THE WILD GOOSE ASSOCIATION

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October 29 - November 1, 1989

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EIGHTEENTH ANNUAL
TECHNICAL SYMPOSIUM
October 29 - November 1, 1989

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THE WILD GOOSE ASSOCIATION

The Wild Goose Association (WGA) is a professional organization of individuals and organizations having an interest in Loran (Long Range Navigation). It is named after the majestic birds that navigate thousands of miles with unerring accuracy. The WGA was organized in 1972 and its membership now includes hundreds of professional engineers, program managers, scientists and operational personnel from all segments of government, industry, academic and research institutions and the user community throughout the world, all working for the advancement of Loran.

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WILD GOOSE ASSOCIATION SUMMARY REPORT
BY
1989 SYMPOSIUM CO-CHAIRMEN

If advances in long range navigation are measured by the quality of papers presented at our technical symposium each Fall, 1989 was a banner year -- as one will note by studying the following pages.

And, if the extent of today's interest in Loran-C needs to be further quantified and qualified, note the numbers and affiliations of those participating in our October 29, 1989 conference at Cape Cod.

Guest speakers had pertinent messages. RADM Robert T. Nelson, USGG, provided a timely update on activities conducted by his office of Navigation Safety and Waterway Services; Congressman Denny Smith (R-OR) covered Washington concerns about Loran-C/GPS interoperability; and our new president, James F. Culbertson (Capt. USGG Ret.), outlined our association's goals for the coming year -- a prelude to our 19th annual meeting in California next October. Our sincere thanks to the guest speakers.

The technical papers are arranged in the order they were presented. Working only with initial abstracts from the authors, our technical co-chairmen, Francis C. Cassidy and Per Enge, did an excellent job organizing the presentations into five very interesting sessions. We are grateful to all.

To assist future authors, we have taken the liberty of reproducing Dr. David Last's podium script in addition to his technical paper. Like many other presenters at Hyannis, he used carefully prepared visual aids -- projecting on the screen most of the graphics used in his paper.

As representatives from more nations participate in future activities, communicating will become increasingly important -- particularly during discussions concluding each session. It was interesting to note that questions from the floor prompted authors to reproject a slide or two in order to clarify their positions.

We trust that you will find these proceedings to be an accurate presentation of the technical program for the 18th annual symposium. We also hope that these proceedings can serve as a guide to future authors as they prepare to write, illustrate and present their papers.

Thanks for coming to Cape Cod. We enjoyed having you.

Ed McGann Mike Moroney

SESSION 1

LORAN RELATED SCIENCES

Opening session participants were (left to right) Wm. A. DeGeorge of Advanced Navigation, Milo Robinson of National Geodetic Survey, Joseph M. Kunches of NOAA, SEL George H. Quinn of the FAA who chaired the session, Elizabeth L. Young of COMSTAT and John S. Kern of the FAA.

SOLAR FLARE ACTIVITY AND PREDICTIONS FOR THE 1990s

J. M. Kunches and J. W. Hirman

National Oceanic and Atmospheric Administration
Space Environment Laboratory

ABSTRACT

This solar cycle, which began in September of 1986, may prove to be the highest ever in terms of sunspot numbers and radio flux. Solar flare activity has also been elevated, with the episode in March 1989 being the most spectacular. Solar flares and their effects disrupt a variety of man-made technologies including low-frequency systems such as LORAN, (LO)ng (RA)nge (N)avigation. Although the maximum of the solar cycle is expected during the first quarter of 1990, flare activity is likely to linger at high levels for a few years to follow. Geomagnetic activity, which also affects LORAN, can occur at any time in the solar cycle, and geomagnetic disruptions are possible at any point in the 1990s.

1. THE EVENTS OF MARCH 1989

1.1 The Space Environment

March 6, 1989, began much like any other day at the Space Environment Services Center (SESC). The midnight shift was winding up a relatively uneventful night, and preparing for the arrival of the day crew, when circumstances changed dramatically. Just before 7 a.m., Mountain Standard Time (1400 UT), x-ray sensors, part of the space environment monitor package on-board the two operational GOES (Geostationary Operational Environmental Satellites), registered a sharp increase in counts at 1350 UT. The rise continued unabated until the detectors saturated about 10 minutes later. Only the most powerful solar flares, sporadic releases of great energy from small areas on the Sun, have ever caused this circumstance to occur. This was the first time an event of this size had been observed since 1984. The flare then slowly decayed, and the count returned to background levels some 6½ hours later.

The detectors saturated at the X12 level (1.2×10^{-3} w/m^{-2}). In hindsight, an analysis of the x-ray flux profile of the event led to an estimated peak of 1.5×10^{-3} w/m^{-2}, or X15; some would estimate the peak at closer to X20. This situation is comparable to a day when the air temperature exceeds the range of a typical thermometer.

1.2 Terrestrial Effects

This flare had some very profound consequences on Earth. Large solar flares have an immediate effect on Earth's ionosphere due to its absorption of solar x-rays. (This increase in ionization wreaks havoc with ionosphere-sensitive radio waves over the dayside of Earth – and may last from minutes to hours.) Among the systems suffering detrimental effects from this flare was LORAN. SESC staff were in contact with LORAN stations at Seneca, New York; Chesapeake, Virginia; Malone, Florida; Middletown, California; and Kodiak, Alaska, during the course of this event. Those of us in Operations came to know personnel at the LORAN sites very well due to our frequent conversations over the following 2 weeks.

The sunspot group responsible for the March 6 flare was on the earthward side of the Sun until March 20. (See Figure 1.) It continued to produce large-magnitude x-ray flares during that time period, but none surpassed the March 6 event. Some of the LORAN technicians jokingly described the LORAN system as a "solar flare detector," *and they could prove it*.

In addition to these immediate solar flare effects from the x-rays, two additional effects related to other emissions produced during solar flares are of interest to this group. They are the polar cap absorption (PCA) and the geomagnetic storm. Both are relatively rare events that sometimes follow major solar flares. Whereas x-rays travel at the speed of light and arrive at Earth in 8 minutes, other emissions take longer to reach Earth and produce operational impacts usually lasting for days. All three phenomena, x-rays, PCAs, and geomagnetic storms, affect the LORAN system in a similar manner. The effective ionospheric reflection height is lowered, resulting in a change in the propagation time of LORAN signals (with phase errors the net result).

Each of these phenomena affect different geographical locations. X-rays will have an immediate effect only on the sunlit side of Earth. PCAs are a polar phenomena, limited to the area inside the polar cap (usually about 60° latitude). Geomagnetic storms are more global and variable. Storm effects will be the most pronounced near the auroral oval, which changes shape and location depending on the severity of the storm.

The flares of March produced only a minor PCA. The geomagnetic storm, however, was the third largest on record (since 1932). This storm began on March 13 and continued for the next 6 days. The aurora which accompanied the geomagnetic storm was visible from the Gulf states, a rare occurrence.

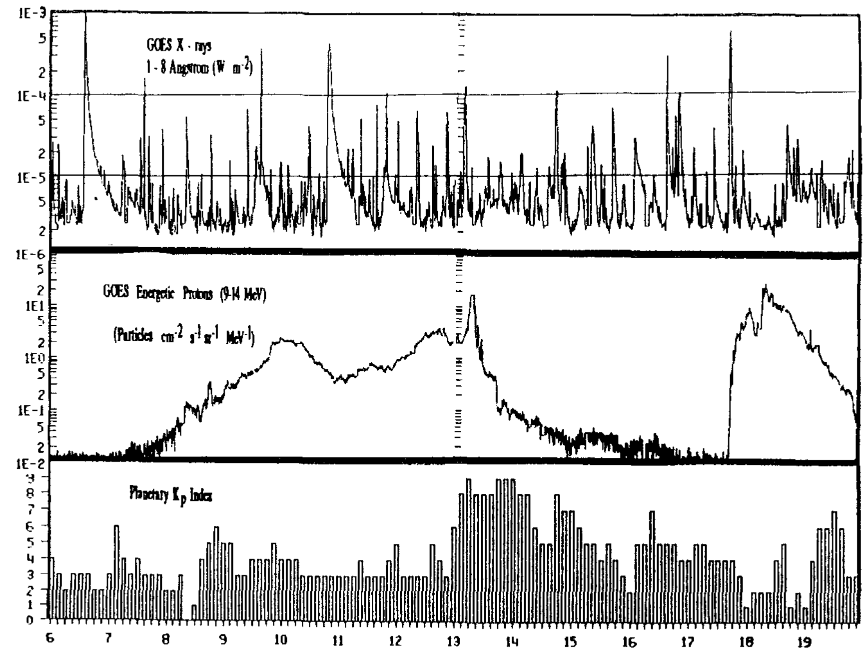


Figure 1. Plot of X-ray, particle and geomagnetic Indications for MARCH 1989

2. SPACE ENVIRONMENT SERVICES

Dealing with situations such as the March 6 flare and the attendant effects is the mission of SESC, the U.S. agency responsible for the Nation's space weather service. Located in Boulder, Colorado, it is a component of the National Oceanic and Atmospheric Administration (NOAA)'s Space Environment Laboratory. The Center is jointly staffed by NOAA and U.S. Air Force personnel, and operates 24 hours a day, 7 days a week. As a national and international focal point for solar-terrestrial forecasting and analysis, the Center's computers digest more than 1,000 real-time data sets on a continuous basis.

The role of SESC is similar to that of its sister organization in NOAA, the National Weather Service. The two groups part company at roughly 100 Km above Earth; the Sun, the interplanetary medium, and Earth's magnetosphere and ionosphere comprise SESC's domain. Another pronounced difference between forecasting Earth's and space's weather is the paucity of in situ information compared to the high density of local weather observations. We are remotely sensing a star (the Sun) with detectors 93 million miles from the source. A crude analogy might be that we (SESC) must forecast the weather in New England using only the most recent available satellite weather image of the Pacific.

As difficult as space weather monitoring and forecasting might seem, the challenge is answered daily. SESC produces an assortment of text and data products that reveal conditions from the Sun to Earth, as well as the behavior of the geomagnetic field at middle latitudes such as New England. The March activity taxed our abilities to satisfy all interested parties. These included the media (wanting to know the chances of viewing the Northern Lights from a particular city); NASA, with a shuttle flight in progress, interested in the potential radiation hazards from an increased population of flare-accelerated energetic particles; and people such as yourselves with sophisticated navigational systems subject to instabilities in the ionosphere due to increased solar x-rays.

The solar region that produced the anomalously large flare activity was, in a sense, a forecaster's dream. It rotated into Earth's field of view and produced large flares on March 6. As it became more visible from Earth, it displayed most of the characteristics generally accepted by solar physicists as necessary for large flares. (See Figure 2.) These attributes include large, dark sunspots oriented relative to one another so as to necessitate severe contortion of a potentially dipolar magnetic field; a large amount of bright chromospheric plage (also an indication of magnetic energy available to fuel a flare); and embedded filaments (a feature whose instability may serve to trigger the flare process).

Optical data from a worldwide telescope network allow forecasters to analyze daily every visible sunspot group. The Sun's strong magnetic fields make it a very interesting star, and it is the strength and configuration of those fields that analysts attempt to understand. Daily flare forecasts are predicated on that day's magnetic field structure.

Magnetic fields and sunspots evolve over time. Some may change in a period of minutes and release energy as flares in the process; on a much larger scale, the evolutionary process proceeds more slowly. This more leisurely reconfiguration is what gives birth to the so-called "solar cycle," or "sunspot cycle." The cycle is determined by the presence or absence of sunspot groups, which are visual manifestations of strong (2,000-3,000 gauss) magnetic fields. On average, a cycle takes about 11 years. However, the distribution is actually bi-modal, with a slightly shorter or longer period more frequently observed. (See Figure 3.)

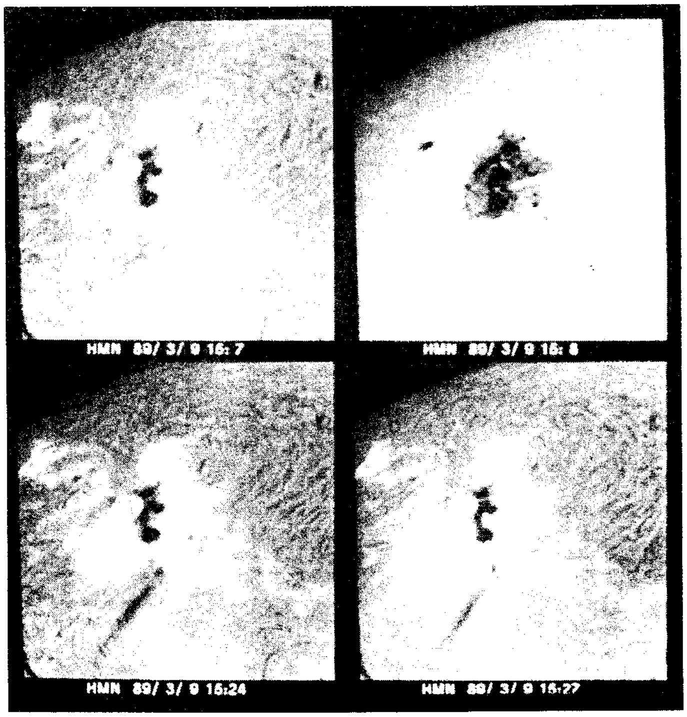


Figure 2. Photograph of Region 5395

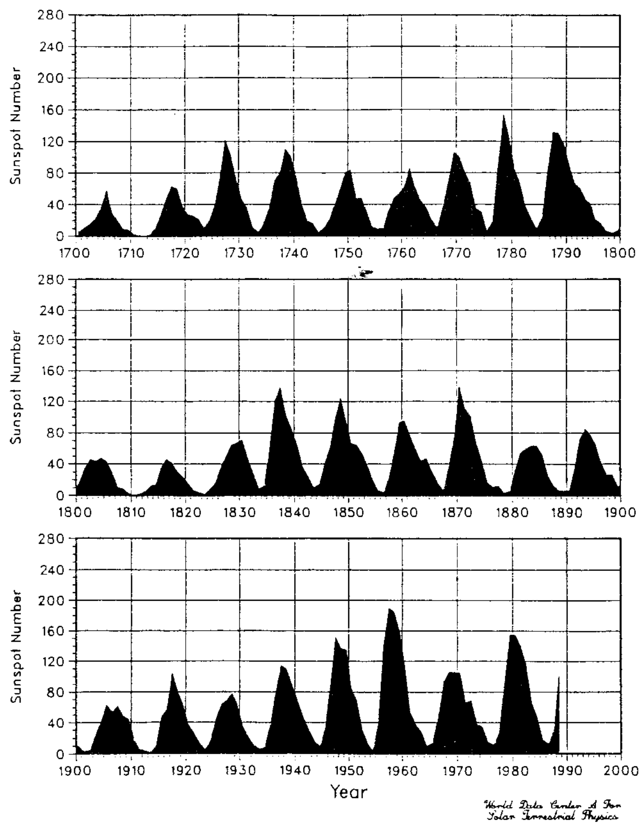


Figure 3. Yearly Mean Sunspot Numbers 1700 - 1988

3. THE FUTURE

The current solar cycle, 22, began in September 1986. Its birth was not impressive, marked only by a featureless solar disk and affirmed by the statistical smoothing of sunspot numbers for the 13-month period of which that month was the midpoint. But Cycle 22 has grown very rapidly, and early data put this current cycle on a pace that, if it persists, will culminate in the highest maximum value ever recorded. The most active cycle to date was Cycle 19, which attained its maximum in March 1958 with a sunspot number of 201.3. That cycle reached its maximum in 47 months (faster than the average time to maximum – 51.5 months – for all observed cycles). (See Table 1.)

(Min = smallest smooth # before Max)
(Smooth # = 13 month average)

Cycle	Start (Solar min) Year	Month	Solar Max Year	Month	End (Month before min) Year	Month	Max SSN	Length Years	Months	Rise to Max Years	Months	Max to End Years	Months
1	1755	Mar	1761	Jun	1766	May	86.5	11.25	135	6.25	75	5.00	60
2	1766	Jun	1769	Sep	1775	May	115.8	9.00	108	3.25	39	5.75	69
3	1775	Jun	1778	May	1784	Aug	158.5	9.25	111	2.92	35	6.33	76
4	1784	Sep	1788	Feb	1798	Apr	141.2	13.67	164	3.42	41	10.25	123
5	1798	May	1805	Feb	1810	Jul	49.2	12.25	147	6.75	81	5.50	66
6	1810	Aug	1816	Apr	1823	Apr	48.7	12.75	153	5.67	68	7.08	85
7	1823	May	1829	Nov	1833	Oct	71.7	10.50	126	6.50	78	4.00	48
8	1833	Nov	1837	Mar	1843	Jun	146.9	9.67	116	3.33	40	6.33	76
9	1843	Jul	1848	Feb	1855	Nov	131.6	12.42	149	4.58	55	7.83	94
10	1855	Dec	1860	Feb	1867	Feb	97.9	11.25	135	4.17	50	7.08	85
11	1867	Mar	1870	Aug	1878	Nov	140.5	11.75	141	3.42	41	8.33	100
12	1878	Dec	1883	Dec	1890	Feb	76.6	11.25	135	5.00	60	6.25	75
13	1890	Mar	1894	Jan	1901	Dec	87.9	11.83	142	3.83	46	8.00	96
14	1902	Jan	1906	Feb	1913	Jul	64.2	11.58	139	4.08	49	7.50	90
15	1913	Aug	1917	Aug	1923	Jul	105.4	10.00	120	4.00	48	6.00	72
16	1923	Aug	1928	Apr	1933	Aug	78.1	10.08	121	4.67	56	5.42	65
17	1933	Sep	1937	Apr	1944	Jan	119.2	10.42	125	3.58	43	6.83	82
18	1944	Feb	1947	May	1954	Mar	151.8	10.17	122	3.25	39	6.92	83
19	1954	Apr	1958	Mar	1964	Sep	201.3	10.50	126	3.92	47	6.58	79
20	1964	Oct	1968	Nov	1976	May	110.6	11.67	140	4.08	49	7.58	91
21	1976	Jun	1979	Dec	1986	Aug	164.5	10.25	123	3.50	42	6.75	81
22	1986	Sep											
Avg							111.7	11.02	133.1	4.29	51.5	6.73	80.8

SESC Form 1 - 39 Herman/Boeder/Greer/Keifert 10 Mar 89

Table 1. Solar Cycles 1 - 22

If the current cycle behaves in a manner similar to Cycle 19, maximum will occur in August 1990. At this point, it seems that maximum will arrive before that time. Compared with the average, that would be an exceptionally fast start to maximum. Current estimates are for maximum to occur late in 1989 or in the first quarter of 1990. (See Figure 4.)

Flare activity, both in magnitude and frequency, is a function of the sunspot cycle. The vast majority of flares are spawned in and around sunspots, where magnetic fields are strong. It is logical to assume that the higher the sunspot number, the more likely the occurrence of a flare-induced equipment problem. It should be noted, though, that the passage of solar maximum does not necessarily mean the return of "blue skies." Solar maximum-like conditions may persist for another 2-3 years after maximum. Very energetic flares, with prodigious amounts of x-rays, may still haunt Operations personnel for several years to come. (See Figures 5 and 6.)

The mid-1990s (the period of the next solar minimum) should bring a relative calm. Flare activity will be less pronounced, and the solar disk will assume a spotless character for days at a time. The contrast between solar maximum and minimum conditions is dramatic indeed. (See Figure 7.) Background solar emissions will drop (x-rays by a factor of ten and the 10-centimeter radio flux by, perhaps, a factor of four or five). But at a time when the Sun is producing few flares, the geomagnetic field will still experience storms ($Ap \geq 50$) at a frequency not significantly less than solar maximum levels. (See Figure 8.) In fact, during Cycle 21 most of the geomagnetic storms occurred during the period after solar maximum. This is partially due to the fact that (for reasons not well known) low-latitude coronal holes, avenues of high-speed solar wind streams, are more prevalent during the declining phase of the solar cycle. This high-speed solar wind, coupled with a southward interplanetary magnetic field vector that may occur at any time in the solar cycle, results in an efficient transfer of the solar wind's energy to Earth's magnetosphere, and Earth's magnetic field experiences a disturbance. Flares are but one source of high-speed solar wind; geomagnetic activity may also be triggered by coronal holes and other, less-dramatic forms of solar stimulus.

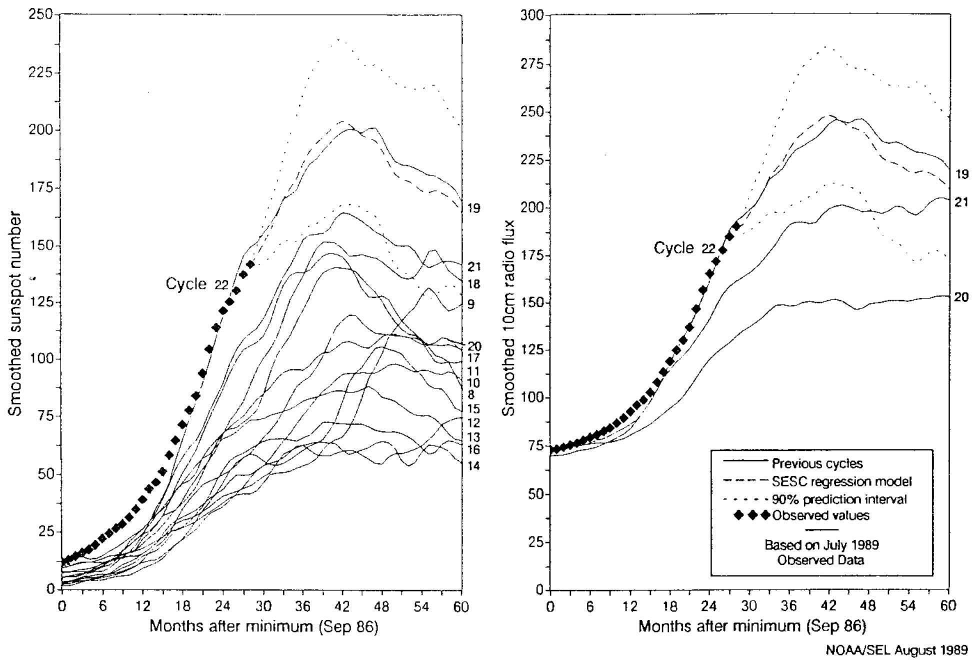


Figure 4. Rise of Solar Cycle 22 compared to previous cycles

4. CONCLUSION

We have learned over the past 20 to 30 years that the Sun has a great impact on communication and navigation systems dependent on the ionosphere for their operation. We have also become increasingly aware of the cyclic behavior of the Sun in various ways that perturb the ionosphere. Until some future time when the systems are engineered to function at any level of solar or geomagnetic activity, LORAN operators must be aware of the Sun's vagaries that affect the performance of their systems. The Space Environment Services Center, as our Nation's center for space weather forecasting, will continue to develop products and services designed to mitigate the effects of solar-terrestrial activity.

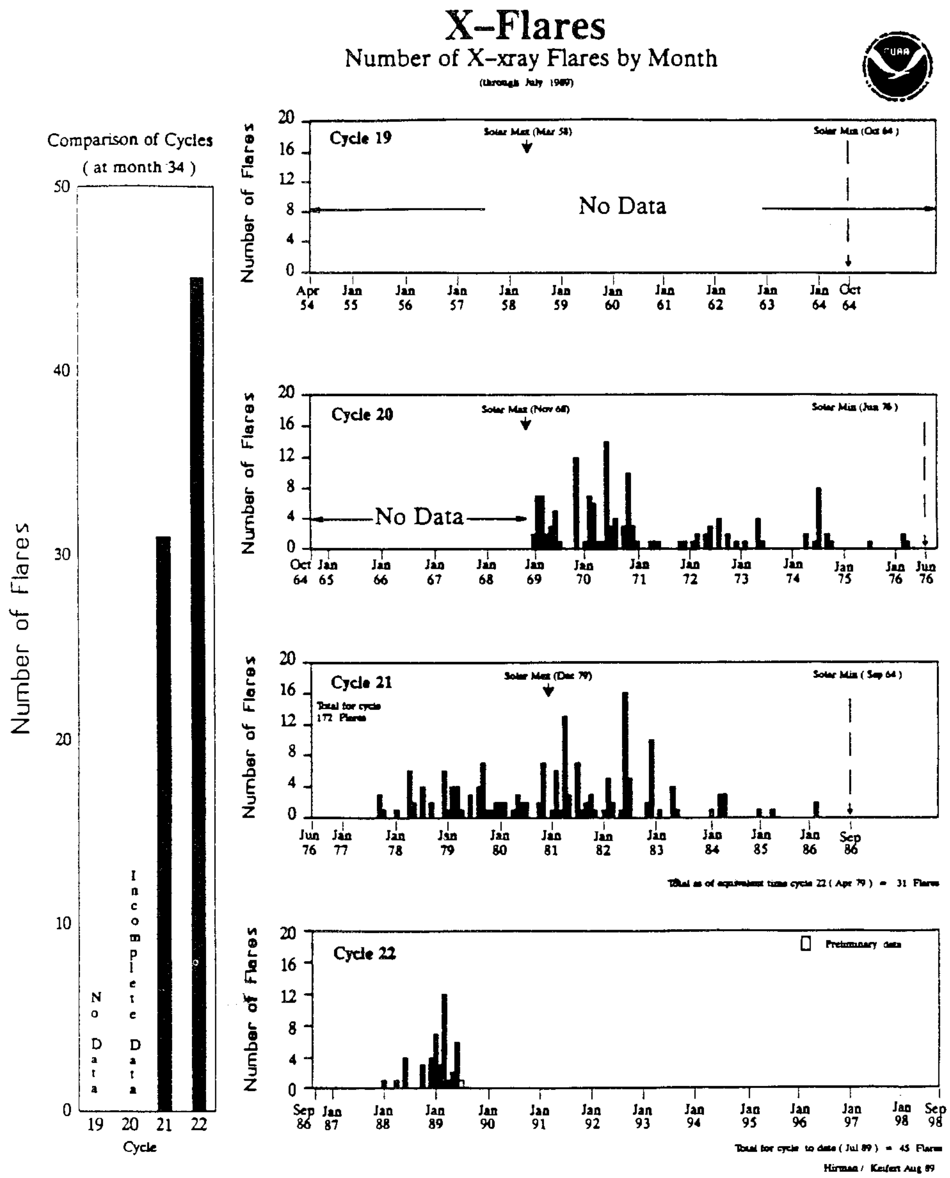


Figure 5. Plot of frequency of X class flares

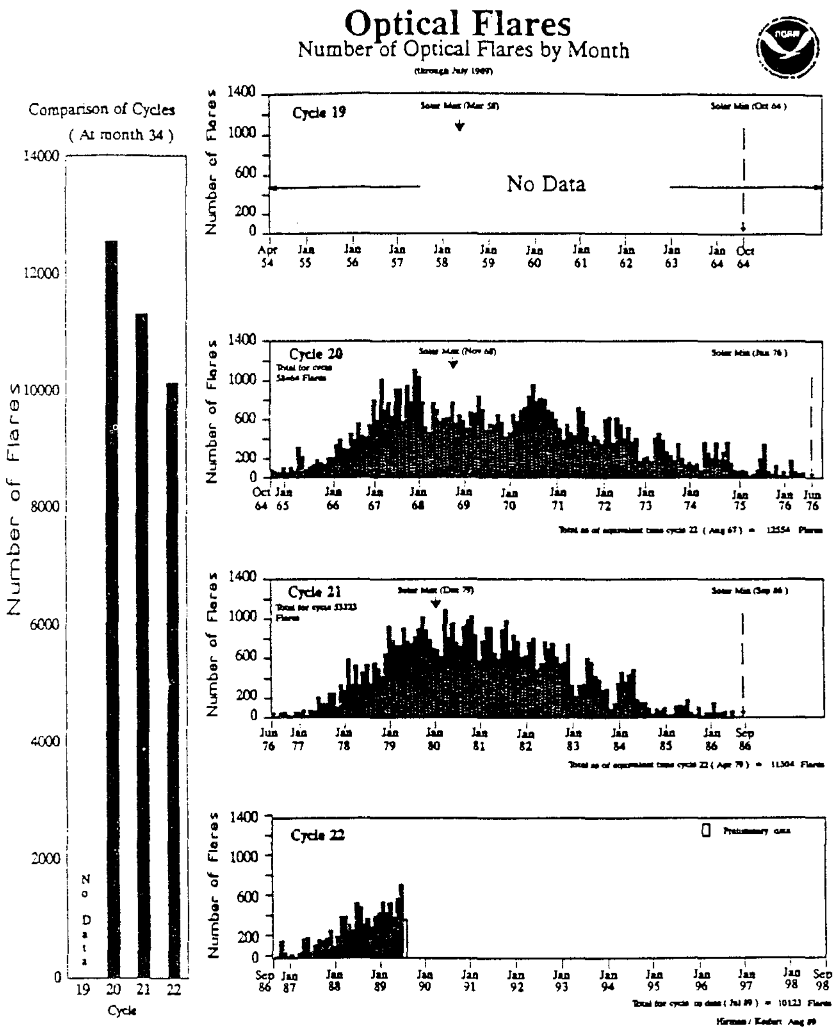
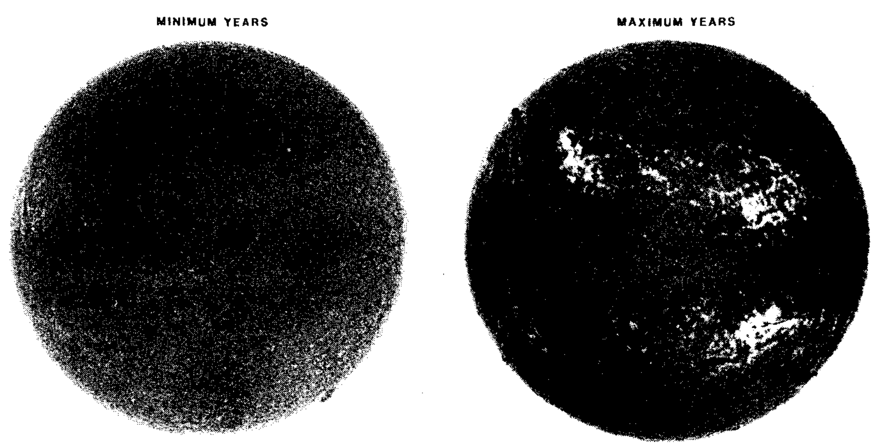


Figure 6. Plot of frequency of optical flares

Figure 7. Hydrogen Alpha image of the Sun comparing solar minimum and maximum



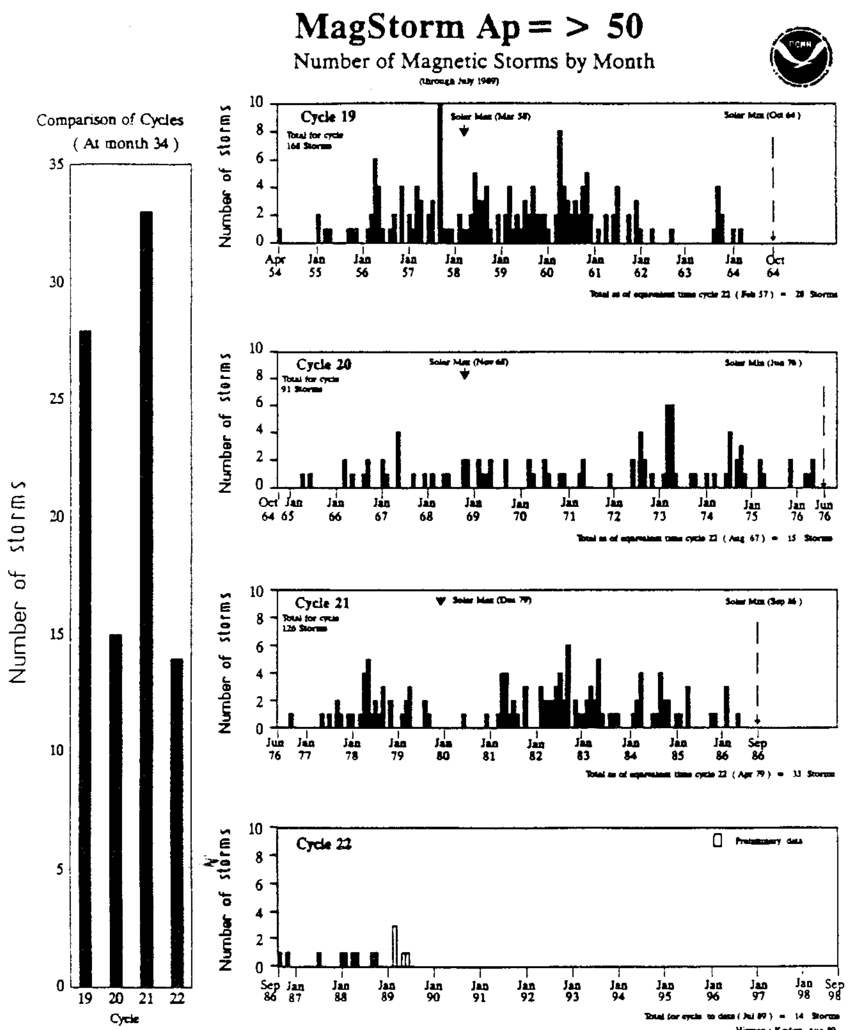


Figure 8. Number of magnetic storms monthly - Cycles 19 - 22

EVOLUTION OF MANUFACTURING TECHNOLOGIES FOR ADVANCED LORAN-C RECEIVERS/NAVIGATORS

Bruce Francis, William DeGeorge

Advanced Navigation, Inc.

ABSTRACT

This paper describes technologies which have been developed to increase the capabilities and reduce the costs of modern LORAN receivers/navigators. In particular the impact of surface mounted technology (SMT) and state-of-the-art methods to manufacture single board LORAN receivers in large quantities at Advanced Navigation, Inc. (ANI) are examined. Four characteristics are critical in the design of LORAN receivers: functionality, manufacturability, reliability and supportability. A few years ago, it was necessary to optimize only one or two of these characteristics to capture a fair share of the market. One example was the ANI 7000 receiver design which emphasized functionality and reliability, but did not have manufacturing technology available to facilitate production of this very complex and flexible system. Nevertheless, user demand for the 7000 continues although each year it is more expensive and difficult to manufacture.

Recognizing the economic disadvantages of this situation, ANI instituted a program to develop LORAN receivers which function as well as the model 7000, but employ technology breakthroughs that enhance manufacturability and supportability. The design process is complete and it has resulted in a LORAN receiver on a single printed circuit board of less than 30 square inches. The manufacturing process, which uses SMT, Application Specific Integrated Circuits (ASIC), and Custom Gate Arrays (CGA), can produce over 100 units a day. In doing so, this advanced process achieves the goal of maintaining functionality while optimizing manufacturability, reliability and supportability.

INTRODUCTION

LORAN-C has been in operation for over 30 years. As the decade of the 80's comes to a close, it is obvious that the system is "alive and well" in spite of the gloomy prognostications heralded during the decade of the 70's. Here we are about to enter the decade of the 90's, culminating in the beginning of the 21st century. The continuing acceptance of this versatile navigation system will surely mark another decade of unprecedented growth in the number of users. The marine and scientific user communities continue to grow. The foundation has been laid for continued growth and expansion in the US National Airspace. The latest growth area is in the various terrestrial applications, with AVL being the leader at present. Why has it taken so long to become "accepted"? Why should its user base continue to grow?

The inputs to a reasonable answer to these questions are multi-varied and convoluted. However, without a doubt, one of the principal parameters in this difficult equation is the LORAN receiver and how it has changed.

The application of developing technologies in designing and manufacturing LORAN receivers is one of the primary reasons for the continued growth and expansion of LORAN system use. Improved performance, reliability, increased functionality, and lower cost to the user have been on going since the first signals were placed in operation over thirty years ago. ANI has been actively involved with applying developing technologies during the past decade. The most popular of these receivers is the Model 7000. In the last half of this decade, ANI has taken the Model 7000 performance features and placed them on a single printed circuit board (PCB). The first of these receivers was built and delivered in quantity in 1987. That receiver resides on a PCB of less than 87 square inches, an area smaller than an 8 1/2 X 11 inch sheet of paper. Successive iterations and several models later we were producing a 30 square inch receiver in commercial quantities by early 1988. Here in 1989 we have been producing these models at an ever increasing rate, having shipped over 11,000 of them since the beginning of this year.

It is tempting to reach back and dig into the details of the ANI receiver designs and talk about linear versus hard limited, or models used for geodetic conversion, etc. Typically, papers and presentations describe only the enjoyable parts of this business. This paper, however is intended to describe the technologies, processes, and philosophies which have been applied at ANI to accommodate this significant change in manufacturing operations.

EVOLUTION OF THE MODEL 7000

The Austron 5000 Navigation System which has been in use since 1970 for precision offshore positioning applications is the grandfather of present day ANI models. In 1975, the U.S. Coast Guard selected the Austron 5000 for use as the System Area Monitor in its plan to expand the U.S. LORAN System for U.S. Coastal coverage. Following several years of hardware and software modifications to that system, it yielded the Model 5000 Monitor which is still in use today controlling most LORAN chains around the world. In 1979, a small group of Austron employees purchased the Navigation Products Division, and formed a new company in Rockville, MD, called Advanced Navigation, Inc. (ANI).

The first new product to be developed by ANI was the Model 7000 Navigator. The goal of this design was to use the proven performance merits of the Model 5000 in a product which could take advantage of new microprocessor technologies. Design criteria included continuing with a computer controlled, multi-chain, linear receiver with enhanced software. Additionally, the design would have to provide a user friendly level of sophistication which would allow operation without detailed knowledge of LORAN systems. Functionality was to be the major improvement by designing a receiver that could automatically select which stations to track from England to Alaska, while automatically detecting and rejecting near band interference with a computer controlled notch filter assembly. Additionally, an interface computer would be added to provide flexibility in connecting the unit to peripheral devices and navigation management systems. The result of this effort was the Model 7000, a highly functional automatic receiver. However, reliability, manufacturability, and supportability did not improve significantly because the manufacturing technologies remained essentially the same for both products. Both products used Through Hole Technology (THT), manual assembly, and predominantly manual testing. Both products used standard small scale integration (SSI) and medium scale integration (MSI) ICs, and required the integration of a number of subassemblies and assemblies to get a final assembly. By 1984, the Model 7000 was in full production at a rate of 20 systems each month.

The Model 7000 consists of three major components: a Receiver Computer Unit (RCU), a Control Display Unit (CDU), and an active antenna. The RCU consists of three groups of assemblies: the LORAN Receiver section (Receiver Computer, RF Amplifier, and Automatic Notch Filters), the Navigation Computer, and the Interface Computer. The CDU operates as an unintelligent peripheral to the Navigation Computer. The antenna (several versions) provides the initial bandpass filtering and matches the antenna to the RF Amplifier.

A Model 7000 with options is made up of eighteen subassemblies, including thirteen printed circuit assemblies. The RCU has eight subassemblies, with seven printed circuit assemblies. The CDU has six subassemblies with five printed circuit assemblies. The antenna has two subassemblies with one printed circuit assembly.

There are more than 600 individual line items for a total of over 2000 parts which are required to manufacture the Model 7000. Figure 1 is a top down family tree for a generic Model 7000. Each block within the family tree requires separate planning, scheduling, assembly and testing before it becomes integrated and tested in the final assembly.

Figure 2 is a family tree for a Model 7000 RCU. As can be seen, there are over 340 individual line items and a total of 1590 parts required in this RCU to provide the equivalent performance of a Model 5306, shown in Figure 3, which has 105 individual line items and a total of 480 parts. The Model 5306 is an SMT receiver and is discussed later in this paper.

The manufacturing methods used for the Model 7000 are typical of low volume system production. Material forecasting is conducted routinely based upon customer requirements. Detailed planning is required to assure adequate quantities of subassemblies and assemblies to accommodate up to five manufacturing levels on a given final assembly. Job orders are written, kits picked, assembled, tested and inspected before the subassemblies and assemblies move to finished goods. When enough completed assemblies have been placed in finished goods, final assembly kits are issued, assembled, tested, and inspected prior to entering the finished goods inventory where they can be picked for shipment to the customer.

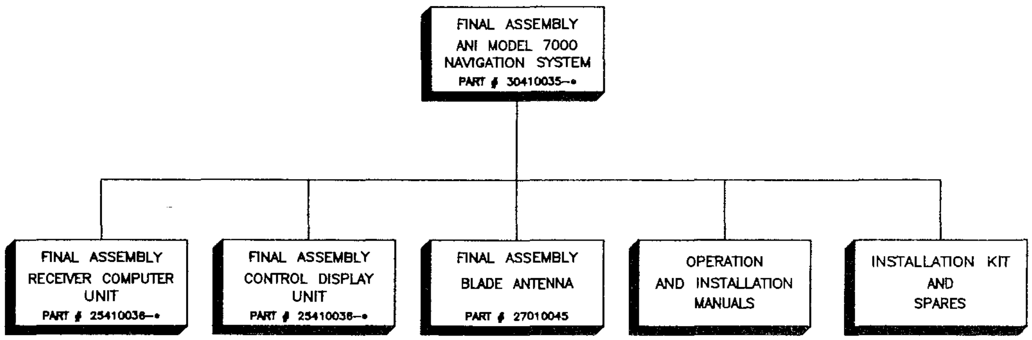


FIGURE 1 – MODEL 7000 TOP LEVEL FAMILY TREE

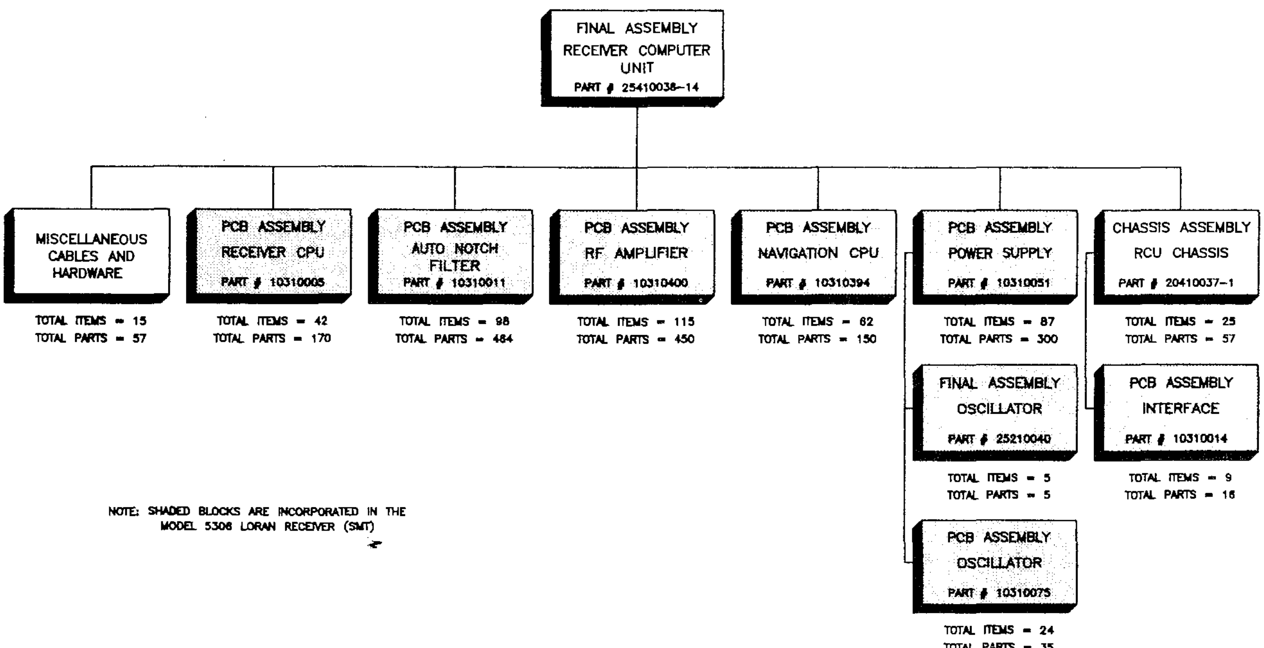


FIGURE 2 – MODEL 7000 RECEIVER COMPUTER UNIT (RCU)

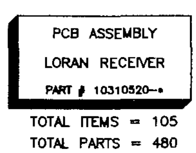


FIGURE 3 – MODEL 5306 LORAN RECEIVER (SMT)

There are over 600 items of raw material, and more than 40 individual manufactured items which require inventory planning and control. Electrical and mechanical assembly are done manually, as is functional testing. In-circuit PCB assembly testing is conducted on a GENRAD system which is shared with SMT production.

While some automation of the THT process is possible, it is generally cost prohibitive because of the low volume. Consequently, the process is labor intensive and requires good knowledge and detailed planning of all manufacturing steps.

THE EVOLUTION TO SMT

In early 1985, ANI was commissioned to supply a large quantity of LORAN receivers for terrestrial vehicle positioning. The major challenges facing ANI were the shift from low volume final system to high volume OEM manufacturing, and the reduction of the packaging size of the existing system components. The basic performance features of the Model 7000, such as linear processing, automatic notch filtering, multi-chain operation, automatic station selection, and automatic ASF corrections were to be included in the new design. A trade-off study was conducted by the ANI engineering group to determine the best approach to satisfy these requirements.

By late 1985 the study was complete. ANI would continue with the same aggressive engineering approach that had made it successful in the past. A highly automated process with the focus on computer control is what had distinguished its receiver designs from the start. The concept, then, was to integrate that approach into manufacturing. The goal was to maintain the functionality of the Model 7000, along with including improvements in manufacturability, reliability, and serviceability of the new products. Surface Mount Technology (SMT) was chosen as the vehicle to accomplish these requirements. The SMT process could be modified in whole or by parts until the output was satisfactory, then computerization could replicate the pieces resulting in a highly automated manufacturing process.

ANI engineers were presented with the challenge of developing a new receiver which would carry the functionality of its predecessors into the future. This new design would be a linear receiver with computer controlled notch filters on a single printed circuit board using automated SMT techniques during manufacturing.

A prototype THT receiver was developed to begin the process. It was built on two 8" by 10" single sided PCBs and is shown in Figure 4. The next step was to develop a customized gate array which integrated over 60 SSI and MSI standard TTL packages into an 84 pin Plastic Leaded Chip Carrier (PLCC). This effort resulted in replacing one of the 8" by 10" THT prototype PCBs with the single 84 pin PLCC as shown in Figure 5. Finally, SMT components were selected, a new board layout was developed, and the prototype SMT board design was complete. The new design was called the Model 5300, shown in Figure 6.

In parallel with the receiver design effort, specifications and selections for the manufacturing equipment were carried out. A conveyorized SMT assembly line was specified with the capability of placing parts and soldering a Model 5300 receiver every two and one half minutes, and to be expandable to allow for future growth. Additional efforts were placed on specifying and designing Automatic Test Equipment (ATE) which would be capable of efficiently handling large volumes of PCBs.

