notch filters: analog or digital, fixed tuned, automatic and level-sensitive or automatically adjusted after the receiver has performed a spectrum analyses.
Using fixed tuned notches is very rigid. The notches are only properly adjusted for a specific area, and not for other areas where the receiver might be used.
Level-sensitive notches have the disadvantage that they will be adjusted towards the strongest interferers, not necessarily the more harmfull ones [4]. These filters are only useful for suppresion of powerful, front-end overloading interference signals. If the center frequency of these filters can be determined during operation, then a pulse matching cycle identification or tracking loop, can calculate the distortion the reference pulse should have to establish an optimal match.
The third way to implement notches is to analyze the spectrum and decide which frequencies should be suppressed[4]. This has the advantage that no notches are used unnecessarily, and that they are always adjusted optimal. The notches can be implemented analog and digital adjustable, or completely in software. The first has the advantage of suppressing harmful interference signals before the A/D conversion but needs dedicated hardware. The software method has the advantage that depth and width can be easily changed, and that it can be implemented without dedicated hardware.
If analog notches are implemented, the signals currently being suppressed are not noticeable in the analysed spectrum. Consequently, the notches have to be switched off every now and then to check if they are still suppressing the more harmful signals. Software notches can be implemented as Infinite Impulse Response (IIR) filters after the FIR filter, thus after the place the spectrum analysis obtains its input signal. In that case the FIR filter should calculate output samples with a constant and sufficiently high rate

The best solution is probably a combination of controlled and automatic notches. The automatic level sensitive notches will suppress strong front-end overloading signals, the software notches will suppress the remaining harmful (near-) synchronous interference signals.
If the frequency of the level sensitive notches can be obtained, the phase and envelope distortion can be taken into account in the tracking and cycle identification loops. This distortion is normally quite small [9], and whether or not compensation is necessary, depends on the sensitivity of the loops for these disturbances.

5 Spectrum analysis

The receiver performs a high resolution spectrum analysis to obtain the necessary information about the presence of interference signals. With this information, notch filters are adjusted to suppress the more harmful interference signals.
The spectrum analysis algorithm [4], applies a Chirp Z-transform (CZT) on segments of data, and is therefore called Segmented Chirp Z-transform (SCZT)(see figure 7). The transformed segments are summed and then the frequency bins (samples) are rotated to cancel ghosting effects, caused by digital quadrature sampling. After these operations, the obtained spectrum is searched for harmful interference signals (see figure 8).

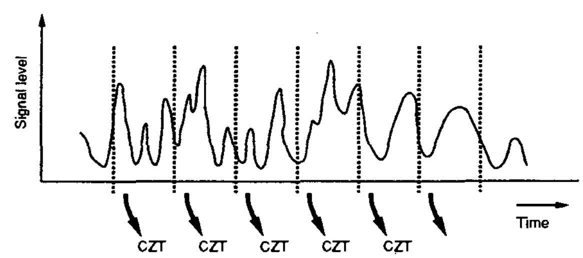

Figure 7: Segmentation in time domain

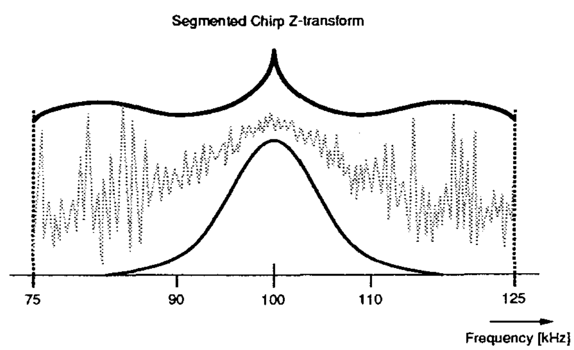

Figure 8: Frequency analysis on total spectrum

Although this algorithm might be "easily" implementable with a dedicated processor and a lot of (preferably fast) memory, using only a dedicated ASP with a (cheap) 16 bit data bus and a limited amount of memory gives extra constraints. Especially when other algorithms should run on the same processor and use the same memory. Because the processor is heavily pipelined and runs on a clock frequency five times higher than the clock frequency of the memory, it might be expected that the memory usage is the first limit that will be encountered.

The algorithm uses 3 Fast Fourier Transforms (FFT) to calculate the frequency bins coinciding with the spectral lines of the Loran-C signal. If the size of the segments is small, the algorithm will approximate a standard Discrete Fourier Transform (DFT) and will be of the order $3 \cdot n^2$ with regard to complex multiplies. If the segmentsize is large, the algorithm will be of the order $3 \cdot n \log(n)$. If we disregard the amount of memory required and use only one large segment, which will be computatially the most efficient, an indication of a possible memory bottleneck can be easily obtained.

The number of samples required is $250 \cdot 10^3$, which resulted from quadrature sampling with 50 kHz for a period of 5 seconds. The number of complex multiplications to be performed is thus $3 \cdot 250 \cdot 10^3 \cdot {}^2\log(250 \cdot 10^3) = 1.34 \cdot 10^7$. If the twiddle factors of the FFT are computed in real time on the chip itself $1.34 \cdot 10^7$ complex numbers have to be fetched from and stored in memory! Storage of one complex value will take at least 6 cycles, and a read at least 4. Since the bus runs on a clockspeed of 20 MHz, the time it will take for the memory transport will be at least $1.34 \cdot 10^7 \cdot 10 \cdot 0.05 \cdot 10^{-6} = 6.72$ seconds. This is more than the 5 seconds it took to acquire the samples. Ergo, it is not possible to perform real time spectrum analysis with this system in this way using smaller segments. Using the largest segment is not a solution either, because this will require at least 2 MB of memory, in the case that the FFT can be performed with 16 bit numbers. This will conflict the design goal, which was a low cost receiver with low power consumption.

Because of this heavy memory usage, it is more useful to use the algorithm based on a DFT with a modified stepsize. Although this Segmented Chirp-DFT (SCDFT) is of order n^2 instead of $3 \cdot n \cdot {}^2\log n$, there is only memory needed for temporary storage of the frequency bins. The algoritm itself can be efficiently implemented by using vector registers. Regarding the number of complex multiplications, this will be the number of datasamples times the number of frequency bins, which is $2.5 \cdot 10^9$. With a 100 MHz clock, and assuming that one complex multiply can be performed within 4 clock cycles, it wil take about 100 seconds to process 5 seconds of data samples. The only way to process the samples in real time and using a limited amount of memory, is estimate only a small part of the spectrum at a time. If 100% of the processor cycles can be used, the total spectrum can be divided in 20 segments, and each of the hese segments can be analyzed in real time (see figure 9).

For the elimination of ghosting effects, 2 frequency segments lying symmetrically around the center frequency should be processed simultaneously, as shown in 9. Estimation of the frequency spectrum in segments from the center frequency towards the edges of the FIR filter, has the advantage of detecting the least suppressed interference signals first.

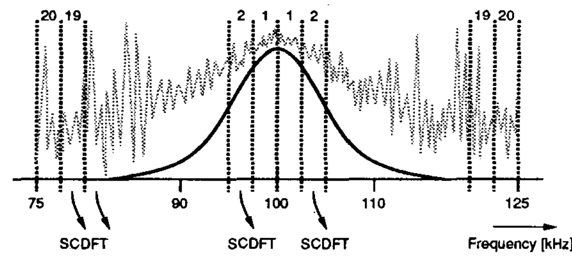

Figure 9: Frequency segments

6 Conclusions

This paper presented design considerations and solutions for the implementation of processing hardware supporting the basic signal processing tasks of Gollum's Loran-C receiver. To obtain a maximum flexibility, the Finite Impulse Response (FIR) filter is implemented in the direct form in full length. Because of its simplicity, a linear 16 bits ADC will be used. The notch filters, used to suppress harmful interferers, will be implemented in software as well as in hardware. The hardware notches are automatic and level sensitive, and prevent the receiver against front-end overloading signals.

Acknowledgements

The authors would like to thank the members of the Electronic Engineering Group, at which the research on the integrated multisystem navigation receiver takes place. Special thanks goes to Mr. Regenbogen, who came with the concept of the keyed-AGC.

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Biography

Eric Aardoom received the Ingenieur (Ir.) degree in Electrical Engineering from Delft University of Technology, the Netherlands, in 1989. He is now a Ph.D. candidate at the same university. His research interests include spread-spectrum communication and navigation systems, mixed-mode circuits for signal processing and high-performance computer systems. He is a member of the Gollum design team at the Electronic Engineering group of the faculty of Electrical Engineering, and specializes in GPS receiver design using semi-custom VLSI technology. He is also involved in the development of a prototype semi-custom microprocessor.

André Nieuwland was born in the Netherlands in 1968 and started to study electrical engineering at the Delft University of Technology in 1986. He concluded this study with the presentation of his master's thesis "Weighted Spectrum Analysis in Loran-C" in 1991. In January 1992, he started a PhD. study at the Electronic Engineering Group, to develop and implement a Loran-C receiver based on digital signal processing techniques. Furthermore, he will be actively involved in future GRI calculations for the North-West European Loran-C chains.

SESSION L

Receiver Techniques

REALTIME MITIGATION OF GPS SA ERRORS USING LORAN-C

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Abstract

The hybrid use of Loran-C with the Global Positioning System (GPS) has been shown capable of providing a sole-means of enroute air radionavigation. By allowing pilots to fly direct to their destinations, use of this system is resulting in significant time savings and therefore fuel savings as well. However, a major error source limiting the accuracy of GPS is the intentional degradation of the GPS signal known as Selective Availability (SA). SA-induced position errors are highly correlated and far exceed all other error sources (horizontal position error: 100 meters, 95%). Realtime mitigation of SA errors from the position solution is highly desirable. This paper discusses how that can be achieved. The stability of Loran-C signals is exploited to reduce SA errors. The theory behind this technique will be discussed and results using bench and flight data will be given.

Introduction

The hybrid use of Loran-C with the Global Positioning System (GPS) has been shown to be capable of providing a sole-means of enroute air radionavigation [1]. Standardization committees such as the RTCA are currently working on developing minimum operational performance standards for this system. By allowing pilots to fly direct to their destinations, use of this system will result in significant time savings and therefore fuel savings as well. By not confining all aircraft to a small portion of the airspace (which results when using the Victor airways), the risk of collision undoubtedly will be reduced as well.

However, a major error source limiting the accuracy of GPS is the intentional degradation of the GPS signal known as Selective Availability (SA). SA manifests itself in the form of erroneous orbital data broadcast by the satellites and in dithering of the satellite clock. The result is position determination which, according to the Department of Defense (DoD), will be in error by one hundred meters 95% of the time in the horizontal plane. Previous work performed at Ohio University showed that SA-induced position errors are highly correlated [2]. Since the correlation time is on the order of minutes, it follows that the error falls well within the passband of the aircraft's dynamic response. The result is that the aircraft will follow the deviations induced by SA.

Realtime mitigation of SA errors from the position solution is highly desirable. This paper discusses how that can be achieved. The stability of Loran-C signals is exploited to reduce SA errors. In the typical hybrid use of Loran-C and GPS, the Loran-C signal stability is not exploited. This stems from the relatively poor absolute accuracy of Loran-C (relative to GPS). However, it is possible to use the stability of Loran-C positioning to reduce SA-induced GPS positioning errors. The theory behind this technique will be discussed and results will be given. First, the phenomenon of SA will be described.

Selective Availability

As mentioned in the introduction, SA is an intentional corruption of the GPS signal by the DoD to limit the accuracy available to the public. The degradation is achieved in two ways. First, false satellite orbit parameters are broadcast to the users. This results in incorrect positioning of the satellites in the navigation solution. Secondly, code and carrier tracking errors are induced through dithering the satellite clock (carrier frequency). The erroneous orbit parameters lead to position errors which vary slowly throughout the satellite pass. Code-phase and carrier-phase errors due to the dithering of the satellite clock are random but also are highly correlated. Correlation times of several minutes are typical. As a result, simple filtering schemes are not effective and aircraft will follow the deviations. Virtually all of the information available to date about SA has been gathered through data collection efforts by civilian organizations. The DoD, however, has stated that SA shall be instituted in such a way as to yield horizontal position errors at a 95% level of 100 meters [3].

Mitigation Methodology

The heart of the mitigation scheme lies in the differences between Loran-C and SA-induced GPS position errors. Loran-C position errors in general are biased and noisy. The level of noise depends upon the receiver architecture and specifically upon the tracking loop bandwidth. However, noise levels on the order of 5 to 10 meters can be achieved for airborne applications. The Loran-C position bias is primarily composed of unmodeled additional secondary phase factors (ASF). In general the bias does not remain constant over any given flight path but the variation is usually quite slow in comparison to the clock component of GPS SA error. This phenomenon is what makes Loran-based SA mitigation possible. The long-term stability of the Loran-C measurements is exploited to smooth the SA-induced variations in the GPS measurements.

Conceptually, the mitigation scheme works as follows. The Loran-C sensor computes the horizontal position of the aircraft. A vertical input is needed and is supplied by the barometric altimeter (again, a sensor which is biased but stable). The combination provides a three-dimensional position of the aircraft. Range values are computed from the GPS satellites to the Loran-C/altimeter position. These range values are then the reference against which the measured GPS pseudoranges are filtered.

Note that the technique depends upon the assumption that SA error is composed only of high frequency components relative to the Loran-C bias error variations. Strictly speaking, this assumption is not valid since the orbital component of SA error is slowly varying. However, as was shown in [2], the clock component of SA error has periods on the order of five to ten minutes. As such it is a high frequency error source relative to the non-noise component of Loran-C error. Although this has not been rigorously proven, flight data (to be shown later) supports the conclusion. Thus, the technique is able to reduce the clock component (or roughly speaking, the variance) of SA error.