Following receipt of the SMT equipment in early 1987, the first of ANI's single board receivers was produced. Later in 1987, the Model 5300M was designed specifically as a monitor receiver, and over 200 were manufactured and shipped along with over 200 Model 2045 SMT simulators to support the FAA LORAN Non-Precision Approach program. The SMT manufacturing process was beginning to take shape as engineering and manufacturing personnel sorted out various problems and began to understand the details of this highly automated operation.

As the manufacturing process continued to develop in 1987, ANI engineering started on the design of a second generation SMT receiver. The new design would be on a board of less than 30 square inches (4.8"x5.8"). In addition to the features of the Model 5300, this receiver included a digitally compensated crystal oscillator and an SMT switching mode power supply which operates at 600 kHz. In order to accommodate the high density of parts, the design would have to use double sided SMT mounting without adhesives, and further integration of components. A second customized IC was developed for this purpose and resulted in an Application Specific Integrated Circuit (ASIC) which combines both digital and analog components for the automatic notch filter circuits. A comparison of the protype two PCB THT 5300 and the present 5306 is shown in Figure 7. This design accommodates

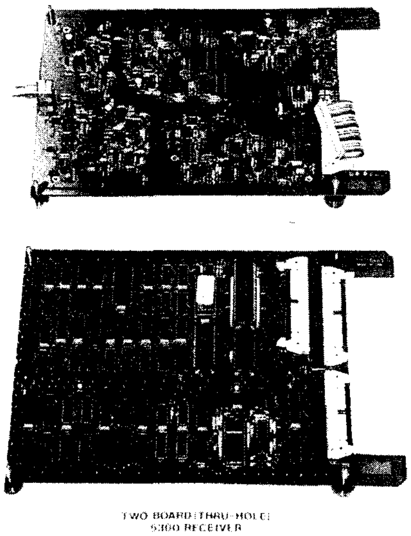


Figure 4
Two Board THT
Receiver

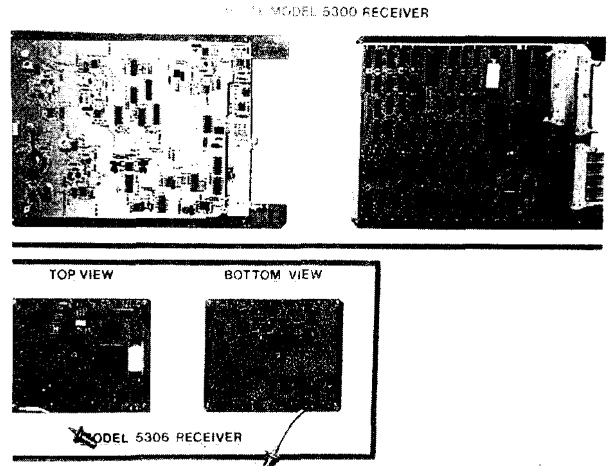


Figure 7. Comparison of
5300 (THT) and 5306 Receivers

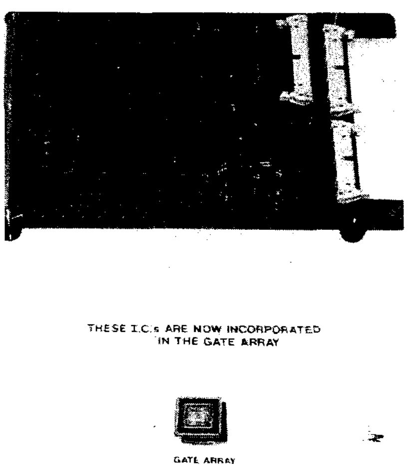


Figure 5
Replacing
One PCB
With Gate
Array

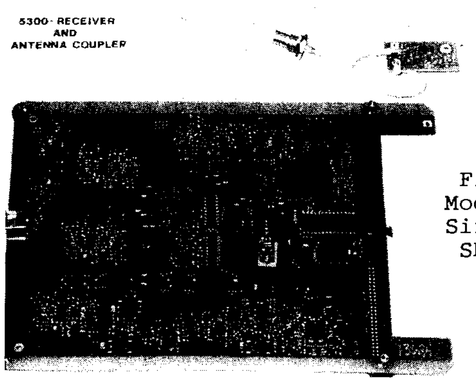


Figure 6
Model 5300
Single PCB
SMT Rcvr

several models by changing a few components and system software which is stored in EPROM. This basic design at present supports the Models 5306, 5306A, 5306C, and 5306IB which are terrestrial receivers, and the Model 7200 which is an avionics receiver that has been qualified to FAA TSO C60B.

A production run begins with first producing a large quantity of PCB bottoms, then running the tops back through the line to complete the assembly. Considerable design effort was required to select component layouts which allow two reflow cycles on the PCB bottoms. Oven profiles and speeds, along with special handling and grading techniques, were found to be critical to the success of this double sided process.

The ANI 5306X/7200 line of LORAN receivers uses fewer than 160 line items and around 400 total parts for a complete assembly. This provides a receiver which uses fewer than one third of the parts required to perform the same function in the Model 7000 (shaded areas in Figure 2). Over 97% of the parts are placed automatically on the SMT Line. A few parts such as cable assemblies require hand attach. The present process requires manual selection of several components in order to balance or align critical circuits. However, a laser-trim system which is now under contract is expected to automate these selections and adjustments.

FINALIZING THE MANUFACTURING PROCESS

Manufacturability, reliability, and supportability are the final test of the design of any component or system. The present SMT LORAN receivers manufactured at ANI are passing these tests with flying colors.

Manufacturability is being optimized by introducing automatic placement and automatic testing. Reliability has been enhanced by the large reduction in parts count and the inherent repeatability of the manufacturing process. Supportability has not as yet been assessed because there has not been a significant number of failed units returned. The few units that have been returned for repair have been accommodated in the production process without any special test equipment or diagnostic tools. The reliability provided by the small parts count, and supportability provided by the automated testing can be expected to continue. These were significant design goals which are being accomplished.

Earlier in this paper it was mentioned that the major operating change at ANI during the development of these SMT products was that of transitioning from low volume systems to high volume PCBs. That process has been every bit as difficult to develop as the requirements which have gone into the engineering aspects. The major philosophical difference in the manufacturing approach stems from the requirement to deal with large volumes of components and assemblies in the various phases of Work In Process (WIP). From the 12,000 components which can be placed each hour on the SMT Line to the 3000 or more PCBs in various stages of WIP, a number of new disciplines and techniques have been established to assure that the products are properly planned, built and shipped on time.

Figure 8 shows the simplified product routing for an SMT assembly at ANI. It looks simple enough by itself. However, when consideration is given for the possibility of having as many as 300 or more PCBs in any or all of the manufacturing steps, it becomes imperative to have good controls to keep the process flowing. ANI has been successful in making this process work. Present single shift capability is more than 1000 receivers per month in a manufacturing area of less than 3500 square feet. Peak production to date has been more than 2200 receivers per month with two shifts. With additional planned emphasis on certain stages of the manufacturing process, further improvements are expected. The following manufacturing areas continue to be developed:

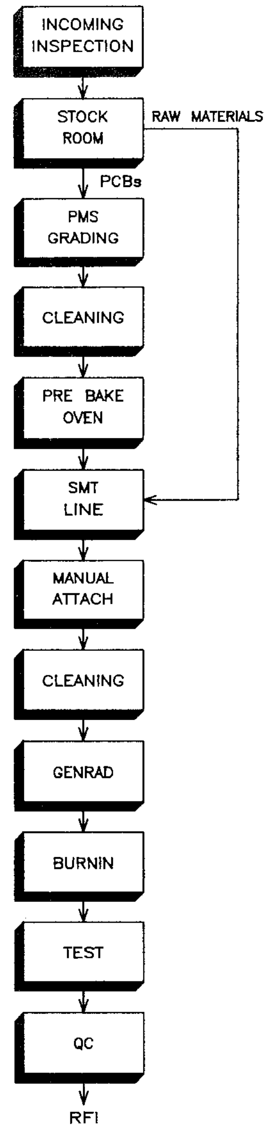


FIGURE 8 – SIMPLIFIED SMT PRODUCT FLOW

Material and Inventory Control.
Parts quality and quantity are key elements in any manufacturing operation. In SMT high volume manufacturing they are critical to the success of the process. Detailed parts specifications and control drawings are essential. Vendor qualifications and performance evaluations are ongoing and the forming of business partnerships is desirable to approach just in time (JIT) purchasing techniques. Incoming inspection and good inventory control are required to insure that only top quality parts are procurred. With a line which is capable of placing 12,000 components per hour, placing a faulty or

incorrect part for even a short period of time can result in much rework and unplanned handling. Material expediting, good internal material handling practices, and an integrated computer system are all tools that are essential to the success of the operation. While ANI has not had the benefit of a fully automated Manufacturing Resources Planning (MRP) system, there is a good basic computerized system that allows automatic transfer of parts lists and bills of materials through planning, purchasing, inventory control, and accounting. This tool is kept current through a disciplined engineering documentation system. Shop floor control and job costing are done separately from the automated computer system. A fully automated MRP system will further enhance the planning and control of material and further improve the efficiency and performance of the manufaturing process by integrating shop floor control and job costing.

Process Controls.
Ideally, total statistical process control (SPC) is the heart of the highly automated manufacturing operation. SPC is typically implemented in the form of continuous data crunching which provides corresponding results and variances in each step of the process. The nearer to real time this data is presented, the better is the control of the process. Realistically, in a small manufacturing operation, the capital investment and development resources are often not available to implement full time total SPC. Consequently, alternative methods are usually implemented. We have accommodated this limitation by placing personnel in the process loops which are not handled by automation. The areas that have been automated and that we have tested with SPC indicate that there is a great deal of process improvement and efficiency that is possible through further implementation of these controls.

Process Enhancements.
There are several process enhancements that are in the implementation stage, and several that are in the planning stage. ANI engineers are actively conducting ATE enhancements designed to consolidate and speed up test activities. One example is the automated functional test which is conducted simultaneously on 64 PCBs. That capability is being expanded to 128 PCBs with only a modest increase in overall time. Another example is total automation and combining of oscillator grading and temperature curve loading which is now done in two steps. Another major enhancement in the process is expected to occur when a laser-trimmer is in full operation. It is being designed to perform real time functional trimming on components used to balance notch filters and A/D convertors. It has the added potential of allowing replacement of many of the 1% components in present use with less expensive components. The present PCB version already contains the layout configuration to accommodate the laser trim process. The final major process enhancement is the addition of Extended Input Modules (EIM) on the SMT Line which will increase throughput and provide increased production.

THE NEXT GENERATION

The present family of ANI SMT LORAN-C receivers are modern, state-of-the-art devices, but by no means the culmination of applying today's technologies. Design and manufacturing process changes are continuing for improved yields, lower material costs, improved testability, better reliability and improved functionality. These improvements are all achievable within the technology base available today. The extent to which they are applied is a function of market demand and investment return ratios.

It is difficult to predict what new technologies will be applied to future generations of LORAN-C receivers. Factors which might have the largest impact are:

Display Technology

Superconductors and Exotic Material development

Device Packaging and Fine Pitch Technologies

Mass Storage and Standard Gate Array development

It is certain that market demand will be the major factor in determining the future of LORAN receiver development. The massive automotive and transportation markets are just beginning to open their doors to LORAN. It's anyone's guess how far that will go, but there is no doubt about the impact on receiver designs if the full market potential is met. Remember back 10 or 15 years when LORAN AVL was hardly more than a concept to a handful of dreamers? By the end of this year, there will be over 20,000 equipped vehicles or contracts for equipping vehicles and no reason to believe that will not increase geometrically as the concept is further accepted. Is there a market for a hand held LORAN receiver small enough to fit in a shirt pocket, with power to last for several days or even weeks? Assuming there is, can a receiver be manufactured and profitably sold at a price which is accepted by the massive consumer market? How many could be sold: a million, ten million? The decade of the 90's may very well answer those questions.

ACKNOWLEDGMENTS

The authors would like to express their gratitude for the pleasure of working with and being a part of the team which developed this process. Without the dedication and hard work of so many individuals at all levels within the company, there would be no success story to write about. As this paper is being finalized, it has been announced that ANI has been purchased by Jet Electronics and Technology, a division of B. F. Goodrich. The authors believe that the new team is well suited to provide further improvements to the manufacturing process, and provide the basis for continuing evolution.

BIOGRAPHIES

Bruce Francis graduated from the University of Kansas in 1972 with Bachelor of Science degrees in Electrical Engineering and Computer Sciences. He attended the University of Texas at Austin from 1972-1974, accumulating over 50 hours of graduate work towards a Ph.D. in Electrical Engineering and Computer Science, with emphasis software engineering.

In January, 1973, he joined Austron, Inc., as a design engineer. He worked on several different software designs for the Model 5000 LORAN Receiver, most notably the operating software for the Model 5000 LORAN Monitor System for the U.S. Coast Guard. In 1975, he was promoted to Vice President, Engineering, supervising Austron's engineering efforts in Time and Frequency, Navigation, component crystal oscillators, and data products.

Mr. Francis helped form Advanced Navigation, Inc., in 1979, and was responsible for the navigation software for the Model 7000 LORAN Navigator. He is presently Vice President, Operations, for Advanced Navigation, Inc., supervising the engineering and manufacturing functions.

William A. DeGeorge was a career Warrant Officer in the U.S. Coast Guard, retiring in 1978. His Coast Guard duties included various assignments in Loran systems engineering, operations, research, and development. Bill joined ITT Avionics in 1981 as a member of the engineering team that designed and installed the Saudi Loran system. Subsequent assignments as principal member technical staff, Advanced Systems Engineering included AVL, TACAN, JTIDS, and LPI communications systems. He joined ANI in 1988 where he is presently Director of Manufacturing.

SPACE CONSIDERATIONS FOR EARTH REFERENCE SYSTEMS

ELIZABETH L. YOUNG

COMMUNICATIONS SATELLITE CORPORATION
WASHINGTON, D.C.

Good Morning! I am very pleased to be here with you today to discuss the links that we are forging internationally between navigation and position locating services, such as LORAN, and communications systems, such as the global satellites operated by INMARSAT. As a sailor myself, I can attest to the importance of knowing where you are and where you are going -- with reliability. The LORAN on our boat is indispensible, even in good weather. As my eyesight gets worse and marker buoys seem to get fewer and fewer between, I am awfully glad to have reliable navigational aides aboard!

My own specialty these days at COMSAT is aeronautical services. And, as you are all aware, while aircraft have both navigation and communications aids aboard now, both systems can be better--and with satellites, we are going to be able to improve precision and reliability. For ships and vehicles, too, the combination of appropriate navigational devices like LORAN, linked with high-quality satellite communications, will mean overall efficiencies in how we navigate and communicate, whether for business or pleasure.

In order to illustrate how navigation and communications can be effectively linked, let me describe the INMARSAT system, how it can be used for aeronautical communications, and what plans we have for the future that may include the GPS/GLONASS systems as well. INMARSAT, the International Maritime Satellite Organization, is a consortium of 57 countries, with headquarters in London. Its mission is to acquire and operate communications satellites that serve mobile users. INMARSAT's charter includes provision of service to the maritime and aeronautical communities, and that charter will soon be amended to include service to the land-mobile community.

At present, INMARSAT uses a constellation of eight satellites that are positioned over the three major ocean regions -- the Atlantic, Indian and Pacific. (INMARSAT's sparing philosophy provides for satellite redundancy in each ocean region.) Since INMARSAT's first constituency was the international maritime community, these satellite locations made ultimate sense. Today, as we look toward aeronautical communications, land mobile services, and increasing maritime traffic, INMARSAT is studying the possibility of moving to a four region system. Either way, the oceanic routes will be covered, as will most of the land mass of the world.

INMARSAT's plans are to launch a second generation of satellites, four in number, beginning in 1990. These satellites, which will provide more than double the capacity of those in use now, will greatly expand INMARSAT's ability to serve its present and future users. The 1987 WARC allocated certain frequencies to be used for mobile communications, and the INMARSAT-II's will include 3 megahertz in the aeronautical band.

INMARSAT's third generation of satellites is in the planning stage, with responses to an RFP due next February. As presently envisioned, these satellites will include spot beams along with global beams, making frequency reuse possible as well as greater efficiency along heavier traffic routes, such as the North Atlantic.

Now, how does INMARSAT make its services available and what are those services? INMARSAT itself operates the satellites; its member countries provide the ground segment -- the earth stations -- that make possible the links with the satellites. COMSAT, the U.S. Signatory to INMARSAT and the largest owner, operates Coast Earth Stations in Southbury, Connecticut (for service in the Atlantic region) and Santa Paula, California (for service in the Pacific region). At present, some 22 Coast Earth Stations serve the maritime community. At least 15 Coast Earth Stations will be equipped to provide aeronautical service during the next few years. By the end of this year, five Coast Earth Stations, including the two owned by COMSAT, will be serving aircraft. Again, the availability of multiple Coast Earth Stations in any ocean region guarantees redundancy and reliability. The satellite link in the communications chain is, of course, not the whole story. Typically, Coast Earth Stations have "tails" into terrestrial networks. We expect aeronautical services to be transmitted and received via a variety of private lines and the public switched network.

Services available via the INMARSAT system include data and voice. For the aeronautical community, this will mean that air traffic services, airline operational and administrative communications, and voice, fax and computer interfaces can all be supported. Of course, both the cockpit and cabin will be able to take advantage of the satellite assisted communications services.

We expect that on commercial flights, cabin calling will be by credit card telephones, much like those in use today in the U.S. on domestic flights. Calls originated on a plane will be able to be terminated anywhere in the world, since the receiving Coast Earth Station can make the additional necessary connections, by terrestrial systems, to the final destination. Similarily, for general aviation, cabin telephones can be interfaced with the satellite data unit to enable calls to be placed from the plane to any ground location.

COMSAT's charges for all the services, whether data or voice, will be on a "per call" basis, with voice calls billed by the minutes (or fractions of minutes) used, and data messages billed by the kilobit.

Because the satellite system establishes links that are highly reliable, redundant and not subject to fading or static, it will be possible to introduce improved services such as Automatic Dependent Surveillance on the transoceanic routes. We expect that the FAA and certain American carriers will conduct extensive tests of the ADS capability, beginning either later this year or in early 1990.

One question that is often asked refers to INMARSAT's space segment capacity. INMARSAT operates on what is called a demand assigned basis. That is, a circuit is made available from the total capacity pool on an as-needed basis. For an aircraft, that means that once a circuit has been requested for a call, it is assigned and is out of the pool as long as the call continues . When the call is terminated, the circuit is returned to the pool. This time-sharing method provides the greatest possible efficiency for the entire system. Fortunately, the second generation satellites will provide more than double the capacity of the present satellites. And the third generation will provide an even greater expansion of capacity. Meanwhile, it is likely that INMARSAT will activate its spare satellites in both the Atlantic and Pacific ocean regions so that two satellites in each ocean region are sharing traffic before the launch of the second generation satellites.

It should be noted that within the past year, INMARSAT has also approved leasing of space segment capacity but on a preemptible basis. This means that a Signatory, like COMSAT, can lease a specified amount of capacity on one or more INMARSAT satellites, for a specific customer and service, but the lease will be preempted if the increase in demand assigned traffic becomes so great that capacity used in the lease is needed to satisfy the demand assigned traffic. Lease prices are established at the time each lease is approved.

Finally, INMARSAT maintains priorities within its system so that emergency messages can always take priority over social traffic. In the design of the aeronautical system, a call request from the cockpit can override a call from the cabin.

In order for an aircraft to take advantage of the INMARSAT aeronautical service, several steps must be taken. First, there needs to be an assessment of whether the candidate aircraft can accommodate an INMARSAT aeronautical antenna and avionics (referred to as the INMARSAT Aircraft Earth Station or AES). At this point in the development of hardware, planes the size of a Falcon 900, Gulfstream III or Challenger are candidates. Eventually, we expect to see the size, weight and cost of the equipment reduced to a level acceptable to smaller general aviation aircraft.

Several manufacturers are developing avionics and antennas. In the U.S., they include Ball Aerospace (low-gain and high-gain antennas), Collins (avionics), and E-Systems (low-gain and high-gain antennas and avionics). Honeywell also plans to produce avionics, and Canadian Marconi is working on an antenna design. Racal in England has produced both an antenna and avionics that are being used in market tests by British Airways. Meanwhile, several commercial airlines, including Northwest and United, have announced that they will equip their new Boeing 747-400's with Ball-Collins low-gain equipment. Antennas currently come in several sizes and designs, including helical, blade and conformal arrays. While potential customers are advised to contact manufacturers directly with regard to prices, a fully installed high-gain AES today will likely cost somewhere between $500,000 to $750,000. These prices probably reflect an attempt to amortize manufacturers' r&d, the newness of the market and the fact that few airlines have made firm commitments to equip entire fleets with aeronautical satcomms. We also understand that manufacturers in several countries are devoting serious efforts to developing AES's more appropriate for smaller aircraft, while still making the equipment compatible with the INMARSAT standards.

INMARSAT itself, and COMSAT as well, have been actively involved in supporting the work of such groups as the ICAO FANS Committee, AEEC and the RTCA in the development of standards compatible with ARINC characteristic 741. While certain elements are still being worked on -- for example, the interface between the cabin telephone system and the satellite data unit and the system design for facsimile -- the intent has been to establish standards that can be applied universally. Ideally, this will mean that if and when other space segment providers come on line, e.g., to provide domestic aeronautical satellite communications services, equipment being used in the aircraft with the INMARSAT system can be interoperable with the domestic system. No one wants an aircraft to have the burden of carrying two sets of satcomm equipment.

After AES equipment has been purchased, arrangements can be made for installation. For new aircraft, this can be done by the airframe manufacturer. For retrofits, a company specializing in retrofitting or the AES supplier can assist. Then, the AES must be commissioned with INMARSAT. COMSAT will assist in this process which usually is quick, and we will provide a User's Manual and other important information to the aircraft owner, including a description of the services COMSAT provides, which will be the following:

DATA: Beginning in 1989, data at 300 bits per second will be offered for two-way (air-ground and ground-air) messages. Typical uses in the cockpit will include position reporting, operational and administrative communications and weather reports. By late 1990, medium and high speed data rates will be offered. To take advantage of data services, aircraft can interconnect with data networks or private lines.

VOICE: By late 1990, voice calling for the cockpit and the cabin will be added. Private aircraft can arrange to use dedicated lines or dial through COMSAT's facilities into the public switched network. Credit card calling (air to ground) will be available to passengers on commercial airlines.

ENHANCED SERVICES: Once an aircraft is equipped with a high-gain antenna, facsimile messages can be sent and received and when aboard the aircraft it will be possible to link a computer (with a modem) into the system for the transfer of data to many locations, including office headquarters, home, or broker. Additionally, COMSAT will make available special news broadcasts and information and can customize individual services to meet our customers' requirements.

Aircraft equipped with low-gain antennas will be able to use only the low-speed data service, while those equipped with high-gain antennas will be able to send and receive at various rates and use voice services.

We recognize, of course, that aircraft will still rely on VHF and HF communications, but on international flights, we believe that the INMARSAT satellite system will offer truly superior communications capability, with additional security and reliability.

Up to this point, we have been talking about how satellite communications can enhance flight. COMSAT and INMARSAT are also taking a look at how we can enhance position location and navigation services. One option is for our system to provide integrity data concerning the GPS satellites. Such integrity messages can be incorporated into the INMARSAT service with no need for modication to the satellites. A more ambitious service would be to provide GPS/GLONASS "look alike" signals originating from the ground. These "look alike" signals would be transmitted in phase quandrature on a single RF carrier. They would also contain correction data to compensate for differences between GPS and GLONASS system reference times and therefore increase the potential of inter-operability between the two systems. This latter service would require the addition of a navigation payload on the INMARSAT third generation satellites and is being considered as an option at this time. One of the driving factors in deciding whether to incorporate a service will be whether there is a clearly definable market ready and willing to pay. At the present time, we understand that INMOS, a UK company, is investigating equipment that would allow GPS receive capability to be added to an INMARSAT Standard-C receiver for maritime applications. (Standard-C is for low bit rate store and forward data.) This same technology is expected to be applicable for aeronautical applications.

As we look ahead to the next decade and, indeed, beyond the year 2000, it is evident that satellites have a very key role to play in aeronautical communications and navigation. Beginning in just a month from now, our company, COMSAT, will offer communications links that can take data from the cockpit, including position data generated by LORAN, and forward it to single or multiple locations, with an equivalent capability to relay real-time messages to the aircraft. This will be but one small step toward a global communications system that should result in improved efficiency, safety of flight and ease of doing business.

I can remember that many years ago, when I was puzzling through the choice of a career, my parents urged me to do anything that appealed to me but to do something that "would make a positive difference to someone somewhere". Just as telephones and telegraphs and LORAN and GPS have made a difference to all of us as we move around the globe (or even around our neighborhood), so, too, I think the communications satellites of INMARSAT and the services of COMSAT will bring forth a new era for aviation. And I am extremely pleased to be at the dawning of that new era even as we meet here.

BIOGRAPHICAL INFORMATION - Elizabeth L. Young is currently Vice President, Aeronautical Services, in COMSAT's Mobile Communications division. She has previously served as Vice President, INMARSAT Policy and Representation and joined COMSAT initially as Vice President for Sales and Marketing in COMSAT General Corporation.

For five years, Dr. Young was President of the Public Service Satellite Consortium, a membership organization that pioneered in the use of communications satellites for public service. During her tenure with PSSC, she also served as President of its subsidiary, Services by Satellite, Inc.

Prior to her work in the satellite industry, Dr. Young held a number of positions in public broadcasting, including the directorship of the public radio and television stations at The Ohio State University, Executive Director of the Kansas Public Television Commission, and Director of Station Relations for National Public Radio.

Dr. Young holds degrees from Columbia University in New York and The American University in Washington, D.C. She completed her undergraduate work at Wellesley College in Massachusetts.

She has published widely in professional journals and has chapters in several books about public broadcasting, cable television, communication satellites and instructional media.

Dr. Young resides in Alexandria Virginia.

IMPACT OF LORAN ON THE NATIONAL AIRSPACE SYSTEM

JOHN S. KERN
ACTING ASSOCIATE ADMINISTRATOR FOR REGULATION AND CERTIFICATION

FEDERAL AVIATION ADMINISTRATION

ABSTRACT

The Federal Aviation Administration (FAA) has been conducting a carefully controlled program to bring LORAN into the National Airspace System (NAS) as a navigation aid for en route, terminal and nonprecision approach phases of flight. Known as the Early Implementation Project, this program has been very successful in that over a dozen LORAN approaches have been approved and considerable data have been accumulated on performance characteristics and reliability of the LORAN system.

Now, however, we are on the verge of a very important and dramatic occurrence in the NAS, i.e., the full operational deployment of LORAN. While LORAN will be a change in the NAS, it also will cause many changes in FAA controlled operations. For example, LORAN is an earth referenced navigation system versus the station referenced navaids presently used in the NAS. LORAN facilitates point-to-point routing; but how can this be reconciled with the current routing structure? Finally, LORAN will make possible thousands of new nonprecision approaches.* Development of these procedures will necessitate extensive operational and organizational changes in the FAA.

This paper will examine the anticipated impact of LORAN on NAS functions, and proffer some solutions to difficulties that must be overcome in order to fully realize the potential of this new aviation navigation aid.

INTRODUCTION

For a number of years, the Federal Aviation Administration (FAA) has been using LORAN in the National Airspace System (NAS) both for en route navigation and for nonprecision approaches. Perhaps this fact is not as widely known as it should be, because LORAN for aviation has been introduced in a limited and carefully controlled manner. This method of implementing LORAN in the NAS was selected not because of any reservations regarding the performance characteristics of the system. After all, the comprehensive Vermont test program[1] which concluded in 1981, erased any doubts that LORAN could meet FAA requirements for Instrument Flight Rules (IFR) operations in the NAS. Rather, LORAN appeared to be a navigation technology radically different from conventional FAA navaids, and wisdom dictated a cautious implementation.

Now, however, we are on the eve of a fully operational LORAN system in the NAS and a new set of challenges must be addressed.

BACKGROUND

In 1983, the National Association of State Aviation Officials (NASAO) met with FAA Administrator, Donald D. Engen, to discuss a phenomenon taking place throughout the country. A growing number of their constituents, particularly in the general aviation, small commuter, and business aircraft communities, were interested in taking advantage of the point-to-point capabilities of LORAN and the potential it represented for IFR approaches to airports presently without any landing aids. The growing swell of LORAN aviation users was fueled in part by the advent of user-friendly receivers at affordable prices.

In partnership with NASAO, the FAA launched an Early Implementation Project (EIP) designed to accomplish the following:

- Develop LORAN nonprecision approaches at a small number of airports suggested by NASAO. To qualify for the EIP, airports had to meet certain criteria:
    - Signals from the primary triad of transmitters selected for nonprecision approach had to have a signal-to-noise ratio (SNR) of 0 dB or better.

- The airport had to have a good geometric location relative to the transmitters so that the accuracy of the navigation solution would not be compromised.

- In the first stages of the project there had to be an existing FAA navaid (e.g., VOR, NDB, ILS) approach over which the LORAN approach could be developed. The reasons for this were twofold. First, LORAN is a supplemental navaid in the NAS, so its use in IFR conditions requires the presence of an approved navaid such as one of the three just mentioned. Second, although EIP was never intended to be a test program, the use of existing approaches gave controllers and pilots a yardstick to assess LORAN performance especially during the early phases of the project.

- Finally a user who was willing to participate in the project and fly LORAN approaches had to be identified. Certification of LORAN receivers was a difficult problem in the initial stages of the project, but once two manufacturers were accredited, it was easier to find qualified participants.

o Provide an opportunity for operating elements of the FAA to become familiar with LORAN and to develop procedures and methods to facilitate its use and to promote its safe application.

Eight airports were designated for the EIP (Fig. 1) and at each of these airports, a LORAN signal monitor was installed. The monitors provided assurance to air traffic controllers that LORAN signals were available from specific transmitters prescribed for each nonprecision approach and that the signals were within the accuracy tolerances of FAA Advisory Circular 90-45A. In addition, the monitors became an invaluable source of information on the performance and stability of the LORAN signal grid.

EARLY IMPLEMENTATION PROJECT

AIRPORTS FOR FIRST LORAN APPROACHES

AIRPORT LOCATION	COMMISSIONING DATE
BEDFORD,MA	NOVEMBER 4,1985
BURLINGTON, VT	FEBRUARY 11, 1986
SALEM, OR	MAY 30, 1986
PORTLAND, OR	MAY 30, 1986
COLUMBUS, OH	OCTOBER 6, 1986
MANSFIELD, OH	OCTOBER 6, 1986
ORLANDO, FL	MAY 22, 1987

FIGURE 1.

On November 4, 1985, the first FAA approved LORAN IFR nonprecision approach was successfully executed at L.G. Hanscom field in Bedford, Massachusetts. Admiral Engen was the copilot on that historic flight. In rapid fashion, LORAN approaches were commissioned at the remaining seven airports.

Two important commitments that the FAA made to the LORAN aviation program were support 1) to fill the signal coverage gap in the mid-continent area of the United States, and 2) to develop and install a nationwide network of LORAN signal monitors. Working with the U.S. Coast Guard, it was determined that adequate signal coverage could be obtained by installing LORAN transmitters in Montana, Wyoming, Oklahoma, and New Mexico.

STATUS OF THE EIP

Literally, hundreds of LORAN approaches have been made since the inception of the EIP. In order to expand FAA and user involvement, four of the monitors were moved to new airports. The FAA and NASAO planning-work group proved to be an excellent forum to resolve developmental and operational problems. The monitors that were deployed for the EIP furnished significant volumes of data on LORAN system performance and they also were sources of valuable design information for the operational monitors. Another vital source of LORAN system performance for aviation has been the users who have been most cooperative in reporting their experiences making EIP approaches. With few exceptions, their comments have been constructive and of a highly favorable nature. In a sense, the user feedback has justified the basic philosophy of the EIP because they have taken advantage of this special communications channel to make solid contributions to the FAA LORAN program.

Over a dozen LORAN approaches have been approved thus far. Originally, a monitor was installed at each airport for which a LORAN procedure was developed. This practice eventually was altered in four instances so that one monitor was employed to support approaches at two different landing facilities. Multiple-site support by a monitor was deemed feasible because of a study[2] that was conducted as part of the EIP. Based on the analysis of data from an extensive field test program, it was shown in the study report that a LORAN monitor can support approaches to airports within a 90-mile radius of the monitor. Good use was made of this principle in Louisiana where a LORAN stand-alone approach was commissioned for the Chevron heliport in Venice, Louisiana. The monitor for Venice is located at Lakefront airport which is 56 miles to the north. This monitor drives a signal annunciator in the Lakefront tower and a second annunciator in the Houston Air Route Traffic Control Center which has the IFR approval authority for Venice.

The FAA intends to continue operation of the EIP until the operational monitors are completely installed and the need for EIP monitors no longer exists.

FULLY OPERATIONAL LORAN IN THE NAS

STATUS OF MID-CONTINENT TRANSMITTER STATIONS

Reports from the Coast Guard continue to indicate that the mid-continent transmitter project is making satisfactory progress. Solid-state transmitters for the four sites have been built and delivered. Property has been acquired for the Montana, Wyoming, and Oklahoma stations and buildings on these sites will be completed this fall. Acquisition of the New Mexico site experienced some delay due to environmental questions; but those concerns have been resolved and the environmental assessment is being reviewed.

Every year the FAA is required to submit to the Coast Guard an updated version of LORAN system requirements. The goal of the FAA is to establish conformity with other navigation aids in the NAS. The Coast Guard has been very responsive to FAA concerns about off air time, maintenance practices, and automatic aviation blink. This is important because there was some apprehension about the introduction of a navigation aid which would not be under the complete control of the FAA. The manner in which FAA operating requirements have been addressed to date insures the smooth incorporation of LORAN operations in the NAS.

OPERATIONAL MONITORS

A system of 197 monitors will be deployed to provide coverage in the conterminous U.S. and Alaska. The monitors will be installed in VOR facilities in order to take advantage of the communications system that exists for the remote maintenance monitoring operations. Approximately 40 monitors have been installed, primarily in Alaska, and the remainder should be in place by August 1990. Interface cards that will allow access to the monitors via the remote maintenance communications channels will be in place by the end of 1990.

When the transmitters are on line, and the national monitor system is functional, the LORAN system will be a fully operational navigation aid in the NAS; but the impact of LORAN on the entire Air Traffic Control System will just begin to surface. What can we expect?

IMPACT OF LORAN ON THE NATIONAL AIRSPACE SYSTEM

The "new" LORAN system will affect virtually every facet of the NAS including airways facilities, aviation standards, procedures development, flight inspection, and air traffic control.

AIRWAYS FACILITIES

Airways Facilities (AF) will perform a number of important tasks to operate and maintain LORAN facilities. For example, AF will maintain five of the U.S. Coast Guard System Area Monitors for the new LORAN chains (North Central U.S. and South Central U.S.) which will be created after the mid-continent transmitters are operational. AF also will maintain the nationwide system of aviation monitors and will be responsible for the installation of any correction values required to keep monitor parameters in tolerance.

Lastly, AF will operate LORAN Site Evaluation Systems (LSES). Prior to flight inspection, the LSES will be used to measure signal suitability at each airport that is a candidate for a LORAN nonprecision approach.

AVIATION STANDARDS

The LORAN monitor system will generate a unique and comprehensive database on the national grid of LORAN signals. This database will be the primary source of information needed to generate corrections to keep monitor performance within acceptable limits. Each monitor can store 60 days of LORAN signal measurements and these will be accessed by the Aviation Standards National Field Office through the

VOR maintenance monitoring communications system. The data will be processed to generate corrections for monitor parameters and to refine a LORAN coordinate adjustment algorithm that can be used to keep the accuracy of LORAN nonprecision approaches within acceptable bounds.

The data collection system is under development at the Transportation Systems Center in Cambridge, Massachusetts. Eventually, it will be relocated as an operating entity in the Aviation Standards National Field Office at the FAA Aeronautical Center in Oklahoma City, Oklahoma.

PROCEDURES DEVELOPMENT

LORAN will cause a major perturbation to the FAA system for Instrument Approach Procedures development. At present, a total of about 300 new procedures are developed annually for all navigation aids in the NAS. LORAN, however, has the potential for supporting an instrument approach into the 17,000 airports in this country. Clearly, extraordinary means are needed to address this problem and the FAA has responded with two initiatives designed to substantially increase their capacity for producing procedures.

First, action by the FAA to establish a National Procedures Development Branch began early this year. The selection process for a branch manager and two supervisors started in September and there are plans to staff the branch with four airspace system inspection pilots, ten aeronautical information specialists, and two procedures clerks. This significant commitment by the FAA will provide coverage for flight procedures development not only for LORAN, but for MLS and GPS as well.

In addition to this increased manual capability, efforts are under way to accelerate the completion of the Instrument Approach Procedure Automation (IAPA) system. This is the basic tool that will be used for LORAN procedure development. Efforts are under way to accelerate the campletion of this system. IAPA will be certified for Area Navigation (RNAV) procedures development approximately eighteen months after the Terminal Instrument Procedures (TERPS), Chapter 15 for RNAV, is approved. TERPS Chapter 15 has been circulated for comment and final coordination of criteria is expected by the end of November 1989.

FLIGHT INSPECTION

In preparation for the volume of flight inspection requests that will come with the advent of LORAN as a nonprecision approach aid in the NAS, LORAN flight inspection criteria were formulated and coordination within the Aviation Standards National Field Office will be completed by November 30, 1989. Two Sabre jets and one Jet Commander have been equipped with LORAN flight inspection systems and at this time one more Sabre jet is in the process of being outfitted with LORAN equipment. Furthermore, LORAN systems have been ordered for nineteen Beech 300 aircraft. In short, the flight inspection fleet will be ready to respond to the influx of LORAN procedure requests. The efficiency of the flight inspection fleet will be enhanced considerably by the LSES which will evaluate an airport's suitability for LORAN operations prior to the performance of a flight inspection.

AIR TRAFFIC CONTROL

Air traffic control operations seem to embody the public's conception of the FAA, and indeed, in the case of LORAN, there will be many changes in the conventional modes of operation, with serious possibilities for large scale innovations and revisions. In its basic operation, LORAN is an atypical navigation aid in the NAS. Traditional navigation aids in the NAS such as VOR, DME, NDB, ILS, and MLS are station-referenced systems in which the aircraft measure of position is computed relative to a ground-based facility. Furthermore, each of these navaids is operated and maintained by the FAA. LORAN, on the other hand, is an earth-referenced system and an aircraft's position is made relative to a mathematical model of the earth in latitude and longitude coordinates. In addition, LORAN will be the first large navigation system in the NAS to be operated and maintained by an organization other than the FAA.

Concern arises when widespread use of an earth-referenced system is proposed for operation in the NAS which was developed for station-referenced navigation systems. The key will be the degree to which the mathematical models used in the former agree with the surveys upon which the navigational charts and maps of the latter are based. The results of the EIP to date indicate that agreement can be attained well within the en route and nonprecision requirements of AC 90-45A.

The real payoff, however, is not in forcing LORAN to comply with station-referenced system requirements, but rather in exploiting possibilities for new, safe, and expanded applications in the NAS. Point-to-point navigation, endemic to LORAN operations, can improve the efficiency, while reducing the congestion, of NAS operations. IFR accessibility to outlying airports will meet the needs of general aviation, small commuter and corporate aircraft users and can be achieved with LORAN without the installation, and attendant maintenance, of costly ground equipment at airports. Finally, the FAA is cognizant of the potential that LORAN has for near-term domestic automatic dependent surveillance applications[3], and will be examining this type of usage soon.

SUMMARY

The introduction of a new navigation aid into the NAS is exciting because concerns about its impact on FAA operations are more than offset by the promise of a major move forward in the air traffic control field. This certainly is the case with LORAN which literally will affect all facets of the NAS, but also is viewed as a means to ameliorate, if not remedy, many problems presently in our system.

The FAA, through the Early Implementation Project, has had an excellent opportunity to view first hand the impact of LORAN on various organizations and functions. Although much remains to be done, preparations have commenced in several areas in anticipation of new demands on the NAS. The outlook is very optimistic.

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1. Flight Evaluation of Loran-C in the State of Vermont. Research and Special Programs Administration/Transportation Systems Center, U.S. Department of Transportation; DOT-TSC-RSPA-81-10, September 1981

2. Range of Validity of Operational FAA Monitors for Loran-C Signals. Federal Aviation Administration; DOT-TSC-FA729-PM-87-14, June 1987

3. Automatic Dependent Surveillance Information Requirements. Proceedings Fourteenth Annual Technical Symposium, Wild Goose Association; Volume 14, pp. 299-323, October 1985

LORAN TRANSMITTERS

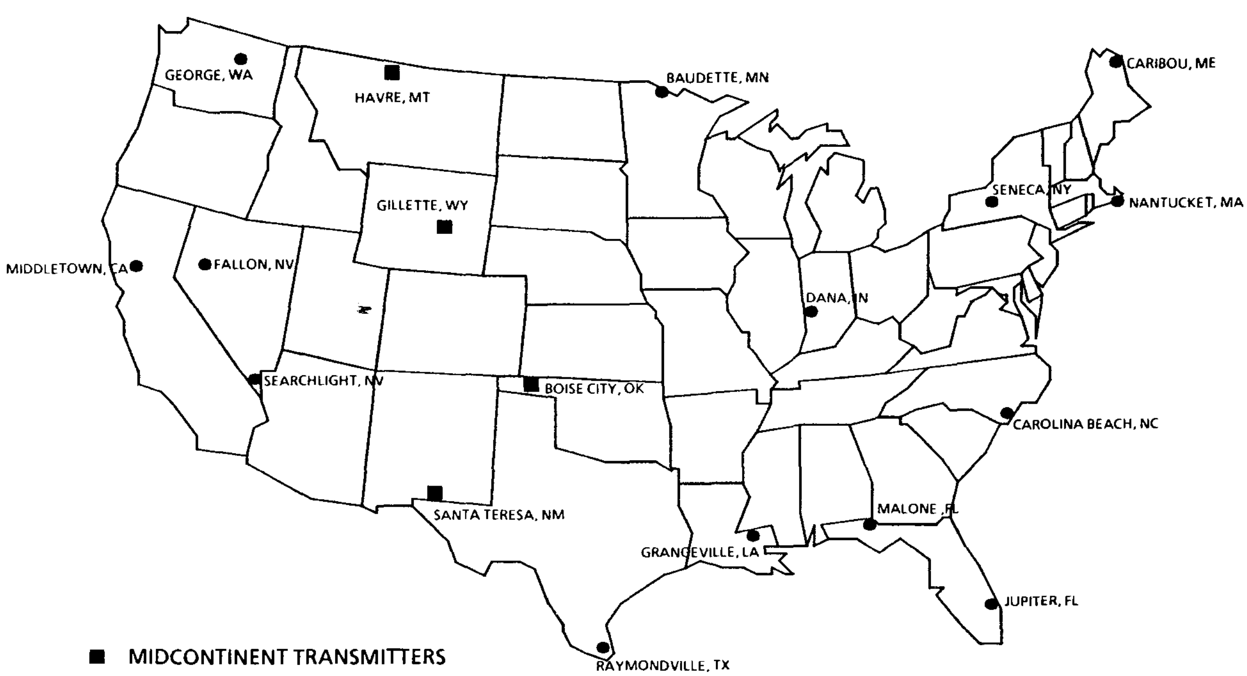

Figure 2

SESSION 2

LORAN INTEGRATION & APPLICATIONS

Participants in this Tuesday afternoon session included (left to right) Douglas Ambos of Datamarine, Jeffrey D. Catlin of Synetics, H. James Rome of the University of Lowell Massachusetts, Peter H. Dana, Consultant, Francis S. Cassidy of Datamarine, Richard Lancaster of Transtrack and Mark Morgenthaler of Trimble Navigation who also chaired the session.

SYNERGISTIC INTEGRATION OF AUTOMATIC DEPENDENT SURVEILLANCE AND LORAN IN THE NORTH CARIBBEAN AREA*

H. James Rome

Department of Electrical Engineering, University of Lowell, Lowell, MA

ABSTRACT

Analytic and simulation models are described which can evaluate the use of Automatic Dependent Surveillance system (ADS) with precise navigation for intersecting track route structures. The analysis is applied for an area where LORAN is available. It is shown that, by combining ADS and LORAN it may be possible to raise the flow rates on intersecting tracks by as much as an order of magnitude over that possible using current over-the-ocean Air Traffic Control (ATC) procedures. This new concept would provide for the same level of safety as current procedures.

BIOGRAPHY

H. James Rome

Dr. Rome received his B.S.E.E. and M.S.E.E. degrees from the University of Michigan, and his Ph.D. from the University of Pennsylvania. Currently he is a Professor of Electrical Engineering at the University of Lowell. He has had about 25 years' experience working on projects in Air Traffic Control, Collision Avoidance, Integrated INS, Satellite Navigation, JTIDS, and Gravity-related studies for submarine inertial navigation.

1. INTRODUCTION

LORAN, with an overall accuracy of 0.1 nm RMS, has generally been considered more than needed for enroute over-the-ocean navigation considering the current form of oceanic air traffic control. Current operational procedures involve relatively infrequent but periodic verbal reports (via HF) of position and track. Thus, maintaining a safe route structure requires large lateral and longitudinal separations. Highly accurate navigation does little, in these circumstances, to improve the capability of the system.

Interest in LORAN for over-the-ocean navigation may again peak as the International Aviation Community considers developing and deploying a satellite-based system: Automatic Dependent Surveillance (ADS). Put simply, the concept involves automatically transmitting aircraft position (as determined by the on-board navigator) and related data, via a satellite link, to Air Traffic Control (ATC) for real-time control of aircraft beyond the range of conventional radar. Some of the anticipated benefits of the system will be closer longitudinal and lateral track spacing in parallel track systems, a freer use of random tracks, and higher capacity in regions where route structures involve intersecting tracks.

This paper will consider the impact of combining LORAN and ADS in an area like the North Caribbean. Here LORAN is available. The air traffic in this area has a significant component of intersecting tracks made up of traffic flying the Caribbean north to New York and traffic flying from Atlanta and Miami to Europe. Current procedures require that aircraft on intersecting paths (same flight level) be separated in time (crossing time difference at intersection) by at least fifteen minutes. During peak traffic periods, the traffic density is often too high to meet the crossing time difference requirement. Thus multiple flight level changes are often required so that traffic on one route can weave its way through the intersections. This may result in longer flight times and a reduction in fuel efficiency.

Analysis in [1] has indicated that if ADS were implemented with LORAN as the primary navigator (having accuracies of the order of .1 nm), it is theoretically possible to achieve flow rates on intersecting tracks as high as 12 aircraft per hour or higher. This could be achieved with no reduction of safety over current procedures. Also it will be shown that LORAN/ADS can provide flow rates several times higher than that possible using ADS with INS for navigation. In addition, results of Monte Carlo simulations show that practical capacities approaching the theoretical capacities can be achieved, assuming random loading of the tracks. Thus it appears possible that use of same level intersecting paths could be practical even during peak traffic periods.

This paper will outline the procedures and results which form the basis of this conclusion. First, models and procedures to numerically evaluate the combination of ADS and accurate navigation will be developed in Section 2. From this, LORAN/ADS can be compared to No ADS and to INS/ADS.

The key feature of the model developed is its simplicity. Because of its simplicity, it is possible to use the model to evaluate collision rate and intersection capacity as they are affected by ADS message content, navigation error characteristics, etc.

Section 3 presents numerical studies used to compare ADS/LORAN to No ADS and ADS/INS providing numerical support to the thesis that LORAN may be capable of providing a quantum improvement in over-the-ocean air traffic control separations reductions and increased flow rates.

*This paper is based on work performed for the U.S. Department of Transportation, Transportation Systems Command, Cambridge, under Contract #DTRS-57-85-C-00088.

Section 4 presents the results of Monte Carlo simulations which can more precisely factor in the effects of winds, axial separation control and queues generated by the ATC procedures. The results of the simulations demonstrate that the relative advantage of using LORAN/ADS over say INS/ADS is even greater than that computed theoretically. Section 5 presents summaries and conclusions.

2. DEVELOPING ANALYTIC MODELS FOR EVALUATING COLLISION RISK ON INTERSECTING TRACKS

A probability model for collision rate must include a strategy for surveillance and control, the navigation and surveillance system error characteristics,and any pertinent geometry. The basis of the model is most easily understood by considering the anatomy of a collision.

See Figure 1. The true paths of the aircraft are represented by the solid lines. A collision is assumed to occur when the centers of the two aircraft are separated by a distance less than RCOL as is shown by the intersecting circles on the figure. These aircraft are being tracked, or at least initially directed such that a collision would *not* occur.

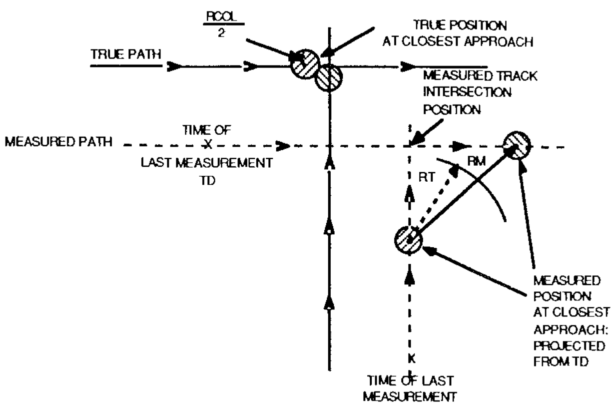

Figure 1. Anatomy of a Collision

What happened? At some time prior to the collision, the last measurement time, as represented by the "X" on the figure, the state of both aircraft are observed (via reports from the aircraft) and their range at closest approach is computed. Because of errors, their "observed" tracks are the dashed lines on the figure. Their projected positions at the point of closest approach are the circles on the dashed lines. The computed or projected range at closest approach, called the measured minimum range hereafter, is RM as shown. On this figure, RM is greater than a threshold range, RT. Thus the aircraft are allowed to proceed, and the collision occurs. Had RM been less than RT, ATC would have instructed the aircraft to take some sort of evasive action in order to negate any probability of collision.

Now define PC as the probability of a collision given that the aircraft are initially on a collision course. It can be expressed as:

$$PC = \text{Prob}(RM > RT/R_{min} < R_{col}) \qquad (1)$$

In the above, R_{min} is the true minimum range at closest approach, R_{col} is the maximum range (separation) at which a collision would occur (typically the diameter of the aircraft). Recall from above that RM is the computed minimum range at closest approach projected from the last measurement made, and RT is the threshold or decision value used to decide whether or not to instruct the aircraft to take evasive action. (In what follows it is assumed that if RM < RT, there is no probability of collision.)

In other words, PC is the probability that the projected (measured) range at closest approach is greater than the decision threshold given that the aircraft are indeed on a collision course. Now define CRT as the collision rate given no control. Thus, the collision rate after control would be:

$$CR = PC * CRT \qquad (2)$$

The remainder of this section develops the details of actually computing eq. (2) in terms of aircraft rates, geometries and tracking errors. Then the results are used to develop the concept of intersection capacity which is used as a measure of effectiveness (MOE) in evaluating the impact of navigation and tracking error on intersecting tracks operation.

A key step is defining range at closest approach in terms of crossing time difference at intersection, t_o, and geometric parameters. It is shown that minimum range and t_o are directly proportional. This allows straightforward analysis to proceed, since the errors in estimating crossing time difference can be written as a linear combination of the navigation and tracking errors.

2.1 Relationship of Range at Closest Approach to Crossing Time Difference

Consider the two tracks shown in Figure 2. Aircraft #2 is on the "horizontal" track, where it crosses the intersecting point at t = 0. Aircraft #1 is on the other track, crossing the intersection point at $t = t_o$. Thus t_o represents the crossing time difference. It is assumed that both aircraft are flying straight and level at constant velocity at the same altitude. By simple calculus and use of trig identities it can be shown that (see [1]):

$$R_{min} = |t_o|\ |V_1|\ |V_2|\ |\sin\theta|/|\Delta V| \qquad (3)$$

Where

V_1 = speed of Aircraft #1
V_2 = speed of Aircraft #2
θ = crossing angle of the tracks
$|\Delta V|$ = the vector velocity difference between the two aircraft

The key to this expression is the fact that (except for the absolute value function) R_{min} varies linearly with t_o. The other terms (for $|\theta| > 10°$) simply represent proportionality factors. Small changes in V_1, V_2 do not significantly change the relationship. There can only be a collision when $t_o \cong 0$.

The measured crossing time difference, that defined by using the observed state of the aircraft and projecting ahead to the intersection, will be a random variable. Define it as TM. As will be shown next, TM can be written :

$$TM = t_o + X \qquad (4)$$

Where

t_o is the true time difference, and
X is the variation caused by navigation and tracking errors

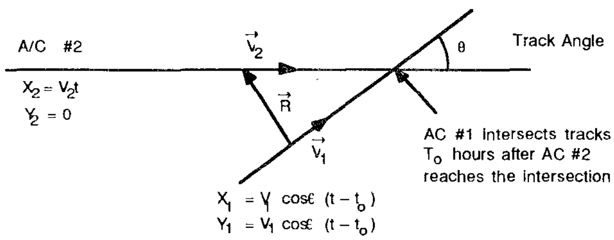

Figure 2. Relating Range at Closest Approach, R_{min}, to "t_o," Time Separation at Intersection

Since the measured range at closest approach is directly related to TM via eq. (3), that is

$$TM = \frac{R_{min}\,|\Delta V|}{V_1 V_2 \sin\theta} + X \qquad (4A)$$

it is possible to use TM, rather than RM in the decision making process outlined above without any loss of generality. In fact projected crossing time difference is the criterion used by Oceanic ATC controllers in maintaining separations at intersections.

Furthermore, X can be written as a linear combination of the along track and cross track perturbations. Thus once the PDF of the perturbations are established, it is straightforward to determine the PDF of TM. Then it is possible to evaluate the decision making process, establish threshold levels, etc.

Shown in Figure 3 are the two true tracks and the observed tracks perturbed in the cross track direction: Observed Track #1 is off by ε_{c1} and Track #2 by ε_{c2}. The intersection of the two "true" tracks is then at the intersection of the solid lines. The observed track intersection is at the intersection of the dashed lines. Aircraft #1 is observed crossing the intersection at $t = t_o$, and Aircraft #2 at $t = 0$. Observed time at intersection vary because of the errors. In addition the along track errors, ε_{t1}, ε_{t2}, will advance or delay the estimated crossing times.

It is shown in [1,2] that the measured crossing time difference can be written as a linear combination of the errors as follows:

$$TM = t_o + \frac{1}{\sin\theta V_1 V_2}\left[\left(V_2\cos\theta - V_1\right)\varepsilon_{c1} + \left(V_1\cos\theta - V_2\right)\varepsilon_{c2}\right] - \frac{\varepsilon_{t1}}{V_1} + \frac{\varepsilon_{t2}}{V_2} \qquad (5)$$

or

$$TM = t_o + X$$

Where X is the random variable dependent on the navigation and tracking errors.

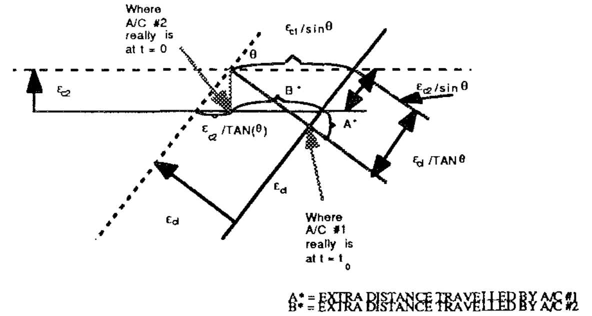

Figure 3. Impact on Navigation and Tracking Errors on Computing T_o (R_{min})

Furthermore the errors in track at the intersection vicinity can be expanded as a function of time since last observation, TD (the decision time before Aircraft #2 crosses the intersection point), as follows:

$$\begin{aligned} \varepsilon_{c1} &= V_1 TD \delta H_1 + \varepsilon_{c10} \\ \varepsilon_{c2} &= V_2 TD \delta H_2 + \varepsilon_{c20} \\ \varepsilon_{t1} &= \delta V_1 TD + \varepsilon_{t10} \\ \varepsilon_{t2} &= TD \delta V_2 + \varepsilon_{t20} \end{aligned} \qquad (6)$$

Where δH_1 and δH_2 are errors in estimating track angle of Aircraft #1 and #2, respectively; ε_{c10} and ε_{c20} are the cross-track errors at the time of measurement (TD); δV_1 and δV_2 are errors in estimation of aircraft speed; ε_{t10} and ε_{t20} are the along-track errors at the time of measurement. It is seen from eq. (6) that the longer time between decision and intersection, the larger the errors.

2.2 Determining Collision Rate

According to the discussions above, minimum range at closest approach and time difference at intersection are proportional for a given intersection geometry. Thus decision making can be transformed from the space dependent variable to the time difference variable.

The decision process becomes: if

$$TM < TOT \qquad (7)$$

where TOT is the threshold time, an alarm sounded. Evasive action is recommended by ATC. Note that

$$TOT = (RT)\,|\Delta V| / \left|V_1 V_2 (\sin\theta)\right| \qquad (8)$$

The probability of a collision given a collision is imminent (see eq. (3)) can then be written in terms of the time difference variables as:

$$PC = P\left(|TM| > TOT / |t_o| < Tcol\right) \qquad (9)$$

where Tcol is the crossing time difference representing a collision:

$$Tcol = (Rcol)\,|\Delta V_1| / \left|V_1 V_2 (\sin\theta)\right| \qquad (10)$$

where $|\Delta V|$, V_1, V_2, and θ are defined for eq. (3).

Recall that TM is a random variable:

$$TM = t_0 + X$$

X is the net effect of the errors in navigation and tracking as defined in eq. (5). t_0 is also a random variable with a PDF, $f_0(t_0)$.

However, X will generally be of the order of minutes for current navigation systems considered, whereas t_0 will be around a second when a collision is imminent (so long as the track crossing angles are greater in magnitude than 10° or less in magnitude than 170°). It is shown in [1] that eq. (1) can then be simplified to

$$PC \cong Pr(|TM| > TOT/to = 0) = PR(|X| > TOT) \quad (11)$$

Thus, once the pdf's of the constituent errors in eq. (5) are defined it is possible to compute PC.

The expression for uncontrolled collision rate, CRT is derived assuming that the flow of m_1 aircraft per hour on Track #1 and m_2 aircraft per hour on Track #2 are Poisson distributed and independent. This is a pessimistic assumption since there will be a minimum spacing. The resulting expression is derived in [1,2] and via a different approach in [3]. It is

$$CRT = 2m_1m_2Tcol = \frac{2m_1m_2|\Delta V|}{|V_1V_2\sin\theta|} Rcol \quad (12)$$

In order to better interpret the formula, set $V_1 = V_2 =$ 500 kts. Rcol is typically .03 nm. If $\theta = 45°$, and $m_1 = m_2 = 5$ aircraft per hour, then CRT = .0038 collisions/hour. This implies a mean time to collision of about 300 hours! If $\theta = 135°$, CRT = .00917 collisions/hour, implying a mean time to collision of about 100 hours. Obviously, control on intersecting routes is imperative. Note that eq. (12) only holds when the track angle has a magnitude of greater than 10°.

2.3 Computation of Collision Rate After Application of ADS

First assume that all navigation and tracking errors are Gaussian. Then X in eq. (5) is also Gaussian with a mean of zero and a variance:

$$\sigma_x^2 = \frac{1}{(\sin\theta V_1 V_2)^2}\left[(V_2\cos\theta - V_1)^2\sigma^2_{\varepsilon_{cl}} + (V_1\cos\theta - V_2)^2\sigma^2_{\varepsilon_{c2}}\right] + \frac{\sigma^2_{\varepsilon_{tl}}}{V_1^2} + \frac{\sigma^2_{\varepsilon_{t2}}}{V_2^2} \quad (13)$$

where $\sigma^2_{\varepsilon_{cl}}$, $\sigma^2_{\varepsilon_{c2}}$, $\sigma^2_{\varepsilon_{tl}}$, and $\sigma^2_{\varepsilon_{t2}}$ are the variances of the appropriate terms defined in eq. (5). Then, in terms of the complementary error function, ERFC,

$$PC = 2\,ERFC\left(\frac{TOT}{\sigma_x}\right) \quad (14)$$

and, using eqs. (12) and (14) in eq. (2),

$$CR = 2\,ERFC\left(\frac{TOT}{\sigma_x}\right)\frac{2m_1m_2|\Delta V|}{\left(V_1V_2|\sin\theta|\right)} Rcol \quad (15)$$

Often in collision risk analysis [4] the navigation and tracking errors are assumed non-Gaussian,for instance a double exponential PDF is commonly assumed. This makes computation of eq. (14) more complex. However there are no real impediments to computing eq. (14). It is shown in [1] that a double exponential PDF can be approximated very closely by a weighted sum of gaussian functions. It is also shown in [1] that if each of the PDF's associated with each of the contributing errors in eq. (5) can be written in terms of a weighted sum of gaussian PDF's then the PDF for X can also be written as a (different) weighted sum of Gaussian functions as shown below.

$$f(X) = \sum_{i=1}^{L} P_i \frac{1}{\sqrt{2\pi}\sigma_i} e^{-x^2/2\sigma_i^2} \quad (16)$$

Then

$$PC = 2\sum_{i=1}^{L} P_i\, ERFC\left(\frac{TOT}{\sigma_i}\right) \quad (17)$$

2.4 Capacity

There is a need to define a single measure of effectiveness which will characterize the intersecting track situation. Its purpose is to determine the impact of ADS and navigation system accuracy on collision risk in an unambiguous manner. Recall that collision rate at an intersection depends on three types of parameters:

1. Flow rate on both tracks
2. Threshold at decision time
3. Probability density functions of the errors of aircraft on both tracks

Flow rates can be irregular, and however they are characterized today, their characterizations may change in the future. This, plus the fact that the thresholds dramatically affect collision rate, appears to complicate the situation. One convenient measure of effectiveness is intersection capacity. It is defined as the maximum number of aircraft per hour which can pass an intersection while a specified level of safety is maintained, within certain operational constraints. Below this concept is developed.

Assume that the speeds and error characteristics of the aircraft navigators are fixed. See Figure 4 which shows hypothetical plots of collision rate vs. threshold time, parameterized on flow rates on each track. It is seen that so long as constraints are not violated, collision rate can be decreased by increasing the threshold at a given flow rate. The dashed line on the figure represents the level of safety, (taken as 1 collision in 1 billion hours). The intersection of the collision rate curves with the level of safety represent the minimum time thresholds capable of achieving the level of safety. It is seen the minimum thresholds monotonically increase with the flow rates. The constraint is that the time threshold cannot be any more than 1/2 the time between aircraft on the other track.

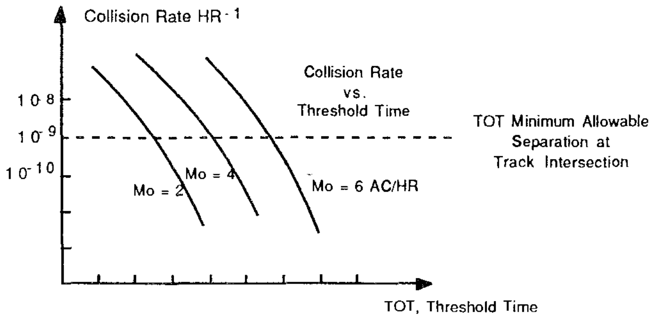

Figure 4. Defining Intersection Capacity

This constraint leads to the concept of "ultimate capacity." See Figure 5. Here the minimum thresholds are plotted vs. flow rates. Also plotted is 1/2 time between aircraft vs. flow rate. Where the two curves intersect is the ultimate capacity. It is defined as the maximum number of aircraft per hour (assuming the flow rate on the both tracks are the same) that can be supported at a specified collision rate while not violating the above constraint. The problem is that to achieve this would require constant control of the aircraft.

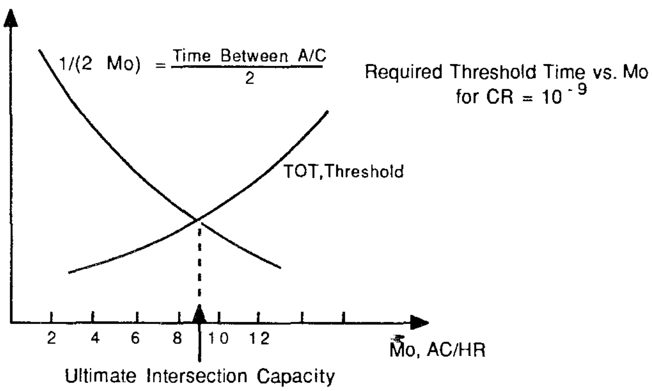

Figure 5. Defining Intersection Capacity

Note that other operational requirements add additional constraints which will lead to the quantity simply defined as "Capacity." This operational constraint is that the aircraft cannot be perfectly controlled such that, at the decision time, its measured crossing time places it exactly halfway between the aircraft on the other track.

In order to specify "Capacity" it is necessary to formulate a scenario. Figure 6 sketches out the situation on a distance from track vs. time plot. The diagonal lines on this plot represent the distance from the intersection point of the aircraft of interest on Track #1 vs. time. The aircraft pictured on the abscissa represent aircraft on Track #2. Their location on the abscissa represent time to intersection of these aircraft. The distance on the abscissa between the aircraft on Track #2 represent their axial time separation when aircraft on Track #1 crosses the intersection. The abscissa distance between the points the diagonal lines cross the abscissa and the aircraft pictured represent the various time difference at intersection values to be discussed next. The scenario follows:

1. At time TA, before track intersection (typically one hour) the aircraft on Track #1 is directed to intersect Track #2 midway between the two aircraft which are assumed uniformly spaced for this mathematical analysis. (Its projected path is represented by the long, dashed line.) Generally, this can be done by directing the aircraft to travel at a slightly different Mach number, or if necessary, holding the aircraft at the remote location (perhaps delaying takeoff) until the above condition can be met.

2. The true observed path of the aircraft is represented by the solid "wavy" line. At the decision time, TD (typically .3 hours), the aircraft on Track #1 is again observed as well as the locations of aircraft on Track #2. Crossing time difference at intersection of the closest aircraft on Track #2 is computed. This is defined as TM(TD). (The projected path to the intersection is represented by the short dashed line.) If |TM(TD)| > TOT, where TOT is the threshold time difference, the aircraft is allowed to proceed.

3. If not (as is shown on the figure), control must be applied. If changing speed is not allowed, the aircraft is directed to change altitude such that it will not be a threat to aircraft on Track #2. This is not desirable.

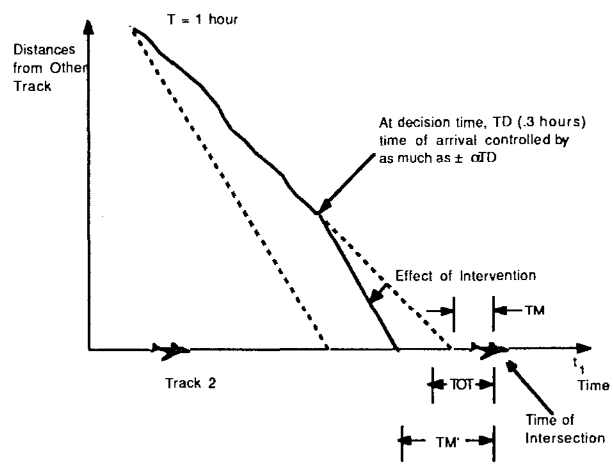

Figure 6. Capacity: Scenario

If speed change is allowed, and the expected crossing time difference after the change command, TM'(TD), is such that |TM'(TD)| > TOT the aircraft is also allowed to proceed at the modified speed. (The projected path after this command is shown by the short solid line on the figure.) However, TM'(TD) can only vary within the limits:

$$-\alpha TD + TM(TD) < TM'(TD) < TM(TD) + \alpha TD$$

Where α is the maximum allowed fraction of time to arrival at the intersection that the aircraft can be commanded to change (typically 0.05). Thus the possibility still exists that $|TM'(TD)| < TOT$. In this case the aircraft is commanded to change altitude so as not to be a threat to aircraft on track #2. Spacing of the aircraft should be such that this happens infrequently.

This leads to the second constraint. Define:

PB = Prob(aircraft must change altitude/speed change).

Refer to [1,2],for a sketch of the mathematical formulation of PB.

The constraints which then define "Capacity" are:

Collision rate	CR = CRO (typically 10^{-9})
Prob action	PB < PBO (typically .01)
Threshold	TOT < $1/2M_o$

In order to compute "Capacity," flow rate (M_o) on both tracks is increased until one (or both) of the two inequality constraints is just violated. Note that for each M_o, TOT is adjusted so that the collision rate is CRO. The flow rate at the first constraint violation is then "Capacity." For fixed CR and PB, Capacity will vary with navigation error characteristics, TD (Decision time), and angle of intersection. It is also an implicit function of the ADS sampling rate.

From Capacity estimates, ATC can plan route structures and define decision thresholds based upon accepted safety standards. For instance the value of TOT at Capacity provides a conservative threshold for use at an intersection, even though traffic is less than Capacity.

In this paper, we will use the concept of Capacity to determine the impact of the decision time, the characteristics of the navigation system errors, and to infer reasonable minimum sampling times for ADS.

3. RESULTS OF THEORETICAL ANALYSIS

3.1 Background and Summary

Currently in the North Caribbean area, pilots report their position and destination approximately every hour via a HF link. According to procedures, aircraft on the same flight level but on intersecting tracks must maintain a fifteen-minute crossing time difference .

It will be shown in this section, based on analysis from the previous section that this separation criteria is generally consistent with a risk factor of one collision per one billion hours per path intersection. These results assume that the aircraft generally carry an INS with a typical accuracy of 1 nm/hour, and that a pessimistic 4 nm error, RMS has built up in the INS by the time of the intersection.

ADS (Automatic Dependent Surveillance) should allow for automatic reporting of aircraft position every .1 hours. With this more reliable and more frequent reporting it should be possible to significantly reduce the separation standard of fifteen-minute crossing time difference while maintaining the same level of safety. In fact it will be shown that the separation standard should be reducible to about .1 hours crossing time difference.

Furthermore, LORAN is generally available in the area. LORAN has an accuracy of about .1 nm, RMS. If LORAN could be used as the primary navigator with ADS, it is shown that crossing time difference could be reduced to .021 hours while maintaining the same level of safety.

Recall that the measure of effectiveness used to compare one system concept to another is "Capacity." "Capacity" is defined as the maximum number of aircraft per hour per path that could pass the intersection with a level of safety of better than 1 collision per one billion hours per path intersection where no more than 1% of the aircraft assigned to the path would have to change altitude because of potential conflict with aircraft on the intersecting path. It is shown next, within the constraints of the mathematical analysis used in evaluation, that the Capacity for the current situation (INS, No ADS) is around two per hour.

With ADS and INS, Capacity rises to about four per hour. This assumes that ATC can use the information obtained to control, if necessary, the time of arrival of an aircraft at the intersection by as much as 5% of the time to go to the intersection. If LORAN were the primary navigator, Capacity would be around 12 per hour or higher.

In deriving this Capacity figure, it is assumed that the aircraft can be lined up like ducks (or Wild Geese) such that at 1-1 1/2 hours before the intersection, the aircraft are aimed such that they will intersect the other path midway between the aircraft on the other path.

3.2 Numerical results

The numerical values identified in the table below are used in the evaluation.

Parameter	Value Normal	Value Degraded/% Time
INS	1 kt Gaussian	3 kts Gaussian, 1%
INS Pos	4 nm Gaussian	12 nm Gaussian, 1%
LORAN Pos	.1 nm Gaussian	.3 nm Gaussian, 1%
Heading/ADS*	.1° Gaussian	—
Heading/No ADS†	.1° Gaussian	3° Gaussian, 1%
Wind	6 kts Gaussian	—
Level of Safety	10^{-9}/flying hrs/path	—
Time of entry before int., ADS	1.0 hrs	—
Time of entry before int., no ADS	1.5 hrs	—

*ATC extrapolates according to planned track.
†"3" represents the potential for waypoint insertion error.

Table 1 presents the Capacity for the INS/No ADS case for various intersection angles and various times when a single intersection control is applied. Table 2 presents the minimum crossing time differences. Note that "No ADS " is considered having only one report at TD = 1.35 hours before the intersection. Thus the column associated with 1.35 provides the information required. The negative signs on the values on Table 1 indicate that Capacity is also Ultimate Capacity. Note that for a 90° intersection, Capacity is 1.91 aircraft per hour per path. The minimum time threshold is 0.266, slightly above the 15 minutes defined by procedures. Recall that this Capacity was derived under the assumption that collision rate should be 1/1,000,000,000. Thus it is apparent that operational procedures provide about that risk.

Table 1. Capacity for INS/No ADS vs. Decision Time, TD, and Angle

TD	θ = 45°	90°	135°
.15	4.200	3.100	1.900
.30	3.690	3.320	1.980
.45	3.980	3.500	1.980
.60	-4.210	-3.020	-1.540
.75	-4.210	-3.020	-1.540
.90	-4.060	-2.650	-1.320
1.05	-3.540	-2.100	-1.170
1.20	-3.540	-2.100	-1.060
1.35	-3.280	-1.910	-0.945

Table 2. Minimum Thresholds (hours) Decision Time (TD) and Angle

TD	θ = 45°	90°	135°
.15	.104	.116	.218
.30	.107	.119	.221
.45	.110	.126	.236
.60	.115	.144	.280
.75	.119	.168	.331
.90	.125	.192	.381
1.05	.132	.217	.431
1.20	.142	.241	.482
1.35	.154	.266	.530

Tables 3 and 4 respectively represent Capacity and minimum crossing time differences for the INS/ADS case. Note that minimum crossing time differences are monotonic with intersection control time. However Capacity generally has a maximum. The reason is that if the intersection control time is too close to the intersection and the measured time difference is below the threshold, there is little opportunity to change speed to modify the crossing time difference. Thus the constraint that: no more than 1% of the aircraft change altitude, limits the flow rate allowed.

Note that the peak Capacity of four per hour for the 90° case occurs at TD = .4 hours. The minimum time threshold is .123. This value is also Ultimate Capacity.

Tables 5 and 6 present results for the LORAN/ADS case. Here it is seen that Capacity is still rising at TD = .1 hours. Furthermore Capacity is no longer Ultimate Capacity. To be on the conservative side, we used the TD = .2 hours as the decision time used for comparisons, and further analysis. Note that at TD = .2 hours Capacity is 12.6/hour and the minimum time threshold is .0189 hours.

Table 3. Capacity for INS/ADS vs. Decision Time, TD, and Angle

TD	θ = 45°	90°	135°
.1	3.81	3.49	2.07
.2	4.04	3.69	2.13
.3	4.29	3.89	-2.20
.4	-4.51	-4.06	-2.24
.5	-4.51	-3.99	-2.24
.6	-4.36	-3.91	-2.24
.7	-4.29	-3.84	-2.21
.8	-4.21	-3.84	-2.21
.9	-4.14	-3.77	-2.17

Table 4. Minimum Thresholds for INS/ADS vs. Decision Time, TD, and Angle

TD	θ = 45°	90°	135°
.1	.106	.118	.220
.2	.107	.119	.222
.3	.109	.121	.223
.4	.111	.123	.224
.5	.113	.125	.225
.6	.11	.127	.226
.7	.117	.129	.228
.8	.120	.132	.229
.9	.123	.135	.231

Table 5. Capacity for LORAN/ADS vs. Decision Time, TD, and Angle

TD	θ = 45°	90°	135°
.1	13.6	13.3	11.3
.2	12.7	12.6	11.7
.3	12.7	12.4	11.7
.4	12.6	12.4	11.6
.5	-11.1	-10.9	-10.3
.6	-9.41	-9.11	-8.66
.7	-8.07	-7.92	-7.55
.8	-7.18	-7.03	-6.66
.9	-6.44	-6.29	-5.99

Table 6. Minimum Thresholds for LORAN/ADS Decision Time per Angle

TD	θ = 45°	90°	135°
.1	.962	.995	.136
.2	.186	.189	.205
.3	.277	.282	.298
.4	.369	.375	.395
.5	.458	.464	.489
.6	.542	.550	.579
.7	.625	.635	.668
.8	.709	.720	.757
.9	.790	.802	.844

Recall that the results obtained above were found assuming only one intersection control decision. That is only once, at "TD" after the aircraft enters the track, is the aircraft observed for the purpose of intersection control. If one allows several times where control can be applied, it is shown in [1] that Capacity for INS/ADS will rise slightly , and that for ADS/INS will be around 20/hour.

Table 7 summarizes results for the three cases for intersection angles 45°, 90° and 135°.

Table 7. Summary of Capacities and Thresholds

Case:	*INS/No ADS TD = 1.35*		*INS/ADS TD = .4*		*LORAN/ADS TD = .2*	
Angle	Cap/Hr/ Path	Thresh Hr	Cap/Hr/ Path	Thresh Hr	Cap/Hr/ Path	Thresh Hr
45°	3.2	.154	4.5	.111	12.7	.0186
90°	1.9	.266	4.06	.123	12.6	.0189
135°	.945	.53	2.2	.224	11.3	.0205

As stated earlier in this section it is seen that using LORAN rather than INS for navigating will provide nearly a factor of three improvement in Capacity when ADS is available.

The theoretical analysis is useful in comparing systems. It is also useful in defining minimum thresholds and in defining minimum axial separations of aircraft entering the track system (A time separation = 1/(Capacity)). It is deficient in several respects.

1. The impact of the stochastic winds on extrapolation is only approximated in the analysis. Therefore the number of blockages (when an aircraft must change altitude) associated with conflict at the intersection may be somewhat different than that computed in the theoretical analysis.

2. The theoretical analysis has no provision for evaluating longitudinal separation control.

3. The aircraft will not arrive at the beginning of the path in a time-ordered manner, that is lined up like ducks. Generally they will arrive at Poisson-distributed times. Thus the Capacity figure is primarily useful for defining the minimum axial separation at track entry. There is the potential for long delays before the aircraft is allowed to proceed on the track. These delays are the result of holds caused by aircraft having to wait to achieve minimum longitudinal time separation , aircraft having to hold because of potential conflict with aircraft on the intersecting track, and aircraft having to hold because the aircraft in front is on hold.

4. FURTHER COMPARISONS OF SYSTEMS USING MONTE CARLO SIMULATION

4.1 Purpose of Monte Carlo Simulation

These deficiencies can be addressed by the Monte Carlo simulation developed.

1. It can simulate random arrival events.

2. It can be used to determine the average number of blockages (altitude changes because of conflict) for realistically simulated winds, and to compare the results to the theoretical values.

3. It can implement realistic intersection and longitudinal control strategies. Thus it can evaluate typical queues which will develop when loading and clearing aircraft through the system. The results of the simulation will allow for the development of a more meaningful measure of effectiveness, called "Practical Capacity." For example, in the studies to be performed here "Practical Capacity" is defined as the average arrival rate which can be supported by an intersecting track system such that 90% of the aircraft are delayed less than .3 hours (for all reasons) in traversing the path, while maintaining the specified level of safety.

The term "all reasons" includes having to hold because of a leading aircraft just entering the track, having to hold because the leading aircraft has to hold, or having to hold because of a conflict observed at track entry indicating a conflict at the intersection. Obviously the qualifiers, "90%" and ".3 hours" are somewhat arbitrary.

Using this measure of effectiveness, meaningful comparisons between the three situations to be evaluated can be made. For instance it will be shown for the 90° intersection, that the Practical Capacity for No ADS is only .8/hour. For the case of INS/ADS, it is about 2.5/hour. But for the case of LORAN/ADS it is higher than 11/hour. The relative advantages of using more accurate navigation and ADS accelerates even more than that indicated by the separation standards reductions or the "Capacity."

4.2 Summary Description of the Simulation Program

The overall structure of the program is described next. Figure 7 represents the flow diagram of the program. More detail on the program can be found in [5]. First the data is read in and printed out. Then various variables are initialized. Parameters are set and various random numbers are generated. This includes the setting up of the winds at various points along the track according to their spacial correlation . Then the major loop begins.

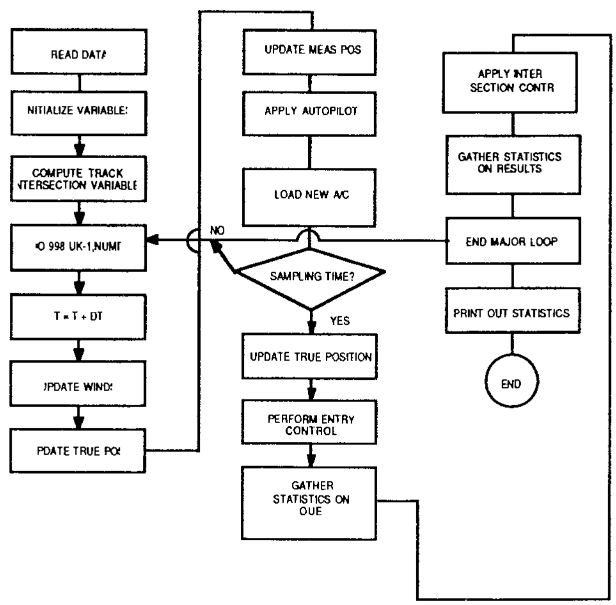

Figure 7. Overall Flow of Program

In the description that follows,it is assumed that the program has been running for a long time so that all the logic involved in starting up the program has been exercised. All paths are loaded with aircraft. All control options can be exercised. There are three major control functions in the simulation. They are:

1. Loading of aircraft onto tracks and levels

2. Entry control. This is generally applied an hour or so before the first track intersection. Here it is determined if an aircraft can proceed (with perhaps a speed change) without being a projected threat to aircraft on intersecting tracks. During

entry control, an aircraft can be placed in a "hold" pattern if conditions are not safe.

3. Intersection control. This is applied after entry control, using essentially the same logic as used in entry control. Here it is determined if and by how much the aircraft must change speed to safely pass the intersection. During intersection control, an aircraft cannot be put on hold. If conditions are not safe, it must (ascend, descend) leave the system. In the descriptions that follow this phenomenon is called a blockage. Intersection control may be applied one or more times during a flight (user defined input). Typically it is applied several tenths of an hour before the intersection.

After an aircraft is loaded, and until it reaches the end of the track, it carries a status number identifying its current situation. The status will change as the aircraft traverses the track. A summary of the status numbers is provided below:

STATUS

0	Aircraft is loaded, but no control is applied.
-1	Aircraft is loaded (arrives on scene), but it is too close to leading aircraft. It must wait for the leading aircraft to pull away.
6	Aircraft is in hold status because aircraft leading is also in hold and separation must be maintained.
10	After entry control, if the aircraft must be put on hold, this is its status.
20-50	Aircraft has passed entry control and is allowed to proceed.
70-100	Aircraft has passed intersection control and is allowed to proceed, after perhaps some time of arrival control.
60	Aircraft has passed intersection control, and is not allowed to proceed on given path.

The major loop operates as defined below. Time is augmented by DT, the incremental time. Next the winds at specified locations along each track are updated (if they are assumed time varying). Wind at a given location along the track is the linear interpolation from the nearest two defined points.

Next, in a sequential manner the true state (position,velocity) of each aircraft defined and loaded is updated according the track entry parameters, the winds at the location, etc. When a given aircraft is updated, it also looks ahead to see if the leading aircraft is in a hold pattern caused by control (Status 6 or 10). If the given aircraft is too close to the holding aircraft, it is assigned a Status 6 which temporarily puts it in a hold pattern.

Next the measured state of the aircraft is computed based on true state and navigation errors which are functions of random numbers generated. This is followed by the autopilot function. This function attempts to keep the aircraft on track based on measured information.

Loading is then is performed one track at a time. There may be one or more levels associated with a track. Aircraft are generated according to a Poisson distribution; they are assigned to the least crowded level and assigned a status of 0 or -1. If tracks are too crowded, (more than say three aircraft waiting on all levels of a track) the aircraft is "rerouted." That is, it is not entered into the system.

Next it is determined whether or not it is possible that any aircraft with Status 6, holding because of delayed traffic ahead, can now start to move. It checks to see if any aircraft with Status -1 can now be loaded onto the track, and assigned a Status 0. It assures that spacing between the aircraft just loaded and the leading aircraft is at least the minimum.

The above procedures are carried out for each track. Statistics on loading are accumulated. These statistics include time aircraft spend in holding patterns, number actually loaded, number rerouted, etc.

The remaining functions only take place at sampling times (a multiple of DTMS). Consider the simulation of a single aircraft after it is successfully loaded and moving through the system. At entry time (about 1 hour before the first track intersection) its speed is modified if necessary such that according measured data, it can pass safely through the first intersection. This may not be possible because

1. The aircraft on the intersecting track are too tightly spaced
2. Or because speed would have to be changed by too large a factor,
3. Or the required speed change would place it too close to the leading adjacent aircraft on the same path.

Then the aircraft is told to hold. That is it is given a Status 10. At the next measurement time, the procedure is repeated, until the aircraft is allowed to pass. After it passes it is given a Status 20-50.

During the remainder of the flight, intersection control is applied one or more times. When the aircraft approaches the intersection within a specified time (say .3 hours from the other track), its speed, track and position is evaluated again to determine if, with perhaps a correction in speed, it can pass though the intersection safely. If it can , it is assigned a Status 70-100. After a potential change in speed it is allowed to proceed. If it cannot, it is assigned a Status 60 (a blockage) and it is assumed that it is shunted to an altitude where it would not be a threat to other aircraft. This aircraft is then ignored in further intersection control on this path or the intersecting path.

If there is a second intersection along the path which is before the intersection for which control is being applied, additional functions are carried out to assure that the latest change in speed does not make passage through the first intersection unsafe. Statistics on various parameters associated with aircraft passage through the system are generated within the simulation.

Now let us consider the simulation from the viewpoint of actual program logic. At a given measurement time, it is determined whether entry control should be applied to any aircraft. For each track and level, when an aircraft with Status 0 approaches the first intersection within a specified time limit or when entry control has already been attempted but the aircraft has been told to hold (i.e., given a Status 10) Entry Control is applied. Next, in a similar manner, intersection control is applied to any aircraft at a specified time separation from the intersection(s).

The situation is more complex when LORAN is simulated because velocity is not a natural output. Measured velocity is obtained in the following way. The latest four differences between air data indicated position change and LORAN indicated position change (each sample separated by .1 hours) are fed into a batch filter (optimal for the statistics above) to estimate wind velocity. Then estimated wind velocity is added to measured air speed to define measured velocity .

Other parameters, pertaining to control vary with the system under consideration and the intersection angle. They are listed below:

Parameter	Meaning
TAV	Mean time between aircraft loaded onto a path according to a Poisson distribution.
THRSHL	Low threshold; minimum time difference at intersection.
TMIN	Minimum time separation between aircraft on same path during loading (typically 1/(Capacity)).
THRSHH	Upper threshold; if time difference at intersection is greater than this value, no control is applied. If time difference at intersection is less than THRSHH, control within constraints is applied to make the projected time difference as close to THRSHH as possible.
TIMMM2	Used during Entry Control; control is constrained such that the time difference between the controlled aircraft and that leading it projected to the intersection is greater than this value. (Rule of Thumb: THRSHH+THRSHL)
TMIN2	Used during intersection; control is constrained such that the time difference between the controlled aircraft and that leading and following it projected to the intersection is greater than this value. (Rule of Thumb: 2THRSHL)

4.4 Specific Inputs for Various Systems

No ADS/INS

First consider the No ADS/INS case. Since the simulation program is set up for ADS and this is a case where there is really no ADS, the program has to be "cludged." This is done by placing the Intersection Control time very close to the Entry Control time. Entry Control time is 1.5 hours. Intersection Control time is 1.35 hours. According to Tables 1 and 2, for the 90° intersection. The low threshold is THRSHL=.266. Note that capacity is Ultimate Capacity.

The value for minimum spacing TMIN, was set slightly larger than the rule of thumb so that any aircraft making it though entry control will make it through intersection control without modification. Specifically, TMIN(.) =.59. In addition the upper threshold THRSHH =.35. Its major contribution to the operation of the system was to force each aircraft to intersect the other track as close to midway between aircraft on the other track as time of arrival control

The Logic then cycles to the beginning of the loop, time is augmented , and the logic repeated. At the termination of the Run, various histograms are printed out. They include:

1. Histograms of total individual holding time until an aircraft successfully passes through entry control.
2. Histograms on the status of the aircraft passing through entry control
3. Histograms on the status of the aircraft passing through intersection control
4. Histograms of the time proximity of the aircraft at intersection.

In addition, other statistics are output:

1. Total number or aircraft loaded
2. Total number of aircraft "rerouted"
3. RMS value of Speed changes when they occur

4.3 Critical Input Parameters

Below are some parameters which are common to all simulations:

Variable	Value	Meaning
DT	.02	Incremental time
DTMS	.1	Measurement time interval
NL	3	Number of levels associated with a track
NUM6	3	If more than NUM6 aircraft are waiting on each level of a track, a new aircraft will be "rerouted" during loading
SIGOM	.1	RMS LORAN Error
OMGT	.3 hrs	LORAN Error Correlation Time
SIGPNS	4 NM	INS Initial RMS Error
SIGVNS	1 NM/hr	INS Error Growth
CONSV	480 kts	Nominal Airspeed during loading
CTW	1 hr	Correlation time of winds
SIGVW	6 kts	RMS Velocity of winds in each direction
CDW	100 NM	Correlation distance of winds
ALPH1	.05	Maximum fraction of speed change allowed during entry or intersection control
DLX	.1	Aircraft on Track #1 are controlled DLX hrs before those on Track #2 to avoid "grid lock"

When INS is present, measured velocity is simply true velocity plus INS velocity error.

will allow. This will happen so long as the aircraft on the intersecting track are closer than .7 hours.

The purpose of running the simulation is to determine Practical Capacity. Thus several runs are made with the same input except that TAV is changed to reflect the average Poisson time between aircraft entry.

Figure 8 shows the percent aircraft waiting less than X hours vs. random arrival rate parameterized on X = .2, .3, .4 hours. It is seen that the Practical Capacity (90% wait .3 hours or less) is around 0.9/hour. Note that this implies an arrival rate of 2.7/hour on the three level system. This verifies what Air Traffic Controllers already know: that with the current system, use of same level intersecting tracks is only practical on low density routes.

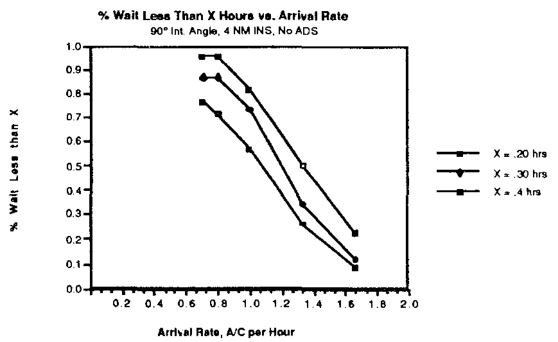

Figure 8

ADS/INS

When the INS/ADS case was evaluated in the simulation program, the parameters used were slightly different than the rule of thumb values because improved performance was observed for these parameters.

First recall that control on track one is accomplished .1 hours before that on Track #2. Thus intersection decisions on track one are made at .4 hours while on Track #2 they are made at .3 hours.

The Maximum Capacity values according to Table 3 are at TD, decision time, = .4 hrs. Values from this time were used to establish minimum spacing during loading. However the minimum threshold was from .3 hours, because the safe threshold is that for the latest time, 0.3 hours. even though passage will generally be controlled by the first decision at .4 hours. The high threshold was taken at 25% higher than the low threshold to drive the aircraft, at entry, midway between aircraft on other track, if possible. Minimum time difference at track entry, was taken at 10% higher than that indicated by Capacity. This was done to cut down on the status 60 blockages. This was deemed acceptable since Practical Capacity is going to be significantly below Capacity.

Minimum extrapolated axial time difference at intersection, TIMMM2, computed at entry control was taken as 1/(Capacity). Extrapolated minimum axial time difference at intersection control, TMIN2, was taken as 2X lower threshold. The duration of the run was computed so that the order of 1000 aircraft would be loaded into the simulation. A table of these parameters is shown below.

Table 8. Input Parameters for the INS/ADS Case

Angle	45°	90°	135°
THRSHL	.109	.121	.223
THRSHH	.132	.155	.278
TMIN(.)	.24	.27	.478
TIMMM2(Entry)	.222	.246	.448
TMIN2(Intersection)	.218	.242	.448
Capacity	4.51	4.06	2.24
Run Time (hrs)	50	50	80

For the LORAN/ADS case ADS the standard rule of thumb procedures were used to define the parameters. A table of the values is shown below. Values were take from Tables 5 and 6 for decision time, TD = .2 hrs.

Table 9. Parameters for the LORAN/ADS Runs

Angle	45°	90°	135°
THRSHL	.0186	.0189	.0205
THRSHH	.0393	.0398	.0427
TMIN(.)	.079	.08	.085
TIMMM2(Entry)	.0579	.0587	.0622
TMIN2(Intersection)	.0327	.0378	.041
Capacity	12.7	12.6	11.7
Run Time (hrs)	20	20	20

4.5 Interpretation of the Simulation Outputs

Figures 9 through 14 present percent wait vs. average path arrival time from the cases of INS/ADS and LORAN/ADS cases for the angles of 45°, 90°, 135°. It is seen that a Practical Capacity of about 2.5/hour (7.5/hour for the three-level track system)is achievable with INS/ADS with an intersection angle less than 90°. This is nearly a factor of three better than that associated with the No ADS case. However at an intersection of 135°,the Practical Capacity drops to below 1/hour. This result would imply procedures consistent with procedures of the Air Traffic Control system where essentially opposite directed traffic is routinely assigned different altitude levels.