The filtering is accomplished by complementary Kalman filters which are applied to each pseudorange measurement [4,5]. The inputs to each filter are the given GPS pseudorange measurement and the corresponding range computed from the satellite to the Loran-C/altimeter position. At each measurement epoch (current time given by the index k), the complementary Kalman filter is executed as follows:

$$d_k^- = d_{k-1}^+ + (L_k - L_{k-1}) \tag{1}$$

$$p_k^- = p_{k-1}^+ + q \tag{2}$$

$$k_k = \frac{p_k^-}{p_k^- + r} \tag{3}$$

$$d_k^+ = d_k^- + k_k(z_k - d_k^-) \tag{4}$$

$$p_k^+ = (1 - k_k)p_k^- \tag{5}$$

where the subscript represents the time index. The superscripts '-' and '+' represent predicted and estimated quantities respectively. 'd^+' represents the estimated pseudorange with variance q. 'z' represents the measured pseudorange with error variance r. Note that r is due primarily to SA. 'L' represents the range computed from the satellite to the Loran-C/altimeter position. 'p' represents the prediction or estimation error variance. 'k' is the Kalman gain. In equation (1), the current pseudorange prediction is computed by updating the previous pseudorange estimate with the difference between the current and previous Loran-C/altimeter ranges. The prediction error variance is computed in equation (2) and is used to compute the Kalman gain in equation (3). The difference between the measured and predicted pseudoranges is weighted by the Kalman gain in the computation of the current estimate (equation 4). Finally, the current estimation error variance is computed (equation 5).

Position Solution

Given at least four GPS pseudoranges, position may be computed. As will be shown in the next two sections, significant reduction in SA-error may be achieved when using the mitigation technique just described.

For both the simulation and flight test results (to be shown later), the ordinary least-squares (OLS) estimator is used to determine position and clock bias from the pseudoranges. In the absence of measurement errors, the relationship between satellite location, receiver location, clock bias and pseudorange is given by:

$$R_i = \sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2} + b \tag{6}$$

where R_i is the pseudorange to the i^{th} satellite, (x_i, y_i, z_i) are the coordinates of the satellite, (x,y,z) are the coordinates of the receiver and b is the receiver clock bias (converted to units of distance through multiplication by the speed of light). Since the receiver coordinates and clock bias must be solved for simultaneously, at least four measurements are required.

However, instead of attempting simultaneous solution of non-linear equations, the standard technique is to solve iteratively a set of equations which have been linearized about an initial estimated position and clock bias

(x_o,y_o,z_o,b_o). This is achieved by forming a Taylor series expansion and retaining the zeroth and first order terms:

$$R_i = R_{io} + (\delta x)\frac{\partial R_i}{\partial x}\Big|_{x_o,y_o,z_o} + (\delta y)\frac{\partial R_i}{\partial y}\Big|_{x_o,y_o,z_o} + (\delta z)\frac{\partial R_i}{\partial y}\Big|_{x_o,y_o,z_o} + (\delta b)\frac{\partial R_i}{\partial b} \quad (7)$$

where R_{io} is the range from the satellite to the initial position estimate. δx, δy, δz and δb represent the corrections to the initial estimates. If the initial estimate is close to the truth, no iterations are required. However, if the initial estimate is not close, the corrections are used to update the initial estimate and the process is repeated. Convergence is declared if the magnitudes of the corrections are below a desired threshold.

The partial derivatives are evaluated as follows:

$$\frac{\partial R_i}{\partial x} = \frac{x_o - x}{R_i - b_o} \equiv \alpha_{i1} \quad (8)$$

$$\frac{\partial R_i}{\partial y} = \frac{y_o - y}{R_i - b_o} \equiv \alpha_{i2} \quad (9)$$

$$\frac{\partial R_i}{\partial z} = \frac{z_o - z}{R_i - b_o} \equiv \alpha_{i3} \quad (10)$$

$$\frac{\partial R_i}{\partial b} = 1 \equiv \alpha_{i4} \quad (11)$$

Substitution of equations (8) through (11) into (7) yields:

$$\delta R_i = (\delta x)\alpha_{i1} + (\delta y)\alpha_{i2} + (\delta z)\alpha_{i3} + (\delta b)\alpha_{i4} \quad (12)$$

where:

$$\delta R_i = R_i - R_{io} \quad (13)$$

Four pseudorange measurements allow for the following simultaneous set of equations:

$$\begin{pmatrix} \delta R_1 \\ \delta R_2 \\ \delta R_3 \\ \delta R_4 \end{pmatrix} = \begin{pmatrix} \alpha_{11} & \alpha_{12} & \alpha_{13} & \alpha_{14} \\ \alpha_{21} & \alpha_{22} & \alpha_{23} & \alpha_{24} \\ \alpha_{31} & \alpha_{32} & \alpha_{33} & \alpha_{34} \\ \alpha_{41} & \alpha_{42} & \alpha_{43} & \alpha_{44} \end{pmatrix} \begin{pmatrix} \delta x \\ \delta y \\ \delta z \\ \delta b \end{pmatrix} \quad (14)$$

which may be rewritten more succinctly:

$$\underline{y} = H\underline{\beta} \quad (15)$$

The presence of measurement errors may be accounted for by the addition of an error vector:

$$\underline{y} = H\underline{\beta} + \underline{\epsilon} \quad (16)$$

The ordinary least-squares solution is then given by:

$$\hat{\underline{\beta}}_{OLS} = (H^T H)^{-1} H^T \underline{y} \quad (17)$$

After one iteration then, the position and clock bias estimate is given by:

$$\begin{pmatrix} \hat{x} \\ \hat{y} \\ \hat{z} \\ \hat{b} \end{pmatrix} = \begin{pmatrix} x_o \\ y_o \\ z_o \\ b_o \end{pmatrix} + \begin{pmatrix} \delta x \\ \delta y \\ \delta z \\ \delta b \end{pmatrix} \quad (18)$$

Simulation

To determine the feasibility of the technique, a simulation was performed. A simple flight-path was modeled with the aircraft traveling to the east for 900 seconds at 100 meters/second, followed by a 2g turn and then returning to the west (figure 1). For the sake of simplicity in the calculations, a static satellite constellation was modeled. In order to focus on the effects of SA, all other GPS error sources were assumed to be zero. The Loran-C/altimeter errors were modeled in the position domain by a constant 200 meter bias on each axis.

The SA model was obtained from collected data using the System Identification procedure described in [2]. In order to model SA rather than the combination of SA and receiver noise, integrated Doppler data (rather than pseudorange data) were used. The System Identification procedure yielded a 16th order autoregressive (AR) filter. When Gaussian white noise (of proper variance) is input to this filter model, the output is statistically equivalent to the collected SA data. An example of the output is given in figure 2.

The positioning errors resulting from the SA corruption are given in figures 3 and 4. Both the east and north components of the position error exhibit similar characteristics to the SA error on the pseudorange measurements. As discussed earlier, the errors are highly correlated and reach up to 100 meters. However, use of the Loran-C/altimeter data in the complementary Kalman filter yields significant reduction of SA error (figures 5 and 6).

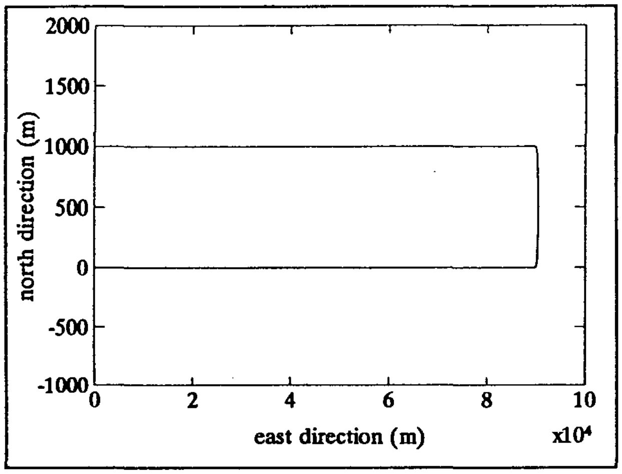

Figure 1. Simulated flight path.

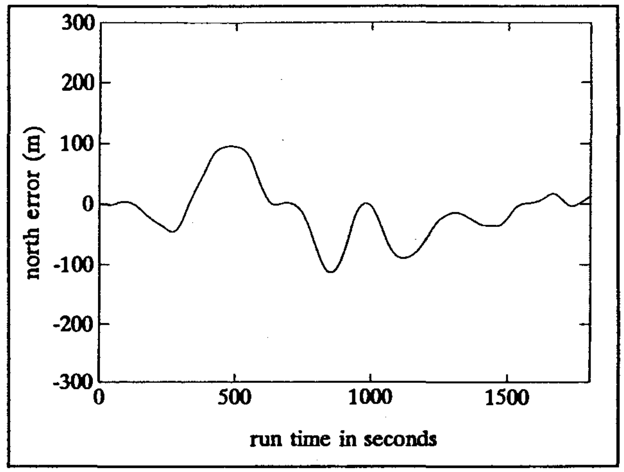

Figure 4. Raw GPS position error due to SA.

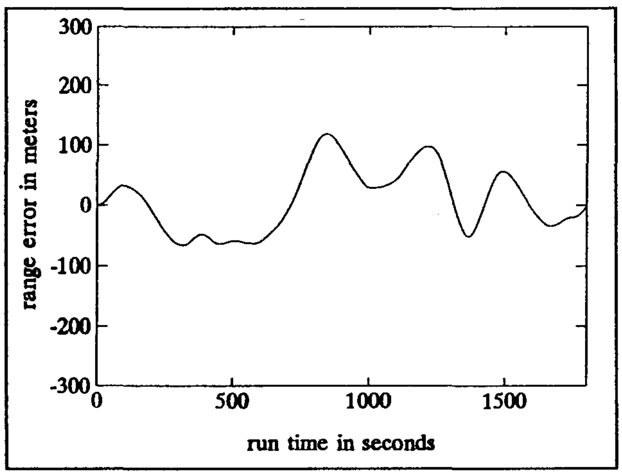

Figure 2. Pseudorange error due to SA.

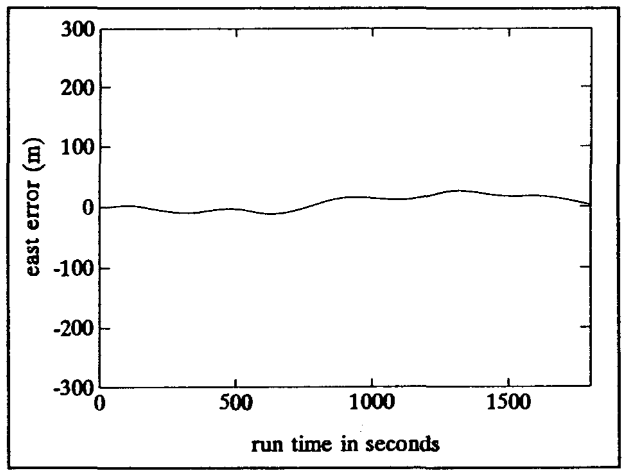

Figure 5. Complementary Kalman filter results.

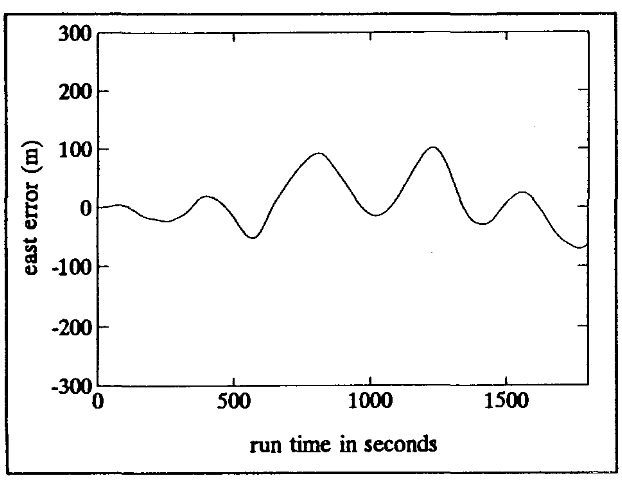

Figure 3. Raw GPS position error due to SA.

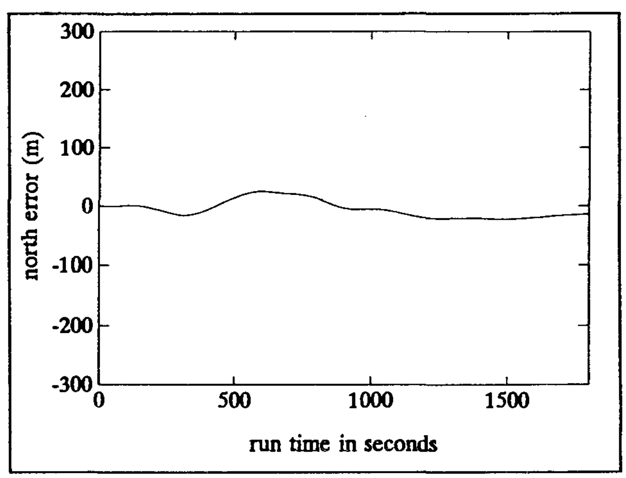

Figure 6. Complementary Kalman filter results.

Flight Test

Although extremely encouraging, the simulation results were obtained using a simple model for Loran-C position errors. In order to verify the robustness of the technique, actual flight data was used. This is necessary since Loran-C position error bias is spatially dependent.

The flight data employed here were collected during a trip from Cleveland to Athens, Ohio in Fall of 1990 (figure 7). It may be recalled that SA was temporarily turned off at that time because of military use of civilian GPS receivers during Operation Desert Shield [6]. As a result, the GPS horizontal positioning accuracy is on the order of 10-20 meters [1]. For this flight, the GPS-derived position was therefore used as a rough truth reference.

SA was generated by the model described earlier and added to the raw GPS pseudorange measurements (figure 8). As expected, the Loran-C position error is biased but the bias is not constant with position (figures 9 and 10). As was done earlier, altimeter error was modeled as a constant 200 meter bias. Raw SA-induced position errors are as expected with large excursions and high correlation (figures 11 and 12). Again, position errors after smoothing are significantly reduced (figures 13 and 14). It is important to note that even in the face of spatially varying Loran-C position errors, the mitigation scheme continues to perform well.

Conclusions

A technique has been described whereby the stability of Loran-C signals are exploited to reduce SA-induced GPS position errors. The viability of the technique has been confirmed using simulations as well as actual flight data. Future work will consider the possibility of realtime SA model identification.