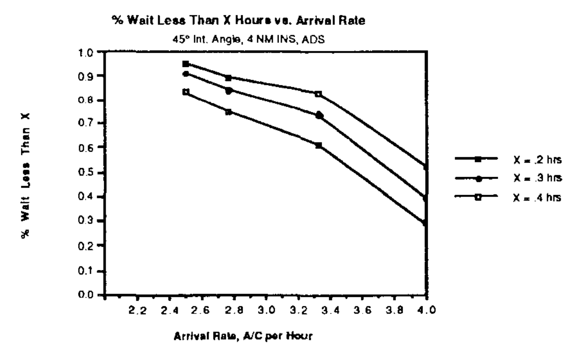

Figure 9

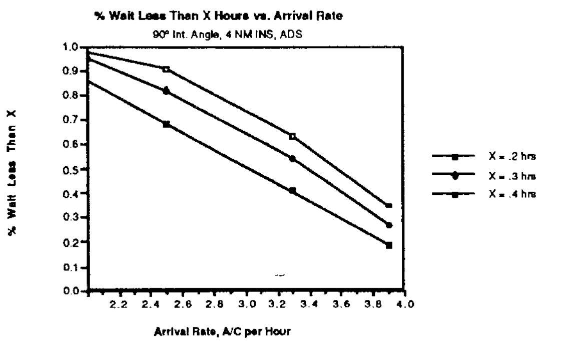

Figure 10

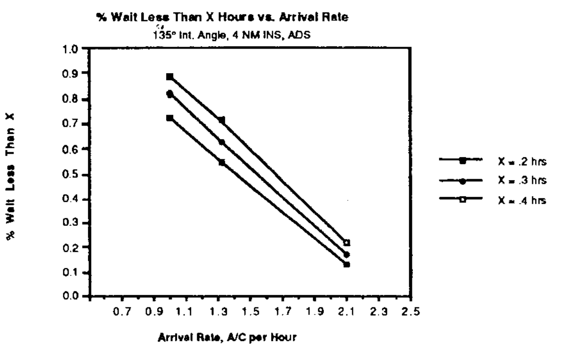

Figure 11

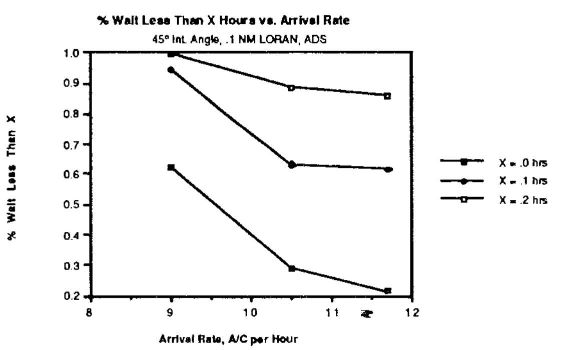

Figure 12

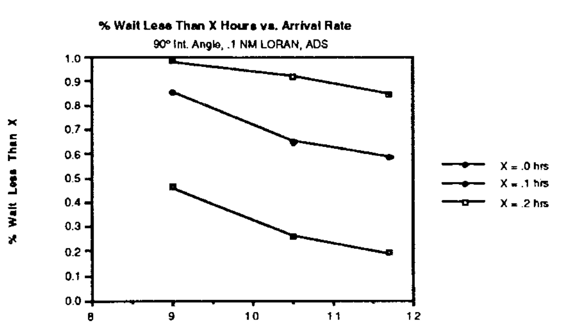

Figure 13

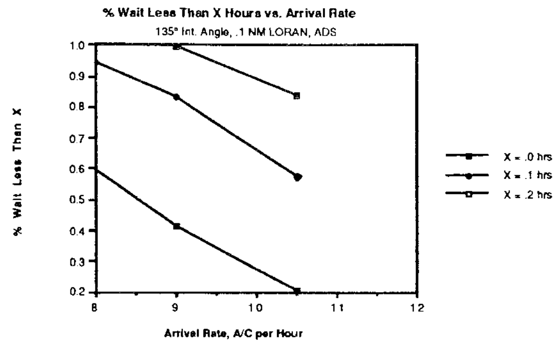

Figure 14

Now consider the cases of LORAN/ADS. Here the Practical Capacity and Capacity are nearly the same. Even for the 135° intersection, practical capacities of better than 10/hour are possible. In fact the curves plotted consider the longest wait time,.2 hours since the number of aircraft waiting more than .3 hours is negligible.

The overall conclusion which can be drawn from this study was stated above. The relative advantages of using more accurate navigation and ADS accelerates even more than that indicated by the separation standards reductions or the "Capacity." With ADS and the current INS systems on the aircraft, it is possible to maintain a single intersection three level track system with upwards of 7.5/hour arrival rate. If LORAN were the basic navigator, arrival rates of over 30/hour (one every two minutes!) could be maintained. Thus operations not much different than that possible with radar control in continental airspace could be supported.

It is also interesting to note that the simulation program here indicates that the number of blockages is generally below the 1-2% indicated by the analytic model. Table 9 below presents results which validate this.

Table 9. Percent Blockages at Practical Capacity for Various Navigation/ADS Configurations and Various Intersection Angles

Nav:	*INS/No ADS*		*INS/ADS*		*LORAN/ADS*	
Angle	Pract Cap	% Block	Pract Cap	% Block	Pract Cap	% Block
45°			2.5	.1%	11.7	.2%
90°	.8°	0%	2.2	.8%	11.7	.6%
135°			< 1.	.4%	10.5	0%

5. SUMMARY AND CONCLUSIONS

This paper has describes analytic and simulation models to evaluate the operation of ADS and associated navigation with intersecting track route structures. The analysis has been applied to evaluating an area like the North Caribbean where LORAN is available. It is shown that, by combining ADS and LORAN, it may be possible to raise the flow rates on intersecting tracks by as much as an order of magnitude over that possible using current over the ocean ATC procedures. This new concept would provide for the same level of safety as current procedures. Furthermore, using LORAN as the navigation system rather than INS can provide better than a factor of three increase in flow rates.

THE AUTOMATED LORAN-C COVERAGE DIAGRAM GENERATOR

Jeff Catlin,
Dean Foulis, and
Gary Noseworthy
SYNETICS Corporation
450 Edgewater Drive
Wakefield MA 01880

Lt. Gene Allard

Commandant (G-TES)
U.S. Coast Guard Headquarters
2100 Second Street, S.W.
Washington, D.C. 20593

ABSTRACT

This paper presents preliminary details of an automated system developed for generating and archiving Loran-C coverage diagrams. A coverage diagram is a graphical representation of the geographic area inside of which a Loran-C receiver can function within specified limits.

The Automated Loran-C Coverage Diagram Generator is currently a PC- based software system that quickly computes and displays estimated service areas for existing and proposed Loran-C chains. This system can generate a coverage diagram for a proposed chain in under 10 minutes, including the time needed to enter station parameters and draw the map. The system is based on existing methods for diagram generation, but has been modified to improve the speed and accuracy of the process.

INTRODUCTION

The United States Coast Guard (USCG) publishes a report entitled "Specification of the Transmitted Loran-C Signal" (reference 1). The report explains the methods used in the computation of coverage limits, presents sample calculations, and includes coverage diagrams for most worldwide Loran-C chains. In the past, the calculations for the service limits were done by hand, and were therefore labor and time-intensive. Consequently, a requirement existed for a software system capable of quickly computing publication quality Loran-C coverage diagrams.

A system was developed to aid in the design of new chains, and in the analyses of the effects on the service boundary caused by changes made to existing chains. It allows a user to display a map of a selected geographic area, to place stations and define their operational parameters, and to generate several different types of diagrams.

SYSTEM DESCRIPTION

The Automated Loran-C Coverage Diagram Generator is a PC- based system that can function both as a diagram generator for publication of service areas of existing Loran-C chains, and as a design tool that will be useful in determining optimal station placement. In it's publication mode, the system can duplicate the coverage diagrams of reference 1 in minutes. The generation of these diagrams takes only slightly longer, and can be performed by an operator not knowledgeable in the field of Loran. The system is mouse and menu driven, resulting in a short learning curve.The system is very flexible, and can be run on IBM PC compatible computers with Hercules, CGA, EGA, and VGA monitors. It was written in Borland's Turbo Pascal 5.0, and can run with or without a numeric coprocessor. It can currently print on a HP Laserjet II laser printer or compatible, and runs with or without a Microsoft mouse.

The software for the signal propagation/ receiver modelling was based on the "Airport Screening Model for Non-Precision Approaches Using Loran-C Navigation" (reference 2), and the initial focus was on the development of an automated software system capable of reproducing the coverage diagrams as presented in reference 1. Several enhancements and augmentations were made to reference 2, including improvements in the selection of an atmospheric noise estimate, a new method for dividing the signal path into segments of constant conductivity for use in the Millington method (described below), use of the NCAR map package (reference 3) map data, and a new method for selecting the points to be tested in order to approximate the service boundary. These new methods will be described below.

COVERAGE DIAGRAM GENERATION

The USCG has recently recommended Loran-C coverage diagrams be presented in the format of figure 1.

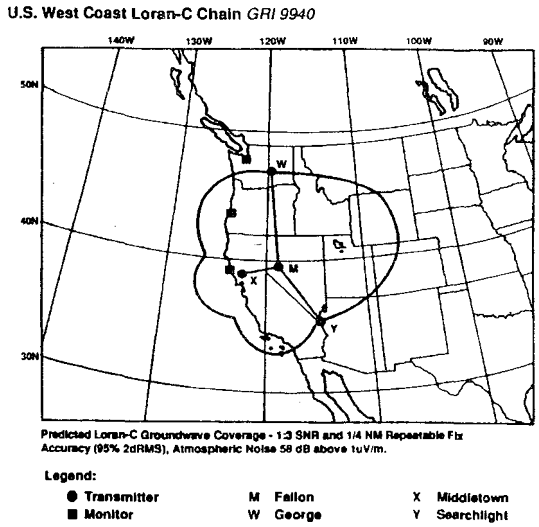

Figure 1. Loran-C Coverage Diagram

The creation of a coverage diagram for a specified Loran-C chain involves computing range and accuracy limits for the chain.

In Loran-C the accuracy limits for the chain are determined by the geometry of the locus of points where the time difference in signal arrival between two transmitted signals is constant. Figure 2 illustrates a Loran-C triad with salient parameters labelled. If the crossing angles (α and β in figure 2) are greater than an allowable minimum (nominally 15 degrees), then a position fix can be made within the specified degree of accuracy. Fix accuracy is computed by the equation

$$2\text{Drms} = \frac{2 \times K \times \sigma}{\sin(\Gamma)} \times \sqrt{\frac{1}{\sin^2(\alpha/2)} + \frac{1}{\sin^2(\beta/2)} + \frac{2 \times \rho \times \cos(\Gamma)}{\sin(\alpha/2) \times \sin(\beta/2)}}$$

where $K = \dfrac{C}{2 \times N}$, $N = 1.000338$ and

$C = 299.792458$ (m/μS), yielding a value for K of 491.62 (ft/μS). The parameter ρ is commonly assigned a value of 0.5, and represents the correlation between TD's. The parameter σ is assigned a value of 0.1, and is the standard deviation of the LOP's. See reference 9 for a detailed discussion of these paramaters.

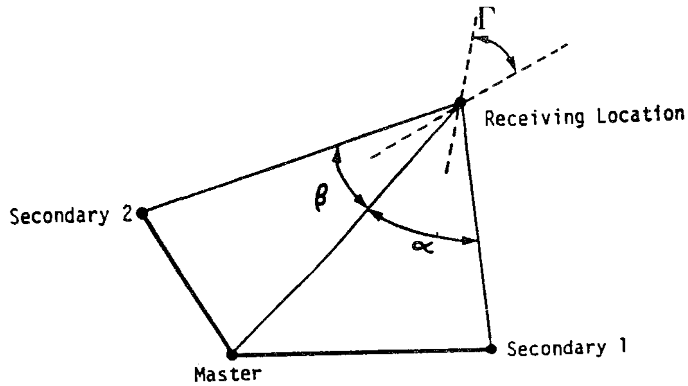

Figure 2. Loran-C Crossing Angles

The range limit of a chain is determined by the amount of atmospheric noise in the local environment and by the conductivity of the earth's surface.

ATMOSPHERIC NOISE

The effect of atmospheric noise is to reduce the capability of a Loran-C receiver to detect and process the transmitted signal, thereby limiting the effective range of the signal. The noise in the region around a Loran-C chain is estimated using CCIR report 322-3 (reference 4), which is an updated database of global atmospheric noise. This database can provide an estimate of the noise at a selected location and for a specific frequency and bandwidth. The atmospheric noise for the region around the chain is obtained by a simple averaging of the noise at selected points in the region.

MILLINGTON/ CONDUCTIVITY

The second step of the process of computing the range limit of a Loran-C signal involves computing the attenuation of the signal due to the conductivity of the earth. Over paths of high conductivity, the signal loses little power as it travels, while over paths of low conductivity, the signal can attenuate drastically. One way to estimate the power of a Loran-C signal at a distance from the transmitter is called Millington's method (reference 5). The method assumes that the signal travels across regions of constant conductivity (Figure 3).

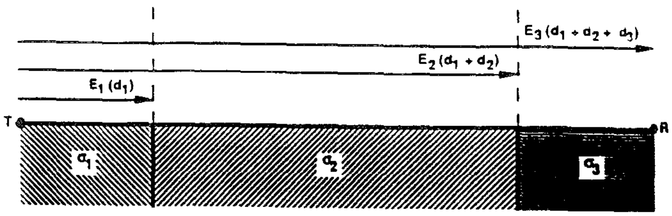

Figure 3. Regions of Constant Conductivity

σ_i = conductivity of region i (mmhos/m)
E_i = field strength in region i (dB above μv/m)
d_i = distance across region i (nmi)

Given these regions of constant conductivity, Millington's method computes the field strength by the equation

$$E = E_1\ (d_1) \times \frac{E_2\ (d_1 + d_2)}{E_2\ (d_1)} \times \frac{E_2\ (d_1 + d_2 + d_3)}{E_3\ (d_1 + d_2)}$$

In this equation, each E_i is obtained from the Van Etten curves (reference 8) which predict signal attenuation over a path of constant conductivity. The field strength at point R is found by first assuming signal propagation from T to R and solving for E (this is $E_{forward}$), and then assuming propagation from R to T and solving for E (this is $E_{backward}$). The total field strength at R is given by

$$E_{total} = (E_{forward} \times E_{backward})^{1/2}$$

To use Millington's method, the path from each transmitter to each tested point must be characterized by paths of constant conductivity. Modelling of the earth's conductivities can be accomplished most easily by assigning large squares of the earth's surface a constant conductivity. To find the conductivities of a path, it is necessary to find the places where the path intersects each conductivity cell. Each of these segments is assigned the conductivity of the cell it crosses. This method imposes artificial conductivity jumps at cell edges, causing apparent jumps in the coverage diagrams where no physical cause exists.

To improve this method, a system was devised whereby land-water interfaces are incorporated into the conductivity model of the earth. Conductivities were assigned based on those in reference 7. The cell structure was maintained, but additional information about land-water interfaces was added to give a more realistic estimate of the earth's surface. In the process of segmenting the path, a test is made to establish whether or not the path crosses these land-water interfaces. If it does, the segment is divided into a water path and a land path. This approach more accurately reflects real-world conductivities.

TEST POINT SELECTION

The coverage boundary on a coverage diagram is drawn by connecting points that are known to lie near the service boundary. Increasing the number of known boundary points makes the boundary appear smoother. A system generating coverage diagrams must use a method to select points for coverage. Once the points are selected and tested, those near the boundary are connected, yielding a coverage boundary.

There are currently two basic methods of selecting test points, to which we have added a third. The methods for point selection are described below.

POINT WISE

The easiest method of point selection, and the most time consuming, is a point wise scan of every "point" in a region. Starting at a corner of a geographical map on which a region of coverage is assumed, points are selected by holding latitude constant and varying longitude by a small number of degrees. This produces a scan line, the resolution being controlled by the size of the step in longitude. Once a scan line has been completed, the latitude is changed by a small amount and another line is scanned. The result of this process is a group of tested points lying on the corners of grid squares superimposed on the coverage region. The problem with this method is that time is wasted by testing points that are far inside or outside the boundary. It's merit is that, given sufficient resolution, the process accurately depicts the complete coverage diagram.

RADIAL SWEEP

The Radial Sweep method is used because it drastically reduces the amount of tested points, and therefore the time needed to compute the boundary. There are a few variations on the method, but they are all basically the same. A point is chosen as the center of the sweep, typically the master transmitter. To find the first boundary point, points due east of the center are tested. The last covered point is taken as the first boundary point (Figure 4).

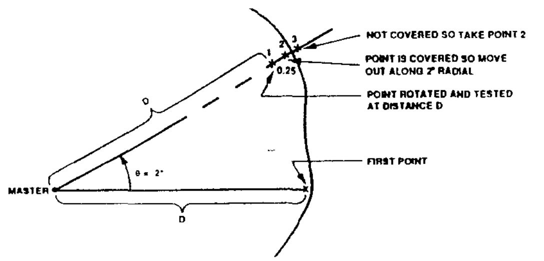

Figure 4. The Radial Sweep Method

The line of testing is then rotated (typically one or two degrees), and the process is repeated.

This method can be much faster then checking every point in and out of the region, since it does not test many points outside the boundary, but it can fail to accurately depict the service boundary for some chain configurations.

WALKING METHOD

The Walking Method was created specifically for chain design. It is much faster than the point-wise scan, and can cope with chain configurations that the Radial Sweep cannot. The algorithm seeks to mimic a person walking along a boundary. If, at each step, the left foot is inside the boundary and the right foot is outside, then the boundary will lie between them (Figure 5, point A). If the feet are misplaced after a step, then the person steps back (a position where it is known that the foot placement is correct) and readjusts his direction. The next few paragraphs will describe the method in detail.

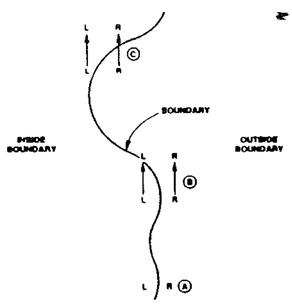

Figure 5. The Walking Method

The first task is to straddle the boundary with the feet (Figure 5, point A). This can be difficult, and care must be taken to insure that the first point is always found. The easiest way to approach this is to step off due east of the master transmitter until the right foot is not covered, and then to step back due west until the left foot is covered. In certain chain configurations, however, there is no coverage due east of the master. Therefore, a safer method is to start in the geographic center of the chain, and step out due east. The distance between the feet is the resolution of the approximation, and the distance of the stride controls the smoothness of the final picture.

Once straddling the boundary, a direction vector is initiated. All subsequent steps will be made in the direction dictated by this vector. By changing the vector's direction, the feet can follow a twisting direction. Then the process of stepping begins.

The left foot leads, followed by the right. With each step, the feet are tested for coverage. If the left foot steps out of the covered region (Figure 5, point B), or the right foot into the covered region (Figure 5, point C), the offending foot takes a step backward, and the direction vector is moved in the proper direction. When the left foot steps out of coverage, the boundary must turn to the right, and the direction vector is then moved to the right a small amount. The opposite holds for the right foot.

After each successful movement of the left and right feet, the left foot's position is plotted. By connecting these points, a service boundary is drawn. Care must be exercised near stations, or the feet might step over a projecting coverage lobe. If the stepsize is reduced near stations, this problem is solved. The only remaining problem is to stop the process, since there is no knowledge beforehand of the number steps needed. Therefore, the first left foot position is saved, and compared to the left foot at each step. When the foot returns to it's original position, the process is halted.

RESULTS

The system described above generates coverage diagrams that compare favorably with the existing published diagrams. The technical models of the system are undergoing tuning for speed and accuracy. A User's Manual is available for the system, explaining every detail of program operation.

ACKNOWLEDGMENTS

Special thanks goes to LCDR Gary Westling and LTJG Doug Heyes for their many valuable suggestions. Thanks also to A.D. Spaulding, who furnished a copy of his report (reference 5) and noise programs.

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A NATIONWIDE LORAN-C/METEOR BURST VEHICLE LOCATION AND COMMUNICATION SYSTEM

James W. Feeney

Transtrack Inc.
13 Marconi Lane
Marion, MA 02738

<u>Biography</u>: Mr. Feeney is President and founder of Transtrack Inc., a Marion, Massachusetts, communications company. He is also president of Horizon Marine, Inc., an oceanographic service company. Horizon was founded in 1982, and Transtrack was spun off to utilize a technology developed by Horizon Marine. Prior to these responsibilities, Mr. Feeney was vice president for marketing at Sippican Inc., also in Marion. He holds a B.S. in Geology from the University of Wisconsin and an M.S. in Oceanography from the University of Hawaii and is a former U.S. Navy officer.

<u>Abstract</u>: Transtrack has combined two technologies, Loran-C and meteor burst communications, to build a system that provides automatic vehicle location and two-way communications in the continental United States. Trucking transportation companies have determined that such capabilities can increase productivity, reduce operating costs, and permit a higher level of service to their customers.

The system takes advantage of the Loran-C terrestrial coverage and the phenomenon of radio wave reflection from the meteor region of the earth's atmosphere. The radio connection between base stations and remote communication units is a random process which provides a natural contention management scheme and permits hundreds of thousands of vehicles to communicate over the same radio frequencies. The nationwide system is designed for an average message delivery time less than ten minutes.

A pilot program conducted with the largest truckload carrier in the United States showed 20-minute average message delivery times and 8-minute average wait interval for radio connections with operational trucks.

INTRODUCTION

The following are the performance specifications for the TRANSTRACK(tm) System:

<u>System Capabilities</u>

- Nationwide two-way digital communications
- Automatic position reporting with no driver interaction
- Ability to service hundreds of thousands of vehicles

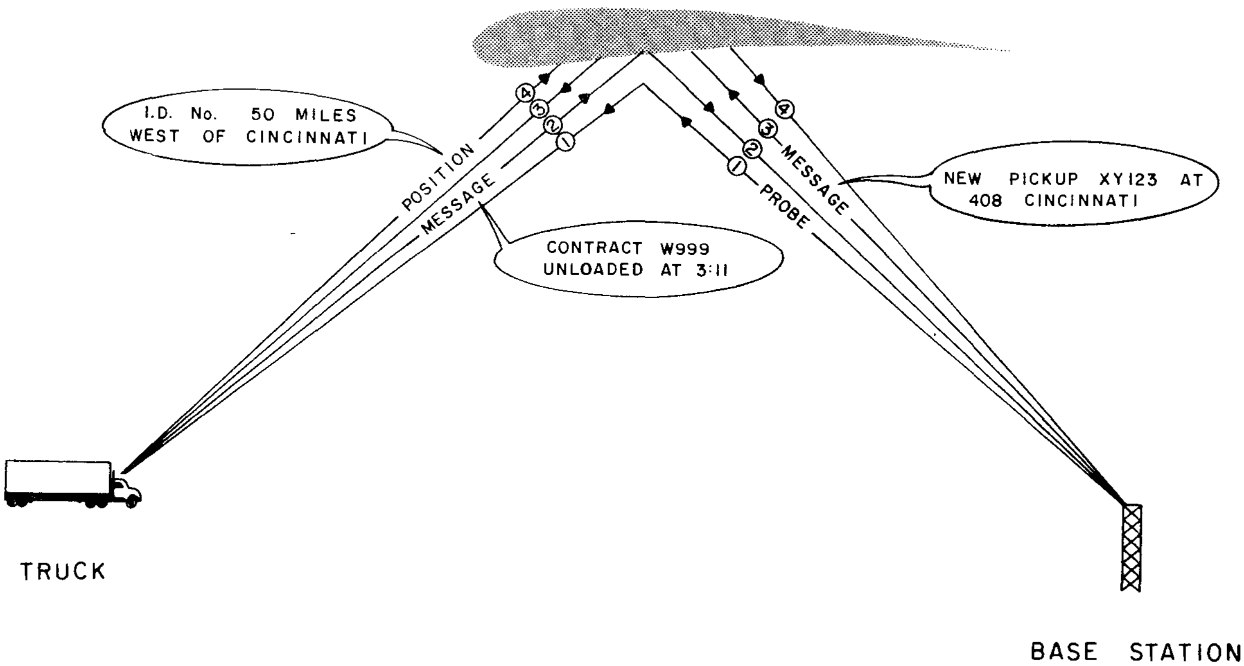
<u>Communications Specifications</u>

- Ten-minute message delivery time
- Two way: driver to dispatch, dispatch to driver
- Alphanumeric free-form messages of any length
- Continental United States, all urban and remote areas

<u>Position Specifications</u>

- Loran-C accuracy--500 yards
- Position in latitude, longitude coordinates no more than three seconds old at time of transmission
- Speed and heading of vehicle
- Automatic chain switching, automatic chain acquisition

The FCC awarded the first operational business radio license for meteor burst communication for the trucking industry to Transtrack in 1987. The license permits use of a nationwide network of ground base stations and 64,000 mobile units. The system is now being implemented, and coverage is complete in the eastern half of the country. The capability was tested in an alpha phase of six months operational use on tractors with the sixth largest U.S. trucking fleet. The test concluded with a new contract to install production units in three divisions. These units will be used to further study operational benefits and permit software development for



In 100 milliseconds and one speck of dust a 4-way example includes: (1) probe, (2) message from truck, (3) message to truck, and (4) position from truck.

FIGURE 1

integration into the management information system.

SYSTEM EQUIPMENT

Microprocessor-Controlled Radio Transceiver Base Station

Meteor burst communication utilizes the radio signals reflected by particles in the meteor region. Each day billions of sand-sized particles enter the earth's atmosphere and burn, leaving an ionized trail that lasts as a radio reflective layer from a few hundred milliseconds to a few seconds. These trails reflect radio transmissions. The phenomenon was known in the early days of radio, but existing electronics technology did not permit effective use of the short duration trails. Recently, meteor burst has become accepted as an effective long distance communication system, and dozens of systems are in use worldwide. However, it was the advent of the microprocessor that made such communications fast enough and affordable for the trucking industry.

The system works with master and slave transceivers. The master typically broadcasts an alert tone. Meteor trails in the atmosphere reflect and "illuminate" footprints on the ground. Any slave within that area will hear the probe tone, know that it has a path to the master, burst the data it has been collecting, and receive messages. The master will then send an acknowledgment to the slave. **Figure 1** graphically portrays a complete radio exchange between a base station and a truck, each with a message loaded and buffered.

The tiny footprints and short durations permit the system to ultimately monitor hundreds of thousands vehicles. Performance intervals for communications are less than 10 minutes with mobile units in service. Ranges of 700 to 800 miles between master and slave are optimum (1,200 miles maximum).

The Transtrack base station network is currently designed with five 2,000-watt base stations providing nationwide service. Overlapping coverage improves reliability and increases performance in high traffic areas. Each base station has six directional receiving antennas with one omnidirectional transmitter antenna array. The base station transceiver operates in full duplex on two separate low VHF frequencies at a data rate of 4K baud. All logical and physical communications functions are controlled in a multi-tasking real time environment by 386 microcomputers. All data delivered to and from user's facilities and vehicles are communicated by the appropriate base stations to Transtrack's Network Operations Center via dedicated and/or dial-up telecommunications lines and will be secured by VSAT backup. **Figure 2** is a map of the five Transtrack base stations, illustrating their effective coverage and zones of double and triple overlap.

Meteor burst communication permits flexibility in base station siting and purpose. Transtrack's mobile radios are able to download information at high data rates with line-of-sight transmissions to mini and micro stations using virtually the same radio frequencies with no vehicle hardware changes. These additional stations permit high-volume data communications in selected zones.

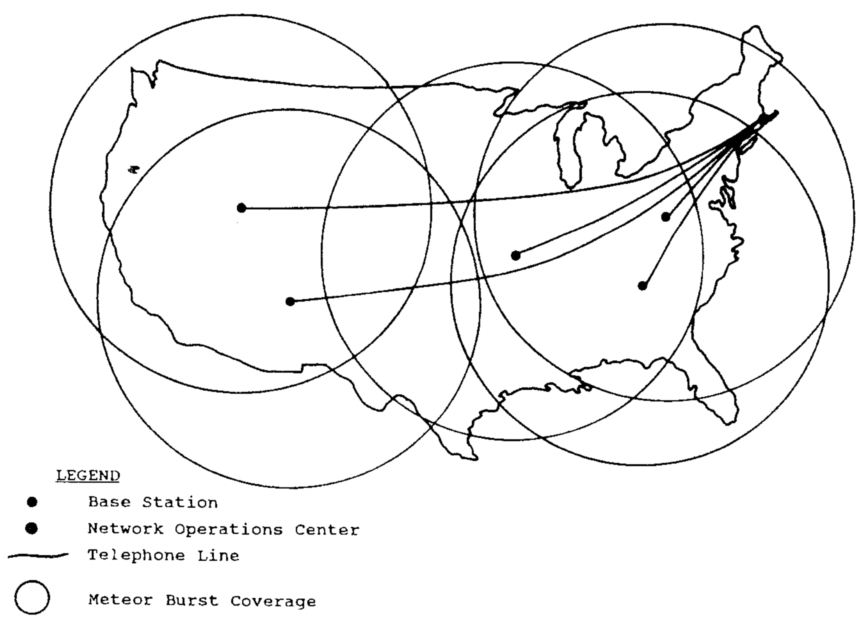
Mobile Communications Unit

Each vehicle is equipped with a display keyboard, a digital communications and Loran-C radio, and an antenna.

Digital Communications Radio: The meteor burst communications radio transmitter/receiver has an embedded system controlled by the Motorola 68HC11. Transtrack custom engineered the radio circuitry and its operating system. A "sliding window protocol" converts ASCII data to sychronize with Manchester encoding for increased reliability and enhanced error detection, using a CRC16 error detection scheme. A typical communication is performed over the ionized meteor trail in 100 milliseconds.

Display Keyboard: The display unit acts as the user interface to send and receive message communications. Its 32K ROM and 32K RAM provide memory for 50 custom programmable QUICK CODES chosen by the user. Free-form messages are typed into the easily mountable or hand-held keyboard using 38 alphanumeric keys with editing and cursor functions. An alert tone identifies all incoming messages. Information is displayed on a two-line by 16-character dot matrix liquid crystal display with scrolling capabilities and a recall feature for previous messages.

Loran-C Positioning: Loran (long



TRANSTRACK DATA COMMUNICATIONS AND VEHICLE TRACKING SYSTEM

FIGURE 2

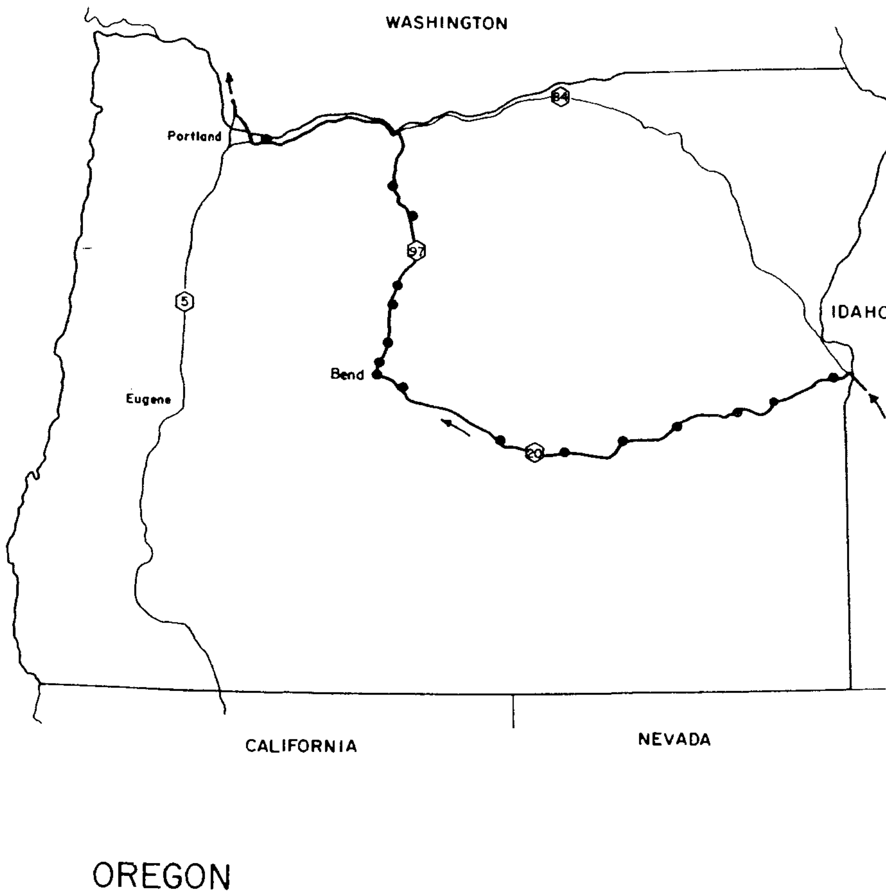


FIGURE 3

range navigation) is an all-weather, 24-hour-per-day, electronic system of land-based radio transmitters. The system includes one master and two to four slave transmitters per chain. Several chains service the continental United States. Signals transmitted from slave stations are synchronized with the master station signal such that the times of arrival of the master and slave signals at a receiver can be measured. These time differences (TD's) are measured in microseconds and are converted into latitude and longitude by algorithms built into the receiver.

Loran was implemented as a marine navigation system. However, its terrestrial use for vehicles is becoming commonplace, and it is used in over 25 percent of general aviation aircraft. The Loran circuitry is included within the radio "black box" and interfaces directly with its microprocessor. **Figure 3** shows truck locations transmitted through the system as a vehicle crossed the state or Oregon.

The role of Loran-C in the vehicle management system is unique among the many uses of such a navigation system. Navigation demands are relaxed while reliability and low cost are paramount.

The Transtrack System uses very few of the features offered by most Loran manufacturers. For example, the only information transmitted over the air is position. Most carriers have no desire to know speed or heading, signal strength, etc. There is no need to display any information from the Loran to the driver. It follows that the processing need not be done in the vehicle if hardware costs could be reduced by processing at the Network Operations Center.

To a motor carrier, the word "accuracy" has a totally different meaning than it does to a navigation expert. It means how often a good position was presented to the dispatcher versus a bad one. It is not measured in feet or meters; rather, is it in the right town name or zip code? Does the dot on a computerized map appear on the highway or in the middle of a lake? To automate the information from a fleet of hundreds or thousands of vehicles, a carrier often must integrate all the position and communication information into a mainframe computer as part of his management information system. Rather than use computer-displayed road maps, the computer system in place often dictates that a proximity report is the most usable form of display which can be distributed to each dispatcher's terminal.

Antenna: The vehicle antenna is a lightweight (only two pounds), attractive halo configuration which can be mounted easily to the cab or wind deflector with glue pads or machine bolts. It is constructed of 3/8-inch and 1/2-inch gauge aluminum tubing with adjustable tripod mount brackets, making it rugged and able to withstand the high shock and vibration levels of tractors on the road.

Network Operations Center

All message communications and tracking data is processed at Transtrack's Network Operations Center in Marion, Massachusetts. The center acts as a hub for Transtrack's base stations and for customer access to send/receive data to/from their vehicles.

386 microcomputers are conformed in a local area network (LAN) and operate in an AT&T System 5, version 3.2, multitasking real time environment. ORACLE is used for all database functions. Daily backup is performed with a magnetic tape archiving system. MICROCOM QX/12K error correcting modems perform all land communications with dedicated and/or dial-up backup lines at 4,000 bps.

The Network Operations Center includes software services for customer data access using B3270 protocol for IBM mainframes or an asynchronous protocol for VAX, PC, or any other equipment interface. Incoming and outgoing messages are given the highest priority in processing. Customers are provided data security as well as organized data management within the electronic mailbox structure.

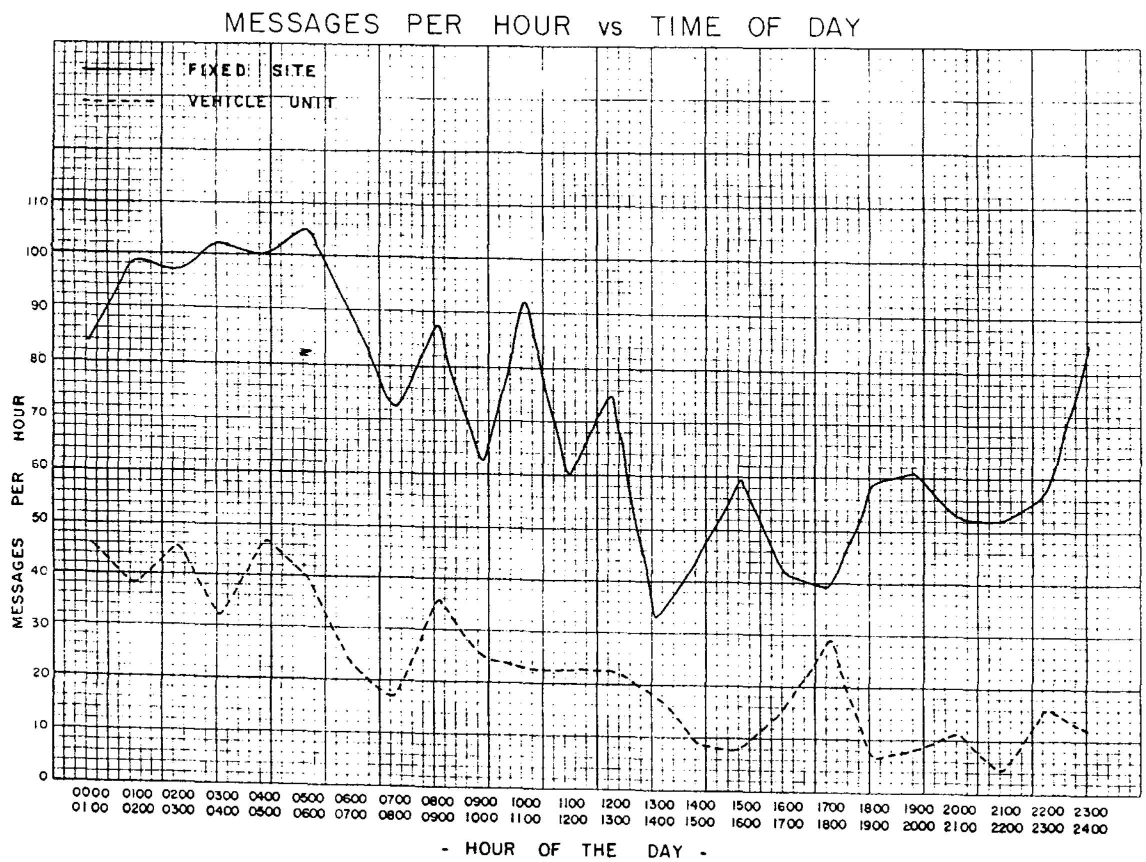


FIGURE 4

Performance Testing

There are approximately 25 meteor burst communications (MBC) systems in operation around the world. The challenge for adapting this to thousands of non-stationary remote sites (vehicles) is one of developing low-cost hardware, rugged mobile omnidirectional antenna systems, and a radio protocol to meet system performance goals.

Other MBC systems have the luxury of fixed antenna sites wherein the remote unit can utilize a directional antenna directed at a base station. **Figure 4** illustrates the performance tradeoff with a system operating on a vehicle utilizing an omnidirectional antenna versus a directed five-element yagi antenna at the same site. This figure also illustrates the typical MBC performance versus time of day (the daily cycle). The number of messages per hour refers to a standard 32-character message used for the tests.

Prior to the full nationwide implementation, Transtrack conducted a pilot program with North American Van Lines. The pilot consisted of only one base station located on a temporary site in Alabama to provide coverage in a north-looking sector of several Midwestern states. The base station was operated at 500 watts in a half-duplex mode. Vehicle radio units were operated at 125 watts. Operational vehicles were chosen to provide thorough benefits testing including empty mile reduction, increased utilization, reduced check calls, driver productivity, and customer service benefit.

Throughput statistics were maintained for system performance in an operational environment. No allowances were made for adverse vehicle location (such as in or beside a metal building).

Performance statistics have maintained under varying conditions of weather, terrain, population density, hour of day, and month of the year. **Figures 5 and 6** summarize the critical performance measurement which is the time to get a position from a truck or a message to and from a truck in its operational environment.

During the pilot program, data interval was a longer average than wait interval. Protocol limitations at that time (high message overhead) forced a longer transaction time (fewer workable meteor paths) for messages than for simple coded messages or "no texts."

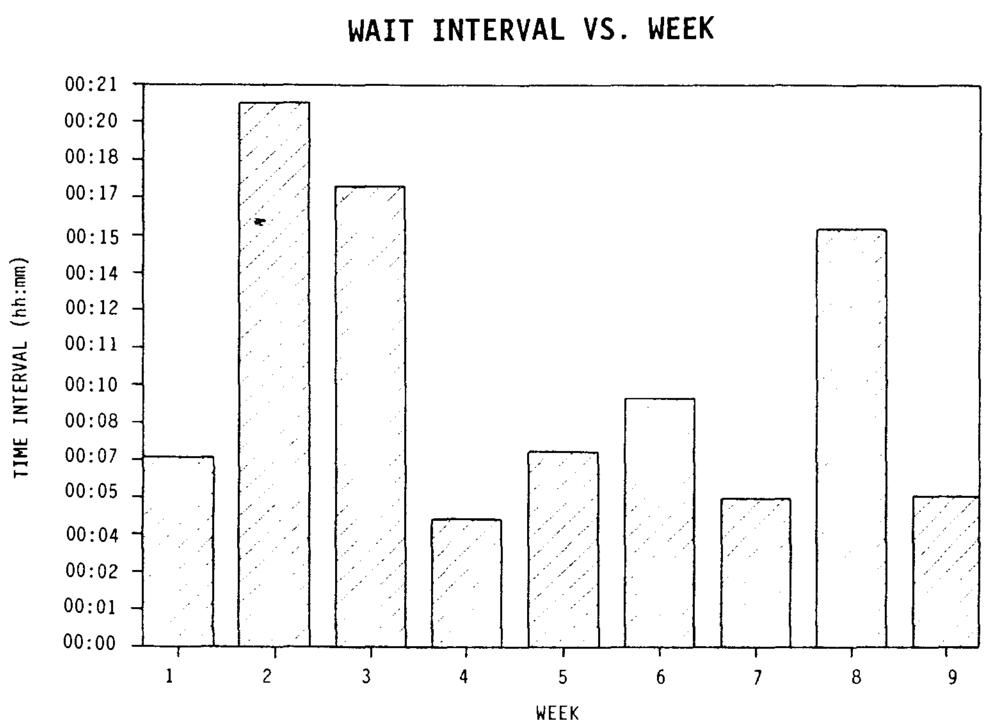


FIGURE 5

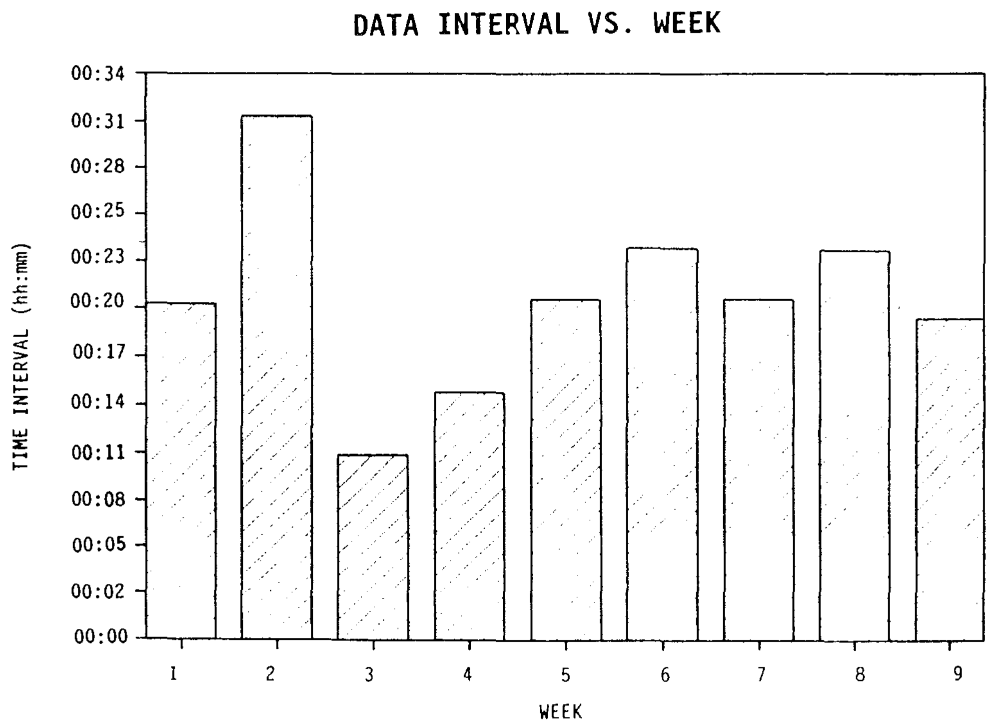


FIGURE 6

Figure 5 shows the average wait time demonstrated for the important communications, and **Figure 6** is a test of the phenomenon or, more importantly, the number of connections with the vehicle.

Conclusions

The combination of Loran-C and meteor burst communications has been proven to be an attractive technique for two-way digital communications and automatic vehicle location. The ground-based network provides flexibility, reliability, and growth potential. Because both technologies are available and use of the media is free, the system provides a cost advantage over other technologies.

Full network implementation will provide improved performance over the road test data shown. The system has been tested in all parts of the country and will be operational on a nationwide basis in the first half of 1990.

AUTOMATED ANIMAL-TRACKING SYSTEM:
Tracking Elk with Retransmitted Loran-C

Peter H. Dana, Consultant
P.O. Box 1297, Georgetown, TX 78627

Walt Fowler and David Hindman, Tracor Aerospace
6500 Tracor Lane, Austin, TX 78725

ABSTRACT

An Automated Animal-Tracking System (AATS) has been deployed at the Starkey Experimental Forest near La Grande, Oregon. AATS provides position data on elk, deer, and cattle using paged animal collars retransmitting 12-second bursts of Loran-C signals. Processing includes cross rate blanking, RF averaging, differential cycle tagging, phase measurements, noise estimates, and computation of differentially corrected time differences. Positioning software provides Easting and Northing coordinates for an animal collar position within the 40-square-mile study area every 15 seconds. Redundant data storage and digital map displays complete the system.

INTRODUCTION

The Starkey Project consists of long-term studies of elk, deer, and cattle in managed forests at the United States Department of Agriculture Forest Service Starkey Experimental Forest and Range near La Grande in northeast Oregon. The 25,000-acre study area is enclosed by 27 miles of specially designed elk- and deer-proof fence. An intensive forest management area and a winter feed and handling area are enclosed within Starkey by an additional 11 miles of "elk fence" [Figure 1].

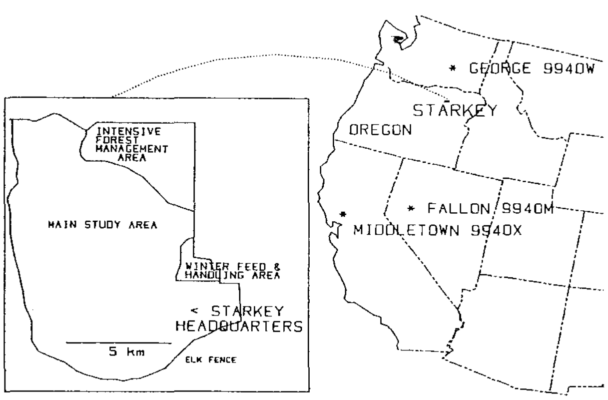


Figure 1. The Starkey Project

Four major studies are being conducted at Starkey by USDA and Oregon Department of Fish and Game researchers. Three studies measure the effects on wildlife of intensive forest management, roads and traffic, and cross-grazing of animals. The fourth investigates the relationship between bull elk age and breeding. A system to provide position information on 60 elk, 60 deer, and 60 cattle is required to implement these studies.

Using retransmitted Loran-C, the Automated Animal-Tracking System (AATS) continuously provides position and air temperature data from collared animals anywhere within the enclosed study area. The data are displayed in real time and stored for later analysis by mainframe computers where they are combined with as many as 80 habitat features and other data such as heart rate and respiration from monitors installed on selected animals.

AATS DESIGN

AATS was designed and built by the Navigation and Weather Division of Tracor Aerospace, Inc., in Austin, Texas. Although the system can be deployed anywhere with Loran-C coverage, AATS was designed to meet the specific requirements of the Starkey Project.

Positioning System Requirements

The system must track 180 collared animals within the enclosed 25,000-acre area of the Starkey Project continuously and automatically without operator intervention. The position of each of the collars must be available at least once an hour with an accuracy of better than 200 meters (one standard deviation). Air temperature at the animal collar position is required, as well as the potential for adding other sensors. Temperature data are used to relate animal energy expenditures to changes in habitat from timber management.

Position, temperature, and signal quality information must be time tagged and saved on mass storage devices. Animal collars are required to weigh less than 3 pounds; because of the difficulties in installing collars on animals, particularly on elk and deer, collar batteries must last at least eight months. The animal collars must allow for battery changing and must be both environmentally sealed and able to withstand the shock and vibration expected on large animals.

Positioning System Selection

The requirements of the Starkey Project dictated the selection of an appropriate positioning system.

Available Systems

Conventional animal telemetry collars and sensors are available from several manufacturers. With these systems, researchers take bearings and/or signal strength readings to locate a collar. Bearing accuracy is limited, requiring researchers to move closer and closer to the target animal to improve position accuracy. Multipath can increase bearing errors further degrading system performance. Conventional telemetry may require more than one researcher and many hours to locate a single animal. If position coordinates are required after the animal is located, the researcher must provide them.

Many dedicated area systems are available; several, including Loran-C minichains and 2-MHz systems, could provide positioning at Starkey. All require large investments in transmitters and control systems. The need for long battery life because of the difficulty of trapping animals made many conventional receivers inappropriate.

Satellite systems are not yet available that could meet the multiple positioning and long battery life requirements at Starkey.

After a feasibility study in the spring of 1988, retransmitted differential Loran-C using paged collars was selected as the positioning system.

Loran-C Coverage

The three Loran-C transmitters that now provide positioning for the Starkey site are George, WA, Fallon, NV, and Middletown, CA, on the 9940 group repetition interval (GRI).

The ranges, predicted signal-to-noise ratios (SNR), and field strengths are given in Table 1. The geometric dilution of precision (GDOP) in meters per microsecond for the site is computed from the gradients of the two time difference (TD) lines of position (LOP) [Table 1]. The GDOP is 814.27, with a Northing component of 218.6 and an Easting component of 784.4. When the Mid-Continent chains are operational in 1991, the GDOP will be reduced to around 420 meters per microsecond with a reduced Easting component.

TRANSMITTER	RANGE (km)	SNR (db)	FIELD STRENGTH (db/uv/m)
George	215	+35	+86
Fallon	640	+12	+63
Middletown	790	+ 8	+59

TIME DIFFERENCE LINE OF POSITION	GRADIENT (m/us)
Fallon-George	153.1
Fallon-Middletown	729.7

Table 1. AATS Loran-C Groundwave Parameters

Skywave arrival time and amplitude computations for the area use prediction methods from Reference 1. The delays with respect to the groundwave given in Table 2 are possible for first-hop skywaves for normal day and night ionospheric heights for ranges +/- 20 km from the center of the Starkey site. The earliest "normal" skywave is at 54 microseconds.

Skywave to groundwave amplitude differential predictions for earth-path conductivity groundwaves are listed in Table 2. The largest "normal" skywave amplitude is +5db above the groundwave amplitude. Envelope correlation between 20 to 40 microseconds is unaffected by skywaves anywhere within the Starkey area.

Skywave Delays +/-20km from AATS Center for Nominal Day and Night Ionospheric Heights

IONOSPHERIC HEIGHT:	DAY (70KM)			NIGHT (90KM)		
RANGES FROM CENTER:	-20KM	0	+20KM	-20KM	0	+20KM
TRANSMITTER	GROUNDWAVE-SKYWAVE DELAY (us)					
George	153	142	132	238	222	208
Fallon	63	62	61	99	97	95
Middletown	56	55	54	86	85	84

Skywave to Groundwave Amplitude Ratios (db)

TRANSMITTER	FIRST HOP DAY	FIRST HOP NIGHT
George	-40	-30
Fallon	-15	0
Middletown	- 5	+ 5

Table 2. AATS Loran-C Skywave Parameters

The predicted envelope to cycle differences (ECD) in microseconds for each transmitter are: George, 2.7; Fallon, 2.6; and Middletown, 1.9. A nominal 2.5-microsecond ECD offset for all three stations allows cycle selection aiding in the envelope correlation software.

The George transmitter transmits at both the 9940 and 5990 rates. The crossing rate between these GRIs is at 59.5406 seconds with a phase interference rate of 119.0812 seconds. Field tests at Starkey indicated that blanking on the George 5990 rate was necessary to avoid cycle tagging problems based on 10-second averages.

An on-site survey of Loran-C signals was conducted in May 1988. The Starkey site is made up of rolling hills covered with pine forests and pastures with elevations ranging from 3200 to 4800 feet. The site was found to be suitable for Loran-C signal reception because the measured signals were within predicted bounds in all but the steepest canyon areas.

AATS Concept

The result of the initial design phase was a system based on paged animal collars and differentially corrected retransmitted Loran-C [Figure 2]. A control and signal processor computer (CSPC) initiates the paging of each collar, the collar electronics are switched on, and Loran-C signals are received and retransmitted on a 216.5-MHz VHF radio signal [Figure 3]. The VHF signal is received and demodulated, and the Loran-C signals are sent over a microwave link [Figure 4] to filtering hardware. The filtered signals are sampled at a 2.5-microsecond rate during 320 millisecond windows triggered by a continuously tracking monitor. The sample windows are centered on the monitor arrival times and span the limits of the possible arrival times of remote signals from anywhere within the limits of the Starkey area. The samples are phase coded and summed over a 100-GRI period by a custom PC/Loran-C interface card (PCLC) and transferred under interrupts to the CSPC. The CSPC processes the Loran-C signals, computes time differences, corrects them differentially and computes collar positions. These positions are time tagged and stored, then displayed and transferred to the data display and storage computer (DDSC) that provides redundant storage and an interactive map display.

Simulation and Concept Testing

Loran-C processing techniques were investigated, and a computer simulation was developed to test methods for envelope and phase correlation. A prototype system was implemented and run in Austin, TX, tracking the 7980 chain. The results of simulations were compared to real tracking data.

In June 1988, a proof of concept test was conducted at the Starkey site. A "PC AT" type of computer, a 400-MHz wind finding receiver, a II Morrow Loran-C receiver, and a wind finding radiosonde retransmitter tested the feasibility of retransmitted Loran-C. The test consisted of tracking a prototype collar carried over much of the Starkey range on an automobile, on a four-wheel all-terrain vehicle, on foot, and on horseback. The II Morrow receiver antenna input was switched from the normal antenna to the retransmitted signal under computer control. Individual position reports were recorded, differentially corrected by position offsets, converted to NAD 1927 UTM coordinates and plotted on a computer map in real time. Since no accurate geodetic reference was available, the position bias was assumed to be zero. The position noise was between 34 and 74 meters (one standard deviation) for static positioning tests.

In February 1989, Forest Service personnel tested a Motorola paging system at Starkey. Pager "beepers" were carried on snowshoes, cross-country skis, and snowmobiles over most of the site. A single 50-foot temporary tower provided paging to all but a few canyon areas of the Starkey range.

A prototype version of the system was tested at Starkey in March 1989. Most of the features of the system were tested with

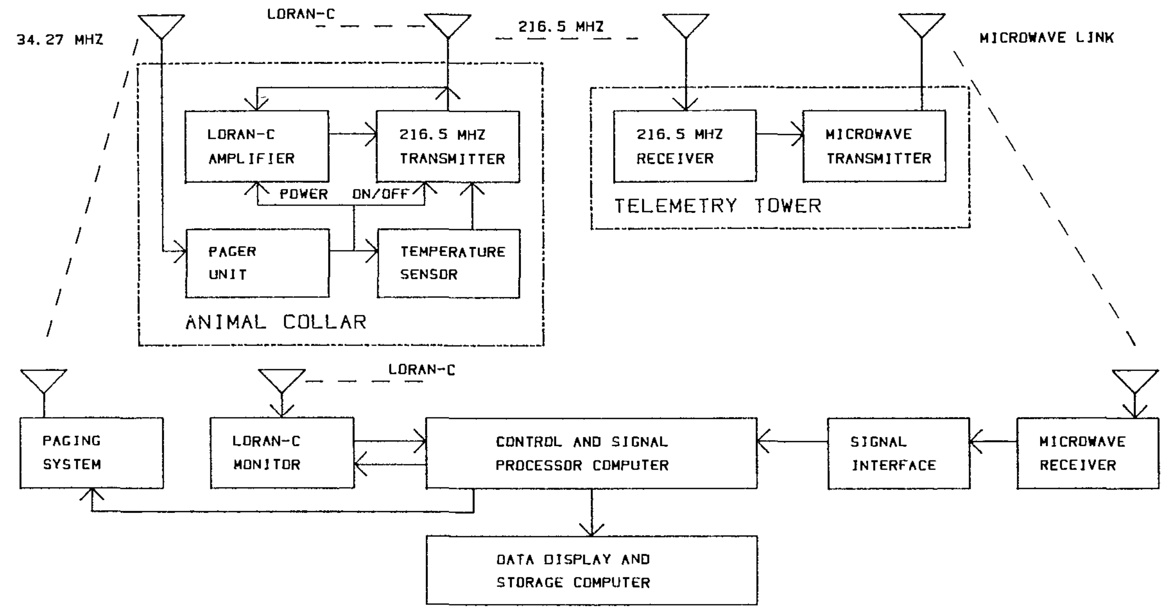


Figure 2. Automated Animal-Tracking System

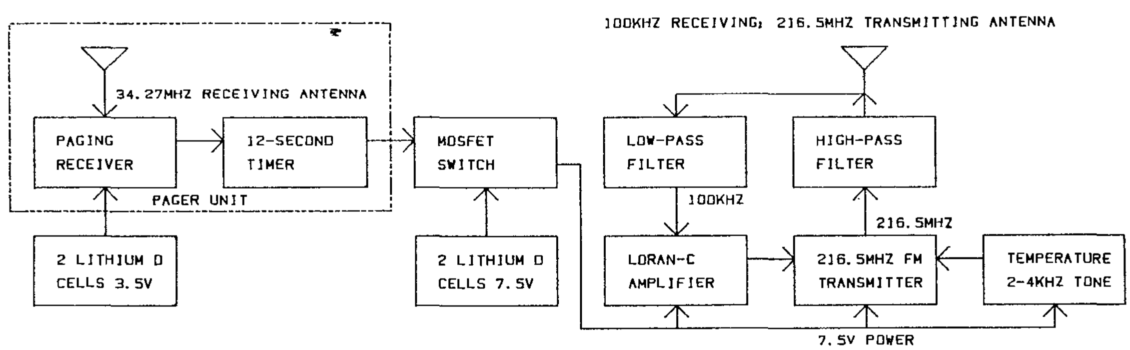


Figure 3. AATS Animal Collar Electronics

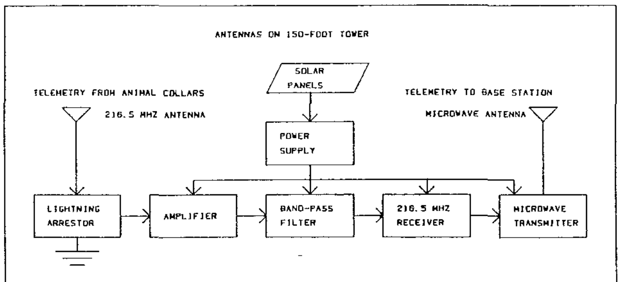


Figure 4. AATS Telemetry Tower

two collar units, the CSPC, an Internav LC408 monitor receiver, and the paging system. Modifications resulting from the test included cross-rate blanking and large-signal attenuation.

AATS IMPLEMENTATION

AATS was contracted for in September 1988 and was to be deployed in June 1989. This nine-month schedule required the use of existing designs and commercially available equipment wherever possible.

Loran-C Monitor Receiver

An Internav LC408 dual-chain Loran-C monitor receiver is the differential system area monitor and the source of hardware strobes to trigger sample taking in the PCLC and to control cross-rate blanking and large-signal attenuation in the signal interface hardware.

The LC408 is controlled over a two-way 9600-baud RS232 link. TDs and status are transmitted on request from the control computer. The monitor is reset over the link if the TDs on the primary chain differ from the predictions for the monitor antenna site by more than 7.5 microseconds. The LC408 has two strobe outputs for each of the two chains it tracks. Sample strobes occur eight times each GRI for each station tracked, and master strobes occur once each GRI. These are used to trigger the sampling of 128-word Loran-C samples in the PCLC.

The PCLC uses the master strobes for the primary chain to synchronize the sampling triggers with the start of the GRI and to maintain phase code counting between requests for 10-second averages. Master strobes trigger the large-signal attenuator for the primary chain and the cross-rate blanker for the secondary chain.

Paging System

A Motorola People Finder paging system polls individual collars. This sub-system consists of a control consol, a 32-MHz transmitter, an antenna, and individual pager units. An RS232 link from the CSPC sequentially pages each collar pager number, the link is tested to ensure that the People Finder is responding, and a timer is started in the software. After 1 second the People Finder transmits. After 2 seconds the paged unit responds by switching on the collar electronics. Signal gathering is done during the middle 10 seconds of the 12-second pager-on cycle. The system reaches pagers over most of the Starkey area with the antenna at the top of a permanent 150-foot tower.

Retransmission System Components

The retransmission system consists of remote and local collars, VHF receiver, microwave link, system clock, and interface hardware.

Animal Collars

The animal collars are completed and installed at the Starkey site by Forest Service personnel. The electronics package is manufactured by the contractor and consists of batteries, Loran-C receiver, VHF transmitter, and a pager connected to a 2-inch strip of rubberized material containing a ground strap and a mounting fixture for the antenna.

The batteries for the collar electronics are lithium cells with a 14-amp-hour continuous load rating. When turned on, the collar electronics draw 100 milliamps allowing 140 hours of continuous operation. Since the electronics are polled and remain on for 12 seconds, the batteries can power 42,000 cycles. The nominal polling cycle for 180 animal collars at 15 seconds each is once each 45 minutes. At that rate a collar can last 1300 days. With a faster update rate of one query every 6 minutes, a collar could remain powered for 8 months. The batteries for the pager are 28-amp-hour lithium cells that can provide continuous operation of the 1.8-milliamp pager for 648 days.

The Motorola pager is modified by removing the light and beeper normally activated by paging, and replacing them with a power-on switch for the collar electronics. The pager is then dipped in a rubberized sealant for attachment to the collar.

A Loran-C amplifier is connected to the collar antenna through a low-pass filter. A 216.5-MHz FM transmitter, modulated by both Loran-C and the 3 kHz temperature sensor tone, is connected to the collar antenna through a high-pass filter.

The collar antenna is both a Loran-C receiving and a 216.5-MHz transmitting antenna. It is a 13-inch quarter-wavelength antenna fabricated from a strong, flexible material and has been field tested on cows and elk for many months without damage beyond a slight bending.

The electronics are placed within a PVC pipe that is heated and placed into one of several molds, depending on the animal type. The heated pipe cools into the final collar shape and is painted with numbers and color codes before being fastened around the neck of the animal.

VHF Receiver

A 216.5-MHz antenna is mounted at the top of a 150-foot remote tower. This antenna is connected through a lightning arrestor to the VHF telemetry receiver at the tower base. This receiver, adapted from a design used for many years by the contractor for wind finding retransmission signals, transfers the Loran-C and temperature signals to the microwave link.

Microwave Link

A Motorola Starpoint microwave link transfers Loran-C and temperature signals from the remote VHF receiver to the 150-foot tower at the control site. The link is run without the normally installed multiplex unit allowing the full bandwidth of the link for Loran-C signals.

System Clock

The system clock is a 10-MHz Efratom rubidium oscillator. The clock is used by the temperature tone decoder, the LC408 monitor receiver, and the PCLC. The frequency stability of the oscillator allows Loran-C samples to be phase coherent during the 10-second averaging.

Local Reference Collar

A collar identical to the animal collars is mounted next to the LC408 antenna. This local collar provides a reference signal used for cycle selection, for timing of the sample windows triggered on the PCLC, and for system self-test through periodic reference collar paging.

Signal Interface Hardware

In the signal interface hardware, an amplifier and a bandwidth-limiting filter condition the Loran-C signals.

The master pulse from the primary LC408 chain triggers an adjustable timer that provides an attenuation window for the

George signal, reducing it by 24 db to lessen the gain variations seen by the PCLC. The master pulse from the secondary chain triggers an adjustable timer that provides a blanking window on the large 5990 George signal. In other locations these timers can be adjusted to attenuate any one large signal and blank any one cross-rate signal.

The air temperature tone is converted in the interface hardware to a binary count. The eight bits are updated once per second, are latched into a parallel port, and are transferred to the CSPC on request.

Control and Signal Processor Computer

The entire system is controlled from the CSPC, a Dell System 200 12-MHz 80286 PC with 3.5- and 5.25-inch drives, 40-Mbyte hard disk, and tape backup system. With the exception of the interrupt code for the PCLC, all the software in this computer is written in "C". The computer has three RS232 links: one controls the People Finder, another controls the LC408, and the third transfers data to the DDSC. A parallel port allows transfer of temperature data from the signal interface hardware.

Initialization and Control

The CSPC reads five ASCII test files on power up that control the operation of the system. Changing these files allows the system to run with new lists of animals, new tracking schedules, or at other locations. The SYSREF.DAT file contains system parameters including monitor antenna location in Loran-C system coordinates (latitude and longitude), monitor UTM Easting and Northing; fixed map scale and center, and Loran-C station identifiers. The LORANC.DAT file contains the Loran-C system coordinates for all of the Loran-C stations by identifier used by the SYSREF.DAT file. The ELKPAGER.DAT file contains the list of pagers to be polled. The SCHEDULE.DAT file contains start and stop times and file names of pager numbers to be scheduled each day. If no file name is present or no file name is scheduled for a particular time, the default file ELKPAGER.DAT is used. The PAGECOLOR.DAT file equates pager numbers with color numbers to represent elk, deer, and cattle on map displays.

PC/Loran-C Interface Card

The PCLC was designed for the AATS application and fits in a slot in the CSPC. The card digitizes 12 bits of Loran-C RF signal at 2.5-microsecond intervals derived from the 10-MHz rubidium clock. Two parallel 128x8-bit FIFO (first in first out) buffers transfer the samples to the CSPC.

To initiate a sampling cycle, the CSPC software clears the FIFO buffers, resets an interrupt request flip-flop, and arms a circuit that detects the LC408 sample strobe (ST).

As RF samples are taken they are pushed into the FIFOs. The oldest samples are discarded to make room for the newest ones so that 127 RF samples are retained. At the ST signal, a counter is enabled to accept 64 more RF samples into the FIFO buffer and then cease sampling. An interrupt request is then generated to signal the software that a digitized RF pulse is available in the FIFO buffer. A flip-flop monitors the LC408 master trigger, returning this event timing to the software for maintaining sample alignment and phase code count.

Since Loran-C pulses are at millisecond intervals, the software has less than a millisecond to process the digitized pulse and initiate the next sampling cycle. To achieve the necessary speed, the interrupt service routine is written in 80286 assembly language.

The application software uses subroutine calls to set up averaging buffers for the master pulses and for each set of secondary pulses. Other calls initiate and terminate averaging into the buffers. A subroutine is called to switch phase coding from ABA to BAB coding whenever the local reference collar signal strength is below a threshold value. The interrupt service routine counts each master strobe to maintain phase code synchronization once achieved. When averaging is active, RF samples are accumulated into appropriate averaging buffers with positive or negative sign as required by the phase code. The CSPC "C" program polls the status of the averaging process. When averaging is complete, the current buffers are released for use by the signal-processing software.

Loran-C Signal-Processing Software

Gathering of RF sample windows is initiated by a call to the PCLC software to begin sampling for 100 GRIs (9.94 seconds). While sampling is in process, the previously gathered samples are processed to form time differences and position data.

Signal processing starts by forming averages from the summed signals. Any DC offset is removed from the 10-second average at this time. An RF envelope is made by taking the square root of successive sums of squared samples [Figure 5 F]. This envelope is then smoothed by an exponentially weighted eleven-point running average [Figure 5 G]. This low-pass smoothing reduces the effects of noise and cross-rate interference on the envelope shape.

The smoothed envelope is processed to find the first peak. The sample index of the maximum envelope value is used as the first candidate index. The search moves toward the front of the pulse, rejecting sample indices any time samples increase in value, until a peak is found that is preceded by only decreasing samples. This process continues until an envelope value 12 db less than the current peak candidate value is reached.

The smoothed envelope is tagged at the "sample point" by searching for the sample index that is the best fit to the "phase" of a theoretical Loran-C envelope passed through the same smoothing. Envelope phase is measured by ratios of envelope samples at 10 microsecond intervals. A best fit is found by minimizing the sum of the squared differences between measured and predicted values [Figure 6].

The averaged RF samples are normalized by the smoothed envelope values around the time-tagged index [Figure 5 H]. Phase is measured by taking the four-quadrant arc-tangent of two consecutive differences of alternate normalized RF samples.

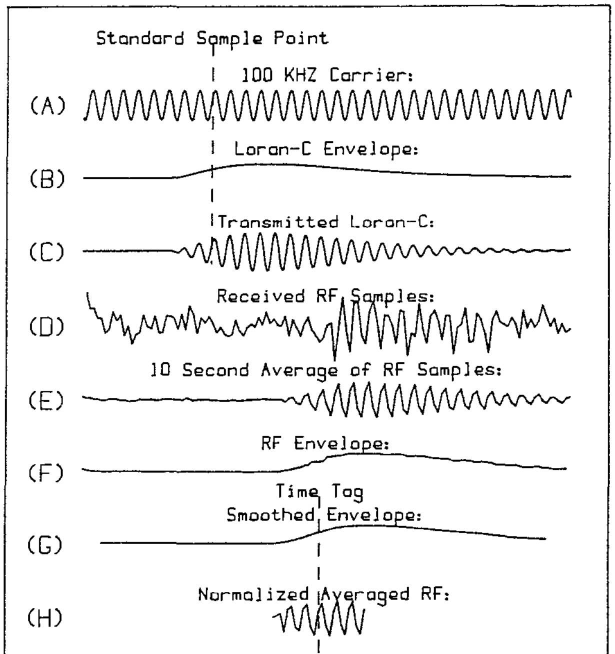


Figure 5. AATS Loran-C Processing

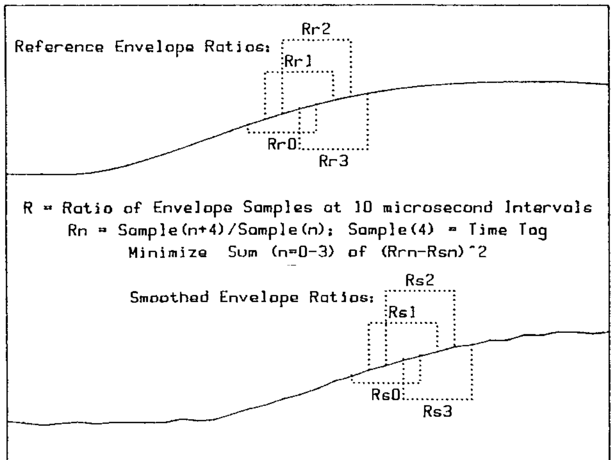


Figure 6. AATS Loran-C Envelope Correlation

Phase differences from the local reference collar are measured and compared to the phase differences measured by the system area monitor (LC408). Corrections are computed that count the number of 2.5-microsecond sampling intervals between windows. These counts correct both for ECD differences between master and secondary and for the exact positioning of LC408 strobes and the sampling triggers derived from the rubidium clock. The 2.5-microsecond local reference collar corrections are applied to the measured index count differences. These 2.5-microsecond count differences are added to the phase differences to produce TDs for tracked secondaries.

Differential corrections are produced by comparing LC408 TDs to TDs predicted for the LC408 antenna location on start-up. The differentially corrected TDs are passed to the positioning software.

Positioning Software

A complete processing cycle for AATS takes place every 15 seconds. Positioning software was optimized for speed with a two-step process that avoids time-consuming recomputation of geodetic ranges and bearings for position solutions.

Remote TDs are differenced with TDs predicted at an estimated position. The estimated position is then moved by multiplying the TD differences by a covariance matrix computed from a matrix of directional derivatives.

In the AATS process, accurate range and azimuth computations are made once, on power-up, from the system area monitor antenna reference position to each of the Loran-C transmitters. Each transmitter is remapped to a local tangent plane system with the reference position as the center. The accurate geodetic ranges and azimuths convert to transmitter positions in X and Y offsets from the reference origin. Directional derivatives for the initial covariance matrix are precomputed from reference azimuths and their sines and cosines.

Earth-path predictions in microseconds are made using a curve fit derived from Reference 2 for 5 millimhos per meter conductivity for ranges in meters at distances over 160 kilometers: path = range/299.691162387 + 6463.270345/range + .649893 + 4.44343E-6Xrange.

For each set of remote collar time differences, the AATS positioning method outline is:

- Set estimated position to the system monitor location.
- Set reference origin to 0,0.
- Set transmitter azimuth sines and cosines to reference values.
- Set TD predictions to precomputed values.
- Fill covariance matrix and inverse from reference azimuth sines and cosines.
- Compute predicted TDs minus observed TDs.
- Solve for the X and Y correction.
- Move the estimated position by the X and Y correction.
- Reset the reference origin to the X and Y correction values.
- Compute new ranges to the transmitters from estimated position XY and transmitter XYs.
- Compute new azimuth sines and cosines from transmitter XY values, new origin, and ranges from the new origin.
- Predict new land-path TDs.
- Compute new directional derivatives and covariance matrix from the new reference azimuth sines and cosines.
- Compute predicted TDs minus observed TDs.
- Solve for X and Y corrections.
- Move the estimated position by the X and Y corrections.
- Return estimated position in UTM Northing and Easting.

Three-station positioning is all that is required for the system used at Starkey now. The software can also do four-station positioning in areas where a fourth transmitter is available. This results in an overdetermined solution and can overcome noise and geometry problems at some locations. The software will use the appropriate methods for three- or four-station positioning automatically as determined by the transmitters defined in the SYSREF.DAT file.

Displays

The CSPC displays in real time the Loran-C signals, signal parameters, position parameters, and a map position for each remote collar as information is processed [Figure 7].

The bottom left of the CSPC screen is a map display of the Starkey area. Both vector and raster map sources are used. The elk fence boundary, roads, contours, and foliage coverage are mapped. Vector maps for the area contain road and fence data provided by the U.S. Forest Service. Other line and text maps can be produced in the required format using a MAKEMAP software package written for this project. A raster map file contains three forage-coverage densities from Landsat imagery: forage, marginal, and satisfactory. The coverage type is mapped by one of three colors and pixel dithering densities. Brown and a medium pixel density are used for medium cover. Green and a high pixel density are used for satisfactory cover. White and no dithering are used for forage (open field) habitats.

The top 80 pixels of the screen display the Loran-C data gathered during the previous interval. The RF samples, the smoothed envelope, and the sampling point are plotted. Under each sample window the phase, sampling point index, amplitude, and SNR are printed.

The right side of the screen is a text display, presenting software status and position and temperature data from each remote collar in turn.

The system stores on disk and outputs over an RS232 link a line of information for each paged unit. A new file name is used each day, composed from the system date and time, automatically sorting tracking data into 24-hour segments. The format for both disk storage and RS232 output is a single line with date, time, pager #, status, TDA, TDB, TDC, Easting, Northing, and temperature. The same line is sent over an RS232 port to the DDSC.

Data Display and Storage Computer

A second Dell System 200 80286 computer receives position reports from the CSPC [Figure 8]. All software for this computer is written in Turbo-C.

The top line of the screen displays the latest RS232 position report line. These are handled by an interrupt routine ensuring that they are not lost during operator interaction with the map display. These reports are stored on the hard disk of the DDSC in the same format as in the CSPC.

Data stored on the hard disk can be transferred to the 40-Mbyte tape backup system by running "Quick Stream" soft-

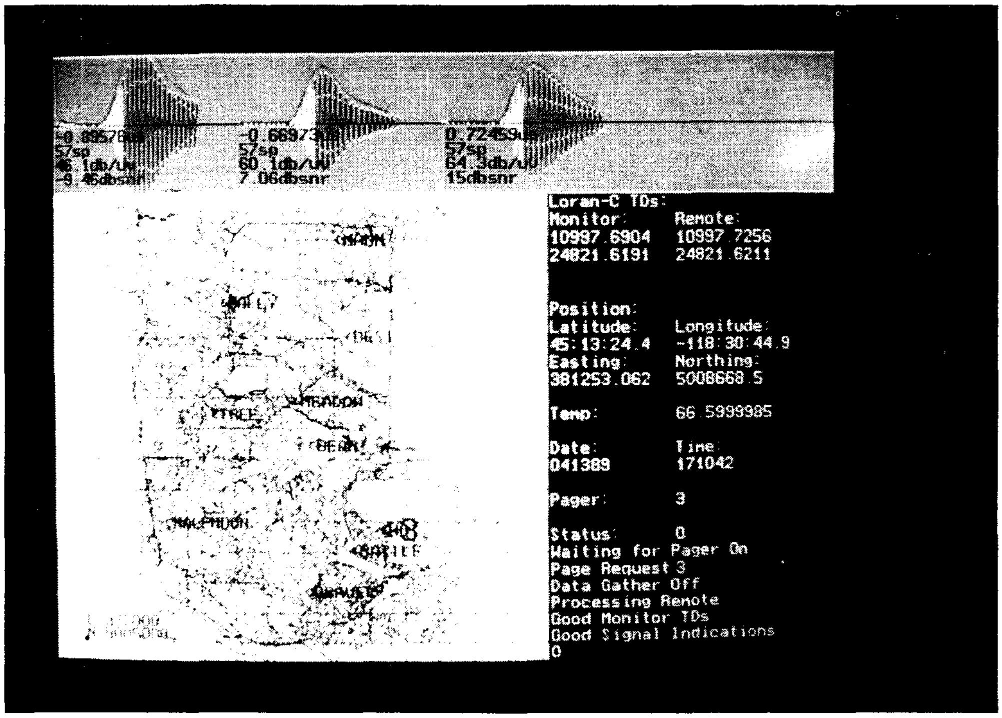


Figure 7. AATS Control and Signal Processing Computer Display

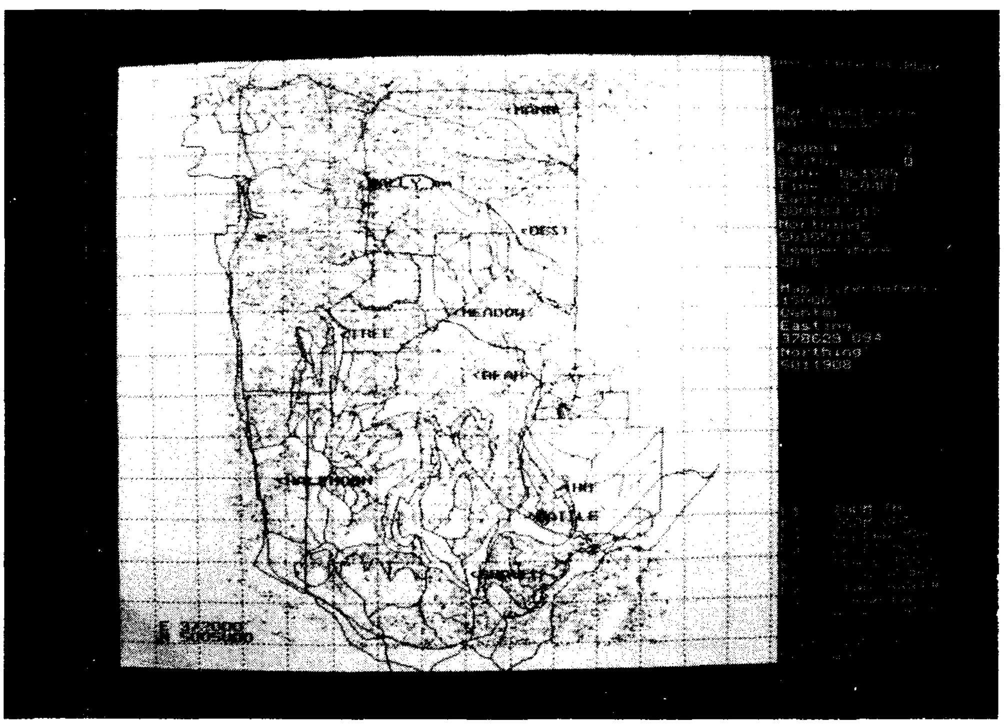


Figure 8. AATS Data Display and Storage Computer Display

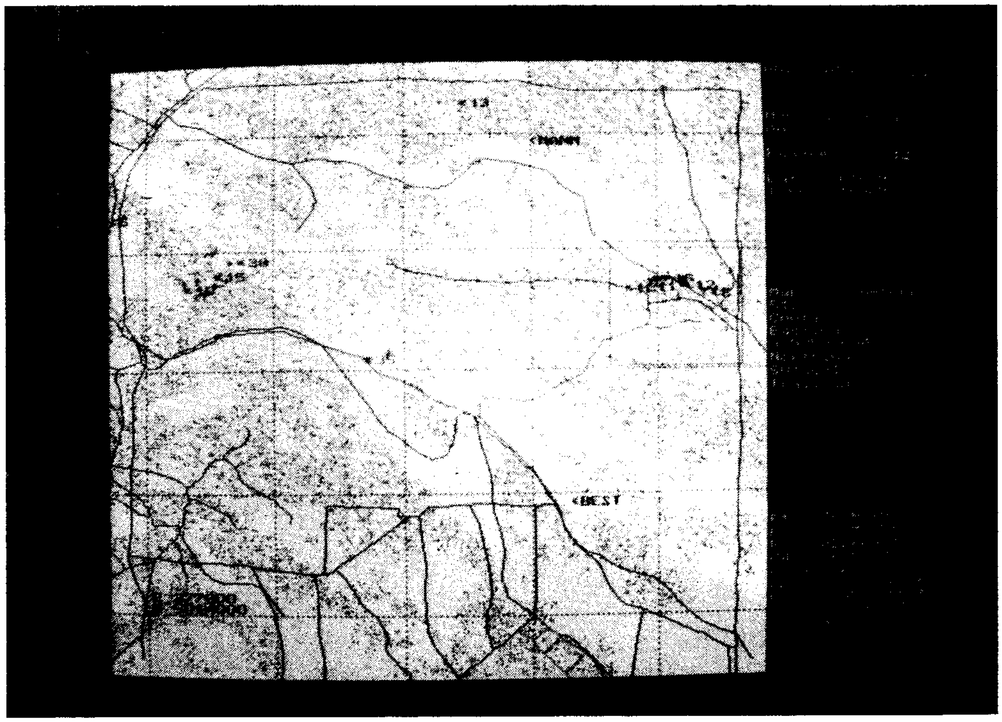


Figure 9. AATS Map Display of Intensive Forest Management Area

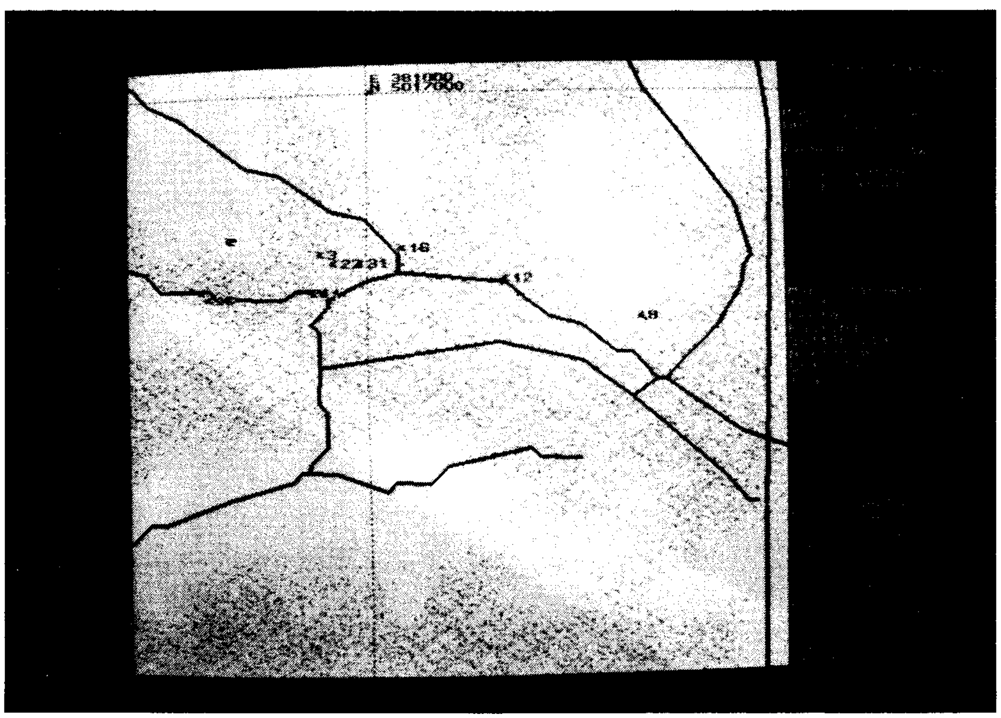


Figure 10. AATS Map Display of Detail in Forest Management Area

ware supplied with the tape system. Sixty days of AATS data can be transferred to the tape in under 30 minutes.

A map screen, using the same format and files as the CSPC, allows operator zoom, window positioning, and display of all pager positions. The map position source can be switched from the RS232 input to any AATS data file on the hard disk. The data from the current day's file can be examined interactively while the file is being updated in real time. Function keys control map source, operator selected zoom, map centering on a specific collar number, and colored position history trails [Figures 9 & 10].

A text display gives date, time, status, position, and temperature data, as well as map scale and center parameters. The size and position of the zoom window are also displayed when the zoom window is active. The minimum time before the disk is full and must be dumped to tape via the "QS" command from DOS is displayed on the text screen. This warning changes to a red display and the time changes from days to hours when the remaining time is less than 48 hours.

AATS DEPLOYMENT

The system was deployed in June 1989. Refinements to the retransmission link were made in July 1989.

Initial tests were done without a geodetic reference system in place, but position noise was computed to be from 45 to 85 meters (one standard deviation) at various static test sites using collars placed on stands.

Nine elk and ten cattle were tracked during the first phase of deployment. The elk collars had been built and installed three months before. The cattle collars were built and installed just prior to deployment. Ten deer collars were supplied, but not used in initial testing. Position reports from the cattle were easy to verify. The cattle remained in the same location for long periods and did not move when approached. Elk positions in the forest were verified by researchers with binoculars carefully approaching the animals on foot. It would have been difficult to find the elk at all without precise and timely position reports from the system.

CONCLUSIONS

The Automated Animal Tracking System has been successfully deployed at the Starkey Project. The system uses techniques for animal tracking that are new to wildlife management. AATS complements existing tracking techniques, geographic information systems, and research technologies in remote sensing, making possible new areas of wildlife study. The next step will be the integration of animal position data into current wildlife studies and the development of new methodologies using this technology.

ACKNOWLEDGMENTS

The authors would like to thank Jack Thomas, Larry Bryant, Glenn McLaughlin, and Floyd Snyder of the U.S. Forest Service for their support and hard work; John Curry and Steve Lilley of Internav for their interest and cooperation; and especially Jimmie Plentl, the AATS Program Manager at Tracor, for his support during every phase of this project.

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"VIDEO NAVIGATION - THE INTEGRATION OF LORAN AND CARTOGRAPHY"

Douglas Ambos & Francis S. Cassidy

DATAMARINE INTERNATIONAL
Pocasset, Massachusetts

ABSTRACT

Loran-C has developed into an extremely accurate and reliable system. User equipment has steadily decreased in size, power consumption and cost while at the same time increasing in capabilities. Advances in C-MOS Integrated Circuit technology have been largely responsible for this giving us highly integrated functions in smaller package sizes.

Navigation using Loran has progressed from manually measuring Time Differences between arriving signals on a oscilloscope screen, through fully automatic digital display Time Difference receivers to low cost navigators displaying Latitude, Longitude and a host of other navigation data on a digital display. The availability of increased density memory devices at lower costs, along with improved display technology, has recently made practical the next step forward in Navigation: situational display of position and movement relative to the vessel's surroundings. Interpretation of numerical data is not automatic for most people, especially in 2-dimensions. The display of a vessels's position and movement, along with other data, on a chart background eliminates this step in navigating and thereby removes a significant source of error from the process.

This paper discusses the evolution of this phase of navigation.

HISTORICAL PERSPECTIVE - Where We Came From

Navigation, the process of directing the movements of a vessel from one point to another, has implied in it accurate positioning, the result of determining your present position. In the past the two of these, both formerly arts now nearly sciences,had been practiced separately. In the very earliest times, without magnetic compass or chart of any kind, navigation even appeared to be practiced without positioning.

Radionavigation, navigation aided by the use of radio waves, is our subject here and can be considered to have started with the use of radio broadcasts of accurate time signals around 1900 thus providing reliable longitude positioning. More general radiopositioning came available after World War I with the establishment of the first radiobeacon for use with shipboard radio direction finding equipment. Work on radar started prior to World War II. Radar served as a radionavigation system in its own right, but in addition the RF pulse techniques developed for radar allowed work to start on Loran during World War II.

Positioning with Loran-A began in the early 1940's and lasted in some regions well into the 1970's. A wonderful system at the time, it required a skilled operator in the early days and there were many opportunities for error. Once over the initial, and difficult, problem of visually identifying the desired received signals, separating the ground wave from the sky wave and matching pulse edges on an oscilloscope to manually determine time differences, position determination became the next challenge. Use of sky waves was sometimes possible and required manually correcting the reading before plotting. Prior to the availability of nautical charts overlaid with Loran-A LOPs the navigator relied on Loran Tables (H.O. Pub. No. 221). The Tables required a double interpolation followed by a single interpolation for each LOP just to get close to the answer. A final graphical interpolation was performed on the chart as the LOP's were plotted.

During this period work started on Low Frequency Loran that lead to Loran-C. While Loran-A equipment and charts had been refined to a fairly high degree, Loran-C started out in the early 1970s with greatly improved accuracy but with semi-automatic receivers and little or nothing available in charts overlaid with Loran-C LOPs. It was common for the navigator to assist the Loran receiver in finding the correct stations, although once found, tracking of the signal was automatic, and then to plot his position on a chart - back to H.O. 221 and interpolation again - or use an overlay provided by the receiver manufacturer that was carefully labeled "NOT TO BE USED FOR NAVIGATION".

By the mid-1970s microprocessors were available to perform the mathematics necessary to convert Loran-C's hyperbolic LOPs to Latitude/Longitude coordinates. This new accessory, as big in cost and size as the Loran receiver itself, made it possible for the role of Loran to be extended from that of a positioning system to being part of an automatic navigation system. In this same period mechanical X-Y plotting equipment became available that produced highly repeatable, if sometimes distorted, plots of the vessel's track on plain paper or nautical chart backgrounds. The financial cost for this sophistication was high, on the order of $5,000 ($10,000 or more in 1989 dollars!) for each piece of equipment: Loran Receiver, Coordinate Converter and Loran Plotter.

The 1980s saw integrated circuit technology soar and prices drop. By the mid 1980s Loran receivers became fully integrated navigators with fully automatic Loran operation, Latitude/Longitude conversion and a full suite of navigation functions. Affordable electronic memory provided storage for destinations, waypoints and routes useful to the navigator. Finally, in what could have been the final link in the nearly fully automatic navigation system, industry cooperation provided for routine inter-connection with competing manufacturer's Loran receivers and various manufacturer's plotters and autopilot steering systems.

We enter the 1990s with full function Loran navigators reduced in size and cost to nearly 1/10 of the early 1980 systems and with the promise of a new dimension to navigation: electronic integration of position, radar target information and other important data overlaid on a high resolution electronically generated chart.

APPLICATIONS OF VIDEO NAVIGATION - What we can do with today's technology

The modern navigator can view digitized charts on a display at the helm and follow his progress with a "you are here" cursor. This instant interpretation of the (otherwise nonintuitive) Loran numerical latitude and longitude fix can be applied in many ways to ease the chores of piloting.

The first advantage that a navigator notices is that changing charts becomes transparent. When the position fix crosses a chart boundary the screen can be instantly redrawn with the new chart. This boundary can be assigned a hysteresis to avoid hasty chart-flipping. The user can "zoom-in" to large scale harbor charts or "zoom-out" to view where he is in the bigger picture.