Acknowledgements

This work was supported by the Federal Aviation Administration and the National Aeronautics and Space Administration through the Joint University Program for Air Transportation Research (Grant NGR 36-009-17). The author would like to express her gratitude to the entire staff of the Avionics Engineering Center at Ohio University for their encouragement and support. Special thanks are also given to Professor Robert W. Lilley and Professor Durk van Willigen for their careful review of this paper.

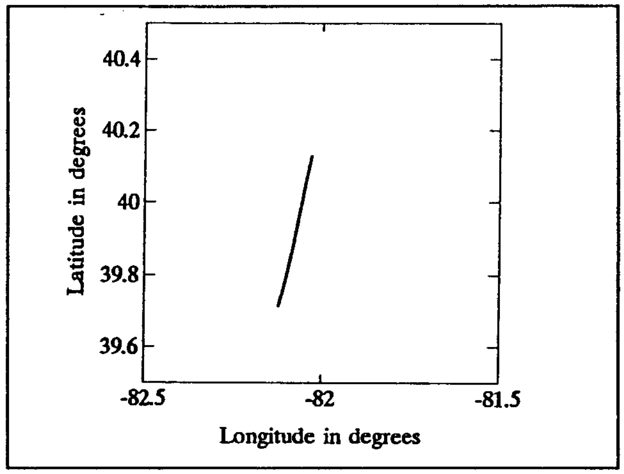

Figure 7. Ground track, 1990-Nov-01.

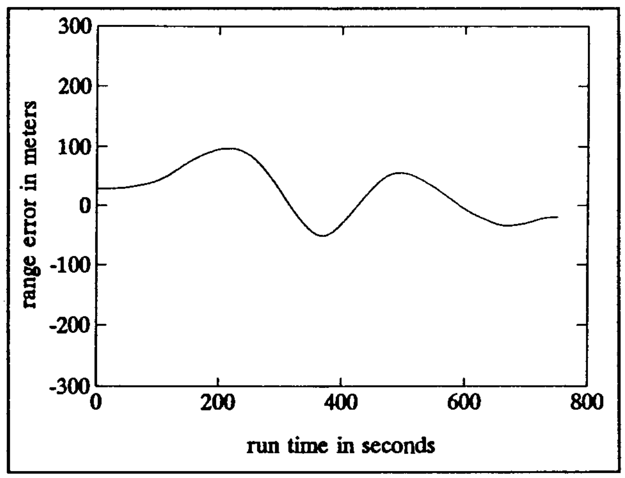

Figure 8. Pseudorange error due to SA.

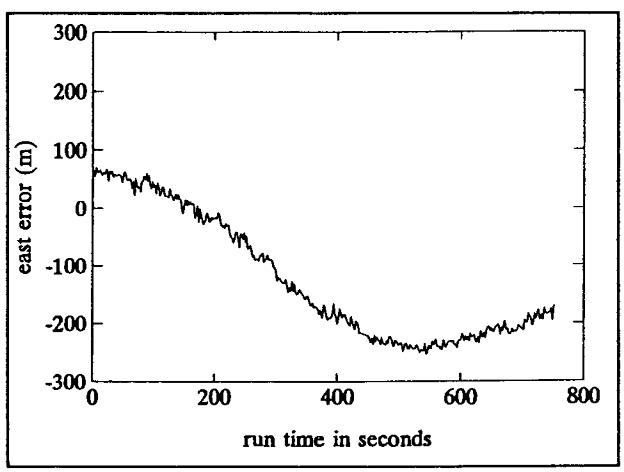

Figure 9. Loran-C position error.

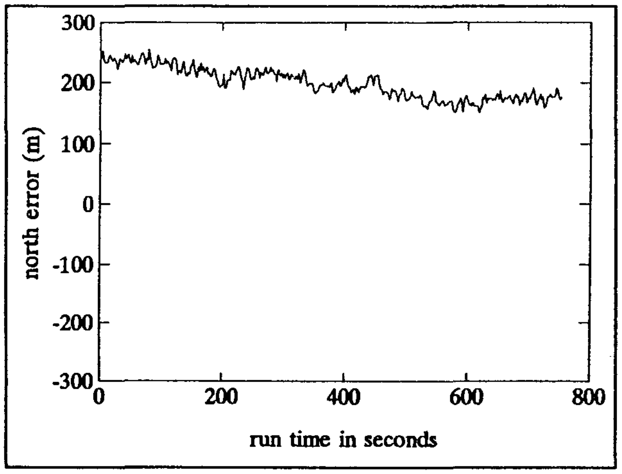

Figure 10. Loran-C position error.

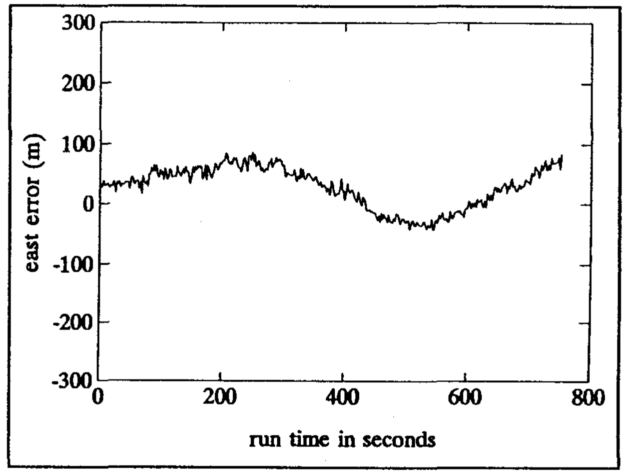

Figure 13. Complementary Kalman filter results.

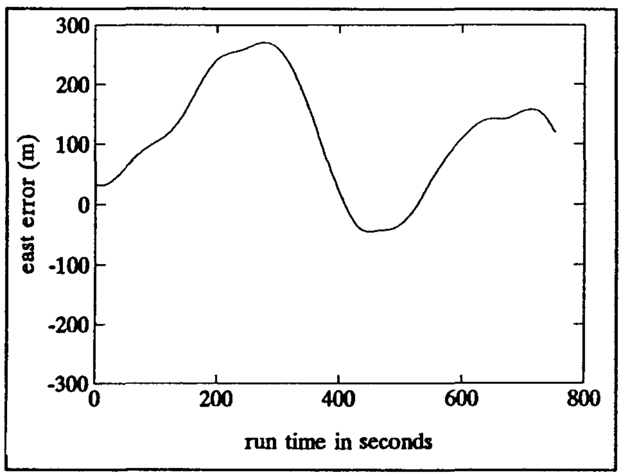

Figure 11. Raw GPS position error due to SA.

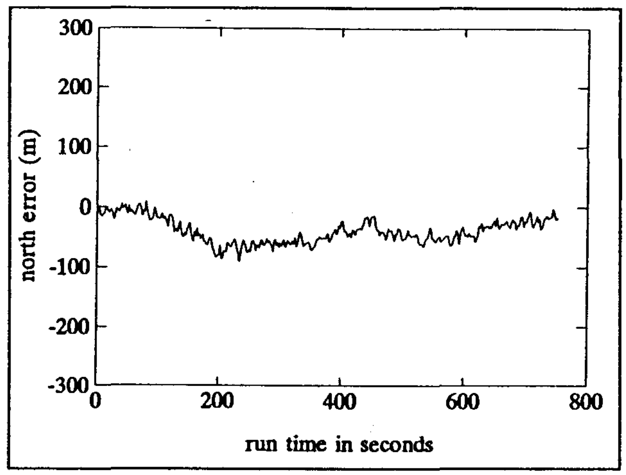

Figure 14. Complementary Kalman filter results.

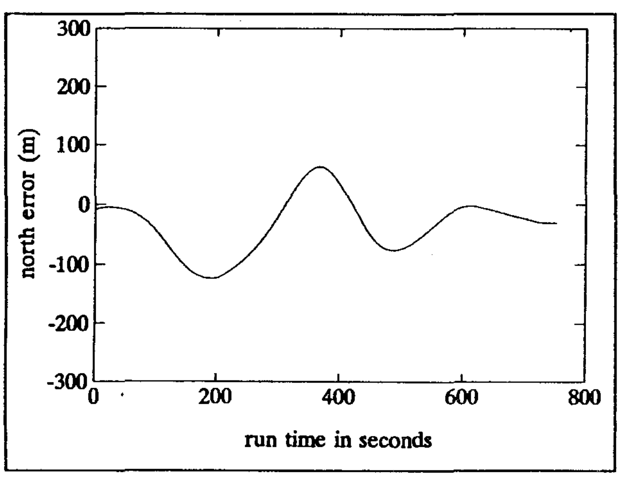

Figure 12. Raw GPS position error due to SA.

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Novel techniques for the identification of Loran-C skywaves

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Abstract

It is conventionally assumed that Loran-C receivers avoid skywave contamination by processing only samples taken prior to the arrival of the first skywave components, typically 35-60 μs after the groundwave. The technique has significant limitations, however, when implemented in receivers of finite bandwidth, since such receivers increase the risetimes of the Loran-C pulses and substantially reduce the amplitudes of the groundwave signals at the 30 μs point. As a result, many current receivers are designed to take samples later in the pulse and consequently suffer skywave errors. This paper will briefly examine the consequences of this practice. It will then propose a new class of techniques which allow the onset of skywave signals to be detected so that the sampling point may be adjusted accordingly. Novel algorithms to distinguish skywaves from the groundwave will be presented. Their benefits will be assessed, together with the cost, in computing resources, of implementing them. The paper will also include theoretical analyses, simulations and Monte Carlo experiments to demonstrate the performance of the techniques.

1 Introduction

The ability of receivers to resist skywave contamination is a major advantage of Loran-C over continuous-wave navigation aids. As a result, a single chain of Loran-C transmitters can provide coverage of a large geographical area. The skywave rejection principle is simple: skywaves travel via longer paths and so arrive at least 35 μs after the groundwave; hence they can be avoided by processing only the first 30 μs of the groundwave signals. The 30 μs timing point, the 'standard zero-crossing', is the third positive-going zero-crossing of the 100 kHz carrier.

In practice, Loran-C receivers are limited in their immunity to skywave errors by the finite bandwidths of the front-end filters required to attenuate noise and interference outside the allocated Loran-C band, 90-110 kHz. Unfortunately such filters increase the rise-times of Loran-C pulses and reduce the amplitudes of the groundwave signals at the standard zero-crossing (Fig. 1). To compensate, many receivers take samples later in the pulse and so suffer skywave errors.

Choosing the optimum sampling point is a compromise. The later the sampling point in the pulse, the less is the noise error but the greater the skywave error. Feldman studied this trade-off in terms of the filter bandwidth [1]. He concluded that skywave delay is more significant than amplitude in causing timing measurement errors.

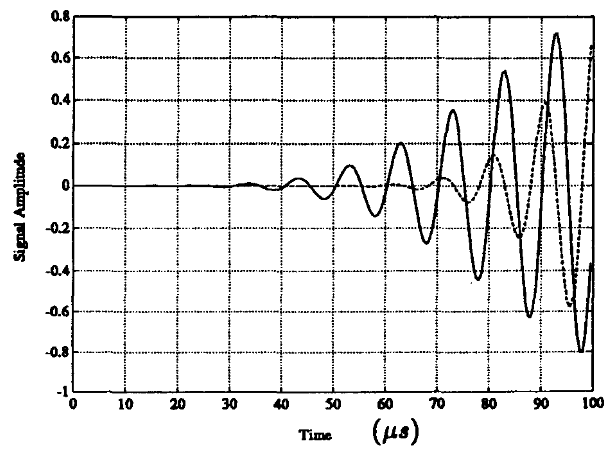

Fig.1 Groundwave (solid) and skywave (dashed) signals out of bandpass filter. Zero time is the start of the input (groundwave) pulse. The bandpass filter is a 5th order Butterworth with 20 kHz pass band and 100 kHz centre frequency. The amplitude (+12 dB) and delay (37.5 μs) of the skywave relative to the groundwave are limiting values specified for minimum Loran-C receiver performance.

Loran-C measurements show that skywaves may arrive with delays between 35 and 500 μs depending on the timeof day and season of the year [2,3]. The Minimum Performance Standards (MPS) specifies the range of skywave parameters within which receivers must work correctly [4,5]. If the receiver always times its phase samples to cope with the limiting skywave conditions , a heavy price is paid in SNR under more typical conditions. To reduce the time-of-arrival (TOA) uncertainty due to skywave interference to 0.5 μs, the sampling must be set to 65 μs. The strength of Loran-C signal at the sampling point is then only about 0.1 of its peak value and poorer SNR results. If the samples are taken later the SNR will be higher but cycle-locking problems may occur [6]. An adaptive receiver which adjusted its sampling point according to the skywave interference conditions would be attractive. This would require a technique for measuring the skywave parameters quickly, accurately and continuously. Unfortunately, little development has been carried out to this end, either by theoretical analysis or in receiver practice.

Section 2 will briefly review the current state and limitations of skywave identification techniques. The formulation of the problem employing a mathematical model of the received signal with groundwave and skywaves components, will be presented in Section 3. Sections 4 and 5 will propose the principle of skywave delay measurement by spectral or cepstral analysis. The performance of these techniques in noisy conditions will be demonstrated by computer simulation in Section 6. Section 7 will discuss the implementation of these techniques in receivers.

2 Current techniques

Current Loran-C receivers cannot identify or monitor skywaves. Some receivers do check for an incorrect skywave lock by means of a guard sample; for example, the Austron 5000 Loran-C Monitor Receiver takes such a sample 37.5 μs before the zero-crossing sample [3]. If the receiver is correctly tracking the 30 μs point no signal should be detected by the guard sample. If it is, the receiver may be tracking the skywave, or synchronous carrier-wave interference. Although this technique may detect the cycle-slips caused by skywave, it cannot measure the skywave parameters when tracking the correct zero-crossing, even when experiencing intolerable phase-tracking errors. Neither can the technique distinguish skywave from carrier-wave interference.