The inclusion of a lat/lon cursor that can move under user control (through a trackball, for example) simplifies all chart-related plotting activities. The range and bearing from the vessel to any point on the electronic chart can be calculated and displayed by moving the cursor to that point and pressing a button. Similarly, the distance and bearing between two arbitrary points can be displayed. Any point on the chart can be instantly identified and entered as a destination -- with one button press instead of several keystrokes to enter a latitude and longitude. Just as easily, waypoints can be graphically linked to form a route. In fact, waypoint management in general is simplified when waypoints become symbols on an electronic chart instead of numbers in a (usually jumbled) list.

When this easily visualized waypoint is selected course information is sent to an autopilot, and the navigational control loop is closed.

Various databases can be created that have much more utility when seen on an electronic chart. The vessel's track can be recorded and overlaid on the chart (with the smallest distance between recorded points and total number of points being a necessary function of the amount of RAM available). This track can be instantly compared with the desired route and surrounding landmarks. The set and drift of current or wind pushing the vessel off course is readily observed, and can be explicitly calculated when dead reckoning data is available from speed and heading sensors.

Important political and fishing boundaries can be easily seen, marked, and even alarmed avoiding costly penalties and delays.

Events can be recorded with a keypress and given a symbol on the display, and can be stored with related time, position, and other data (depth, wind, temperature, etc). In fact, a complete navigational history can be continuously recorded following the track of the vessel. In this way, a track of depth soundings or wind directions and velocities can be displayed to further assist the navigator.

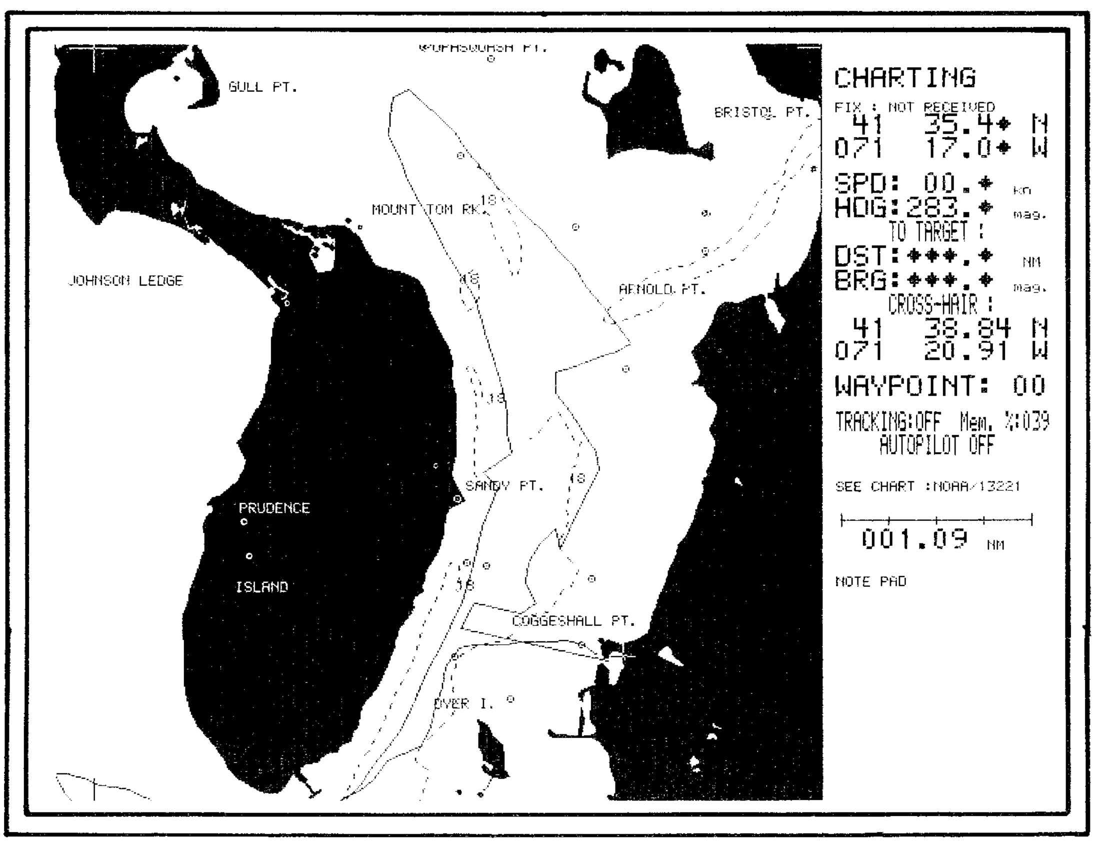
Another advantage of an electronic chart is that data can be "layered", allowing the selectable addition or removal of data like depth contours, aids to navigation, latitude/longitude grids, and land features. This unclutters the chart and speeds display regeneration. Hidden data can be displayed in a "pop-up" fashion when requested.

Data received from RADAR can be layered on top of the electronic chart, giving a second view of surrounding land masses and dynamic information on other vessels and objects, as well as providing a ready way of detecting system positioning errors.

While navigators are used to the less than perfect absolute positional accuracy of Loran, the "you are here" display of a fix on electronic charts can be disconcerting when ASF corrections or geographic Datum are inaccurate. Fortunately, latitude and longitude corrections can be applied with a move of the cursor and a press of a button. It is possible for a Loran to adaptively learn from these user-entered corrections, running a backward solution to update the database for the ASF corrections.

Similarly, the lag due to the long time constants traditionally used in the Loran's position and speed filters becomes more noticeable when displayed on an electronic chart. As a result, a Loran integrated into a Video Navigation machine needs to use a predictive filtering scheme. Dead reckoning data can also be used to intelligently guide the filtering.

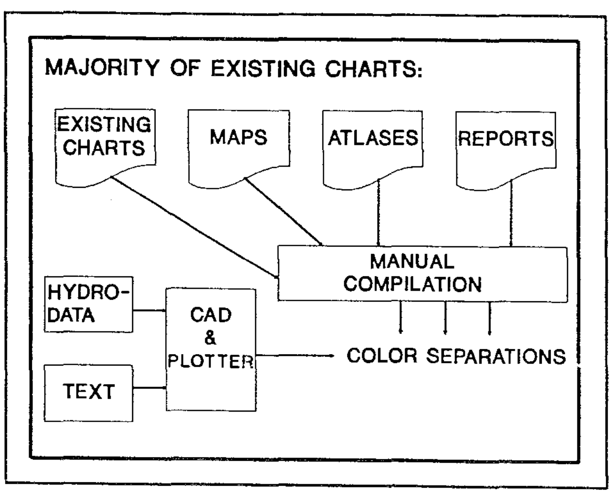
Today's systems provide safer, easier and more comprehensive tools for the navigator than thought possible a few years ago.



CARTOGRAPHY -
What's Available Now

The standard nautical chart is an artform and a scientific document all in one. It is a compilation of data from numerous sources and has developed into a reliable, and hence trusted,reference that is considered essential for safe navigation. Its production has involved a tremendous amount of detailed data, labor, time, checking, controls and on-going monitoring. In the United States nautical charts are produced by the National Ocean Survey/NOAA (coastal confluence zone), the U.S. Army Corps of Engineers (inland lakes and rivers) and the Defense Mapping Agency (foreign charts).

Certain new nautical charts are produced using computer aided design systems, employing database storage of lines, features and text, and offering very powerful drawing and editing features to aid in creating and maintaining the new chart. Interfaced to sophisticated plotting equipment, digital data is transformed to original negative plots of each color layer for reproduction. While this type of equipment can greatly speed the development of new charts, the fact is that the library of nautical charts available today contain very few new charts. Most of the chart data available has been gathered and refined over a long period, sometimes a century or more, and generally exists in "hardcopy" form. Original drawings and composites are maintained for each color layer and duplicate negative copies (stored separately) are provided for the photolithography process, or equivalent, used to reproduce the chart. Except in the case of the very first map and chart makers such as Ptolemy, there has almost never been a single source of chart data.

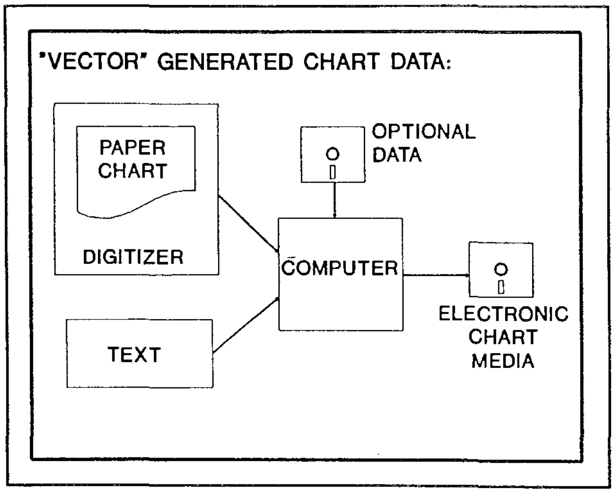


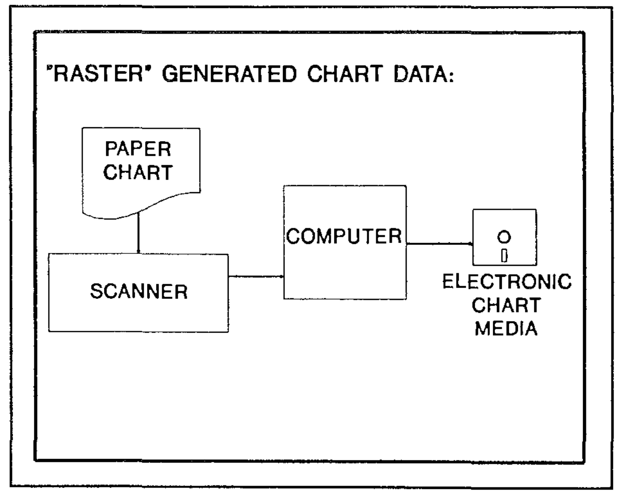
The existing base of charts now in use throughout the world is a compilation of hydrographic data, preexisting charts, land maps, aerial photographic data, travel folders, atlases, mariner's reports and sketches.

Establishing electronic databases from this kind of information is a formidable task! The fact that it can be done and the fact that the resulting data can be manipulated and displayed on affordable equipment results from a number of across the board technology advances made during roughly the past ten years. Part of this advancement is in the area of integrated circuits: high speed microprocessors and graphic controllers, high density and lower cost memory devices, ready access to high levels of both standard and custom integrated circuits. Also contributing in a major way are the development tools now available to the industry: fast, flexible software development equipment, standard system architectures and high level software languages have reduced risk, development costs and time to market.

At present all electronic chart systems use data obtained chiefly from the various nautical charting agencies throughout the world. For the most part this data exists in the form of paper charts, the exceptions being some existing data bases for Navigation Aids, some data files for political boundaries and coastlines and files of unprocessed depth and contour data. While potentially useful, the existing data files are often incomplete and may not always match one-to-one with the detailed hardcopy charts. The task of converting this largely "paper" data source into an electronic database is now handled in one of two ways:

"Vector" databases result from the process of manually digitizing by tracing the source charts using a large, high resolution digitizing tablet connected to a computer. Text, symbols and various attributes are entered via the computer keyboard and "positioned" in the database by further use of the digitizing tablet. This approach can result in as much detail and resolution as the developer has time, patience and memory space for. Full color high resolution charts can be produced using this process, but a lesser approximation is the usual result.





"Raster" databases result from the process of electronically "reading" the source charts using a high resolution line scanner or solid-state camera system. Except for a certain amount of image processing employed to compress data and reduce "noise" introduced by the system, what you get is what you see. The product of this is an electronic chart that has all the content and detail as the original paper chart. Full color and detail is possible on a chart image that is nearly the quality of the original.

The vector approach has several advantages: minimum memory required for storage, ease of editing and updating, data can be manipulated to allow true zooming functions and most important screen clutter can be reduced by controlling the screen content to match the application and the zoom level. Chart data can be separated, or layered, allowing removal or addition of depth contours, soundings, place names, etc. The vector process, however, is very labor intensive and the potential for transcription error exist.

Today the chief disadvantage of the raster approach is that the resulting data is actually an electronic image and not a database and very limited processing or manipulation of the data is possible. Screen content, and hence clutter, generally cannot be controlled, although lines and text can be overlaid, and limited editing is possible. Large amounts of memory are required, and while that is not a problem in itself with today's technology, handling all of this data will often result in slow panning and zooming functions. The process offers the advantage of error free detail, as good and as complete as the original, with much less labor. In addition the resulting video chart looks like the original paper chart that the navigator is already familiar with.

Both approaches produce highly usable results but neither is ideal. Efforts are now underway, however, in the National Ocean Survey and in the Hydrographic Offices in other countries to produce a standardized format for electronic chart data and to both produce new and convert existing charts to an electronic form. The reasons for this effort are two fold: these agencies throughout the world have the monumental task of maintaining a huge amount of current and growing data, now nearly all in hardcopy form, with an increasing need to exchange data between agencies. Second they have the foresight to recognize that electronic chart systems are coming fast and are legitimately concerned about the content and quality of the data that will be used in these systems.

Parallel to the effort of developing an official database for use in electronic chart systems the international community has started to develop standards for the content and display characteristics of electronic chart systems. To date standards have evolved through multiple Draft Standards and are ready to emerge as Provisional Standards. It is anticipated that the standards will remain Provisional "... until electronic chart systems have been adequately demonstrated ...".

The standards may vary somewhat depending on the type of vessel and application but in general will cover the following:

- Minimum data available for display and standard default displays
- Priority of displayed information
- Displayed symbols, abbreviations and colors
- Updating and integrity of the database
- Minimum display size and resolution
- Minimum positioning and sensor inputs to the system
- Chart orientation and motion
- Chart scales and zooming
- Automatic logging of data and time
- Warnings and alerts

The technology is moving fast and today's systems will improve rapidly as memory expands, processors get still faster and color display devices improve in price and performance. Today's provisional standards are designed to follow technology as much as the manufactured equipment is to follow the standard.

TECHNOLOGY APPLIED TO NAVIGATION

Stand-alone Loran receivers have reached technological maturity. The state of the art receiver today is completely digital, using digital processing of flash A-D samples of the 100KHz Loran signal. R-L-C tuned circuits now can be replaced with the polynomial coefficients of digital filters. These units represent the high end of the market. The savings offered by reduced part count and reduction of labor content (since bandpass and notch filter adjustments are not required) do not yet compensate for the high cost of DSP chips or recovery of the development investment. Loran receivers in the low end of the market have become a commodity item, with prices in the $300 range. These receivers utilize linear tuned circuit front-ends and inexpensive microcontrollers. The timing and sampling for Loran signal acquisition and tracking is done completely in software. This can cause a slight reduction in performance, since timing resolution cannot exceed machine cycle times (presently about 0.5 microseconds in these processors).

Today's Loran receivers can be very small (the circuitry can fit on a 3" by 5" index card, for example), yet are full featured. They typically offer storage for at least 100 waypoints, full navigational operations including route following, automatic everything (cycle selection, station selection, GRI selection, ASF corrections, magnetic variation) and interface with plotters and autopilots using the industry-accepted NMEA 0183 communications standard.

The small size and big capabilities of the modern Loran receiver have made it possible to build a Video Loran: an integrated Loran and electronic chart machine.

Display technologies have contributed to a lesser degree, however more choices are now available and affordable than ever before. The venerable CRT is still the cost-performance leader for many applications but plasma type displays, available 10 or 15 years ago have made significant strides in quality and price and large high-density graphic LCDs, not available a few years ago are now common. CRTs, in spite of their apparent complexity and large component count, remain the most affordable approach in both monochrome and color and provide the most satisfactory resolution and density. LCDs, with resolutions exceeding 640x480 and shrinking pixel size, have improved dramatically in the areas of contrast ratios, viewing angles and backlighting techniques. Gray scales are available and practical color systems are not far away. LCDs and plasma displays are rugged and overcome the bulk and weight of CRTs. LCDs in addition offer the advantage of enhanced operation in bright sunlight, that washes out the other displays, and very low power consumption and heat dissipation.

Video Navigation with an electronic chart machine offers many benefits to the navigator because of the intuitive interpretation of positional data. In addition, integrating a Loran receiver into the same box eases user operation and unburdens the Loran through a more logical distribution of tasks.

Communication between the Loran and the charting section is now internal, and can be more time efficient, being either in parallel or packed binary serial form. The Loran no longer has a display or keypad, since the user interface is a task handled by the graphics section. In fact, because of the emphasis on the "you are here" cursor, the display of TD numbers and manual control of the Loran becomes much less important, and only must be included to satisfy the most careful user.

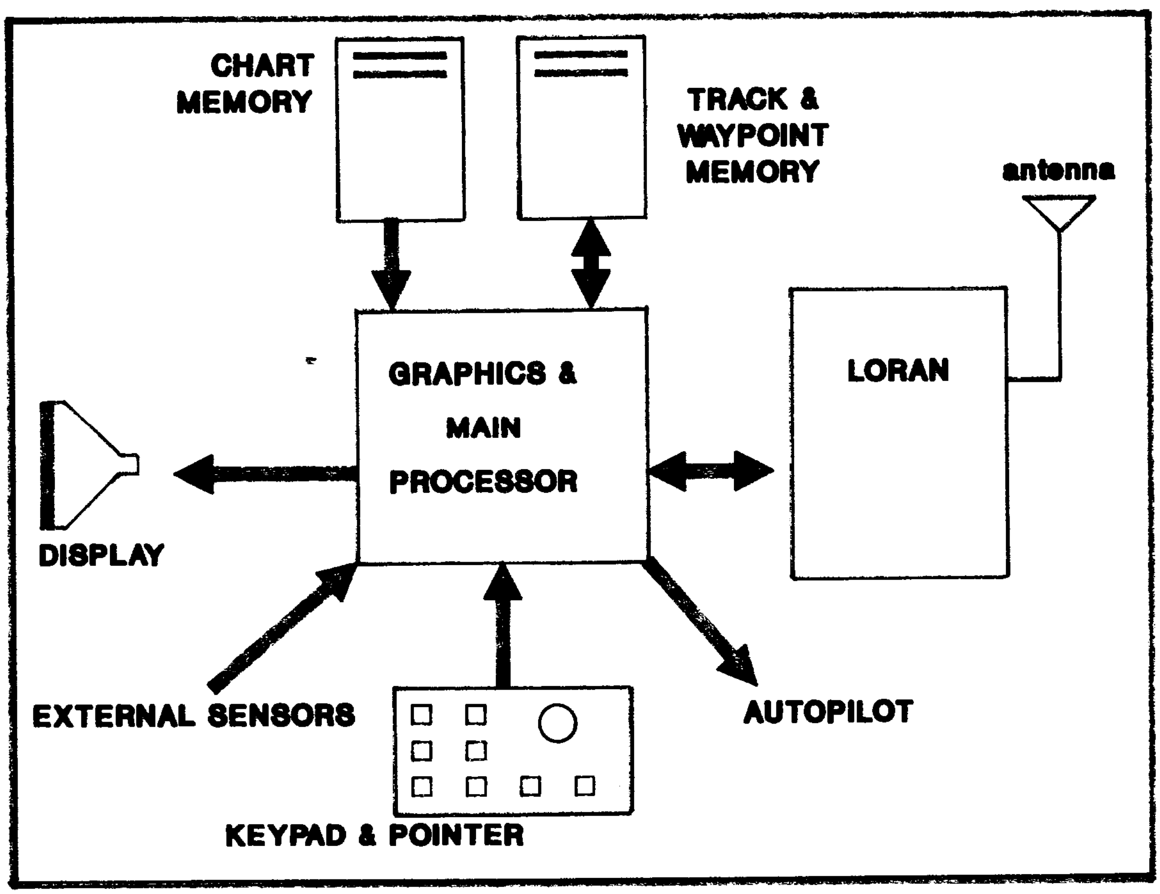
Because of the graphical interpretation of waypoints, the task of the waypoint database management most logically falls to the electronic chart section. Further, navigation calculations when using waypoints as destinations become charting tasks as well. This frees the Loran of all range and bearing calculations beyond those required in normal TD to latitude/longitude coordinate conversions. The embedded Loran can now spend more software overhead on improving signal reception performance.

If it is necessary to initialize the Loran with a seed latitude and longitude, it is an easy job for the user to move the cursor to the general vicinity on the chart and press a button. This avoids the problem of lengthy all-GRI searches for signals when the Loran has no idea where on Earth it is, and instant resolving of position ambiguities.

There are some difficulties in developing a Video Loran machine. The display technology most used in electronic chart machines today is the CRT -- chosen for its high resolution, small pixel size and low cost. Integrating a Loran into the same box means bringing a sensitive radio receiver in close proximity to a major source of radio frequency noise! In fact, many stand-alone Lorans mounted some distance away from CRT-based instruments (RADARs, plotters, etc.) have signal reception problems due to this interference.

To make a Loran work in the same box as a CRT requires careful RF shielding with the right materials and equally careful electrical grounding. High resolution CRT screens use a horizontal sync frequency somewhere in the 15KHz to 30KHz region. With an economy of parts, this frequency is usually also used in the switching power supply generating the kilovolt-level CRT anode and 80V to 500V grid voltages. The inductive kick of the flyback transformer can create interesting harmonics in the 100KHz region -- right in the Loran signal band. In addition, the high-current yoke deflection coils set up magnetic interference with similar in-band harmonics.

Other available display technologies pose fewer noise interference problems. High resolution LCD panels, for example, are low power devices and do not generate much noise in the Loran frequency band. However, care must be taken when using



fluorescent backlighting, since the switching power supply used to generate the 1000VAC needed may radiate interfering noise. Plasma display panels are medium power devices that generate some noise associated with the video signals, but do not have the magnetic interference of CRTs. 200VDC is required for the panel drive, however, and normal precautions must be taken as with any switching power supply.

Once interference problems are solved, the combination of a Loran with an electronic chart display results in a powerful Video Navigation machine, with single unit convenience and intuitive lat/lon data entry.

CONCLUSION

25 years ago the "American Practical Navigator" noted that "The modern navigator is still seeking further release from the work of navigation ..." and predicted that "It is not inconceivable that a fix may someday be automatically and continuously available, perhaps on latitude and longitude dials. However, when this is accomplished it will be but a short additional step to feed this information electronically to a pen which will automatically trace the path of the vessel across a chart. Another short step would be to feed the information electrically to a device to control the movements of the vessel, so that it would automatically follow a predetermined track".

The predictions of 25 years ago have been exceeded by the realities of today's available technology.

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BIOGRAPHIES

Doug Ambos earned his B.S.E.E. in 1983 and M.S.E.E. in 1985, both from the University of Massachusetts, Amherst. His graduate work specialized in Digital Control Systems as applied to robotics. From 1985 to 1987 he designed microprocessor based process control instruments for LFE Corporation, of Clinton, Massachusetts. He has been with Datamarine since 1987, designing Loran-C receivers and other marine navigation instruments.

Frank Cassidy 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 Vessels Traffic Management System. At Datamarine Frank is involved in the design and development of Loran-C and GPS receivers and Electronic Chart Systems.

THE LORAN-C MID-CONTINENT EXPANSION PROJECT; A STATUS REPORT

LTJG Roger D. Barnett, USCG

U. S. Coast Guard
Office of Navigation Safety and Waterway Services
Radionavigation Division

ABSTRACT:

The Loran-C Mid-Continent Expansion Project (MEP) is a joint U.S. Coast Guard (USCG) and Federal Aviation Administration (FAA) project designed to provide coverage in the midcontinental U.S. The FAA needs this coverage for use in enroute navigation for the aviation user. After studying the coverage needed, the USCG determined that two new chains would meet this need to cover the mid-continent gap.

BACKGROUND:

In March 1986, the Coast Guard and the Federal Aviation Administration (FAA) agreed to establish a project to close the gap in Loran-C coverage in the midcontinental United States. Since then, the Coast Guard, as overall project manager, has worked with the FAA to construct two new Loran-C chains in the central U.S. These new chains will provide coverage across the central United States, closing a gap in Loran-C coverage. This expanded coverage will allow aircraft to use Loran-C for enroute navigation and non-precision approaches. In a non-precision approach, the aircraft will use information from the Loran-C receiver to fly to within a published minimum altitude and distance of the airfield. The FAA is in the process of establishing non-precision approach procedures using Loran-C at airports throughout the United States. The major reason for the focus on Loran-C is that over 60,000 civil aircraft use Loran-C receivers. Aircraft owners and operators have requested this expansion through state and civil aircraft organizations. The FAA is providing $36.5 million for the MEP under the National Airspace System. The FAA is obtaining the land for the project and the Coast Guard is tasked with constructing and operating the new stations.

PLANS FOR NEW CHAINS:

The new mid-continent chains will consist of four new transmitter stations, two of which will be dual-rated. In addition, five existing stations will be dual-rated. The new stations will be located in Boise City, OK; Las Cruces, NM; Gillette, WY; and Havre, MT.

The South Central U.S. (SOCUS) chain will consist of Boise City, OK as master (M) and will have the following secondaries: Gillette, WY (V); Searchlight, NV (W); Las Cruces, NM (X); Raymondville, TX (Y); and Grangeville, LA (Z) (see figure 1).

The station at Boise City, OK will be dual-rated as the (Z) secondary to the Great Lakes chain to expand its coverage over the central U.S. (see figure 2).

The North Central U.S. (NOCUS) chain will consist of Havre, MT as master (M) and will have the following secondaries: Baudette, MN (W); Gillette, WY (X); and Williams Lake, BC (Y). Nearly forty percent of the NOCUS coverage will be over Canada (see figure 3).

The new transmitter stations will use 32 Half Cycle Generator (HCG) solid state transmitters (except for Boise City, OK which will use a 56 HCG) manufactured by MegaPulse, Inc. Each of these stations will be controlled by the remote operating system in an unattended mode.

This project marks a milestone for the U. S. Coast Guard; we will establish the SOCUS chain as our first use of a chain having a master with five secondary stations. This has caused us to select a Group Repetition Interval (GRI) which is long because along with five secondaries many of the baselines are long.

STATUS:

The Coast Guard has received three of the four new solid-state transmitters from MegaPulse Inc. and has placed them in a

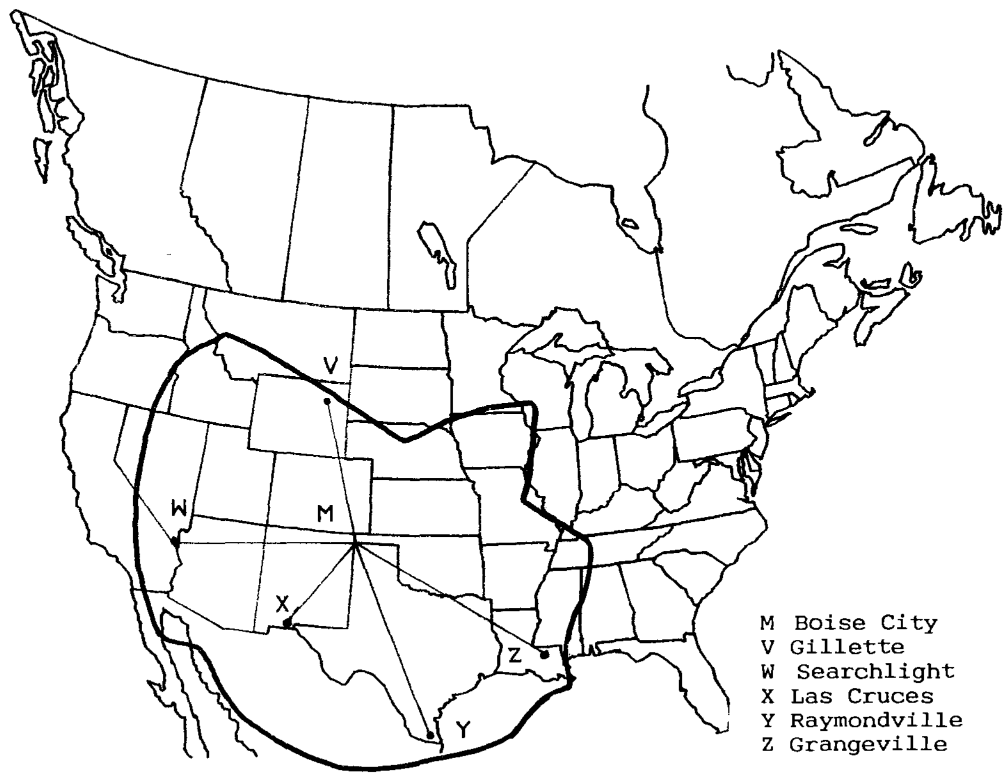

Figure 1 9610 SOCUS Loran-C Coverage

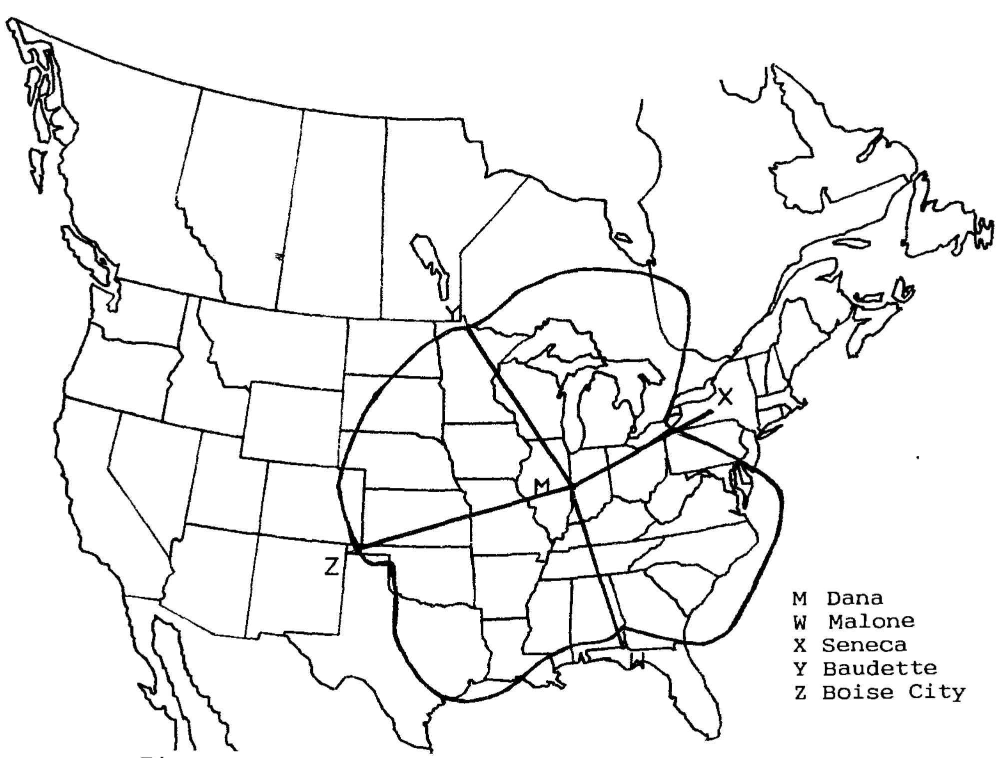

Figure 2 8970 Expanded Great Lakes Loran-C Coverage climate-controlled storage facility. These transmitters and the necessary timing and control electronics will be installed in the buildings when their construction is complete.

The 700 foot Loran-C towers have been designed and are awaiting selection of another manufacturer. The original contract was awarded to Tower Engineering Company who was defaulted in August 1989. Presently, the bonding company is negotiating with the original bidders to re-award the tower manufacture contract and expects to have a new contract in place by December 1989.

The dual rating of Searchlight, Raymondville, Grangeville, Baudette, and Williams Lake have been completed. We plan to begin early operation of these stations (excluding Williams Lake) starting in early 1990. This will allow our transmitter station personnel and control station personnel to become accustomed to handling dual-rated operations.

The FAA has acquired the land for three of the four transmitter sites. Acquisition of the Las Cruces site is pending completion of the Environmental Assessment documents. The U.S. Bureau of Land Management has prepared a land use permit for this site. The construction contract for three of the four new transmitter stations (Montana, Wyoming, and Oklahoma) was awarded on 14 July 1989 and groundbreaking began in late September 1989. The construction contract for the Las Cruces site has been awarded pending the FAA's approval of the Finding Of No Significant Impact and the Department of Transportation Section 4(f) statement. A Section 4(f) statement allows public multi-use lands to be used for specific purposes.

The estimated dates for operation are late Dec 1990 for SOCUS (operations at Las Cruces will be added in April 1991) and April 1991 for NOCUS. The Group Repetition Intervals (GRIs) have been selected; SOCUS 9610 and NOCUS 8290.

Figure 3 8290 NOCUS Loran-C Coverage

EXPERIMENTAL RESULTS USING DIFFERENTIAL LORAN/GPS FOR NON-PRECISION APPROACHES

Mark Morgenthaler
Glenn Steiner

Trimble Navigation Limited
585 North Mary Avenue
Sunnyvale, California 94086

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INTRODUCTION

In recent years, the science of navigation has dramatically increased its standards of accuracy and reliability. Accuracy requirements have changed from nautical miles to meters. Reliability standards have changed to equipment that can monitor its own integrity and mathematically prove that the position reported is correct.

LORAN has had a significant impact on this trend. During the last ten years, LORAN has made reliable and accurate equipment easy to afford and use. GPS promises yet greater accuracy and inherently better reliability. Recent activities in the area of interoperable LORAN/GPS look towards a combined system in which the redundancy of information assures that navigation can be foolproof.

For airborne applications, one of the most challenging sets of accuracy and reliability requirements can be found in the FAA's future requirements for non-precision approaches. LORAN has been approved on an experimental basis for such use. GPS, while inherently accurate enough to handle the 100m accuracy requirement, suffers from the lack of consistently good geometry and the cloud of Selective Availability.

In the case of both LORAN and GPS, real time differential corrections can greatly improve the accuracy, increase the reliability, and eliminate the effects of Selective Availability. A differential, interoperable LORAN/GPS system might provide all the accuracy, reliability, redundancy, and integrity monitoring required, both now and in the future.

1. THE INTERROPERABLE LORAN/GPS MODEL

Figure 1 shows the model used for an interoperable LORAN/GPS system. The basic concept is that the sensors in the receiver are capable of tracking the signals impinging on its antennae regardless of whether those signals are GPS or LORAN, or whether they are from one LORAN chain or many. It is assumed that all of the signals are synchronized at the transmitters, and that the receiver measures the signals relative to one common local oscillator. To the extent that the transmissions are not truly synchronized (SAM control, GPS-UTC timing differences, etc), the receiver will degrade in accuracy because of the need to model additional errors or will require more signals in order to solve for unknown biases.

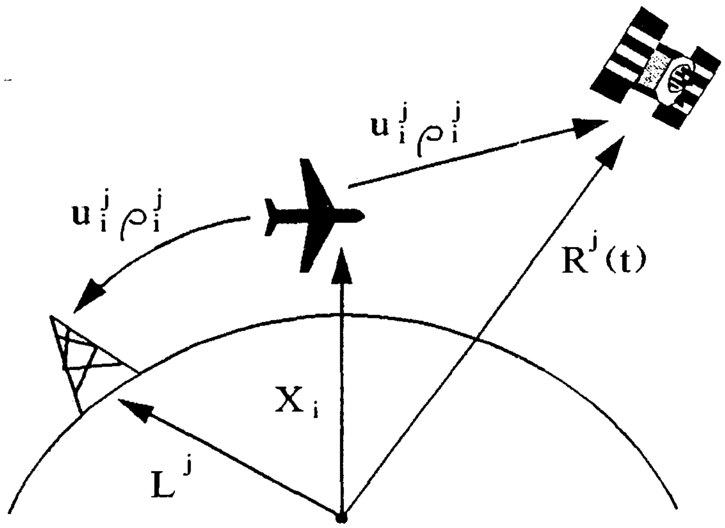

FIGURE 1. INTEROPERABLE LORAN/GPS SYSTEM DIAGRAM

2. PSEUDORANGE DEFINITION

The basic measurement made by the receiver is the pseudorange observable, $\tau^j(t)$, and is defined as the difference between the time of transmission (in the time scale of the transmitter $T(t_e)$) and the time of arrival (in the receiver time scale should be arrival - transmission $T(t_a)$) of a particular transmitted signal. In addition to the transmitter and receiver time scales, there is a more or less ideal time scale, called UTC time, t. For the pseudorange, we can write:

$$\tau^j(t) = (T(t_a) - T(t_e))$$

Adding and subtracting the elapsed UTC time $(t_e - t_a)$ we obtain the equation below:

$$\tau^j(t) = (t_a - t_e) + [(t_e - T(t_e)] - [(t_a - T(t_a)]$$

Ideally, the first term is the travel time of the signal which, when multiplied by c (the speed of light) is equal to the true range ρ to the transmitter, ignoring atmospheric effects. The second term represents the offset dT of the transmitter clock from UTC time. The third term represents the offset dT of the receiver clock from UTC time. When anomalous delays are taken into account, the complete generalized pseudorange equation takes the form

$$PR^j(t) = c\,\tau^j(t) = \rho + c\,(dT(t_e) - dT(t_a)) + m^j \lambda^j_{Epoch} + d_{errors}$$

The ambiguity regarding the wavelength of the Code Epoch is of central importance in an interoperable receiver. Because of known relationships between the epoch's of different chains, solution for the epoch ambiguity is possible. Without exploitation of these relationships, extra measurements may be necessary to solve for the ambiguities.

The pseudoranges can therefore be considered to consist of several terms, i.e.,

$$PR^{j}(t) = \{ \rho, cdt, d_{err}, m^{j} \lambda^{j} \}$$

where ρ is the desired range measurement and the other terms are nuisance factors that must be either modeled or solved.

If the signal is GPS, $\rho = \mathbf{D}[\mathbf{X}(t), \mathbf{R}^{j}(t)]$ where $\mathbf{D}[]$ is the line-of-sight distance between two points. If the signal is LORAN, the function $D[\mathbf{X}(t), \mathbf{L}^{j}]$ is the great-circle distance between two points and is used to compute the distance between a LORAN transmitter and receiver since the propagation is over the surface of the earth.

3. PSEUDORANGE RESIDUALS

The Kalman Filter uses pseudorange residuals as its inputs. These are formed by predicting the pseudoranges that the sensor should be measuring given the current state of the system, and comparing those predicted pseudorange with the actual measurements made by the sensors. In the remainder of this discussion, the predicted pseudoranges are indicated with a ^. These predictions are formed using the equations below and combine all of the effects that must be modeled for the system to perform correctly.

The Kalman filter can be formulated to use both pseudorange and pseudorange rate residual inputs. Hence there are four quantities of interest for every signal received: 1) the predicted pseudorange, 2) the measured pseudorange, 3) the predicted pseudorange rate and 4) the measured pseudorange rate. Depending on whether the signal is a GPS or a LORAN signal the residuals are formed in slightly different manners. The GPS sensor uses the Code Phase Observable (discussed below) to form the pseudorange and uses the Carrier Phase Observable to form the pseudorange rate. The LORAN Sensor uses the Code Phase Observable to determine the cycle ambiguity in the carrier phase, but uses the Carrier Phase Observable to form both the pseudorange and range rate residuals. We will now describe the terms that go into the calculations of the predicted observables.

4. PSEUDORANGE CODE PHASE OBSERVABLES

In GPS the phase of the code can be measured relative to the local oscillator and expressed as in the generalized equation above. For GPS, the code rate is 1.023 MHz (ten times the frequency of the LORAN carrier!) and can be used directly for ranging. Hence it is possible to develop equations to predict the code phase pseudorange given estimates of position and time.

The GPS Code Phase pseudorange is given by the formula below:

GPS:

$$\hat{PR}_i{}^{j}{}_{gps}(t) = \mathbf{D}[\mathbf{X}_i(t), \mathbf{R}^{j}(t)] + c_{gps}\,(dT^{j}(t_e) - dT_i(t_a)) + m^{j}\lambda^{j}{}_{Epoch} + \hat{d}_{trop} + \hat{d}_{ion}$$

Where

$\hat{PR}_i{}^{j}{}_{gps}(t)$	is the GPS pseudorange
$\mathbf{D}[\mathbf{X}_i(t), \mathbf{R}^{j}(t)]$	is the Line of Sight Distance from the ith receiver to the jth satellite
c_{gps}	is the speed of propagation for GPS
$dT^{j}(t_e)$	is the error in the time of transmission for the j^{th} satellite
$dT_i(t_a)$	is the error in the time of arrival as measured by the i^{th} receiver
$\lambda^{j}{}_{Epoch}$	is the wave length of the code epoch
m^{j}	is an integer number of code epoch ambiguities
$\hat{d}_{trop}$	is the propagation error due to the troposphere
$\hat{d}_{ion}$	is the propagation error due to the ionosphere

The GPS signal is especially kind to receiver designers and transmits the values of most of the terms necessary to accurately predict the pseudorange given an accurate position and time (state estimate). The GPS clock correction, $dT^{j}(t_e)$, the ionospheric and tropospheric corrections and the code epoch ambiguity are all transmitted as part of the message from the satellite. The only remaining terms that must be resolved are the receiver clock error and true range.

In LORAN, the code phase observable is measured in the envelope channel and runs at 1 KHz. This signal is not generally useful for positioning, but is used to disambiguate cycles in the carrier channel. In order to form a residual, a predicted pseudorange must also be described for the LORAN code phase.

One of the difficulties of designing a good LORAN receiver is modeling the large number of terms necessary to accurately predict the pseudorange. The formula for the predicted pseudorange is:

LORAN:

$$\hat{PR}_i{}^j{}_{lrn}(t) = D[\mathbf{X}_i(t), \mathbf{L}^j] + c_{lrn}(dT^j(t_e) - dT_i(t_a)) + m^j \lambda^j{}_{PCI} + \hat{prop}^j[\mathbf{X}_i(t)] + \hat{d}_{fe}[atten] + \hat{ECD}^j[\mathbf{X}_i(t), \mathbf{L}^j] + bias^j[\mathbf{X}_i(t) - \mathbf{X}(t_{cal})]$$

Where

$\hat{PR}_i{}^j{}_{lrn}(t)$	is the LORAN pseudorange
$D[\mathbf{X}_i(t), \mathbf{L}^j]$	is the Great Circle Distance from the ith receiver to the jth transmitter
c_{lrn}	is the speed of propagation for the LORAN carrier
$dT^j(t_e)$	is the error in the time of transmission for the jth transmitter
$dT_i(t_a)$	is the error in the time of arrival as measured by the ith receiver
$\lambda^j{}_{PCI}$	is the wave length of the LORAN Phase code epoch
m^j	is an integer number of code epoch ambiguities
$\hat{d}_{fe}[atten]$	is the delay through the front end of the receiver
$\hat{prop}^j[\mathbf{X}_i(t), L^j]$	is the propagation delay of the carrier from the j^{th} transmitter to the i^{th} receiver
$\hat{ECD}^j[\mathbf{X}_i(t), \mathbf{L}^j]$	is the "Envelope to Cycle Delay" associated with the jth transmitter
$bias^j[\mathbf{X}_i(t) - \mathbf{X}(t_{cal})]$	is the bias at ith receiver based on data computed at $\mathbf{X}(t_{cal})$

The $\hat{prop}^j[\mathbf{X}_i(t), \mathbf{L}^j]$ term is itself a complex formula and consists of four parts:

PF	the primary factor which is a constant
SF	the secondary factor which is a function of range
ASF	the additional secondary factor computed as a line integral of the propagation speed over the stored conductivity map of the world along the line connecting the transmitter and receiver.
$dbprop^j[\mathbf{X}_i(t), \mathbf{X}_{cal})]$	the delta prop delay stored in the data base for the jth transmitter and calibrated at the point $\mathbf{X}_{cal}$.

5. CARRIER PHASE OBSERVABLES

Some GPS receivers (for instance the Trimble Navigation TANS) and all LORAN's are able to measure the difference between the signal generated by their internal oscillators and the carrier signal coming in from the transmitter. This difference is the Carrier Phase Observable, and is equal to the phase of the signal which remains when the incoming Doppler-shifted carrier signal is beat with the nominally-constant reference frequency generated in the receiver:

Therefore:

$$\Phi = \Phi_i{}^j = \Phi^j(t) - \Phi_i(T(t))$$

where

Φ^j	is the phase of the signal transmitted by the jth transmitter at time t
Φ_i	is the phase at the ith receiver at reception time T(t)

The carrier phase model can be formulated using a derivation similar to that used for the code phase pseudorange observable. The only difference in the formulation is that the ambiguities and the biases on the carrier beat observable are different. The ambiguity on the carrier is the wavelength of the carrier not the code. Also, in the case of LORAN, the carrier propagates at a different rate than the code. In the case of GPS, the sign of the tropospheric delay is reversed.

Hence, one can obtain the corresponding carrier phase equations for both LORAN and GPS:

$$\hat{\Phi}_i{}^j{}_{gps}(t) = \mathbf{D}[\mathbf{X}_i(t), \mathbf{R}^j(t)] + c_{gps}\,(dT^j(t_a) - dT_i(t_b)) - \hat{d}_{trop} + \hat{d}_{ion} + n^j\lambda^j{}_{f0}$$

$$\hat{\Phi}_i{}^j{}_{lrn}(t) = D[\mathbf{X}_i(t), \mathbf{L}^j] + c_{lrn}\,(dT^j(t_a) - dT_i(t_b)) + m^j\lambda^j_{PCI} + \hat{prop}^j[\mathbf{X}_i(t)]$$
$$+ \hat{d}_{fe}[\text{atten}] + \text{bias}^j[\mathbf{X}_i(t) - \mathbf{X}(t_{cal})] + n^j\lambda^j{}_{100KHz}$$

which is directly comparable with the code phase equations, except for the additional ambiguity terms related to the carrier wavelength, the sign of the ionospheric term in the GPS observable, and the exclusion of the ECD term in the LORAN. This clearly indicates that except for the initial ambiguity, $n\,\lambda$, Φ can be thought of as a range, and its observation equation is almost the same as that of the biased range. The biases for this kind of measurement are the same as for pseudoranges, except that the ambiguity term has been added.

6. KALMAN FILTER EQUATIONS

The filter processes all available pseudorange and pseudorange rate measurements (from LORAN or GPS) with a dual four-state Kalman filter. Each of the available LORAN pseudoranges are calibrated using single-state bias estimation filters. Hence the Measurement Equation is:

$$\mathbf{Z} = \mathbf{Hx} + \mathbf{B} + \mathbf{n}$$

where $\mathbf{Z}$ is a 2M x 1 vector consisting of the pseudorange and pseudorange rate measurements made on each of the available M signals, $\mathbf{H}$ is the 2M x 2N measurement matrix which transforms the state space to the measurement space, $\mathbf{x}$ is the 2N x 1 state vector consisting of both position and time components and their derivatives with respect to time. $\mathbf{B}$ is an 2M x 1 vector of biases whose values are estimated depending on the configuration of LORAN and GPS measurements available. $\mathbf{n}$ is an 2M x 1 vector of guassian measurement noise.

In order to minimize the computational burden on the processor, the filter is actually implemented as two, 4-state filters, one filter for position and the other for velocity. These two filters are coupled by the covariance propagation equations.