Peterson and Dewalt have recently studied the problem of skywave interference and measured skywave parameters [6]. They first modelled the groundwave, assuming that it was an ideal Loran-C pulse distorted during propagation and by the front end filters of the receiver. A least-squares best fit to the leading edge of the received groundwave revealed its parameters. Then the groundwave was subtracted from the composite signal to disclose the skywave. The same least-squares procedure was then applied to the skywave to determine its parameters. It is believed that this method works well when the skywave delay is long but it may be difficult to apply to short-delay skywaves when relatively little of the groundwave is available on which to attempt the least-squares fit.

Lievin and others have measured skywave parameters in Europe [7], also by modelling the groundwave and subtracting it from the received signal to reveal the skywave. They pointed out that accurate modelling of skywave parameters depends on an accurate knowledge of the groundwave. They measured the groundwave, free of skywave contamination, close to the transmitter. However, this still begs the question of how to model the groundwave accurately, or measure skywave parameters, in a receiver.

3 Formulation of the problem

In this subsection we set up a signal model which will used later when we attempt to identify skywave parameters. Loran-C receivers must process signals that contain the groundwave and skywaves, plus noise and interference. These components are added together at the receiver antenna. The composite signal received is:

$$x_c(t) = x_g(t) + x_s(t) + e(t) \tag{1}$$

where $x_g(t)$ and $x_s(t)$ represent the groundwave and skywaves, and $e(t)$ the total noise and interference.

The skywave signal may contain many components which have arrived via different paths. Let us assume that these all have the same shape as the groundwave signal; they may then be viewed as delayed and linearly-scaled versions of the groundwave. Using Delta function notation, these skywave components may be represented as the groundwave signal convolved with a train of impulses which describe the start time of each component. That is,

$$x_s(t) \quad = \quad \sum_{n=1}^{N} k_n x_g(t - \tau_n)$$

$$= \quad x_g(t) * \sum_{n=1}^{N} k_n \delta(t - \tau_n) \qquad (2)$$

where N is the number of skywave components and k_n and τ_n represent the amplitude and delay of the n-th skywave component relative to the groundwave. Hence, equation (1) can be rewritten as:

$$x_c(t) = x_g(t) * h(t) + e(t) \qquad (3)$$

where the function $h(t)$ is defined as

$$h(t) = \delta(t) + \sum_{n=1}^{N} [k_n \delta(t - \tau_n)] \qquad (4)$$

Equations (3) and (4) constitute the basic model which will be used in developing the process for estimating the skywave parameters to be described in the following sections.

4 Spectral analysis method of skywave detection

Equation (3) represents the composite received signal as the groundwave signal $x_g(t)$ convolved with the function $h(t)$ which characterises both the groundwave and the delay times and amplitudes of the skywaves. The methodology used for isolating the skywave is to separate, or deconvolve $x_g(t)$ and $h(t)$, and hence estimate the skywave delay from $h(t)$. In general, such deconvolution is difficult in the time domain. However, it will be shown to be possible in the frequency domain provided the structure of the spectrum of the groundwave is known.

Since the Fourier Transform converts convolution into a multiplication, take the Fourier Transform of equation (3) to obtain its equivalent in the frequency domain:

$$\begin{aligned} X_c(f) &= X_g(f)\, H(f) + E(f) \\ &= X_g(f) \left[1 + \sum_{n=1}^{N} k_n\, e^{j2\pi f \tau_n} \right] + E(f) \qquad (5) \end{aligned}$$

where $X_c(f)$, $X_g(f)$, $H(f)$ and $E(f)$ represent the Fourier Transforms of $x_c(t)$, $x_g(t)$, $h(t)$, and $e(t)$, respectively. If the spectrum of the groundwave signal is known, then $H(f)$ should easily be obtainable by dividing $X_c(f)$ by $x_g(f)$. In general, $x_g(f)$ is not known before the separation of groundwave from skywave components. However, if the distortion of the groundwave pulse can be ignored, then at least its spectrum $X_g(f)$ is known, apart from the amplitude scaling factor:

$$X_g(f) = k_g X_0(f) \qquad (6)$$

where $X_0(f)$ is the spectrum of the well-defined, normalised standard Loran-C pulse, and k_g is a constant related to the amplitude of the groundwave. Substituting equation (6) into (5) and then dividing $X_c(f)$ by $X_o(f)$, we get

$$\frac{X_c(f)}{X_0(f)} = k_g \left[1 + \sum_{n=1}^{N} k_n\, e^{j2\pi f \tau_n} \right] + \frac{E(f)}{X_0(f)} \qquad (7)$$

Taking the inverse Fourier Transform of both sides:

$$\begin{aligned} F^{-1}\left\{ \frac{X_c(f)}{X_0(f)} \right\} &= k_g \left[\delta(t) + \sum_{n=1}^{N} k_n\, \delta(t - \tau_n) \right] \\ &\quad + F^{-1}\left\{ \frac{E(f)}{X_0(f)} \right\} \qquad (8) \end{aligned}$$

This equation shows that a complete knowledge of the groundwave spectrum, $X_g(f)$ is unnecessary, but the method does require the structure of $X_g(f)$ to be known if the function $h(t)$ is to be recovered. The first term on the right of side of (8) clearly shows that any skywave delay time may be found from the corresponding impulses caused by that skywave component, when we take the inverse Fourier Transform of $\frac{X_c(f)}{X_0(f)}$. Ignoring noise for the time being, the strengths of the groundwave and skywave components may also be found from the heights of these impulses. Fig. 2 shows a sample result to demonstrate the principle. The performance of the technique in noisy environments will be discussed in section 5.

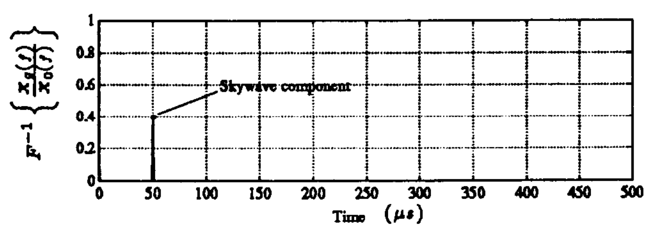

Fig.2 Skywave detection using the spectral analysis technique. Skywave parameters: skywave delay=50 μs, skywave-to-groundwave ratio = 12 dB.

5 Cepstral analysis

In this section we present a theoretical tool, cepstral analysis, which is new to Loran-C, and explain how it may be used to detect skywave delay. The technique does not require any *a priori* knowledge of the groundwave.

Cepstral analysis is a nonlinear processing technique for analysing data that contain an arbitrary unknown signal and its echoes. The effectiveness of the technique is due to its superior ability to detect the presence of certain features hidden in the original time data, when compared to time domain analysis.

The concept of the 'cepstrum' was introduced by Bogert, Healy, and Tukey in a paper with a rather unusual title [9]. They showed that the logarithm of the power spectrum of a signal containing an echo had an additive periodic component due to the echo, and demonstrated that the Fourier Transform of this log-power spectrum exhibited a peak at the echo delay. The log-power spectrum they termed the *cepstrum*, a play on the word *spectrum*, because: "In general, we find ourselves operating on the frequency side in ways customary on the time side and vice versa"[9].

Cepstral analysis has been applied to many diverse fields [10 and its references, 11-14]. Childers and others have provided an excellent tutorial on cepstral processing techniques in [10] and introductory material on this subject may also be found in [15] .Some of the variety of forms of cepstrum which have been defined will now be considered and applied to the Loran-C skywave measurement problem.

5.1 The Power Cepstrum

The power cepstrum of a signal $g(t)$ is defined as

$$\hat{g}_p(\tau) = F^{-1}\{ln|G(f)|\} \tag{9}$$

where $G(f)$ is the Fourier Transform of $g(t)$, ln represents the natural algorithm operation, and F^{-1} the inverse Fourier Transform operator. Notice that the power cepstrum is a function of τ, which has the units of time, but is termed "quefrency" in the literature to distinguish it from normal time.

To illustrate how the power cepstrum can be used to estimate skywave parameters, consider a signal that contains only the groundwave and a single skywave component:

$$\begin{aligned} x_c(t) &= x_g * h(t) \\ &= x_g(t) * [\delta(t) + k_1\delta(t-\tau_1)] \end{aligned} \tag{10}$$

To calculate the cepstrum of this signal, we first calculate its log-power spectrum

$$\begin{aligned} ln|X_c(f)| &= ln|X_g(f)\left[1 + k_1\ e^{j2\pi f\tau_1}\right]| \\ &= ln|X_g(f)| + ln\sqrt{1 + k_1^2 + 2k_1 cos2\pi\tau_1} \\ &= ln|X_g(f)| + \frac{1}{2}ln(1+k_1^2) \\ &\quad + ln\left(1 + \frac{2k_1}{1+k_1^2}cos(2\pi f\tau_1)\right) \end{aligned} \tag{11}$$

The last term of this log-power spectrum may be further expanded into a power series (except for the point values $k_1 = 1$ and $cos(2\pi f\tau_1) = \pm 1$) as:

$$\begin{aligned} & ln\left(1 + \frac{2k_1}{1+k_1^2}cos(\pi f\tau_1)\right) \\ = & \sum_{m=1}^{\infty} \frac{(-1)^{m+1}}{m}\left[1 + \frac{2k_1}{1+k_1^2}cos(\pi f\tau_1)\right]^m \end{aligned} \tag{12}$$

This log-power spectrum exhibits ripples whose amplitude and quefrency (their frequency) are related to the amplitude k_1 and delay τ_1, respectively, of the skywave component. Consequently the cepstrum of the signal, which is the inverse Fourier Transform of the log-power spectrum, has peaks at quefrencies τ_1 and its multiples. The skywave delay can be obtained simply by noting the quefrency of the first peak in the power cepstrum domain. In principle, the amplitude of the skywave may also be estimated from this impulse peak by intepretating equation (8) in the cepstrum domain.

The necessary condition for the skywave delay to be detectable is that its corresponding impulse should not be buried under the cepstrum of the groundwave signal. This requires that the cepstra of $x_g(t)$ and $h(t)$ should occupy different regions of the quefrency axis, or, at least, that the cepstrum of $x_g(t)$ should be fairly smooth in the region occupied by the cepstrum of $h(t)$.

5.2 The Complex Cepstrum

The complex cepstrum of a signal g(t) is defined as the inverse Fourier Transform of the complex logarithm of the spectrum of that signal. That is

$$\hat{g}(\tau) = F^{-1}\{lnG(f)\} \tag{13}$$

Here ln represents the complex logarithm operation which is defined as

$$lnG(f) = ln|G(f)| + j\ \Phi_G(f) \tag{14}$$

where $|G(f)|$ and $\Phi_G(f)$ are the amplitude and phase functions of $G(f)$, which satisfy the relation:

$$G(f) = |G(f)| \cdot e^{j\,\Phi_G(f)} \tag{15}$$

The complex and power cepstra are closely related. From their definitions, it can easily be shown that the power cepstrum is actually the real part of the complex cepstrum. However, unlike the power cepstrum whose phase information is disregarded, the complex cepstrum retains the phase information of the composite signal. Because of this, it has many applications where the power cepstrum fails [10]. A very important application is in homomorphic deconvolution or homomorphic filtering: these allow the basic wavelet (the groundwave here) to be separated from its echoes (the skywaves), the echoes to be separated out in the cepstrum domain, and the original wavelet recovered [10,15].

To show how, in principle, that the complex cepstrum may be used to identify skywave parameters, we calculate it for the composite signal $x_c(t)$ in equation (6):

$$\begin{aligned} \hat{x}_c(\tau) &= F^{-1}\{ln\{F\{x_g(t) * h(t)\}\}\} \\ &= \hat{x}_g(\tau) + F^{-1}\{ln\{F\{h(t)\}\}\} \end{aligned} \tag{16}$$

where F represents the Fourier Transform, and the contents of the outer braces of the last term equal

$$\begin{aligned} ln\{F\{h(t)\}\} &= ln\{F\{\delta(t) + k_1\delta(t-\tau_1)\}\} \\ &= ln\{1 + k_1 e^{j2\pi f\tau_1}\} \end{aligned} \tag{17}$$

When $k_1 < 1$, this term can be further expanded into a power series:

$$ln\{1 + k_1 e^{j2\pi f\tau_1}\} = \sum_{m=1}^{\infty} \frac{(-1)^{m+1}}{m} \left(k_1^m e^{j2\pi fm\tau_1}\right) \tag{18}$$

Thus the complex cepstrum becomes:

$$\hat{x}_c(\tau) = \hat{x}_g(\tau) + \sum_{m=1}^{\infty} \frac{(-1)^{m+1}}{m} k_1^m \delta(\tau - m\tau_1) \tag{19}$$

When $k_1 > 1$, the right side of equation (17) may be expanded into another power series:

$$\begin{aligned} & ln\{1 + k_1 e^{j2\pi f\tau_1}\} \\ = \; & ln\{k_1 e^{j2\pi f\tau_1}(1 + \frac{1}{k_1} e^{-j2\pi f\tau_1})\} \\ = \; & lnk_1 + j2\pi f\tau_1 + \sum_{m=1}^{\infty} \frac{(-1)^{m+1}}{mk_1^m} e^{-j2\pi fm\tau_1} \end{aligned} \tag{20}$$

After removing the linear term $j2\pi f\tau_1$, the cepstrum yields

$$\begin{aligned} \hat{x}_c(\tau) &= \hat{x}_g(\tau) + (lnk_1)\delta(\tau) \\ &+ \sum_{m=1}^{\infty} \frac{(-1)^{m+1}}{mk_1^m} \delta(\tau + m\tau_1) \end{aligned} \tag{21}$$

In both equations, (19) and (21), the complex cepstrum of the composite signal containing a skywave will always have peaks at the skywave delay and its multiples. However, if the skywave amplitude is greater than the groundwave, these peaks occur at negative rather than positive quefrencies.

5.3 The Phase Cepstrum

The phase cepstrum of a signal is the counterpart of its power cepstrum in that it is defined as the inverse Fourier Transform of the phase function of the complex logarithm of the original signal. Using the same notation as in equations (12) and (13), it is formally defined as:

$$\hat{g}_\phi(\tau) = F^{-1}\{\Phi_G(f)\} \tag{22}$$

By definition, $\hat{g}_c(\tau) = \hat{g}_p(\tau) + \hat{g}_\phi(\tau)$. As with the complex and power cepstra, we can show that a signal containing a skywave will yield peaks at the skywave delay in its phase cepstrum. In practice, however, the phase cepstrum is less useful than the power cepstrum in estimating skywave delay times, since reliable computation of the unwrapped phase is exceptionally difficult [10].

6 Performance evaluation under noisy conditions

Sections 4 and 5 explained the principle of using spectral and cepstral techniques to estimate skywave delay. For simplicity, the noise and interference terms were ignored. A computer simulation, employing a Monte-Carlo method, will now be employed to estimate their performance when noise is present.

6.1 Simulation arrangement

All simulations were written using the advanced software package Pro-Matlab [16] and run on a Sun Workstation. Fig. 3 shows a functional block diagram of the simulation program.

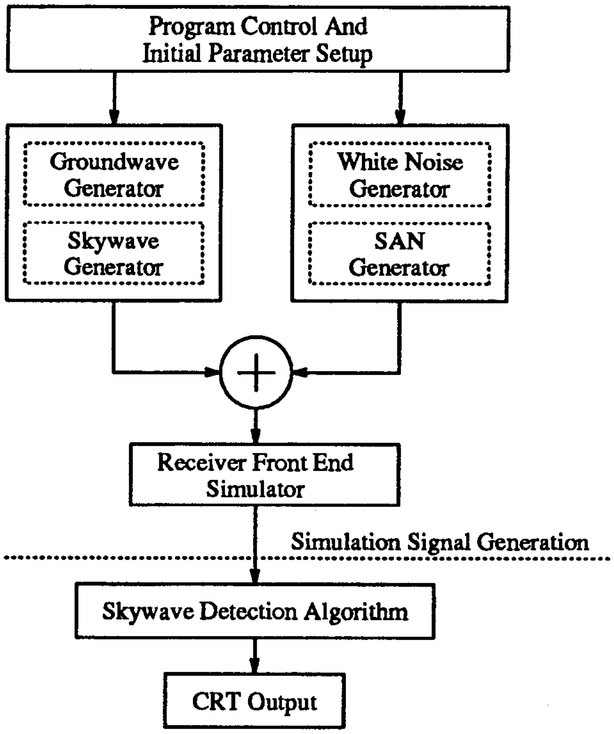

Fig.3 Functional block diagram of programs which simulate the operation of the proposed skywave detection techniques under noisy conditions.

The Program Control block controls the operation of the functional blocks and sets up the initial parameters for the other blocks. These parameters include the strength of the groundwave and skywaves, the skywave delay, the strength and bandwidth of the noise, and the bandwidth used in the Receiver Front End Simulator block. In accordance with MPS practice [4,5], Simulated Atmospheric Noise (SAN) is generated. This noise is added to the separately-generated Loran-C groundwave and skywaves, and fed into the Front End Simulator block. Then the Skywave Detection Algorithm block estimates the skywave delay.

Many special problems arise in computing the various forms of the cepstrum of the composite signal in the presence of noise. A common problem is that the nonlinear logarithmic operation magnifies substantially the noise in those parts of the Loran-C spectrum where the signal energy is low. Our solution was to design a window which suppresses the log-spectrum in the frequency bands, outside 90-110 kHz, where the noise power density exceeds that of the groundwave signal. Experience has shown that a substantial improvement of estimation accuracy may be achieved by using this technique, especially when the SNR is below 40 dB.

Other problems associated with cepstrum calculation include reliable phase unwrapping for the complex and phase cepstra, the effects of notches in the spectrum, oversampling, aliasing, and the need to append zeroes to increase the resolution in the frequency and quefrency domains. Interested readers are referred to [10,13, 15,17,18]

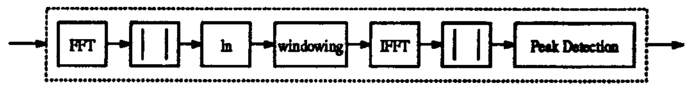

Fig.4 Implementation of skywave detection algorithm by power cepstrum method.

A block diagram of the implementation of the power cepstral analysis method is shown in Fig.4. The spectrum of the composite signal is calculated by calling the Fast Fourier Transform (FFT) routine provided by Pro-Matlab, which uses a radix-two algorithm if the length of the signal is a power of two, and a mixed radix algorithm if the length is not a power of two [15,16].

6.2 Results of the Simulation

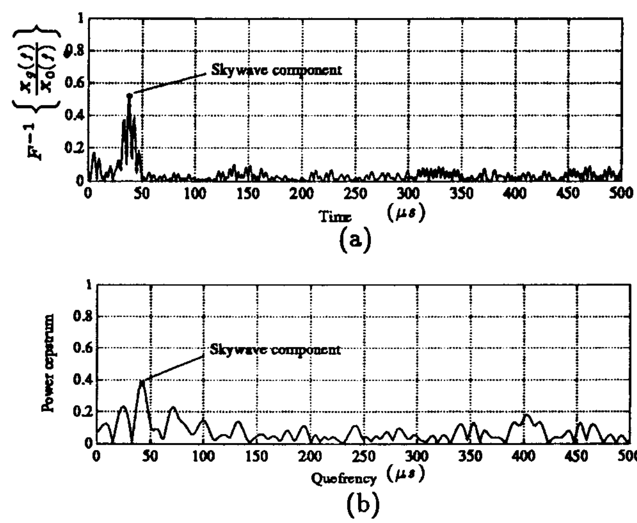

Fig.5 Examples of the proposed skywave detection techniques in operation, (a) the spectral analysis method (section 4), (b) power-cepstral method (section 5.1). SNR = 24 dB.

Simulation programs for all four methods described in sections 4 and 5 have been developed and extensive simulations performed. Table 1 summarises the results of 100 simulations of the spectral analysis (Section 4) and the power cepstral analysis (Section 5.1) algorithms. Sample outputs of these simulations are shown in Fig. 5. The phase calculation in the phase and complex cepstrum methods turned out to be very sensitive to noise due to the phase-unwrapping errors and, consequently, it was decided not to pursue these methods.

Delay time (μs)	SGR (dB)	Spectral method		Power cepstral	
		Mean	SD	Mean	SD
37.5	12	38.0	0.0	40.34	2.2
60	26	60.0	0.0	60.1	3.6

Table 1. Mean and standard deviation of the estimation of skywave delay time, in μs, for 100 simulations of the spectral and power cepstral algorithms.

Fig. 5 and Table 1 show that both the spectral and power cepstral methods sucessfully detected the skywave at an SNR of 24 dB. It is also seen that the cepstral method is more sensitive to noise than the spectral method. Computer simulations show that, as the SNR falls below a threshold, the performance of both the spectral and power cepstral methods degrades rapidly, and the techniques lose their ability to detect skywaves. These threshold values appear to be about 14 dB for the spectral method and 21 dB for the power cepstral method.

It should be noted that these SNR values are the values *after* integration of the Loran-C pulses. The threshold SNR for skywave detection by the more noise-sensitive power cepstral method, 21 dB, corresponds to a standard deviation (SD) uncertainty in time-of-arrival (TOA) measurement of approximately 140 ns. Two signals of this SNR would yield a time-difference SD uncertainty of approximately 200 ns. This is twice the value the US Coast Guard employ to set their minimum SNR value of -10 dB at the input to a receiver in predicting the coverage of Loran-C chains. Thus the power cepstral technique appears to operate successfully at values of SNR 6 dB below the minimum specified by the USCG, and the spectral technique at 13 dB lower.

7 Implementing the algorithms in receivers

The algorithms developed in the earlier sections offer the possibility of receivers' detecting and monitoring skywave delays continuously and so minimising errors. Fig. 6 shows the block diagram of a receiver in which an additional channel for skywave detection is added to a conventional receiver.

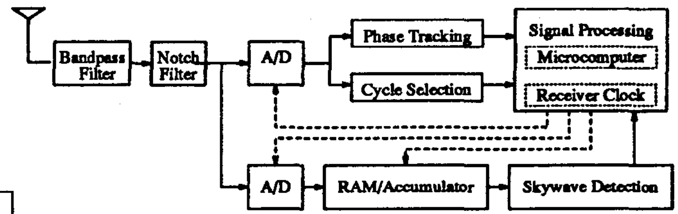

Fig.6 Block diagram of Loran-C receiver with skywave detection capability.

Signals entering the skywave channel are sampled to generate an accurate spectrum in the frequency band where the Loran-C signal is dominant. The samples are fed to the RAM/Accumulator block which accumulates or averages the received Loran-C pulses to improve the SNR of the composite signal before the spectrum is calculated. A high-speed analog-to-digital (A/D) sampler of approximately 1 MHz sampling rate is required. The maximum update time for the RAM/Accumulator would be 1 μs. The memory requirement is modest, however, since only the outputs of the RAM/Accumulator need be stored. The processing power required for the cepstra calculation is mainly that needed for the Fourier and inverse Fourier Transformations. The number of multiplication operations required in a radix two FFT or IFFT is $N log_2 N$, where N is the number of samples transformed [15]. For example, doing an FFT on 2048 samples would requires 22,528 multiplications. Therefore the memory and computing resources required for implementing the techniques proposed in this paper may easily be satistied by the current state of the art.

8 Conclusions

Skywave interference commonly affects Loran-C receivers. Current designs of Loran-C receiver are not optimal in rejecting skywaves because they lack techniques to identify and monitor them. A group of new algorithms which use spectral or cepstral analysis have been proposed for this purpose. The performance of these algorithms has been evaluated by computer simulation. It has been shown that even under poor signal-to-noise ratio conditions, the time delay of the skywave may be measured successfully. The implementation of these algorithm in receivers has also been discussed. These requirements appear to be well within current hardware capabilities.

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GENERAL ASSEMBLY

Adopted Resolutions

The following are Resolutions adopted by the General Assembly of the Wild Goose Association at its 21st Annual Convention.

Resolution 1.

The Wild Goose Association having concluded its 21st Annual Convention and Technical Symposium in Birmingham, England with the theme "Loran-C/GPS Mix — Sharing the Future" over the period 24-27 August 1992, the General Assembly considered recent international Loran-C developments.

Noting: The continuing rapid expansion of the Loran-C and Chayka radionavigation systems throughout many parts of the world and in particular:

(a) That the North West Europe Loran-C Agreement between Norway, Denmark, Germany, Ireland, France and The Netherlands to adopt the Loran-C system was signed on August 6, 1992;
(b) That China, The Republic of Korea, Japan, and the Russian Federation will sign an Agreement in September 1992 to provide a Far East radionavigation service using Loran-C and Chayka;
(c) That in India the Decca Navigator Systems at Calcutta and Bombay have been replaced by Loran-C systems;
(d) That the littoral states of the Mediterranean Sea are pursuing the retention of the present Loran-C chain, the provision of Loran-C coverage of the Iberian Peninsula and means of linking with the Chayka chain covering the Black Sea;
(e) That joint Loran-C/Chayka chains are being discussed for the Barents Sea, Baltic Sea and Bering Sea;
(f) That coverage of the land mass in addition to the Coastal Confluence Zone of the United States and Canada has now been completed.

Noting Further: That the United Kingdom and Iceland withdrew from the North West Europe discussions before the Agreement was signed.

Recognizing:

(1) The Policy of the International Association of Lighthouse Authorities on Terrestrial Navigation Services; and,
(2) The decision of the Council of European Communities dated 25 February 1992 on Radionavigation Systems for Europe.

Recognizing also: That the full potential of the Loran-C and Chayka systems is only achieved by validating system performance in conjunction with the use of receivers employing modern digital techniques.

Resolves: That Administrations in areas covered by the Loran-C and Chayka systems be urged to:

(1) Recognize these systems as being acceptable for providing a Radionavigation Service in their area.
(2) Consider becoming signatories to the appropriate Agreement where one exists. In particular that the United Kingdom and Iceland reconsider their decision regarding the North West Europe Agreement.
(3) Promulgate a means for timely notification of the Radionavigation System operational status.

Recommends: This resolution be brought to the attention of all administrations in areas covered, or to be covered by the Loran-C and Chayka systems.

Resolution 2

The Wild Goose Association, The International Loran Radionavigation Forum, at its 21st Annual Convention and Technical Symposium held in Birmingham, England, considered international developments in terrestrial and satellite radionavigation systems.

Noting:

(a) The continuing rapid expansion of the Loran-C and Chayka radionavigation systems throughout many parts of the world;

(b) The increasing development of satellite navigation capabilities including GPS and GLONASS, leading toward a Global Navigation Satellite System (GNSS) service;

Recognizing:

(a) That while each of the terrestrial and satellite radionavigation systems individually provide benefits to users, the complimentary use of these systems will significantly enhance the navigational information available.

(b) That the highest practicable degree of navigational information should be used for the maximum possible benefit to marine, aeronautical and land users, including all safety, economic and environmental applications.

Resolves:

That administrations and authorities responsible for navigation in their areas be urged to promote the complementary use of Loran-C and Chayka with Global Navigation Satellite Systems, as they become available, as a means of providing the most complete and accurate navigational information to marine, aeronautical and land users, and

Recommends:

That Administrations, Authorities, Navigational Institutions and Associations worldwide:

(1) Take due notice of this resolution of the Wild Goose Association;

(2) Support the complementary use of terrestrial and satellite radionavigation systems; and

(3) Publicize widely information on the specifications, characteristics, benefits, status and plans of these systems.