The definition of the state vectors for the two 4-state filters are given below:

$$\mathbf{x}^{(1)} = \begin{bmatrix} \delta p_e \\ \delta p_n \\ \delta p_u \\ \delta\phi \end{bmatrix}$$

$$\mathbf{x}^{(2)} = \begin{bmatrix} \delta v_e \\ \delta v_n \\ \delta v_u \\ \delta f \end{bmatrix}$$

In defining the states of the first four-state filter, δp_e, δp_n, and δp_u represent the east, north, and up position corrections, respectively, and $\delta\Delta\phi$ the correction to the user clock error estimate. All are in units of meters. In the above equation, defining the states of the second four-state filter, δv_e, δv_n, and δv_u represent the east, north, and up velocity corrections, respectively, and δf the correction to the user clock frequency estimate. All are in units of meters/second.

The definition of the measurement vectors for the two 4-state filters are given below:

$$z^{(1)} = \begin{bmatrix} \delta PR_0 \\ \delta PR_1 \\ \cdots \\ \delta PR_m \end{bmatrix}$$

$$z^{(2)} = \begin{bmatrix} \delta PRR_0 \\ \delta PRR_1 \\ \cdots\cdot \\ \delta PRR_m \end{bmatrix}$$

In defining the measurement residuals, δPR is the pseudorange residual in meters and δPRR is the pseudorange rate residual. These measurements are made for each of the received LORAN or GPS signals.

Since the navigation state is corrected using the Kalman filter estimates following the processing of each available pair of pseudoranges and range rates, there is no requirement to propagate the Kalman filter estimates ahead in time. Only the covariance matrices need to be propagated, therefore. Covariance propagation is effected using routines of the Bierman Software Package[1], so will not be described here.

7. CONCEPTUAL DESCRIPTION OF A DIFFERENTIAL, INTERROPERABLE RECEIVER

The Block Diagram of a Differential, Interoperable System is show below. It's primary advantage is that many of the error terms modeled in the case of a single, stand-alone receiver can be estimated in real time by a monitor base station and removed from the position solution. In a word, *accuracy* is increased. Additionally, detection of failures can be greatly improved. The integrity monitoring at the monitor station has a distinct advantage over receiver autonomous integrity monitoring (RAIM) because the monitor knows where it is. This means that any deviation of the signal from nominal values that are larger than predetermined error thresholds can easily be detected without having to differentiate between true movement and signal inconsistencies as in the case of RAIM.

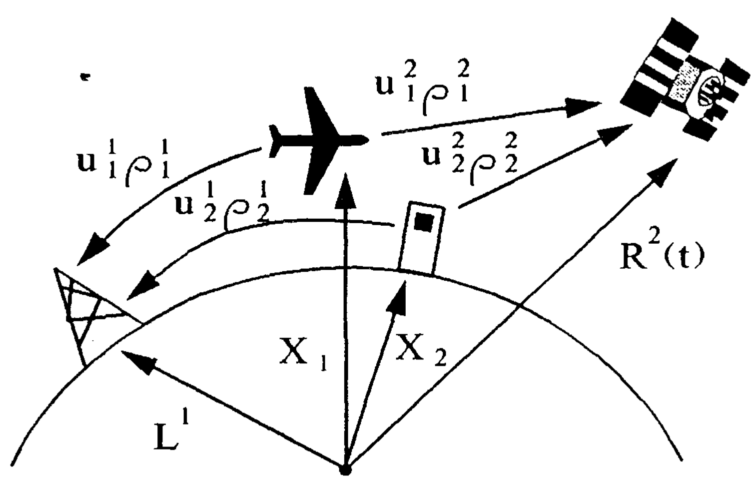

FIGURE 2. DIFFERENTIAL INTEROPERABLE SYSTEM DIAGRAM

The radio link connecting the plane and the tower can take many forms. It has been suggested that the link be in the form of a GPS "pseudolite"[2] wherein the differential data is encoded as a message on a GPS compatible signal sent from a point near the airport. The pseudolite configuration has the added advantage of offering an extra measurement and improving geometry. The protocols for differential communication established by RTCM Committee 104 were designed to allow differential operation within the 50 Bits/sec capacity of a GPS Channel[3]. It has also been suggested that a S-Mode Transponder could be used. It is not the purpose of this paper to conjecture on the form of the data link, but rather to collect certain experimental data and postulate a theoretical framework for such a system.

8. LINEAR COMBINATIONS OF MEASUREMENTS

Depending on the type of application and the level of accuracy one seeks, there are significant advantages and disadvantages in forming certain linear combinations of the basic code phase pseudorange, or carrier phase observables. Measurements can be differenced between receivers, between transmitters, and between epochs, or combinations thereof. Many different differencing combinations are possible.

The notation we use for taking these differences is intended to be mnemonic[4]:

(d) denotes differences between two measurements.
(δ) denotes differences between two epochs.
(Δ) denotes differences between two receivers
(∇) denotes differences between two transmitters

For differential LORAN/GPS there are many combinations of pseudorange that can be formed. By differencing pseudoranges obtained from different transmitters by the same receiver, the ∇PR's can be formed removing the effects of local oscillator drift, and differential front-end delay. This difference is commonly referred to as a TD and is well known to LORAN users. The PRR's can also be differenced, thereby forming the $\nabla\delta$PR's.

Another combination that can be formed is a between receiver difference or a ΔPR which removes most propagation errors such as ionospheric and tropospheric anomalies for GPS and conductivity anomalies and time of transmission errors for LORAN.

The so-called double difference equations, or the $\nabla\Delta$PR's offer the best of both worlds. Receiver clock errors and front-end delays are removed by one difference and propagation and time of transmission errors are removed by the other. The result is a pseudorange that consists only of the true $\nabla\Delta\rho(t)$ term and second order error terms.

GPS survey equipment has long employed this sort of double difference to perform their millimeter accurate positioning. They also use these double differences to detect and correct cycle slips that they encounter on their measurements of the 20cm carrier of GPS[5]. As an unanswered question, we might ask if differential interoperable LORAN/GPS receivers could use the same techniques to detect and correct cycle slips?

9. DIFFERENTIAL KALMAN FILTER EQUATIONS

The differential Kalman filter equations follow closely from the previous formulation. Instead of processing pseudoranges, however, between receiver differences are processed. The state vecotr therefore becomes the delta position, velocity and time vector (as shown below). All other processing remains the same.

$$\Delta z = H\,\Delta x + n$$

10. EXPECTED ACCURACIES

As discussed, a GPS or LORAN receiver can basically make only two kinds of measurements: code phase measurements, and carrier phase measurements. As a rule of thumb, the precision with which the phase of either the code or the carrier can be maintained is 1% of the code or phase period. For the GPS P-code, successive epochs are 0.1 microsecond apart, implying a 1% measurement precision of 1 nanosecond. When multiplied by the speed of light, this implies a range measurement precision of 30 centimeters. For the GPS C/A-code, the numbers are ten times less precise, or a range measurement precision of 3 metres. For LORAN, the code-chip is 1 msec. One percent of these values is approximately 10 microseconds or 3000 meters. Obviously, the LORAN code phase pseudorange measurements are not very useful for ranging and must be determined more accurately than 1% to even be useful for removing ambiguates in the carrier cycle (cycle selection).

The GPS L1 and L2 carriers have approximately the same carrier wavelength. For the L1 carrier that wavelength is about 20cm. For survey quality GPS receivers that operate off the carrier phase, millimeter accuracies can be obtained. The LORAN carrier is at 100KHz and has a wavelength of 3000m. Its phase can be resolved to 1% of the wavelength or about 30m.

Comparisons of the relative accuracies are seen in the Table below:

	Freq	λ	1%Phase
Code Phase Pseudorange			
GPS C/A Code	1MHz	300m	3m
GPS P-Code	10MHz	30m	.3m
LRN Phase Code	1KHz	300000m	3000m
Carrier Phase Pseudorange			
GPS L1	1575MHz	0.02m	.0002m
GPS L2	1227MHz	0.02m	.0002m
LRN 100 KHz	100KHz	3000m	30m

TABLE 1. MEASUREMENTS AND ASSOCIATED ACCURACIES

A more scientific examination of the errors that can be expected from the LORAN sensor is found in Enge and McCullough's[6] computations. In the table below, they compute that the expected LORAN pseudorange errors vary from 1400m (2 dRMS) to 300m (2dRMS) depending on the method of time of transmission control and the techniques used for ASF correction. Using this same form of derivation, the double differenced pseudoranges could expect 50nsecs of random error (noise) for each transmitter-receiver pair, but negligible differences due to ASF or time of transmission anomalies. The expected double differenced pseudorange errors would be on the order of 100nsecs due only to the four random 50nsec noise errors. If the GDOP is 2, the expected 2 dRMS error would be approximately 140 meters.

Approach	Ignored Variations	A Priori Predictions	Real-Time Calibration
TOT control and/or short distances	$\sqrt{50^2 + 200^2 + 300^2}$ $\approx$ 350 ns $\rightarrow$500 m (2 dRMS)	$\sqrt{50^2 + 200^2 + 100^2}$ $\approx$ 250 ns $\rightarrow$300 m (2 dRMS)	$\sqrt{50^2 + 200^2 + 50^2}$ $\approx$ 200 ns $\rightarrow$300 m (2 dRMS)
SAM control and/or long distances	$\sqrt{50^2 + 200^2 + 900^2}$ $\approx$1000 ns $\rightarrow$1400 m (2 dRMS)	$\sqrt{50^2 + 200^2 + 300^2}$ $\approx$ 350 ns $\rightarrow$500 m (2 dRMS)	$\sqrt{50^2 + 200^2 + 150^2}$ $\approx$ 250 ns $\rightarrow$300 m (2 dRMS)

TABLE 2. EXPECTED LORAN PSEUDORANGE ERRORS

Recently, several of the GPS satellites were placed into a selective availability status. At Trimble, we continuously monitor both LORAN and GPS signals and Greg Kremer has collected and analyzed the data collected during the Julian days of 88, 90, 124, 131, 132, and 133 of 1989. In a paper presented at the recent ION meeting[7], he published the expected performance of both a stand-alone and a differential set of GPS receivers under the conditions of SA. Those results are tabulated below. They suggest that the differential range errors for GPS would be in the 1 to 2 meter range even with Selective Availability. Typically, the GPS constellation will achieve a GDOP of 6 and hence these pseudorange errors would account for a 2 dRMS error of approximately 12 meters. This is ten times better than that expected from LORAN.

	BLOCK I	EXPECTED (S/A)	JULIAN 124 (URA=32)	JULIAN 259 (URA=64)
RANGE ERROR				
Mean	0	0	75 m	-52 to 36 m
1-σ	1 - 1.5 m	30 m	29 m	48 to 56 m
RANGE ERROR RATE				
Mean	0	0	0.01 m/s	0.01 m/s
1-σ	0.0055 mm/s	0.14 m/s	0.12 m/s	0.20 to 0.21 m/s
RANGE ERROR ACC				
Mean	0	0	0	0
1-σ	0.4 mm/s^2	3.7 mm/s^2	2.0 mm/s^2	3.4 to 3.6 mm/s^2
CORRELATION TIME				
90%	N/A	180 s	180 s	180 s
RMS RANGE ERR DIFF				
t = 10 s	N/A	0.3 m	0.2 m	0.2 to 0.3 m
t = 30 s	N/S	1.7 m	1.2 m	1.5 to 1.9 m

TABLE 3. EXPECTED GPS PSEUDORANGE ERRORS

13. EXPERIMENTAL DATA

The four figures that follow are each, three hours of actual data collected from LORAN and GPS. The GPS data includes both satellites 6 and 14 when sattelite 14 was displaying S/A-like behavior. The data is expressed in the same units of meters and meters/second for the pseudorange and pseudorange rate respectively. The pseudorange data confirms our expectations as listed earlier, i.e., that LORAN signals with SNR > 0 have approximately 30 meters of random noise. This makes them more repeatable than GPS signals with SA but noisier and less repeatable than GPS signals without SA. The pseudorange rate measurements from GPS are always better than the rates obtained from LORAN. This is because the GPS range rates are measured from the L1 Carrier which provides a 15750:1 processing advantage over the 100 KHz LORAN carrier. In both cases, the zero-baseline absolute errors were negligible.

14. CONCLUSIONS

LORAN and GPS measurements can be combined together in measurement space and effectively used to determine a position. This is due, in part, to their similar noise and accuracy characteristics. We have expanded this concept to include differential measurements on both the LORAN and GPS signals. This technique removes the relatively large and uncertain ASF errors inherent in LORAN and can be used to remove the artifically induced S/A errors in GPS. There are both technical and political ramifications to this observation. Together LORAN and GPS might provide the needed accuracy, reliability and monitored integrity necessary for the future.

15. ACKNOWLEDGEMENTS

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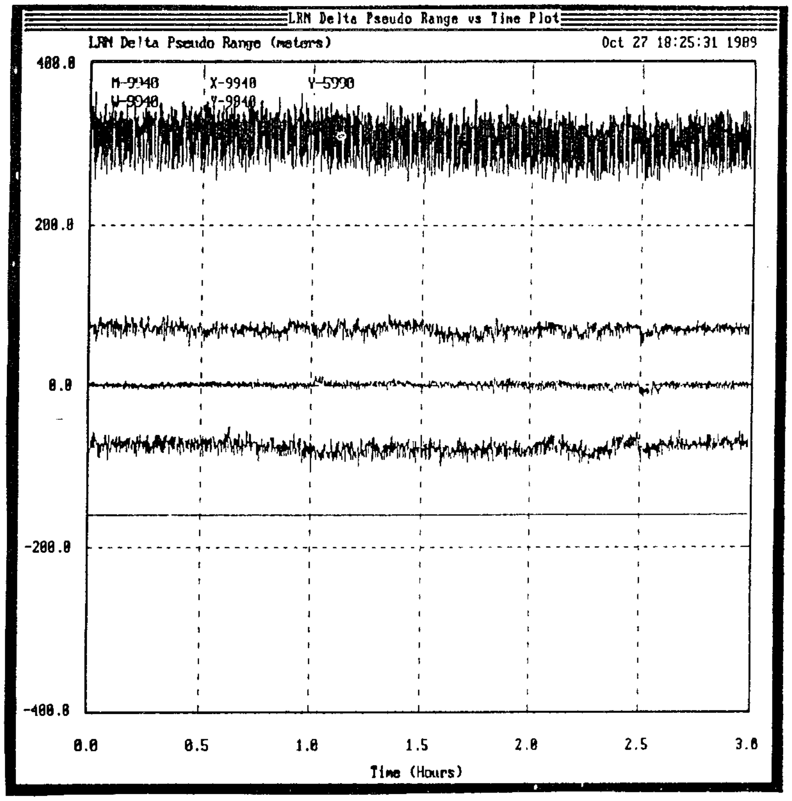

FIGURE 3. LORAN DELTA PSEUDORANGE ERROR

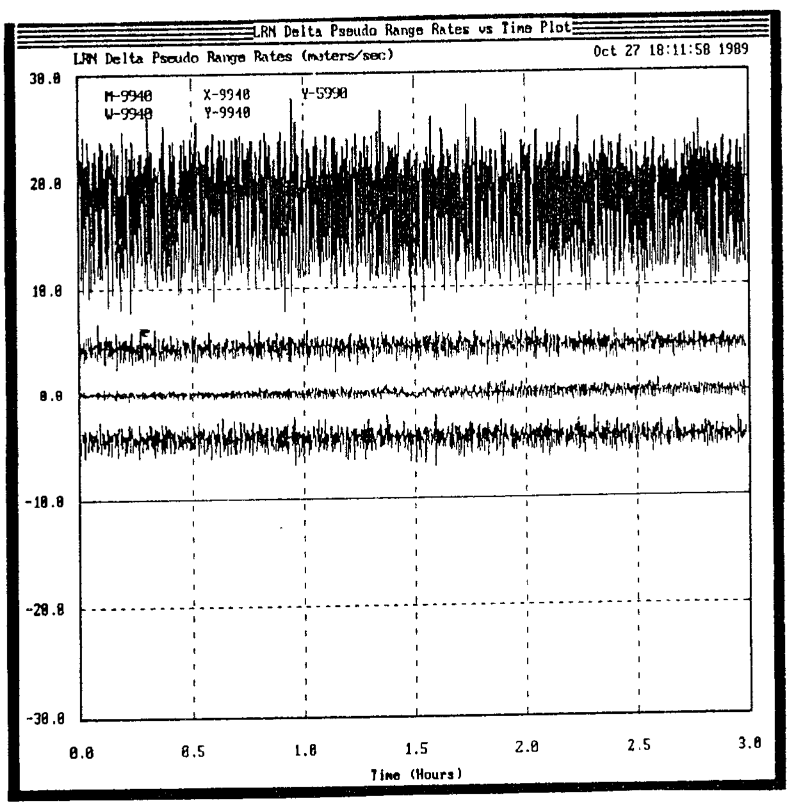

FIGURE 4. LORAN DELTA PSEUDORANGE RATE ERROR

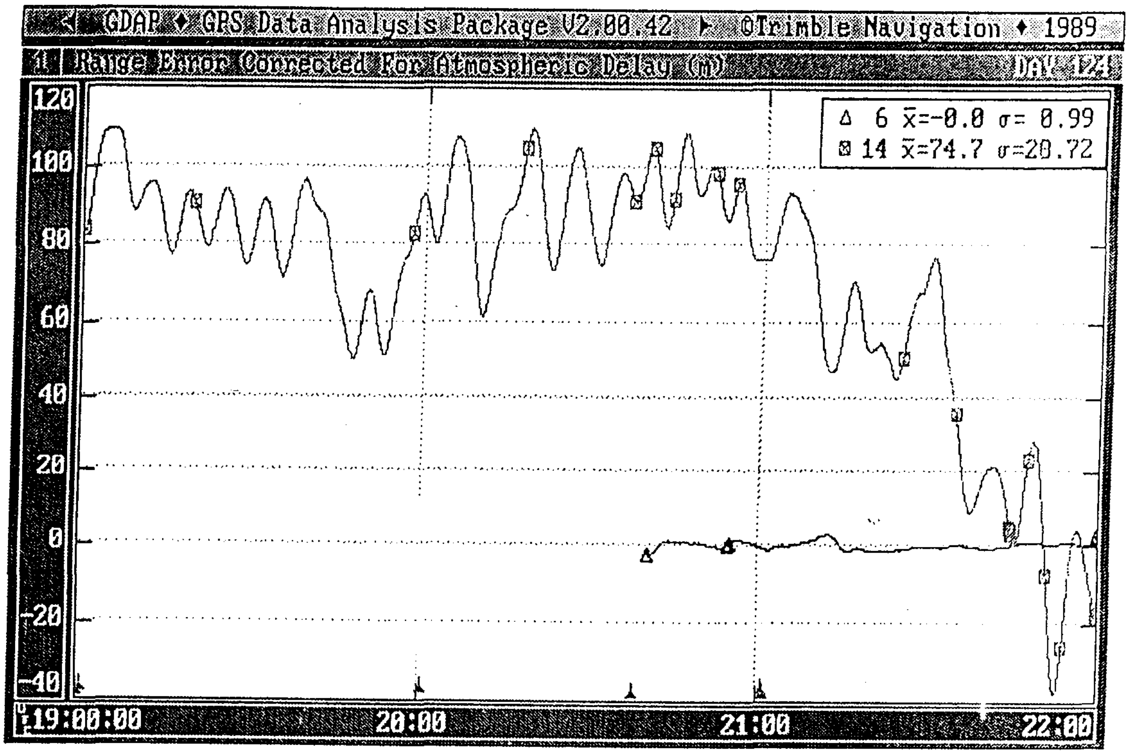

FIGURE 5. GPS DIFFERENTIAL PSEUDORANGE ERROR WITH AND WITHOUT SELECTIVE AVAILABILIY

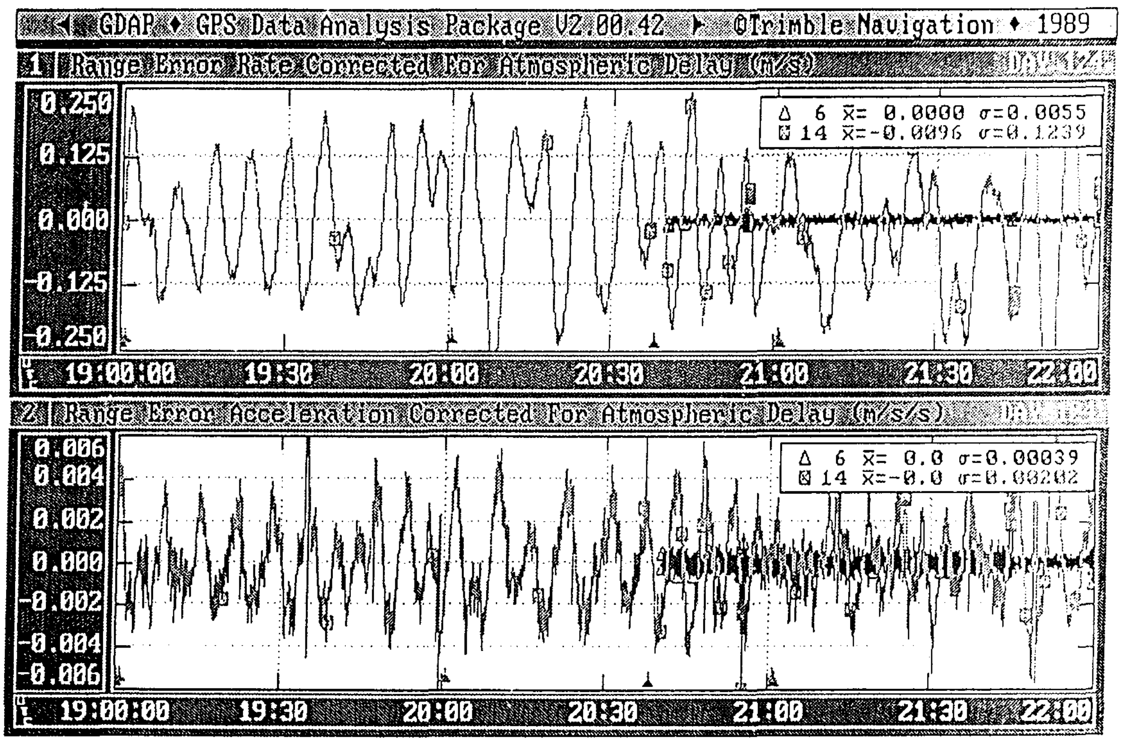

FIGURE 6. GPS DIFFERENTIAL PSEUDORANGE RATE ERROR WITH AND WITHOUT SELECTIVE AVAILABILIY

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SESSION 3

LORAN WORLDWIDE ACTIVITIES

Tuesday morning's session participants included (left to right seated) session chairman Edward L. McGann of Megapulse, Norman F. Matthews of the International Ass'n of Lighthouse Authorities, technical co-chairman Francis S. Cassidy of Datamarine, Dr. David Last of the University of Wales and (standing) Lt. Cdr. Gary R. Westling USCG, Durk Van Willigen of the Delft University of Technology in the Netherlands, Andreas Stenseth of the Norwegian Defense Communications & Data Services Administration and John M. Beukers of Beukers Technologies, WGA secretary.

西安导航技术研究所

XIAN RESEARCH INSTITUTE OF NAVIGATION TECHNOLOGY

P.O. Box 92 Xian, China Tel: 52886 Cable: 0092

August 1, 1989

Warm congratulations to 1989's WGA Annual Technical Meeting

Dear Sirs:

On the occasion of the 1989's WGA Annual Technical Meeting, I would like to express my personal cordial greetings and the greetings from the Xian Research Institute of Navigation Technology in China.

Just as pointed out by the organizer of this annual meeting: "Loran-C will be boldly into 1990's!", the construction work of the China Loran-C systems is rapidly in progress. While I write this letter, I am very glad to say: the building of the first China Loran-C system, which is located at the south of China, has been basically completed.

During this one year, we have made the primary tests of the system's performance, and they are very satisfactory. The whole system could be expected to be put into operation in very near future.

At the same time, the building of the second China Loran-C system, which will be located at the east and north coast area of China, has already begun. It will be certainly put into operation in 1990s.

From this, with my full confidence, I would like to affirmatively expect: at the end of 1990s, in the whole coast area of China - from the northeast to the southeast, there will be China Loran-C signals operating.

In this letter, I would also like to point out that international technology cooperation is very important to promote Loran-C system development in the world. For example, since 1984, based on mutual confidence and mutual understanding, the friendly technical cooperation between the Xian Research Institute of Navigation Technology of China and Megapulse Inc. of America has been playing a very important part in promoting and speeding the development of China Loran-C systems.

With this letter, I would like to say thanks to Megapulse Inc. and all gentlemen and ladies, who are attending this meeting and have been concerned with the development of China's Loran-C system for a long time past.

For reasons of time and procedure, I feel sorry for not attending this WGA annual meeting, but I expect to meet everyone at the next WGA annual meeting in 1990.

My best congratulations on this successful meeting.

干国强

Gan Guo-qiang
Director of Xian RINT.

Presented on behalf of Mr. Gan Guo-qiang and XIAN RINT by Mr. Edward L. McGann.

IALA'S ROLE IN THE DEVELOPMENT OF MARITIME AIDS TO NAVIGATION FOR THE FORESEEABLE FUTURE

Norman F. MATTHEWS

Secretary General,
International Association of Lighthouse Authorities (I.A.L.A.)
Paris, France

ABSTRACT :

The paper presents a brief history of IALA and its involvement in the development of standards for marine aids to navigation. An indication of the likely future mix of aids is given. In particular IALA's role in the retention and extension of Loran-C coverage after 1994 is reviewed.

1. The purpose of IALA

The International Association of Lighthouse Authorities, generally known by its acronym IALA, is a non governmental Association bringing together services or organisations concerned with the provision or maintenance of marine aids to navigation systems and allied activities.

The aim of IALA is to foster and improve the safe, economic and expeditious movement of vessels through harmonization of aids to navigation and marine traffic management practices, or any other appropriate means.

The aim of IALA is achieved, by among other things:

1 - Promoting co-operation and assistance between members.

2 - Establishing Technical Committees or Working Groups to study special problems, and formulating and publishing appropriate recommendations on standards.

3 - Organising Conferences and Seminars relevant to its work.

4 - Promoting assistance to services or organisations requesting help within the marine aids to navigation and allied fields, whether technical, organisational or training.

2. History

The idea of forming IALA first arose from a series of international lighthouse conferences which were held about every five years before and after World War II. At a Conference in Scheveningen, The Netherlands, in 1955 it was unanimously decided that in view of rapid changes in technology a permanent International Association should be formed to give continuity to the work between the five yearly conferences. Today some 80 national Lighthouse Services throughout the world belong to IALA; and there are 72 Industrial Members, of which 50 are manufacturers of aids to navigation equipment.

3. Organisation

The policy of IALA is determined by its members through an Executive Committee currently comprising the heads of the Lighthouse Services of Canada, Denmark, England, France, German Federal Republic, India, Japan, Netherlands, Peru, Saudi Arabia, U.S.A. and U.S.S.R.

The Secretary General who is the Chief Executive of the Association is responsible for carrying out policy, controlling the finances and the day to day running of the Association; He is assisted by a Permanent Secretariat based in Paris.

4. Technical work of the Association

The technical work of IALA is achieved through committees of experts drawn from the Lighthouse Authorities of many countries. These Technical Committees study problems of current importance to Lighthouse Authorities and their findings are often published in the form of official IALA Recommendations.

The Association also co-operates with other international bodies, and in particular is in consultative status with the International Maritime Organisation (IMO).

5. Present day needs

The major problems facing lighthouse services today tend to be economic and managerial rather than technical.

The technology that now exists enables most technical problems to be resolved. The question is no longer "Can it be done" but rather "Is it cost effective".

In many countries, the aids to navigation in use owe as much to historical accident as to forward planning. Aids to navigation that have existed for many decades, meeting needs of bygone traffic, have been retained and added to from time to time.

There is often an inbuilt tendency for local people to resist the discontinuance of aids to navigation irrespective of need.

From time to time the aids in use must be re-examined to ensure that the aids provided meet current needs but without unnecessary redundancy.

The changes that have taken place have also led to Authorities reappraising their long term strategy and investments policies. It has also led to a reassessment of the needs of mariners.

For position fixing and navigation the user may have available visual aids, radar aids and radionavigation systems. Radio aids to navigation cannot for the moment completely supercede visual aids as these latter are not only of use for position fixing but also have the functions of hazard warning and traffic organisation. However, the need for very long range lights is diminishing.

The mariners needs therefore have to be considered in consultation with all interested parties to ensure that navigation can be carried out with the accuracy required and that dangers can be avoided. The optimum mix of visual, radio and radar aids has to be provided, bearing in mind the traffic being catered for, but without waste.

6. IALA Principles on Radio Aids to Navigation

Whilst visual aids still have a place in the mix of aids to be provided, it cannot be denied that radio and electronic devices will play the major role in future developments.

The development of electronic aids if carried out in a haphazard manner will bring about its own problems. As long ago as 1975, IALA recognized this problem and developed certain principles which are still valid today:

1) To promote the international standardisation of an optimum number of radio aids throughout the world to meet requirements of the various users.

2) To promote the scientific and technical evaluation of newly developed radio aids systems by assisting where possible in the development and operational evaluation of those systems which are economically feasible and potentially capable of meeting recognised operational requirements.

3) To uphold the principle that the emissions from radio aids should be available to users of all nations.

4) To uphold the principle that the emissions integrity and reliable operation of land based transmitters for radio aids systems be the responsibility of the national administration, and operate on those frequencies conforming to the Radio Regulations approved by the International Telecommunication Union, with the support of other international bodies if necessary.

5) To uphold the principle that the receivers required for radio aids should be subject to standards satisfactory to the appropriate administrations, and available to all who wish to use them.

6) To advise on and provide technical assistance, where appropriate, in the establishment of radio aids and services in the territories of any nation, which will facilitate the safe passage of ships in their adjacent waters and oceans.

7) To encourage and promote the international exchange of scientific and technical information concerning maritime radio aids.

8) To co-operate with international bodies in the planning for the efficient use of the electromagnetic spectrum to avoid disruptive interference among systems and to avoid the unnecessary duplication of systems.

9) To keep abreast of new and improved techniques in radio and other aids to navigation and to take account of them in future planning.

10) To keep under review future developments in marine craft and their impact on navigation techniques and to take steps to satisfy these new requirements.

7. The involvement of IALA in Loran-C

IALA has always been involved with all kinds of available radionavigation systems. So far as terrestrially based systems are concerned Loran-C and Decca Navigator were the two of principal interest to its members. This was the situation from the early days of IALA in the late 1950's.

The operation of the Omega system involved only a few countries and these were organised together to run the system.

Decca Navigator chains were run more or less unilaterally by the countries concerned, although in some cases bilateral agreements allowed one country to have a transmitter within the territory of another for reasons of geometry.

Loran-C was almost entirely run by or under the general control of the US Coast Guard.

IALA became more deeply involved when the situation first changed in 1981. The US Coast Guard informed host countries that they would cease to operate Loran-C outside the United States by the end of 1992, due to the advent of GPS in 1988.

8. Loran-C in North West Europe

It seems that for some time the host countries of North West Europe did not fully appreciate the implications of the changes proposed for 1992 (later to become 1994).

It was not until April 1984 that the Loran-C Working Group actually met. IALA was represented on this Group but only by observer status. The Working Group produced their report in July 1985, which strongly recommended the maintenance and possibly the expansion of the Loran-C system in North West Europe after the withdrawal of the US Coast Guard.

9. Decca Navigator System in North West Europe

Another matter of significance in 1984 concerned the Decca Navigator System. Decca Navigator chains were run as a private entreprise by the Decca Navigator Company. The income to maintain the system was derived from the rental of Decca Navigator receivers. Decca receivers were not for sale and the Decca Company maintained that they had copyright over the transmissions.

However around 1984, a number of companies outside the UK started marketing receivers capable of operating from the Decca Navigator transmissions. These receivers were comparatively cheap compared with rental charges. Clearly, once the rental monopoly was broken, running the system would became financially untenable.

In an effort to stop the use of allegedly pirate receivers the Decca Company changed the transmitted signal format without warning, a number of times. This move caused considerable consternation in marine circles due to the possible danger to vessels using "non approved" Decca receivers, bought in good faith.

10. IALA Decca Navigator Working Group

It was evident that eventually some kind of a crisis would arise with regard to the operation of the Decca chains due to lack of funding. Furthermore all existing Decca chains were operated by IALA members. Thus in February 1984 the Association took the initiative and set up a Working Group to seek possible solutions. One of the solutions proposed was to encourage Administrations to install Loran-C as an alternative to Decca. A temporary resolution of the Decca problem was that the UK and Danish governments agreed to take over financial responsibility for running their Decca chains for 7 years from 1st January 1987. However this was a short term solution as the Decca transmitters are now rather old and renewal has to be faced. It will be much cheaper to maintain adequate coverage by replacing the many Decca transmitters by a few Loran-C transmitters.

11. IALA Special Radionavigation Conference, London 1987

To break the log jam of inaction on the part of administrations, in March 1987 IALA convened a meeting of all interested parties in London to seek a way forward.

The Conference proved to be a catalyst, as the administrations of North West Europe decided at the meeting that they would begin serious talks about taking over existing Loran-C stations and indeed extending coverage to link up with the French stations, which were operating independently.

The Conference reached the following conclusions and it can be seen that some of them are of great importance:

1. It was noted with great satisfaction that following the Conference, the Governments of the countries listed below will enter into direct negotiations with one another to consider the possibility of extending Loran-C coverage in North West Europe:

   Denmark, France, Fed. Rep. of Germany, Iceland, Netherlands, Norway, United Kingdom.
2. IALA will continue to pursue the possibility of extending Loran-C coverage along the Iberian Peninsula, and in the Mediterranean, until such time as the Governments concerned are in a position to enter into direct negotiations with each other.
3. It was requested that IALA be kept generally informed of the progress of the negotiations in 1. above to assist IALA in the pursuit of 2. above.
4. It was agreed that users should be given adequate notice by the Authorities concerned of their intentions to change from one system to another.

   It was further agreed that an adequate period of overlap should be maintained when changing from one system to another.
5. The efficiency of Loran-C for civil aviation users and land users should be borne in mind when considering the economics of introducing Loran-C.
6. It was agreed that in appropriate national and regional areas, terrestrial radionavigation systems should be maintained after the introduction of new satellite navigation systems for the foreseeable future.
7. It was agreed that IALA will support the standardization of the co-ordinate conversion process whether it is accomplished through the Loran-C receiver automatically or through corrections applied to charts.

Significantly, Conclusion 6 agreed that Loran-C and possibly Decca still have an important future. Furthermore IALA was charged with trying to persuade Mediterranean countries to follow the lead of North West Europe.

12. The choice of Decca or Loran-C

Shortly after the London Conference, due to pressure from its members, IALA was obliged to take a stand on the question of Loran-C versus Decca. In May 1987 the IALA Executive Committee issued the following statement:

" Although some Administrations intend to retain their existing Decca Navigator chains, others are newly introducing Loran-C and some are considering converting from Decca Navigator to Loran-C.

However, for the moment we do not know that any Administration is currently planning to invest in Decca Navigator chains; and thus in the Executive Committee's opinion on a global basis the future is likely to lie with the Loran-C system as the primary terrestrially based wide area radio aid to marine navigation until well after the turn of the century."

Following the publication of this statement, the Indian Administration, which had in mind the refurbishment of its two Decca chains, decided to replace these chains with Loran-C installations.

13. Progress in North West Europe

The North West European group pursued its studies and in August 1989 published its report. Among other things, the report proposes solutions to the various technical problems, including system control. It also details a "memorandum of understanding" (MOU) between the parties which includes agreement on the difficult problem of cost sharing.

The final political decision as to whether to maintain and expand Loran-C coverage, and to accept the provisions of the MOU is expected towards the end of 1989.

14. IALA Conference on Loran-C in the Mediterranean, Paris January 1989

During 1988, in pursuance of Conclusion No. 2 of the London Conference, IALA entered into a dialogue with Mediterranean countries to persuade them to maintain their chains after the US Coast Guard withdrawal.

A first meeting of Mediterranean countries was convened and hosted by IALA in January 1989. Unfortunately it was not possible to indentify and establish a positive contact with the appropriate Turkish authority (a situation that still obtains at the time of writing this report). Nevertheless the following conclusions were reached:

" To assist in the safe and expeditious movement of vessels, enhance the safety of life at sea and to assist in the protection of the environment, the following general conclusions were reached by the Conference:

1. There was a general consensus in favour of maintaining the existing Loran-C stations in Spain and Italy (1) and in maintaining the existing coverage in the Mediterranean for the benefit of merchant ships, fishing vessels, pleasure craft and hydrographic surveys, after the USCG cease to operate the stations in 1994.
2. There was a firm indication that the extension of Loran-C coverage to other parts of the Mediterranean and the Iberian Peninsula should be considered. The linkages with the coverage of Loran-C chains adjacent to the Mediterranean and the Iberian Peninsula should be a matter for study with the countries concerned.
3. It was agreed in principle that a meeting of Administrations of the littoral States concerned should be convened to establish studies on the technical, economic, financial, including cost sharing, and political aspects of Conclusions 1 and 2.
4. The meeting of Administrations of the littoral States concerned will be convened by IALA before the end of June 1989, in a host country to be decided.

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(1) This was the general consensus of the meeting, because in the absence of a representative of the Turkish Administration, no specific views were made concerning the retention of the station of Kargaburun. The Secretary General of IALA was invited to pursue the matter with the appropriate Authority in Turkey as a matter of urgency."

15. IALA 2nd Conference on Loran-C in the Mediterranean, Madrid, June 1989

Following the Paris meeting, IALA and the US Coast Guard continued to develop their contacts with Mediterranean countries.

In accordance with Conclusion No. 4 of the Paris meeting, IALA convened a second meeting of Mediterranean countries in June 1989, which was hosted in Madrid by the Spanish Administration.

The conclusions of the second meeting were as follows:

1. There is a general interest in continuing the studies, as it is considered that Loran-C could be useful in the Mediterranean Sea as an alternative system, even beyond 1994.
2. It is considered advisable that the goal should be to have a single terrestrially based radionavigation system, stretching from North Europe to the Mediterranean and through the Atlantic.

   From this point of view it can be considered that Loran-C is the most suitable as it is distributed worldwide and because it is a cheap and accurate system for users.
3. It is necessary to know as soon as possible the position of the Turkish Administration with regard to the station at Kargaburun.

   It is also necessary to ascertain the reliability, efficiency and effectiveness of the entire Mediterranean Loran-C chain.

   There is some doubt that a chain without the Turkish station will as reliable as now. The possibility of an alternative location for a transmitter can be studied but it is strongly hoped that the Turkish station will continue to operate.
4. With regard to the Estartit station, Spain is interested to see the station not only as part of the Mediterranean chain, but also as part of an Iberian chain.
5. It was decided to continue the work with the participation of the Mediterranean countries and with the initial support of IALA, as coordinator.

   During at least the first stages, the co-operation of the US Coast Guard will be sought, as technical experts.
6. Each country represented at the Working Group should investigate the potential users of the system (land, air and maritime users).
7. The possibility is to be explored of involving the EEC in order to obtain a financial contribution to the establishement of a new station, if necessary.

16. Progress in the Mediterranean

There is an evident willingness on the part of the countries concerned to maintain Loran-C after 1994. In addition, the French, Spanish and Portuguese Administrations are keen to extend coverage around the Iberian Peninsula.

However, progress in the Mediterranean is inevitably much slower than in North West Europe. The two principal reasons for this are:

a) National personnel have not been involved in the running of the stations, and there is a consequent lack of expertise.

b) Until recently, all discussions concerning Loran-C have been between the US Coast Guard and the national military authorities. There is no continuing military requirement for Loran-C and it has been difficult to identify the appropriate civilian authority. This has been made worse by the fact that existing civilian authorities have never hitherto been involved with radionavigation matters.

However, these problems are gradually being resolved

and IALA will convene a third meeting hosted by Italy in November 1989.
This opportunity is taken for IALA to acknowledge the indispensable assistance of the US Coast Guard in the Mediterranean Group meetings. It has largely been their expertise and willingness to ensure a smooth transition and handover from US Coast Guard to national civil administrations control that has made progress possible.

Tribute is also due to the contribution made by the North West Europe Loran-C Policy Group. In particular its Chairman, Mr. Kjell Raasok of the Royal Norwegian Ministry of Fisheries, and two of its members Mr. Andrea Stenseth, NODECA, Norway, and Mr. Frank Holden of Trinity House, England.

These members from North West European Group have been generous with their expertise and have helped their Mediterranean colleagues to avoid some of the pitfalls that they themselves suffered.

17. Loran-C in Japan and Korea

IALA is currently engaged in discussions with Japan and Korea with regard to the future of their Loran-C stations after 1994. It is hoped that these nations will also be willing to accept responsibility for the continuing maintenance of Loran-C coverage. The Japanese Maritime Safety Agency has asked IALA to take part in a Seminar dealing with these problems in October 1989.

18. Conclusions on the future mix of aids to navigation

As stated earlier, a continuing need for traditional visual aids to navigation will exist for the foreseeable future. Such aids of comparatively short range will be especially useful at the beginning and end of voyages, in port approaches and in channels close to land.

Visual aids will be supplemented by radar aids both passive and active, particularly in the hazard warning role.

It is in the field of electronic and radio aids where the major decisions need to be taken.

There is no doubt that satellite navigation systems provide an answer and will be increasingly used. However the expense of providing such systems is outside the scope of most civilian budgets.

Continuation of a system such as GPS depends on funds made available by the defence sector at any one time.

These circumstances make it unlikely that GPS can be accepted as a truly international system for civilian use by organisations such as IMO and ICAO in the foreseeable future. As a consequence of this and to make an independent alternative available, IALA has accepted the potential of Loran-C to fulfil the role of a regional radionavigation system to meet civil requirements for the next 20 years or more. This choice is made on the understanding that GPS, under the present policy of Selective Availability, does not offer any advantage over Loran-C for conventional navigation in terms of accuracy in areas covered by LoranC. Moreover Loran-C navigation receivers are cheaper and simpler to use than GPS equipment, and this situation is not thought likely to change for many years to come.

Apart from Loran-C and Decca Navigator, where it continues to exist, there are other ground based radionavigation systems, most of them specialised and of limited coverage but with high accuracy for specific purposes such as local surveys, pipe laying operations, etc. They are not suitable for more general navigational purposes. Omega is the only system covering larger areas which could be considered but it suffers from lack of accuracy; it is likely to be replaced by GPS but may be available for marine use at least until the turn of the century.

Thus in summary it can be foreseen that many marine administrations either acting alone, or in cooperation with neighbouring administrations will provide marine navigators with a terrestrially based radionavigation position fixing service for general navigation. This will be supplemented as necessary by visual and radar aids at arrival and departure areas, and such aids will also be used for the marking of particular hazards.

The increasing introduction of Vessel Traffic Services (VTS) will also play an important part in the determination of the final mix adopted.

Beyond the influence of most administrations, the navigator will also hopefully have continuous access to a satellite based position fixing system for all stages of his voyage.

THE NORTH WEST EUROPEAN LORAN C SYSTEM A STATUS REPORT

ANDREAS STENSETH

NORWEGIAN DEFENCE COMMUNICATIONS AND DATA SEVICES ADMINISTRATION (NODECA)

ABSTRACT

The US decision to terminate its Loran C commitment in North West Europe and the North Atlantic led to the establishment of the Loran C Working Group in 1984.

Based on the recommendation given by this group in 1985 and subsequent discussions in international fora, the Loran C Policy Group was established in 1987.

The Policy Group is to consider enhancements of the present USCG system in North West Europe to meet civilian European requirements and propose an organizational structure and cost sharing arrangements for a future regional system in the area.
The text of a Memorandum of Understanding (MoU) is expected to be agreed in September. In this MoU Norway is given the task as Coordinating Agency for the whole system. NODECA will execute this task on behalf of Norway.

The developments by the Loran C Working Group and the Loran C Policy Group have been reported to WGA at the Annual Conventions in 1984, 1987 and 1988.

This paper presents the developments since the 1988 WGA convention and in particular the main conclusions from the Policy Group Draft Final Report, including the North West European Loran C Project organization and schedule. It will also give an overview of the NODECA organization and how the coordinating agency functions will be integrated into this organization.

1. INTRODUCTION

As a common basis for the brief I will very shortly review the main events leading to where we were one year ago, even if this for some of you will be a repetition of what you have heard at previous conventions.

1.2 In 1981 US Coast Guard notified the Host Nations of the US plans to cease funding of Loran C stations in the North Atlantic and North West Europe by mid 1990's.
This led to the establishment in 1984 of the Loran C Working Group, recommending in its Final Report continued operation of the stations under some sort of multinational arrangement.
The Group also indicated that the European requirement for a terrestial radionavigation system would not be met by the USCG system in its present form and configuration and that as a consequence of a takeover enhancements of the system should be considered. The economical basis for operation of the commercially operated DECCA system in the United Kingdom and other countries, was in 1987 threatened by widespread use of pirate receivers. As a result of this, a new way of financing continued operation of the system was proposed.
In this situation the United Kingdom caught interest in Loran C as a possible substitute for DECCA, and, after a special IALA Conference in London the same year, the Loran C Policy Group was established with members from eight European Countries. After two years of negotiations we are close to a final decision.

1.3 The final slide presented in Portland, Oregon last year summarized the 1987/88 activities in the Policy Group as follows:

PARIS Meeting November 1987

- French coverage requirements were not met. Technical Working Group (TWG) to recommend modified configuration
- TWG to study and recommend method of timing control
- Canada to be invited to consider participation

BREMEN Meeting March 1988	- Ireland became new member - TWO project phases identified 1) North West Europe and North Atlantic 2) Baltic/German Bight - Field trials to be conducted
REYKJAVIK Meeting June 1988	- TWG recommend/Policy Group accept Time of Transmission Control (ToT) - Revised configuration accepted - Investment Cost Sharing Agreed - Draft MoU Discussed.

1.4 The Phase 1 system configuration as agreed in Bremen consisted of the establishment of 4 chains by

a) Using 4 out of 6 existing USCG stations without modification.

b) Modifying 2 out of 6 existing USCG stations to obtain dual rate capability.

c) Building 4 new transmitter stations.

d) Connecting 2 existing French stations to the system.

e) Establishing necessary control stations, management organisation, communications etc.

2. POLICY GROUP ACTIVITIES SINCE WGA 1988 CONVENTION

The Policy Group has at the time of preparing this paper met 3 times since October 1988. (A further meeting will be held in Sep 89).

2.1 The first meeting in Copenhagen in November 1988 was rather disappointing from a progress point of view - as we did not obtain the expected agreements. However, two major achievments were obtained:

a) Canada joined the Policy Group as a permanent member to protect her interests at Anguissoq, Greenland.

b) The question of modernizing all the existing USCG stations in order to save O&M costs was raised. A special working group was set up to perform a cost/benefit analysis to provide a basis for a decision.