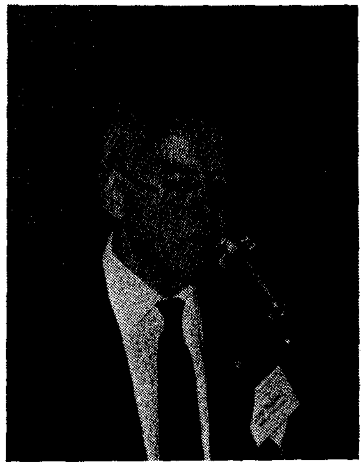
Authors

Aardoom, Eric		Last, David	
Bian, Yi		Matthews, Norman F.	
Blanchard, Walter F.		Mattos, Philip	
Braasch, Soo Y.		McGann, Ed	
Carroll, J.V.		Nash, J	
Cassidy, Frank		Nieuwland, Andre	
Dao, B.T.		Oakley, T.J.	
Dean, Walter N.		Peterson, B. B.	
Denisov, Vladimir I.		Qianzi, Wei	1
Dewalt, K.M.		Roland, William F.	
Farnworth, Richard		Rubiola, Enrico	
Fox, Mike		Serle, Mark	
Frank, Robert F.		Stenseth, Andreas	
Guoquiang, Gan	1	Thrall, William J.	2
Holden, Frank E.J.		van Nee, Richard D.J.	
Illgen, John D.		Watanabe, Clyde	
Jiaping, Yan	1	Weitzen, J.A.	
Kim, Jae Kuk	1	Wuwei, Bao	1
Kobayashi, Masamitsu	1	Xin, Guo	1

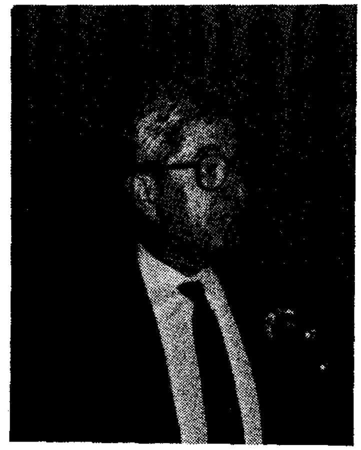
1. Report presented by Norman Matthews
2. Paper presented by Clyde Watanabe

Opening Ceremony

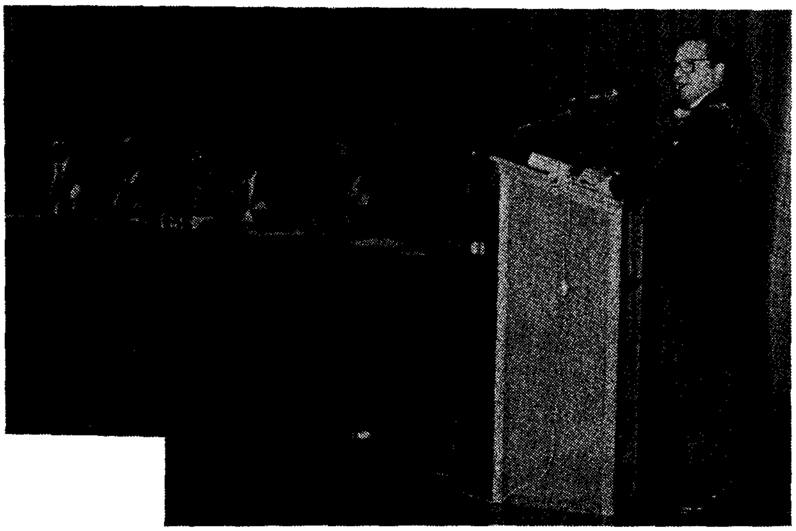
WGA President
Robert W. Lilley



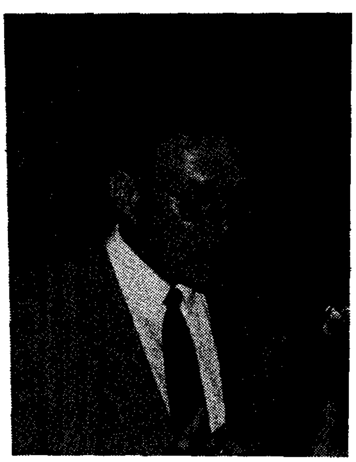
Convention Chairman
John M. Beukers



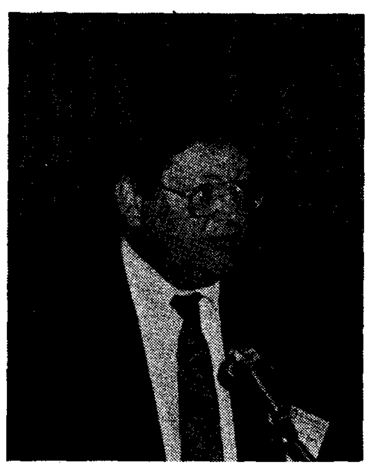
Chief Executive, Birmingham
Convention and Visitor Bureau
Philippe Taylor



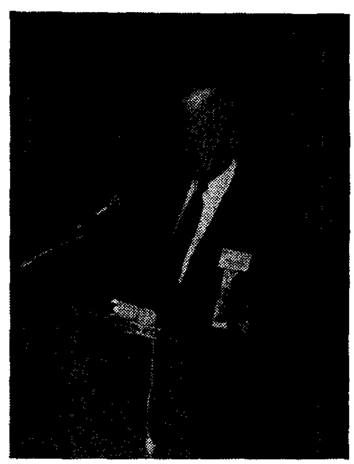
Welcome Address from the Right Worshipful
the Lord Mayor of Birmingham, Councillor Peter J. P. Barwell MBE



European Commission
Directorate of Transportation
Jacques de Dieu



Technical Chairman
John D. Illgen



Convention Co-Chairman
Maurice J. Moroney

Session Chairmen and Speakers - 1

Many contributed to the Technical Sessions and some were unable to avoid our photographers. Here is a sampling, with apologies to those we missed.

Left to right:

Richard van Nee
Frank Cassidy
Maurice Moroney
Vladimir Denisov
Andre Nieuwland
Eric Aardoom

Left to right:

Durk van Willigan
Andre Nieuwland
Jim Carroll
John Illgen

Left to right:

Frank Cassidy
Soo Braasch
Stuart Ruttle
Yi Bian

Session Chairmen and Speakers - 2

Left to right:

Andre Nieuwland
Laura Charron
Rolf Johannessen
Eric Aardoom
Philip Mattos

Left to right:

John Butler
Walter Dean
Robert Frank

Left to right:

Maurice Moroney
Walter Blanchard
(luncheon speaker)
Peter Ryder
Jacques de Dieu

1992 Convention Awards

1992 Awards Committee Chairman: James Van Etten
Committee Members: Frank Cassidy, Vernon Johnson

The WGA Constitution authorizes the presentation of a number of non-monetary awards to further the aims and purposes of the Association. The Medal of Merit and the President's awards were presented at the Civic Dinner held in the Birmingham City Council House; the remainder were presented at the second Convention luncheon held in the Copthorne Hotel.

Medal of Merit — Norman Matthews

The Medal of Merit is awarded for a particular contribution of outstanding value to the development or fostering of loran. This award is given only after the exceptional nature of the contribution is clearly recognized.

The Medal of Merit was awarded to Norman Matthews, Secretary General of the International Association of Lighthouse Authorities (IALA), in recognition of his dedicated efforts in fostering and coordinating Loran-C radionavigation policies of IALA Member States throughout the world.

President's Award — Andreas Stenseth and Kjell Enerstad

The President's Award is given to persons or organizations designated by the President of the Association. This year two awards were given.

One of the President's Awards was presented to Andreas Stenseth as Chairman of the North West Europe Loran-C Policy Group. Under his leadership Loran-C has been adopted for the European coastal waterways.

The second President's Award was presented to Kjell Enerstad as Secretary of the North West Europe Loran-C Policy Group. His support of member interests contributed to the adoption of Loran-C for the European coastal waterways.

Best Paper Award — David Last, Richard Farnworth and Mark Searle

The Best Paper Award is given to a person or persons for the best paper published on any aspect of loran.

The Best Paper Award went to David Last, Richard Farnworth and Mark Searlé from the Radionavigation Group, University of Wales, for their presentation of "Ionospheric Propagation & Loran-C Range - The Sky's the Limit" at the Twentieth Annual Technical Symposium and published in the Proceedings of that event.

Best Student Paper Award —Andre Nieuwland

The Best Student Paper Award is given to a bone fide student for the the best paper published on any aspect of loran.

The Best Student Paper Award went to Andre Nieuwland of Delft University of Technology, The Netherlands, for the publication of the paper entitled "Weighted Spectrum Analysis in Loran-C Receivers" presented at the Twentieth Annual Technical Symposium.

Convention Awards continued.......

Outstanding Service Awards

Service Awards are given to the persons who distinguish themselves by service to the Association

Elijah "Zeke" Jackson — For service as General Chairman of the Twentieth Annual Convention held in Williamsburg, Virgina, October 1991.

David C. Scull and David L. Olsen — For service as Technical Chairman and Technical Co-Chairman respectively, of the Twentieth Annual Technical Symposium held in Williamsburg, Virginia, October 1991.

Robert L. Frank — For service as Awards Chairman for the period 1980 to 1991.

Robert W. Lilley — For service as Editor of the WGA Newsletter *The Goose Gazette* for the period 1989 to 1991.

Industry Reception Sponsors

Bendix-King. Inc
Beukers Technologies, Inc.
Cambridge Engineering, Inc.
Coastwatch, Inc.
Datamarine International
Illgen Simulation Technologies, Inc.
Jet Electronics and Technology, Inc.
Megapulse, Inc.
Navcom Systems, Inc.
Northstar
Synetics Corporation
Trimble Navigation, Inc.

Hospitality Suite Sponsor

This year the Hospitality Suite was sponsored by the Wild Goose Association's treasury.

Exhibitors

Industry

Beukers Technologies, Inc.
Datamarine International
II Morrow, Inc.
Jet Electronics and Technology, Inc.
Megapulse, Inc.
Navtech Seminars, Inc.

Institutions

Commissioners of Irish Lights
Delft University of Technology
International Association of Lighthouse Authorities
North West Europe Loran-C Policy Group
Northern Lighthouse Board
Norwegian Defence Comm. & Data Services Admin.
Ohio University College of Engineering
Trinity House Lighthouse Service
United Kingdom Meteorological Office
University College of North Wales
Volpe National Transportation Systems Center

1992 Convention Awards

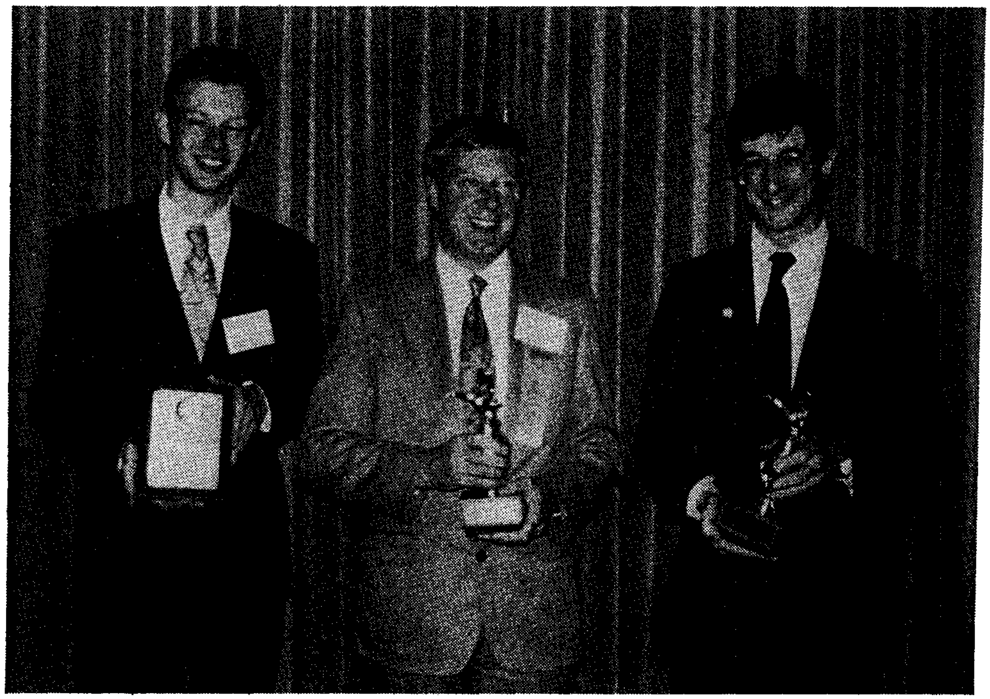
Breaking with tradition, the Service and Best Paper Awards were given at one of the luncheons. The Medal of Merit and President's awards were presented at the banquet.

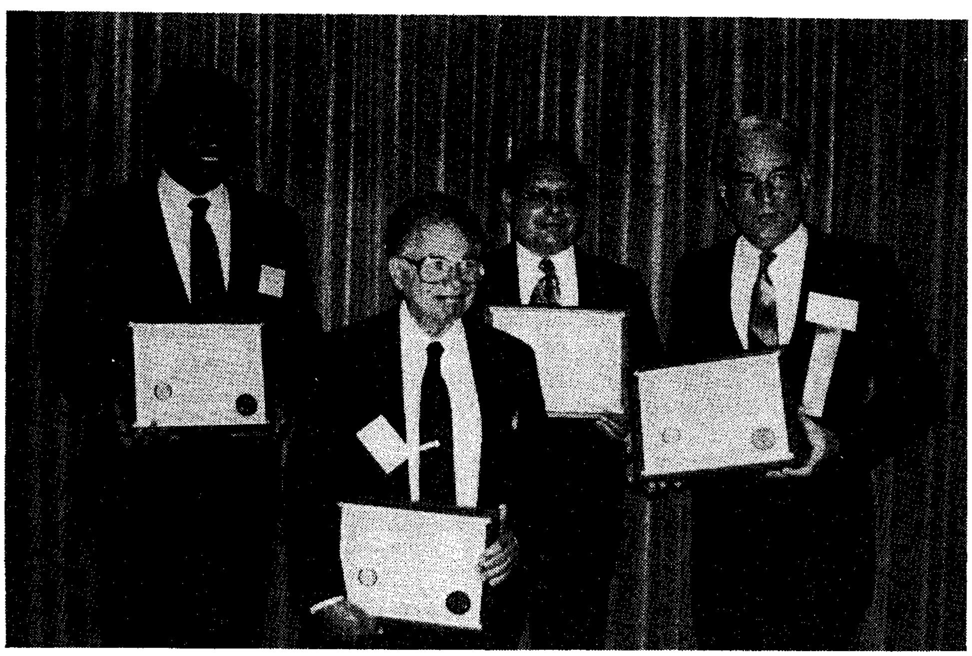
Best Paper Award

David Last (center)
Richard Farnworth (not shown)
Mark Searle (right)

Best Student Paper

Andre Nieuwland (left)





Service Awards
Left to right:

Elijah "Zeke" Jackson
Robert Frank
David Scull
Robert Lilley

Civic Dinner Invitation

The Traditional Convention Banquet was hosted by the City of Birmingham in the form of a Reception and Civic Dinner held in the City Council House.

The Lord Mayor of Birmingham
Councillor Peter J. P. Barwell M.B.E.
requests the pleasure of your company at a
Civic Dinner in the Banqueting Suite at
The Council House, Victoria Square, Birmingham
on Wednesday 26th August 1992 at 1900 for 1930 hours
on the occasion of the 21st Annual Convention and Technical
Symposium of the Wild Goose Association

To be presented upon arrival *Black Tie*

That's one headline we won't be writing

A Birmingham City Council employee came across a rather unusual entry in the Lord Mayor's diary the other day.

It read: "The Lord Mayor will be welcoming delegates to the 21st annual convention and technical symposium of the Wild Goose Association."

"I can see the newspaper headline now," he chuckled; "*Lord Mayor Goes on Wild Goose Chase!*"

Courtesy:
The Birmingham Post

Civic Dinner Preliminaries

Preparing to leave
for the Civic Dinner from
the Copthorne Hotel.

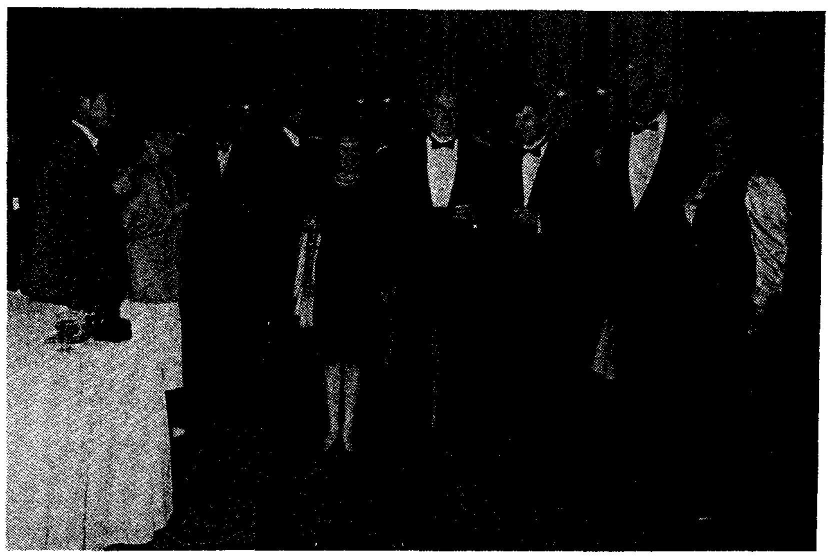
Reception in the
Lord Mayor's Parlour.
Left to right:
WGA President Robert Lilley,
Ellen Lilley, The Lord Mayor,
Marilyn Beukers, The Lady Mayoress,
and Convention Chairman John Beukers.

The Head Table is
announced into the
Banquet Hall.

Reception in the Council House

The Russian Delegation headed by Vladimir Denisov (left) with the Lord Mayor in ceremonial attire.

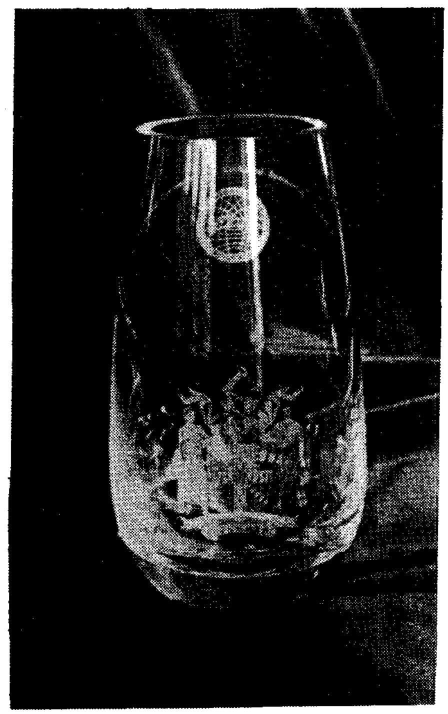
Enjoying a glass of wine and a chat before dinner.



Formal dress for the Dinner made for a truly elegant evening.
Left to right:
Astrid and Paul Johannessen,
Pauline Moroney,
Wilfred (Bill) St. John White.

Speeches and Presentations - Civic Dinner

WGA President Robert Lilley receives a gift (below) from the Lord Mayor of Birmingham.

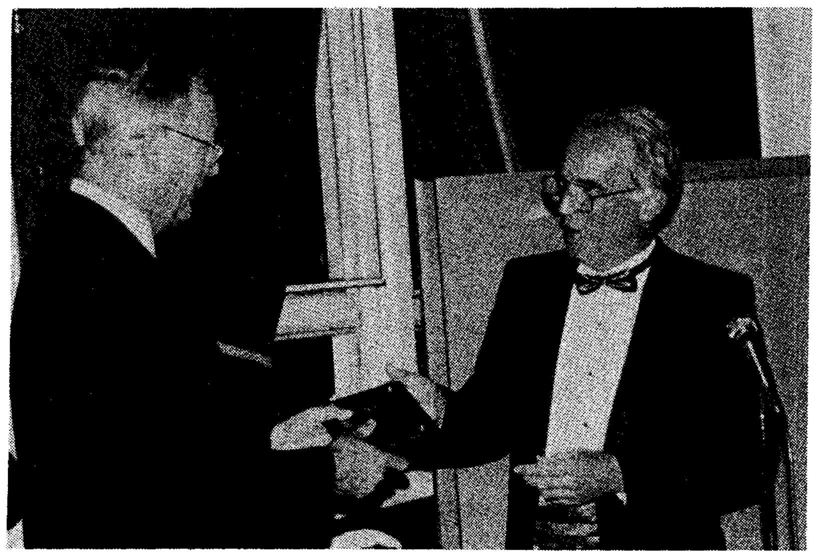


Engraved Glass Vase presented to the WGA by the Lord Mayor on behalf of the City of Birmingham.

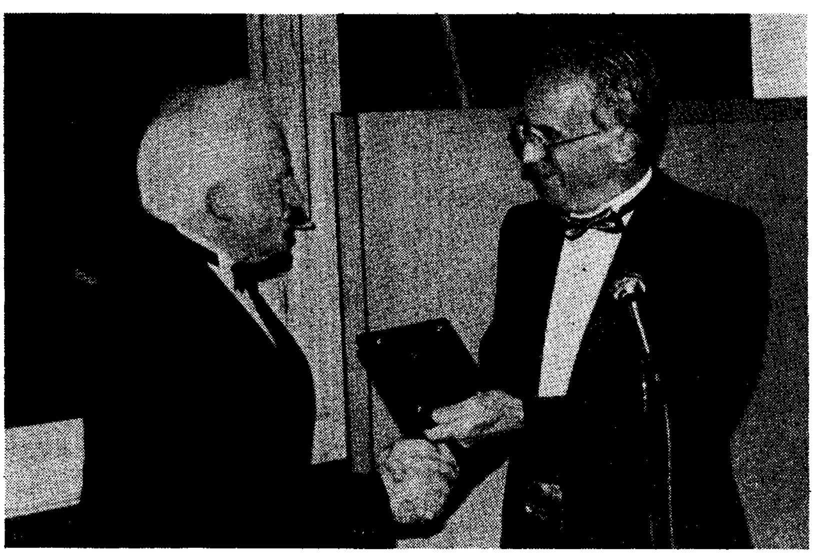
The Lord Mayor receiving an Engraved Plaque from the WGA President.

Awards Presentation - Civic Dinner

Awards Committee Chairman
James Van Etten (right)
presenting the 1992
Medal of Merit to
Norman F. Matthews (left),
as President Robert Lilley looks on.



WGA President Robert Lilley
presenting one of the two
President's Awards to
Andreas Stenseth,
Chairman of the North West
Europe Loran-C Policy Group.



WGA President Robert Lilley
presenting the second of the
two President's Awards to
Kjell Enerstad, Secretary
of the North West Europe
Loran-C Policy Group.

Civic Dinner Address by the Lord Mayor of Birmingham Councillor Peter J. Barwell M.B.E.

Lady Mayoress, Mr. President, Mr. Conference Chairman, Distinguished Guests.

I have a confession to make. In the course of my civic duties as Lord Mayor of this great City of Birmingham, I am called upon to make many speeches. My genius in this area is very limited, and has already been fully exercised in the preparation of certain standard texts.

So, I have a speech for visits by Government Ministers, a speech when I meet Community Workers, a speech for officially opening new buildings - and I opened a new wing to our Winson Green Prison (Penitentiary) the other day and managed to get out! These speeches are all environmentally friendly, they are recycled. But of course I have one for welcoming honoured guests who are holding conferences in our city.

You were to be treated to this speech extolling the virtues of Birmingham and its achievements and its future.

Unfortunately, a good friend of mine and yours, Mr. Philippe Taylor stole this speech when he addressed you yesterday and even my prowess at re-cycling is now exhausted. I may say Mr. Taylor used to be a very good friend of mine.

To compound this felony, as you have heard, Mr. Taylor happens to have a degree of knowledge and acumen in your line of work, fully appreciating the benefits or otherwise of Loran-C. I have none, so to resort to puns or jokes about Birmingham steering its way through choppy waters of economic change or needing to change course to meet our long term target, will pail into insignificance besides the speech that Philippe should have made.

Thus Mr. President, this speech is a unique one but none the less most sincere.

As a Birmingham born person of nearly 3 score years I have lived through many changes in my City. I have seen changes both good and bad, but in Birmingham there is always change. As a City we have always responded swiftly to economic and social pressures. Part of this response has been our proud record of welcoming people from all over the world into our multicultural city as resident Brummies and now this City of ours is on the threshold of welcoming guests at Conventions and exhibitions from all over the world as in the jargon - BUSINESS VISITORS.

We pride ourselves on our friendliness and hospitality. - I hope you have experienced this.

We pride ourselves on our efficiency - and I hope you have experienced this too.

Mr. President, they say that genius is found in simplicity. My speech has consequently been a simple welcome. But to succeed in life one needs more than genius to be practical. I shall be practical, I now have another speech to re-cycle but first may I present your Association with a non-recyleable momento of your visit to our great City of Birmingham.

At this point the Lord Mayor presented WGA President Dr. Robert W. Lilley with an English Crystal Vase engraved and decorated with the City of Birmingham Coat of Arms and the Wild Goose logo with the following text:

On the front sweeping down around and below the Birmingham Coat of Arms and returning upwards -

"Presented by the Right Worshipful The Lord Mayor of Birmingham, Councillor Peter J. Barwell M.B.E. on 26th August 1992"

and on the rear in reversed print to be viewed through the glass sweeping up, above and around the reverse etched WGA logo and returning downward -

"on the occasion of the 21st Annual Convention and Technical Symposium of the Wild Goose Association"

The art work was executed at the Lord Mayor's printing company and work on the vase was performed by visually impaired students at the Queen Alexandria College.

Response by the President of the Wild Goose Asociation, Dr. Robert W. Lilley

My Lord Mayor, Lady Mayoress, City Councillors, Ladies and Gentlemen —

In the United States, as in England, I understand, one's twenty-first year is the year in which one comes of age and takes up the responsibilities of the adult world. This is the 21st Annual Convention of the Wild Goose Association and the first that we have held beyond the shores of the United States. It is also the year that loran comes of age internationally.

Let me explain to our hosts and guests that loran stands for Long Range Navigation and that the name of our Association was chosen in recognition of the legendary navigational skills of the Canada Goose during its migration. No, we are not a wild life conservation group although that mistake is sometimes made, and the name always prompts some smiles and lively discussion.

The loran system of radionavigation evolved from British developments during World War II. Later, it was refined by the United States Department of Defence and then, in 1974 as Loran-C, it was handed off to the United States Coast Guard for civilian control and use.

Hundreds of thousands of water, land and air vehicles make use of Loran-C for positioning and navigation. Today we are going one step further with the international navigating community taking ownership and local operating responsibility for the system. For several years a committee known as the Northwest Europe Policy Group has worked hard and long to resolve the radionavigation future of this area. There have been disappointments and frustrations along the way but I am pleased to be able to report to you that an international treaty was signed by six of the original nine countries just three weeks ago.

The United Kingdom was not one of the signatories having backed away from the agreement. I would be remiss not to say that we, in the WGA, have some difficulty with the basis for the U.K.'s decision to withdraw from the group. However, we are encouraged by the positive indications that the UK and the remaining original members may reconsider their positions and eventually become signatories to the agreement.

Two years ago the WGA looked into its crystal ball and speculated that the agreement would be in place and decided to hold its Convention in Europe, bringing with it some of the fathers of loran. Europe is a big place and deciding upon a venue could have become time consuming. Fortunately, one of our directors with a British heritage, John Beukers, took on the Chairmanship of the Convention, and sold the WGA Board of Directors on holding the convention in the Heart of England.

He approached the Birmingham Convention and Visitor Bureau and came across one Philippe Taylor, the organization's chief executive. John Beukers tells me that after stumbling though the usual speech about the WGA not having anything to do with wild life and explaining that we would like to hold our convention in Birmingham, Philippe Taylor replied "That's great, and we can help you but now tell me about the Global Positioning System and loran." By remarkable coincidence Philippe runs a sailing school and is particularly interested in what navigation equipment he should have on board. Perhaps that has something to do with why we are here tonight.

We are impressed with the City of Birmingham and the progress being made to provide the City with a new face. The recent full length feature article that appeared in the U.S. Wall Street Journal accurately portrayed the City's image and the results being achieved by a forward looking council. We congratulate you and wish you further success with these projects.

My comments would not be complete if I did not refer to the beauty and history of the country surrounding the City. While we, as delegates, are required to sit inside attending to our convention, our spouses and guests are thoroughly enjoying the day trips to some of England's finest attractions - just a few miles from the City's center.

My Lord Mayor, we are honored and feel privileged to be hosted by the City of Birmingham and on behalf of our Association we wish to thank you for your hospitality and present this plaque as a token of our appreciation.

At this point the President presented the Lord Mayor with an engraved plaque containing the Wild Goose Logo with the following words inscribed:

**"The Right Worshipful The Lord Mayor of Birmingham,
Councillor Peter J. Barwell M.B.E.
In recognition of the hospitality shown by the City of Birmingham on the occasion of the 21st Annual Convention, Birmingham, 1992."**

Wild Goose Association

CITATION on the Award of the MEDAL OF MERIT to

NORMAN MATTHEWS

The Medal of Merit is awarded to Norman Matthews, Secretary General International Association of Lighthouse Authorities (IALA), in recognition of his dedicated efforts in fostering and coordinating Loran-C radionavigation policies of IALA member states throughout the world.

In his role, first as Deputy Secretary General and since 1989, as Secretary General of IALA, Mr. Matthews has been the driving force behind the activities of IALA to ensure, as far as practicable, that Loran-C continues to be available to shipping, and with extended coverage if possible, after the withdrawal of support for the system by the USCG in December 1994.

In 1987 IALA initiated a Special Radionavigation Conference in London to review the requirements and future of radionavigation in general and Loran-C in particular. It was noted that several governments would together consider the possibility of extending the Loran-C coverage in NW Europe; IALA then undertook to pursue the possibility of extending Loran-C coverage along the Iberian peninsula and into the Mediterranean. After preliminary discussions with Mediterranean countries, the first meeting to consider this extension of coverage was convened by IALA in January 1989. Initially these multi-national meetings were chaired by Mr. Matthews. More recently he has acted as Secretary with IALA providing full secretarial support to the group.

In 1990 Mr. Matthews chaired a technical workshop in Japan called "Radionav Far East 90." A technical working group was established to develop a Radio Navigation Service based upon Loran-C and Chayka. At the next (fourth) meeting of the group (scheduled for September 1992), it is expected that representatives of Authorities from Japan, the Russian federation, the Peoples Republic of China, and the Republic of Korea will sign a formal agreement to provide this Far East Radionavigation Service. All meetings have been convened by IALA and chaired by Mr. Matthews.

Mr. Matthews initiated the development in IALA of its policy on terrestrial navigation systems which urges Authorities to support and encourage cooperative efforts between member nations to expand and improve Loran-C and Chayka coverage throughout the world.

The Wild Goose Association believes Mr. Matthews' contributions have had a most favorable effect on the stature of the Loran-C system and its expanded use throughout the world, and for this we are forever grateful.

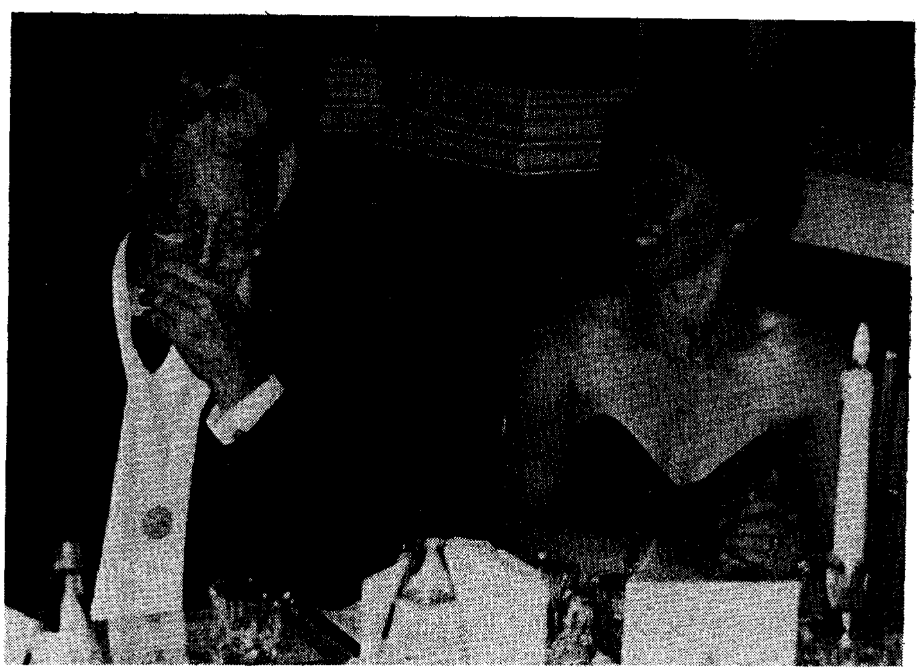
Awarded this 26th day of August 1992.

Robert W. Lilley, President

Socials - 1

The Rolands return from Hawaii.
Good to have you back on
the Mainland, Elena and Bill.

Left to right:
Christopher (an endangered species of Flying Tigers' fame),
and Lee Barrett,
Pauline Moroney,
Grace and founding WGA member
Jim Van Etten.



Norman Matthews visibly surprised and overcome by his Medal of Merit award while Mary Matthews looks on approvingly.

Jim Culbertson - looking great;
Carolyn McDonald -
thanks for your help;,
and Jo Anne Culbertson.

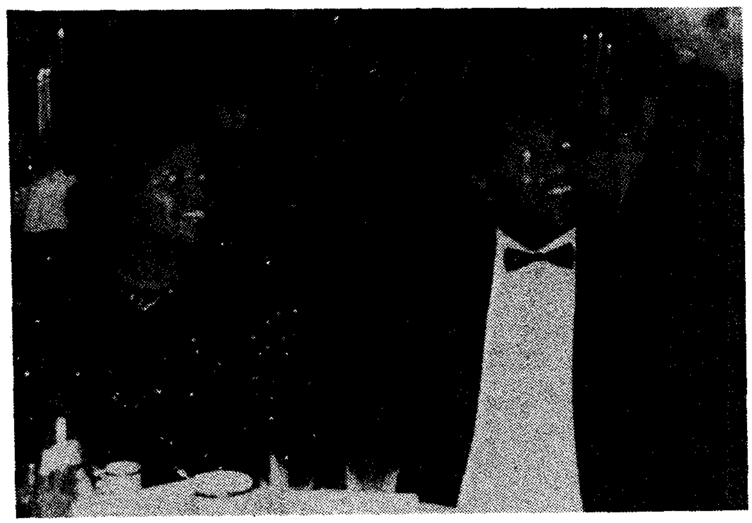
Sing Up!

Pianist and avionics expert
Robert Lilley
with singers: (left to right)
Bill Roland, Marilyn Beukers,
Marty Poppe and Pauline Moroney.

"We must go where the Wild Goose goes..."

Shirley and founding member
Walt Dean - a father of
and significant contributor
to loran.

Ingrid and President's Award recipient Kjell Enerstad - a true statesman and negotiator.



Mary and Elijah "Zeke" Jackson - We're sorry you missed so much of the Convention.

Left to right:
Joyce Malkmes of the Ninety Nines Women Pilots Association, Marilyn Beukers, Bahar Uttam of Synetics, and Cathy Beukers who flew in from Mainz, Germany.

Socials - 4

Ann and Marty Shuey -
Pleased to have AOPA
representation.

We must be doing
something right!
International smiles from
(left to right)
John Morgan, South Africa,
Dave Olsen, U.S.A.,
George Preiss, Norway,
Frank Holden and
Basil D'Oliveira, U.K.

Marilyn and Convention Chairman
John Beukers.
It was fun, but we think
we will wait a couple of years
before doing it again!

Socials - 5

Bob and Marie McKeown
with their granddaughter Dina.

Pauline and Convention
Co-Chairman, U.S.A, Mike Moroney.
Thanks, Mike, and great to have
DoT's Volpe National Transportation
Systems Center represented.

Ruth and ION Executive
Director Dave Scull -
Keep reminding the ION
there are navigation systems
other than GPS, like loran!

Socials - 6

Patty Alexander and Joyce Malkmes obviousl talking politics with the Lord Mayor, Peter Barwell.

Delegation of the Russian Internavigation Committee headed by Vladimir Denisov (2nd from left) with interpreter (right) - popular participants of the hospitality suite.

Technical Chairman, John Illgen with wife Suzanne and daughter Anne - great program, John, and thanks for pulling it together.

Spouse and Guest Program - 1

Four days of tours were enjoyed by some 25 spouses and guests, and the Convention got off to a flying start with an Ice-breaker Mediaeval Banquet at historic Coombe Abbey for everyone on Monday. The evening of revelling and entertainment gave weary travellers from the U.S. a second breath and helped overcome the unavoidable jet lag.

Monday, being an open day, some delegates elected to join the coach trip to **Blenheim Palace**, the boyhood home of Winston Churchill. Our professional Blue Badge guide provided a lesson in English history on our journey to the Palace, and we were then conducted on an interesting tour of the Palace's interior. A late return to the hotel, due to a major accident on the Motorway, left little time before we were whisked off to **Coombe Abbey** for the 14th century style banquet.

Stratford-upon-Avon and a tour of the four Shakespearean properties was on the agenda for Tuesday. We visited Shakespeare's birthplace, his paramour Ann Hathaway's Cottage, the Nash House and Mary Arden's Farm. The remainder of the day was spent shopping in Stratford with a stop for a pub lunch - some of us risking refreshments at *The Slug and the Lettuce*, a Stratford pub of fame!

Wednesday saw us on the coach again to ancient **Warwick Castle**. By special arrangement we were guided through the State Rooms and experienced the flavor of living there enhanced by the life-like wax figures by Madame Tussauds in scenes illustrating preparations for a party. After yet another pub lunch, this time at the *Nasty Cheese*, an early start back was required to allow plenty of time to get dressed for the formal Civic Dinner being thrown by the City of Birmingham for the WGA.

The weather had held up for us until our tour of the **Cotswold countryside** on Thursday. While the rain was wet, it certainly didn't dampen our spirits and interest. Stops at Broadway and Stow-in-the-Wold allowed us to do some shopping and see that the 14th century Cotswold villages remain unspoiled. We ended our tour, somewhat bedraggled, at East Ridge in Longborough, the England home of the Beukers', where we enjoyed a magnificent lunch and had a chance to dry out before returning back to the Copthorne hotel.

This was a most enjoyable four days that we are sure will hold memories for many of us in the years to come.

Reporting: Joyce Malkmes
Ninety Nines

With just a knife to eat a soup-to-nuts banquet, Joyce Malkmes and John Beukers demonstrate how to eat the main course of lamb ribs, baked potato and vegetables. Baroness for the evening, Pauline Moroney, wife of Baron Mike, sneaks in the picture at the left.

Spouse and Guest Program - 2

Lunch break and a well earned pint at the *Nasty Cheese* pub after the tour of Warwick Castle.

Lunch at the Beukers' home, East Ridge in Longborough, after a rainy tour of the Cotswold area with stops at Broadway and Stow-on-the-Wold.

Spouse and Guest Program - 3

Ann Hathaway's cottage in Stratford-upon-Avon. One of the four Shakespearean locations visited on the tour to Stratford.

Some of the tour participants relaxing in the Copthorne hospitality suite after a full day of activities. Left to right: Marilyn Beukers, Astrid Johannessen, Pauline Moroney, Suzanne Illgen, Joyce Malkmes and Anne Illgen.

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	Mike Moroney	Convention Co-Chairman (U.S.)
Technical Program	John Illgen	Technical Chairman
	David Last	Technical Co-Chairman (Europe)
	Frank Cassidy	Technical Co-Chairman (U.S.)
	Carolyn McDonald	Technical Program Manager
	Session Chairman	
	Speakers	
Luncheon Speaker	Walter Blanchard	Radionavigation Consultant
Awards Committee	Jim Van Etten	Chairman
Exhibition	John Beukers	
	Tony Good	Modular Displays
Spouse and Guest Program	Marilyn Beukers	
	Pauline Moroney	
	Jo Anne Culbertson	
Hospitality and Industry Liaison	Ed McGann	Megapulse, Inc.
Publicity	Paul Ridgway	
International Liaison	Norm Matthews	Secretary General IALA
Copthorne Hotel	Helen Relihan	Sales Manager
	Madelyn	Reservations
	Paul Barnett	Conference & Banqueting Manager
	Peter Dornom	Food & Beverage Manager
	Judi Nock	Rooms Development Manager
	Bar Tenders	
	Bell Capt & staff	
Birmingham Convention & Visitor Bureau	Philippe Taylor	Chief Executive
	Kim Bate	Conference Officer
	Christine Naylor	Office Manager
	Sabine	Registration
	Antonia & others	Registration
		NEC printer
City Library	Des Workman	Supervisor
		Security staff

Convention Staff and Credits *(continued)*

Function	Individual	Position
Cine Equipments Ltd.		Microphone Rental
Birmingham Conservatoire	Sally Frankish	Complex Manager
	Alan Smallman	Supervisor
	Steve Ferguson & staff	Catering Service (Coffee and Tea breaks)
Printing	Keith Kirtland	The Print Room (Registration, Program etc.)
	Rebecca Biehl	Omnipress (Proceedings)
Photographers	Carolyn McDonald	
	Prestige Photography	
City Council	Cathy Dukes	Civic Affairs Officer
		Calligrapher
	Gareth Lewis	Photographer
Coach Company	Kevin Legg	Midland Red West
	Colin Sheppard	Spouse/Guest program driver
	Other drivers	
Coombe Abbey	Vi Warren	
	Lois Parteger	
Warwick Castle	Paul Barker	Curator
	McGarry	Guide
Blenheim Palace	Marigold Lankester	Blue Badge Guide
East Ridge Caterers	Keith Maby and Staff	Spouse Program Caterers
Flight Line	Heathrow Supervisor	