2.2 The next meeting in Dublin in March 1989 could be considered the real break-through. The group concluded that:

a) The existing USCG stations should all be modernized in order to reduce the running costs. The required investments are estimated to be recovered in a 5-6 years timeframe.

b) The formula for sharing Operation and Maintenance costs was agreed.

c) A revised final configuration and control concept was agreed. (ToT)

d) A MoU between the nations covering the establishment and operation of a North West European Loran C System was, with some minor outstanding issues, agreed.

e) Norway accepted the role as the Coordinating Agency for the North West European system and to establish a Project Management Organization. The Norwegian Defence Communications and Data Services Administration (NODECA) will be the executive body for these activities.

f) A number of follow on activities should take place immediately in order to reach the goal, namely to be able to sign a contract early 1990. These activities were:

i) To start the work of providing technical and contractual specifications.

ii) To start negotiations with the vendor.

iii) To seek USCG formal agreement on a number of important issues.

2.3 The negotiations with USCG is of special importance since present plans will have to be based on a fixed date for a takeover, and imply encroachment on the present USCG system prior to takeover. The main issues to be discussed with US Authorities in this regard are:

a) Commitment on the part of the Unites States to a date of bringing USCG Loran C activities in North West Europe to a conclusion.

b) Terms and conditions for take over of existing stations - including bilateral termination of MoU's with present host countries.

c) Practical arrangements regarding equipment replacement prior to the conclusion of USCG Loran C activities in North West Europe.

d) Transfer from present configuration to the agreed North West European configuration.

e) Method of timing control prior to the conclusion of USCG Loran C activities in North West Europe.

NODECA was tasked to negotiate these issues with USCG on behalf of the Policy Group, and these negotiations are in process.

2.4 The provisional plan as agreed in Dublin called for a "Final Report Meeting" in Oslo in June 1989, MoU signature in December 1989 and contract signature January 1990.

This plan does now seem rather optimistic, partly because we did not succeed in clarifying all necessary issues in time. The meeting in Oslo took however, place as planned, but the time schedule had to be amended as shown in Fig 1.

3. DRAFT FINAL REPORT

The Policy Group Recommendations to the respective Governments are contained in a Final Report, from which the following is quoted:

- "The work of the Policy Group is based on a continued requirement for a terrestial radio-navigation system in the North West European area for the forseeable future even in the phase of new satellite systems under implementation. There is general agreement in the Group that Loran C will meet this requirement

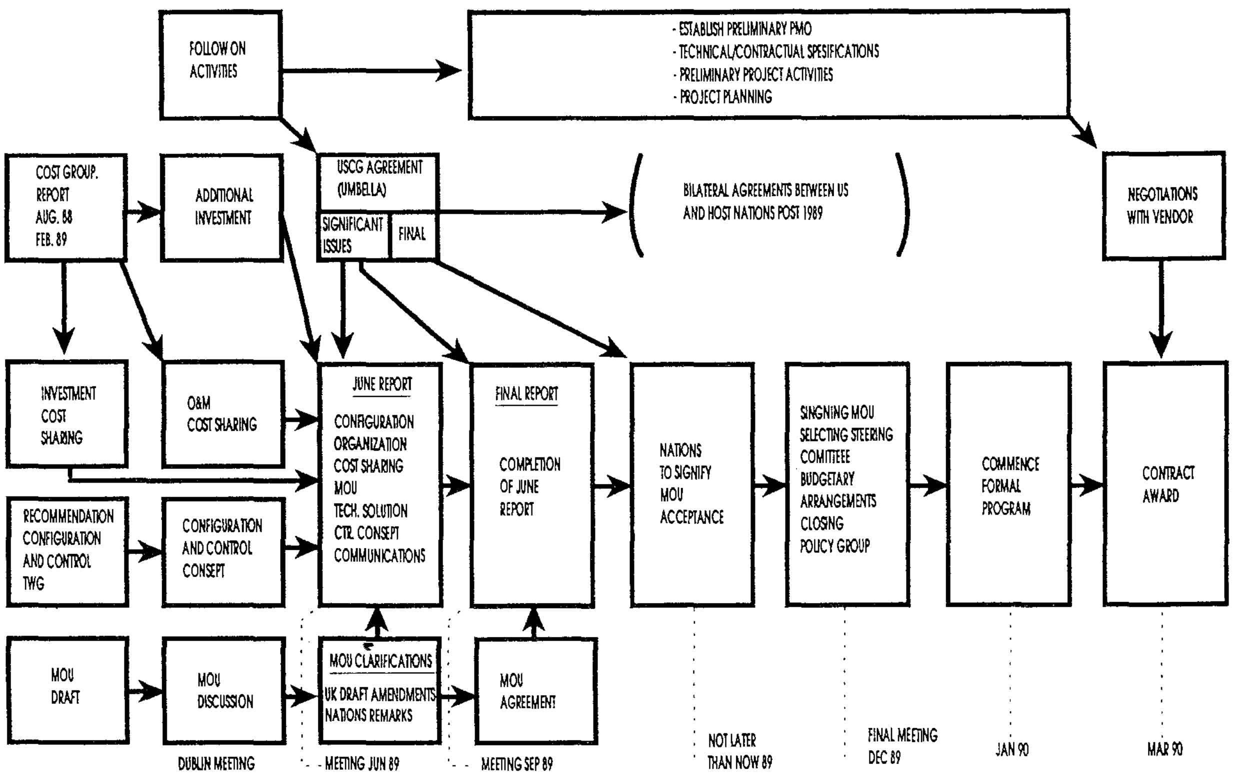


Fig. 1: North West European Loran C Progress

The main changes from the previous plans are that additional negotiations with USCG and MoU clarifications (mainly with France) had to take place, and an additional meeting of the Policy Group had to be scheduled. We still aim for a contract award early 1990, however all subject to political concurrence in the participating nations.

- Governments participating in the Loran C Policy Group should be invited to establish a Loran C system for the Northern Europe and the North Atlantic.

The new chains should be arranged as follows:

	MASTER	SECONDARIES
The Iceland Chain	Sandur	Angissoq*, Jan Mayen, Ejde
The Norwegian Sea Chain	Boe	Jan Mayen, Gamvik, Fedje
The North Sea Chain	N.E. England	S.W. Ireland Lessay, Sylt Ejde
The Biscay Chain	Lessay	Soustons. S.W. Ireland

*Dual-rated as part of the Labrador Sea Chain (The coverage provided by these chains is shown in Fig 2)

- This configuration covers the main part of the North West European area. It does not, however, satisfactorily cover Danish waters, the Baltic, and areas North East of Norway. To rectify for this, a Phase II of the programme is proposed for Denmark and the Baltic. This proposes a mini Loran C chain comprising 3 low power Loran C stations cooperating with the present station at Sylt, in a dualrated configuration. Phase II needs further study before it can be costed and discussion could take place at a later time. The problem of North East of Norway can be solved by local Norwegian measures or cooperation with the Soviet Union along the same line as for the agreement between the United States and the Soviet Union in May 1988.

- It was demonstrated by the Cost Working Group that investment in new transmitter equipment at four USCG stations not included in the basic programme, would be economically beneficial by reducing overall O&M costs.

- The Policy Group has prepared the text of a MoU to be signed if and when each of the participating countries have approved participation in the North West European Loran C system at the appropriate political level. If the MoU is approved and signed, the Policy Group will be closed down and replaced by a Steering Committee taking charge of the overall control of the system. As a working tool for the Steering Committee a Coordinating Agency will be established. The Government of Norway has voluntered to take on the job as Coordinating Agency".

- Operation and Maintenance

  The proposed budget for Management costs is based on management of the North West European Loran C system as an integrated element within an existing organization. Since Norway has accepted the responsibility as Coordinating Agency with NODECA as the executive organization, the functions of the Coordinating Agency will be integrated in the NODECA staff at its Headquarters in Oslo. Even if the full weight of operating the system does not materialize until handover from USCG has actually taken place, the Coordinating Agency will have to be activated immediately after the signing of the MoU to take care of its function as secretariat of the Steering Committee, and for logistics planning and other planning activities leading to the final take-over from USCG.

- Project Management

  A Project Management Team will be established to direct the overall planning and execution of the project over a period of three years. This team will also be organized within the NODECA central staff and supported by NODECA's general staff elements.

4. PROJECT IMPLEMENTATION

4,1 As already mentioned, NODECA has, on behalf of the Government of Norway, been tasked with two major functions related to the North West European Loran C system. These are

a) The Coordinating Agency functions dealing with all coordinating activities related to the operation of the system

and

b) the Project Management function for implementation of the investment program.

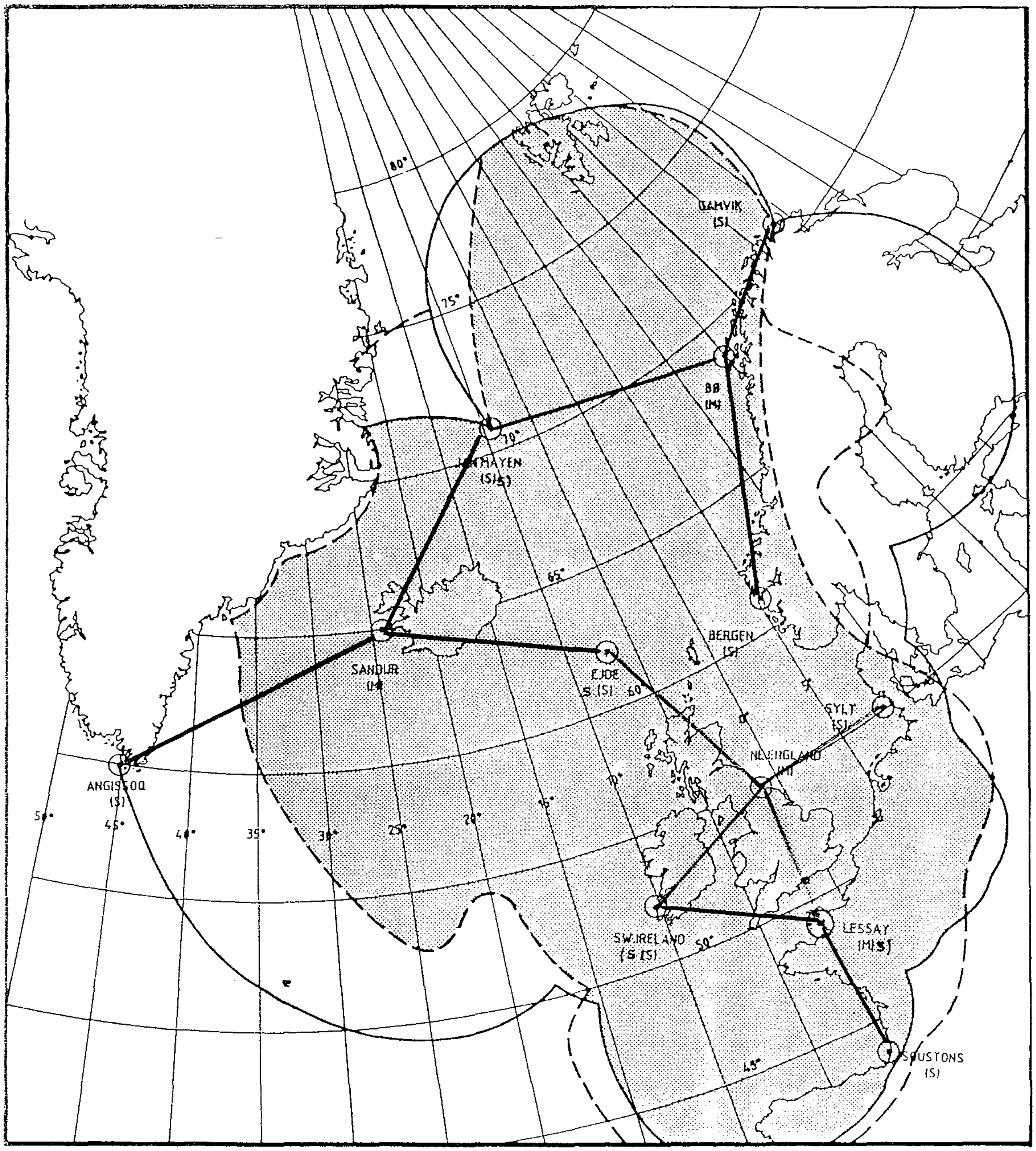
Since these functions will be integrated in the NODECA organization and draw general support from the Headquarters in Oslo, I find it appropriate to give you an overview of the NODECA organization.

4.2 The Norwegian Defence Communications and Data Services Administration, abbreviated NODECA, was establish the first of August 1986. This new Defence Administration is an amalgamation of the former Norwegian Defence Communications Administration and the Norwegian Defence Automatic Data Processing Centre

The digital technique has gradually led to an increased integration of communications and data systems.
As a consequence of this evolution it was decided to merge the two areas of technology into a new administration serving the Armed Forces.
The new administration has been given the following main tasks:

- to plan, implement and operate communi-cations-, data- and navigation systems

- to carry out development, system tests and evaluation



NORTH WEST EUROPEAN LORAN C SYSTEM
PROPOSED STATION CONFIGURATION

——————— 465 METRE ERROR CONTOUR 2drms
– – – – – – SIGNAL COVERAGE, NOISE 61db uV/M.
Rx - 10db SNR.
RESULTING COVERAGE

(LABRADOR SEA CHAIN NOT INCLUDED)

NOTE: COVERAGE LIMITED TO DOTTED LINES OVER NORWAY AND GREENLAND BECAUSE OF UNCERTAINTY OVER CONDUCTIVITY VALUES AND EFFECT OF TERRAIN.

Fig. 2 COVERAGE DIAGRAM

- to prepare memorandum for application of new technology

- to recommend standards and issue directives for development, procurement, operation and maintenance of communications and data systems

- to exercise configuration management over communications and data systems

- to give engineering and planning support to users and act as technological adviser to Military Authorities regarding communications and data systems and to the Ministry of Fishery regarding navigation.

4.3 The NODECA organization is shown in Fig 3. The central staff of the organization is located in Oslo, with a manning of approximately 250 persons, partly military and partly civilian.

<u>The Management Support Division</u>
is responsible for duties within personnel and training, budget and accounting, purchase, contracting and administration.

<u>The Operations and Maintenance Division</u>
performs management, operation and maintenance of the systems.

<u>The Systems Implementation Division</u>
will plan & implement national- and NATO-funded projects.

<u>The Systems Design and Planning Division</u>
will convert new technology into serviceable systems.

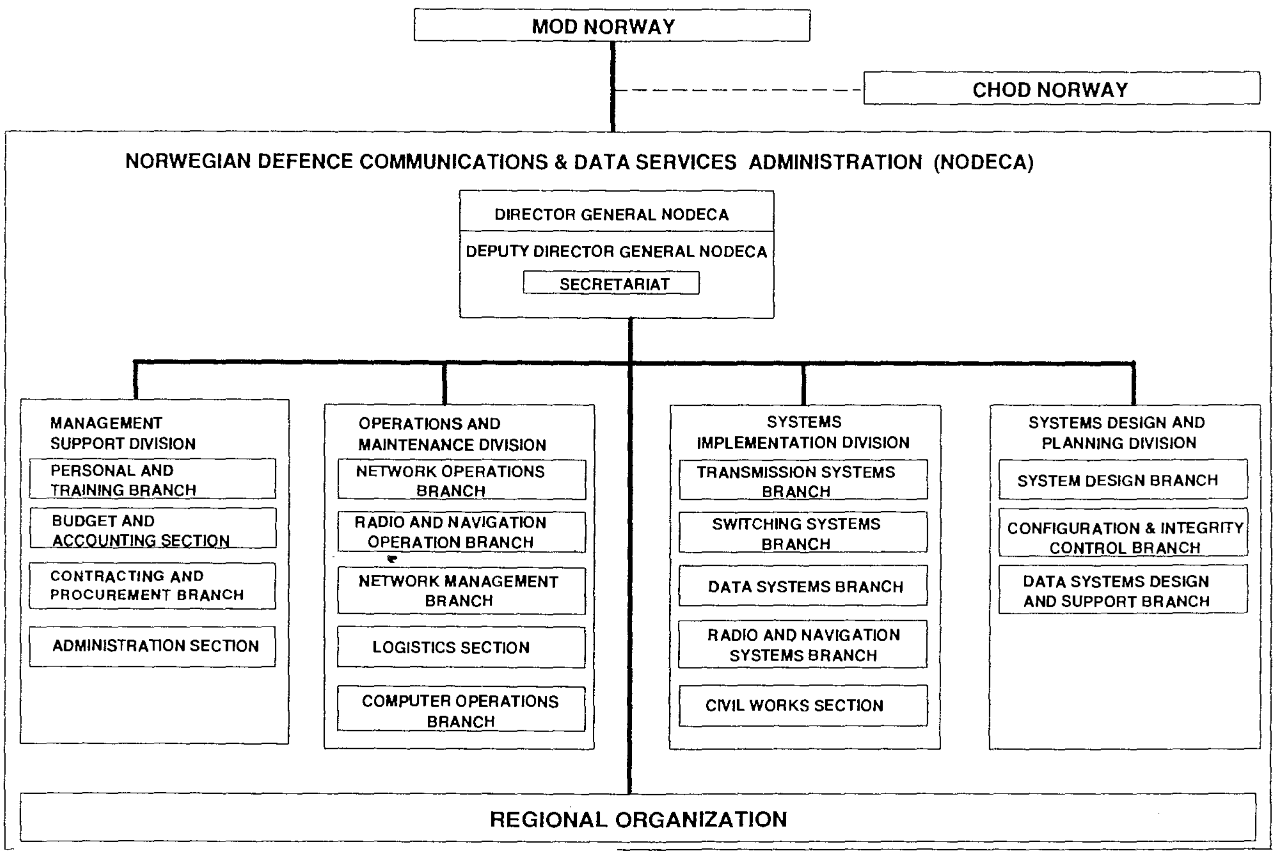


Fig 3 NODECA organization

In peacetime NODECA is directly subordinate to the Ministry of Defence. The organization is under the leadership of a Director General. He has a Deputy Director General/Chief of Staff with a secretariat for coordination and supporting functions. The central staff is organized in four main Divisions:

4.4 <u>The external organization</u> of NODECA consists of more than 300 different stations ranging from VLF Broadcast, LF and HF radiostations to satellite terminals, microwave link and modern digital switches in a countrywide digital service integrated switched network. It also includes 23 Decca Navigator stations and the two USCG funded Loran C stations on Norwegian soil.

4.5 The NODECA organization already contains staff elements within both the Operation- and Maintainance Division and the System Implementation Division dealing with Radio Navigation and Loran C. These elements could in principle, with a proper supplement of manpower also take on the tasks of the Coordinating Agency and the Loran C Project Implementation respectively. Since, however, this is a relatively large and complex multinational project with 8 nations involved it has been a desire to place these funcions as close to the top management as possible.

on these planning documents: a System Implementation Schedule has been developed. This schedule calls for an operational system by 1.jan 95 in its final configuration. And this coincides with the date for US termination of overseas Loran C activities as stated in the Federal Radio Navigation Plan. It should, however, be noted that parts of the system will be operational before that date, and that coverage in most of the area is planned to be available from 1993, but not in the final configuration.

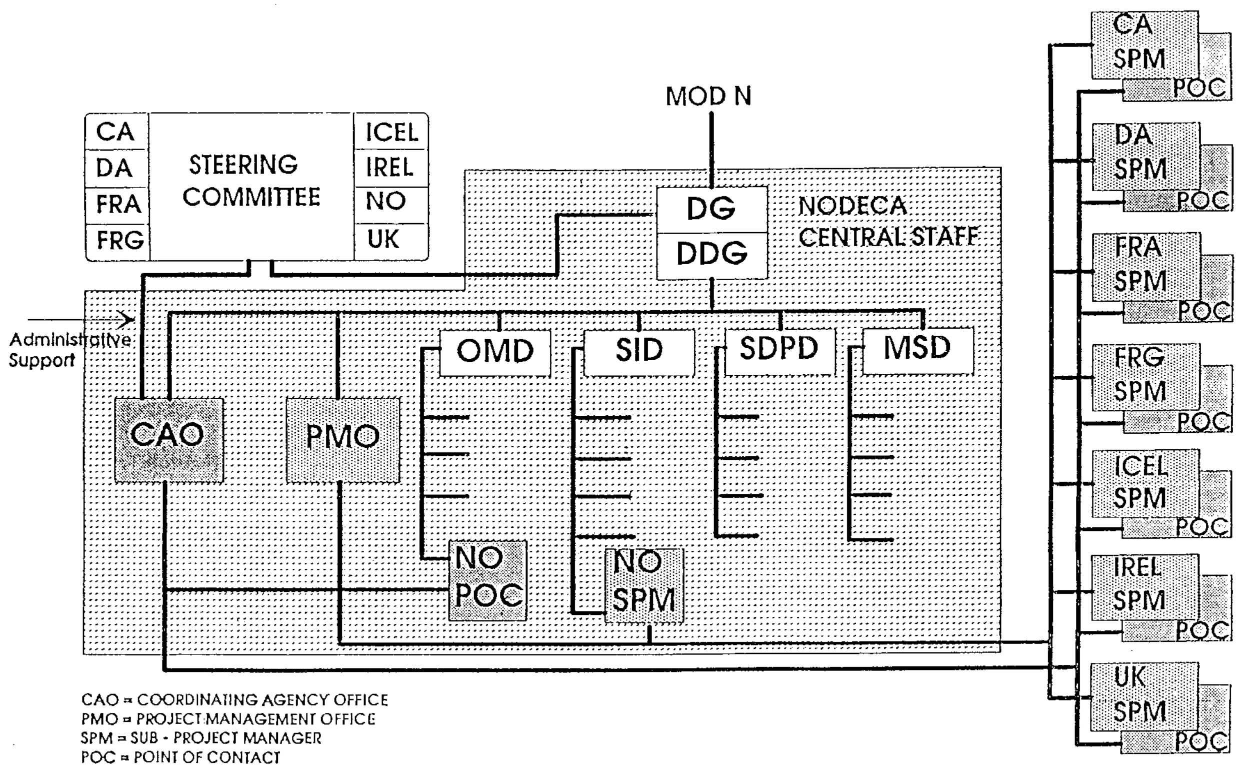


Fig. 4. North West European Loran C organization

Hence, they will be placed directly under DDG NODECA as shown in Fig 4.

4.6 Each participating nation will have to appoint a Sub Project Manager (SPM) responsible to the NODECA Project Manager for the execution of that part of the project delegated to her. This will mainly be to take care of Civil Works, i.e. have the buildings ready for installation at the time specified in the Project Implementation Plan. Other host nation responsibilities will be support in connection with shipment, transportation, storage, customs clearance etc.

4.7 A preliminary Work Breakdown Structure has already been provided for the program, and NODECA has produced the first detailed Pert network and Cost/Time/Resource estimates. Based

5. CLOSING REMARKS

The final, and most important, question still remains to be answered - WILL THERE EVER BE A NORTH WEST EUROPEAN LORAN C SYSTEM?
I believe that it has been demonstrated, not only in Europe, but world wide, that there is a need for a land based system. The question in Europe is therefore not whether we should go for GPS or Loran C, they are supplementary to each other. The question is, what terrestial system do we choose - Loran C or Decca Navigator. To me the answer is obvious! And the fact that the European nations have spent all this time and effort in order to arrive at a final recommendation, which is - GO FOR LORAN C - is to me a strong indication of what is the likely final conclusion. A final political decision cannot wait much longer. We are close, the Policy Group recommendation is clear, and I would be very disappointed if I am not in the position to report progress from an ongoing project at the 1990 WGA Convention.

LORAN-C MEASUREMENT TRIALS IN IRELAND & UK - INTERFERENCE, NOISE & FIELD STRENGTH RESULTS

David Last, University of Wales, Bangor, Gwynedd LL33 0EG, United Kingdom

Nick Ward, Trinity House Lighthouse Service, East Cowes, Isle of Wight PO32 6RE, United Kingdom

Abstract A programme of measurements is reported which has confirmed that carrier-wave interference is the key factor controlling LORAN-C signal-to-noise ratio in North-West Europe. The tests, at 8 sites in Ireland and the United Kingdom, identified 68 interfering signals, 17 of which exceeded the worst-case atmospheric noise. Many interferers were synchronous with LORAN-C spectral lines. Especially prominent among the most serious interferers were Decca Navigator signals. The paper discusses the need for efficient filtering techniques and, for notch filters, the development of strategies to balance the conflicting claims of high-powered, wide-area interferers with those of the many low-powered Decca stations.

Dr. David Last is a Reader in the University of Wales. He was awarded the degree of B.Sc(Eng). by the University of Bristol, England in 1961 and the degree of Ph.D. by the University of Sheffield, England in 1966. Dr. Last is a Fellow of the Institution of Electrical Engineers, a Member of the Royal Institute of Navigation and a Chartered Engineer. He has published many papers on Radio Navigation systems, especially on applications of Decca Navigator. He acts as a Consultant on Radio Navigation and Communications to Companies and Government Departments. He is an Instrument-Rated Pilot - and aeronautical user of LORAN-C!

Dr. Nick Ward is Senior Development Engineer at Trinity House, the Lighthouse Service for England and Wales. He is also responsible for managing R & D on behalf of the Northern Lighthouse Board for Scotland and the Commissioners of Irish Lights in Ireland. He was awarded a B.Sc. by the Council for National Academic Awards in the UK in 1970 and the degree of Ph.D. by the University of Reading, England in 1980. Dr. Ward is a Member of the Royal Institute of Navigation and has published papers on the computer modelling of navigation systems. He is currently Secretary of the LORAN-C Technical Working Group for NW Europe and of the International Association of Lighthouse Authorities' Technical Committee on Radionavigation Systems.

1 Introduction

This is a time of rapid change for LORAN-C in Europe. The installations of the US Coast Guard Norwegian Sea and Mediterranean chains have been offered to the host nations from 1994 for their continued operation. The states of North-West Europe, however, are studying the much bolder proposal of integrating the existing stations with the two stations of the French rho-rho chain (Fig. 1), and adding sufficient additional stations to give high-quality LORAN-C coverage throughout the region.

Europe is a difficult area for LORAN-C because of its high levels of carrier-wave interference. Wenzel & Thrall [1] of the US Coast Guard have

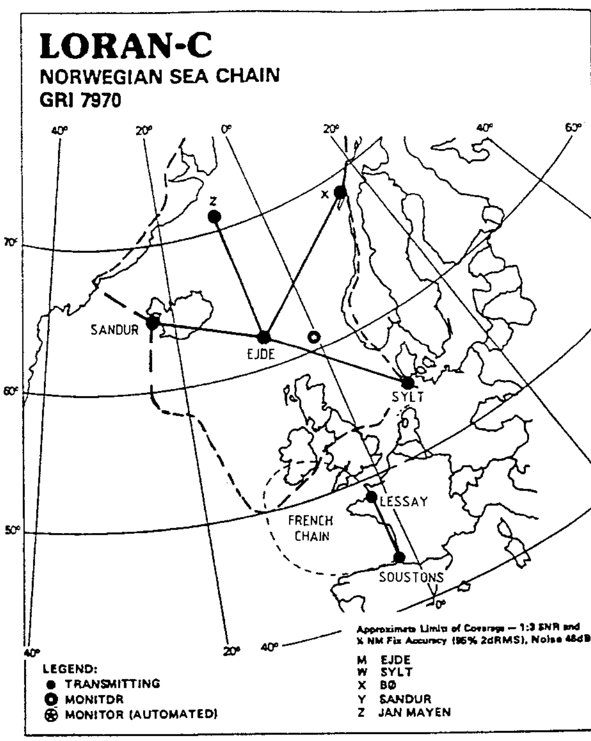


Fig. 1 Current LORAN-C installations in North-West Europe.

spoken of the 'harsh man-made noise environment of NW Europe' where the 'allocation of the LF frequency band is much less favorable to LORAN-C than in the US/Canada'. They warn of 'real problems - about what might be expected of receivers not designed to contend with the European LF environment'.

There are known to be many sources of carrier-wave interference which reduce signal-to-noise ratios and increase the random variations of measured positions. Worse, a significant number of these interferers are synchronous with LORAN-C spectral components. De Bruin & van Willigen [2], and others, have shown that synchronous and near-synchronous interferers can cause cycle slips and gross position errors. Prominent among both synchronous and non-synchronous interferers are the signals of the 83 European Decca Navigator stations.

The European interference problem is not new, of course: Wenzel and Thrall [1] comment that 'the USCG has operated LORAN-C on the outskirts of NW Europe for many years and is concerned about the high noise level'. They recommend carrying out proper coverage surveys. Civil users also have experience of LORAN-C operation in the areas of existing coverage whilst the mini-LORAN system, Pulse/8, is widely deployed for off-shore work in Europe. Nevertheless, a great deal of additional quantitative information regarding interference is now required. Given knowledge of the interfering signals and current developments in receiver design it should be possible to achieve satisfactory performance.

Planning European LORAN-C coverage means predicting the field strengths of the LORAN signals, and also those of the atmospheric noise and the carrier-wave interference. The prediction techniques used need to be validated under European conditions and actual levels of noise and interference measured. This paper reviews the prediction methods currently employed and describes trials in Ireland and the United Kingdom [3] in which field strength predictions were checked and noise and interference levels sampled.

The trials also measured times of arrival, time differences, ASF values, ECD changes, receiver cycle locking performance and compared the operation of a number of receivers under European conditions. This paper, however, concentrates on the factors which determine the signal-to-noise ratios with which receivers must contend: field strength, atmospheric noise and, predominantly, carrier-wave interference.

Given knowledge of the interfering signals and current developments in receiver design it should be possible to achieve satisfactory performance.

2 Predictions

2.1 Field strength

The standard USCG technique, based on Millington's method, was employed [4]. The quality of ground conductivity data varies greatly: in some countries it is as detailed as in the US, in others sparse. Confidence in the data is reduced by substantial changes at national borders!

The predicted values of field strength at the trials sites ranged from 42.5 to 78 dB/μV/m.

2.2 Atmospheric noise

Atmospheric noise was estimated from the data in CCIR Report 322 [5]. The UK Admiralty Research Establishment [6,7], using the standard USCG method of analysis [8], estimated the atmospheric noise at typical location 55°N 00°W as follows:-

Mean noise level	= 49.3 dB/μV/m
1σ	= 7.6 dB
90 percentile	= 56.0 dB/μV/m
Worst case	= 60.5 dB/μV/m

2.3 Carrier-wave interference

With the exception of frequency allocation lists of dubious value there appears to be no data-base of potential interferers to LORAN-C in Europe. The operators of Pulse/8 have identified the strongest interferers which affect the performance of their system, but this is of limited value given the restricted areas in which Pulse/8 is deployed and the differences between its spectrum and that of LORAN-C. Prediction of carrier-wave interference levels is not feasible without preliminary measurement.

3 Measurements

3.1 Sites and organisation

Measurements were made at the 8 sites shown in Fig. 2. These sites were chosen for a variety of reasons: as possible locations for LORAN-C stations; to sample direct sea paths; or to measure the effects of land paths. The area investigated also has a relatively high population density of Decca Navigator stations.

The trial lasted from 30 April to 29 May 1988. One team of observers visited each site in turn to measure the field strengths and sample the noise and interference. A second team remained at Mizen Head (Ireland) for the full period of 30 days sampling the temporal variations of these parameters. In order to be sure to identify interferers which operated for short periods each day, observations were taken at intervals of 8.33 hours. In this way, over the period of the trials, samples were taken around the clock at 20-minute intervals.

3.2 Field strength

Field strength measurements were taken on the transmissions from the stations of the French chain (GRI 8940) at Lessay and Soustons and those of the Norwegian Sea chain (GRI 7970) at Ejde (Faeroes), Sandur (Iceland) and Sylt (West Germany) (Fig. 1).

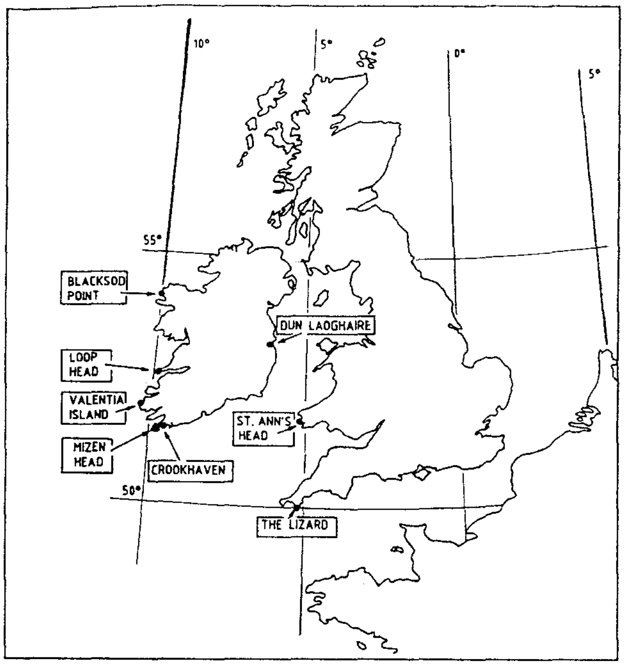


Fig. 2 Locations of trials sites in Ireland and the United Kingdom.

Signal strengths were measured by two Accufix 500 receivers fed by 108-inch whip antennas mounted on the roof of the vehicle. Measurement errors, due to the poorly-defined ground-plane, were removed and field strengths established by calibration: a Rohde & Schwarz Loop Antenna and Field Strength Meter (type ESH2) were used to measure the peak field strength of the strongest LORAN-C signal at each site. Corrections were applied for the limited band-width of the receiver and for the LORAN-C peak:sampling-point ratio. The field strengths of the other signals were calculated relative to this value, the accuracies of the receivers' signal strength readouts having been confirmed by reference to a LORAN-C signal generator.

3.3 Carrier-wave interference

The Rohde & Schwarz Field Strength Meter, coupled to a -20 dBi omni-directional whip antenna mounted on a tripod, was used to measure and identify interfering signals. Frequency-domain plots were recorded using an Anritsu Spectrum Analyser (type MS2601A). The equipment was again calibrated to indicate field strength values by reference to a loop antenna.

The measurement procedure was to sweep the band manually using the Rohde & Schwarz equipment from 50 to 150 kHz, identifying and measuring the field strength of each interferer and its frequency to a resolution of 100 Hz. Only interferers which exceeded a threshold value were recorded; this threshold was 40 dB/μV/m for signals close to the LORAN band, between 80 and 120 kHz, and 50 dB/μV/m for other signals. Note that 50 dB/μV/m is close to the mean predicted atmospheric noise level so significantly weaker interferers than this would have little effect. The spectrum from 50 to 150 kHz was also recorded photographically (eg Fig. 3) as were the spectra of each of the 5 Decca Navigator frequency bands. The type of transmission - Decca, FSK, facsimile, etc. - of each interferer was also noted.

3.4 Noise

In a short trial at a single season of the year one can sample atmospheric noise and check the reasonableness of predictions, but certainly not verify the statistics of its distribution in time or space.

Noise values were estimated from the spectrum analyser photographic records (eg Fig. 3) by visual inspection of the minimum levels in the gaps which appear between the interfering transmissions when the analyser is operated at a bandwidth of 100 Hz. It was assumed that the atmospheric noise was less than, or equal to, these values. This measurement is not feasible at frequencies where the LORAN-C sideband energy exceeds the atmospheric noise; Fig. 3 shows that frequencies around 135 kHz are suitable. Atmospheric noise also falls with frequency [5], so a correction must be applied to give the equivalent noise level at 100 kHz. Finally, the noise power in the typical LORAN-C 'effective receiver noise bandwidth' [8] is estimated from the narrow-band value measured.

This technique is of limited accuracy: there is an uncertainty of several decibels in estimating the amplitude of the noise from the photographic record; there is a further error in converting from one bandwidth to the other since the noise is impulsive, not Gaussian; and the technique cannot distinguish between atmospheric and man-made electrical noise.

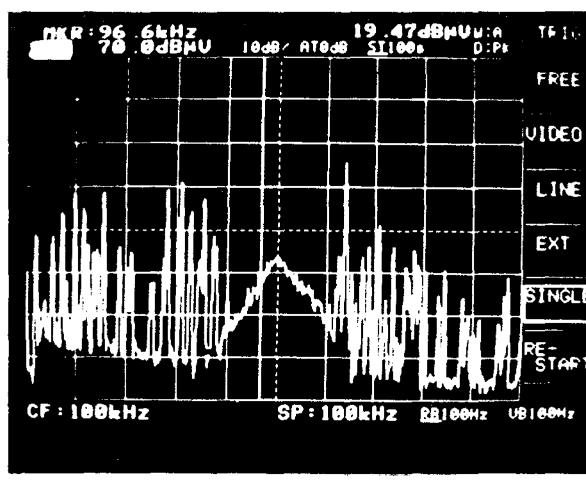


Fig. 3 Spectrum of LORAN-C, interfering signals and noise recorded at Loop Head, Ireland, (1230 UTC, 11 May 1988, omni-directional antenna).

3.5 Signal-to-noise ratio

Receiver readouts of signal-to-noise ratio were also recorded during the trials. However, they are of limited value for the purposes of these experiments since they do not distinguish between atmospheric noise and carrier-wave interference.

4 Results

4.1 Field strength

The discrepancies between the measured and predicted values of field strength varied from 0 to 7 dB. On average the values measured exceeded those predicted by 1.7 dB, with a standard deviation of 2.8 dB. These averages, however, conceal the difficulties which were experienced in making accurate field strength measurements on LORAN-C signals, especially at sites distant from transmitters and in the presence of high levels of carrier-wave interference. They also conceal unexplained variations of measured field strengths with time.

4.2 Noise

The values of the atmospheric noise samples are shown in Table 1. Each reading taken was an average for the short period of observation; the table shows the minimum and maximum values for each site. The readings fall within the range predicted and their average value is 41 dB/μV/m. The highest reading, 60 dB/μV/m at The Lizard, is suspect; a noisy power line was subsequently identified in the vicinity of this site.

4.3 Carrier-wave interference

Fig. 4 shows the maximum field strengths and the transmission types of the 57 interferers

Site	Noise level (dB/μV/m) Min	Max
Mizen Head	37	46
Crookhaven	36	37
Valentia Island	37	41
Loop Head	35	43
Blacksod Point	33	36
Dun Laoghaire	36	47
St. Ann's Head	37	42
The Lizard	46	60

Table 1 Estimates of average atmospheric noise field strengths in LORAN-C receiver bandwidth

identified at Mizen Head. Fig. 5 is the equivalent diagram created by combining the data from the 8 'mobile' sites and showing the maximum field strength values of the 63 interferers detected. Table 2 summarises and compares data from the fixed and mobile trials, listing the interferers in frequency order and attempting to identify them where possible from international frequency lists. The Table also shows the percentage of observations at which each of the interferers exceeded the threshold field strength.

The interferers have been classified in terms of the anticipated severity of their effects on LORAN-C receivers as follows:-

(a) The frequencies of interferers marked with an asterisk (*) in the 'Sync' column of Table 2 are understood to be locked to UTC and each of them is synchronous with spectral lines of all LORAN-C chains.

(b) The frequencies of interferers marked 'S' in the 'Sync' column appear to be synchronous with a spectral line of either the French or the Norwegian Sea LORAN-C chain. Those marked 'N' are near-synchronous: that is, they fall within 100 mHz of a spectral line.

(c) The field strengths of interferers detected during the mobile trials have also been weighted according to their frequency separation from 100 kHz and whether they are synchronous, near-synchronous or neither. Weighting is based on curves published by the Transportation Systems Center [9] extrapolated beyond 30 kHz (Fig. 6), the 'near-synchronous continuous-wave interference' curve being used for * and S interferers and the 'FSK' curve for others. The results are listed in the 'Weighted' column of Table 2 and plotted in Fig. 7.

(d) The rank orders of the 10 strongest weighted interferers are shown in the extreme right-hand column.

5 Discussion on interference

5.1 Strength of interfering signals

The data may be interpreted as broadly representing the conditions experienced by a receiver operating in the South-West of the British Isles which approaches no closer than 30 km to any local interfering station. The trials have identified 68 interferers whose field strengths exceeded either 40 or 50 dB/μV/m. At least 8 of these are known to be synchronous with a spectral line of either the French or the Norwegian Sea LORAN-C chain; 4 of these synchronous interferers are time signals which are locked to UTC. A further 8 signals, all from Decca Navigator stations, fall within 100 mHz of a spectral line. Thus at least 16 signals must be treated as being more serious potential interferers than their field strengths alone imply. There may well be other such signals which have not yet been identified.

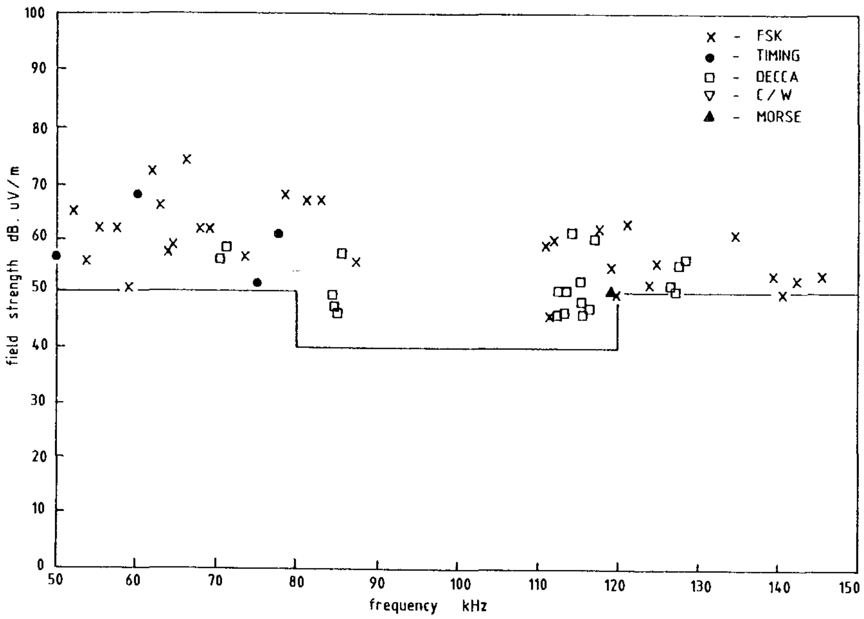


Fig. 4 Maximum field strengths and transmission types of interferers observed at Mizen Head, Ireland, (30 Apr-29 May 1988).

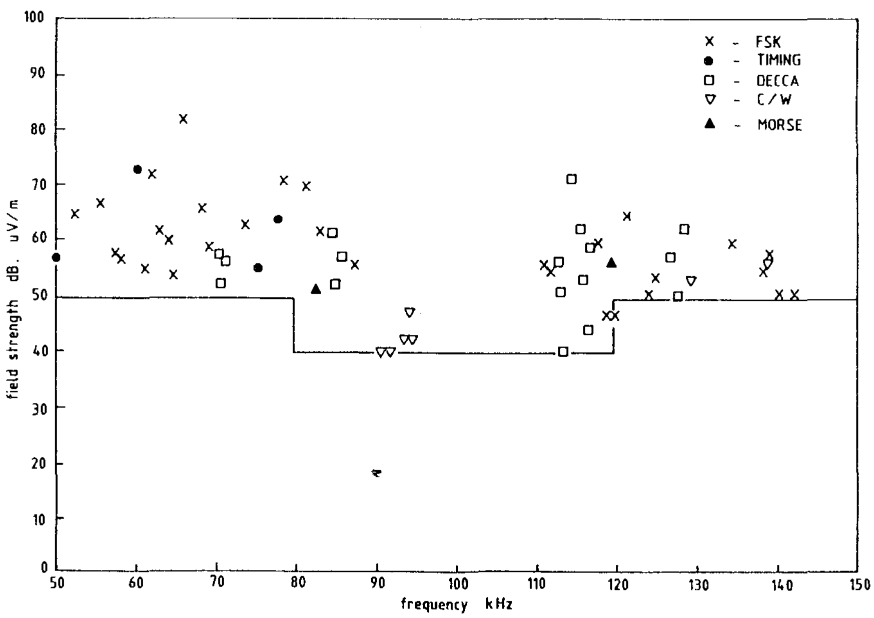


Fig. 5 Maximum field strengths and transmission types of interferers observed at 8 'mobile' sites in Ireland and UK (30 Apr-29 May 1988).

Clearly, carrier-wave interference levels greatly exceed atmospheric noise levels: 17 interferers exceeded even the highest noise level recorded, the strongest of them by 22 dB. When the interference levels are weighted to allow for the filter performance of a typical receiver, 18 interferers still exceed the overall average of the atmospheric noise levels measured.

Five interfering signals were detected inside the LORAN-C 90-110 kHz band. All of them were very weak, unmodulated, continuous wave signals, between 40 and 47 dB/μV/m, which exceeded the 40 dB/μV/m threshold during fewer than 10% of observations. In comparison with out-of-band signals, these in-band interferers were of little significance. However, 84 non-LORAN-C stations with frequencies between 90 and 110 kHz appear in the international frequency assignment lists appropriate to Europe.

5.2 Worst interferers

The 10 worst potential interferers identified by the weighting process are ranked in Table 3. Weighting changes the order of prominence of interferers profoundly: for instance, the strongest signal recorded, the FSK transmission from Kerlouan (France) on 65.8 kHz, does not appear in this list because of its separation from

Freq (kHz)	Type	Identity	Mizen %	Mizen Max	Mobile %	Mobile Max	Mobile Sync	Weighted
50.0	TS	OMA, Prague, Czech.	32	57	20	57	*S	-43
52.0	FSK		95	65	82	65		6
53.6	FAX	RTO, Moscow, USSR	8	56				
55.3	FSK	DCF55, Mainflingen, WG	88	62	70	67		12
57.4	FSK		88	62	39	58		7
57.9	FSK				2	57		7
59.0	FSK		3	51				
60.0	TS	MSF, Rugby, GB	100	68	100	73	*S	0
61.0	FSK				11	55		9
61.8	FSK	GIZ, London, GB	92	72	84	72		28
62.6	FSK	FTA, Paris, France	47	66	50	62		19
63.9	FSK		42	58	41	60		19
64.5	FSK		32	59	5	54		14
65.8	FSK	Kerlouan, France	100	74	98	82		43
68.0	FSK		87	62	59	66		30
68.9	FSK			62	36	59		25
70.2	DECCA	SW British, 1B			18	57	N	11
70.5	DECCA	N British, 3B	8	56	5	52	N	9
71.2	DECCA	Irish, 7D	100	58	41	56	N	13
73.4	FSK		73	57	48	63		36
75.0	TS	HBG, Nyon, Switzerland	7	52	9	55	*S	23
77.5	TS	DCF77, Mainflingen, WG	60	61	34	64	*S	38
78.2	FSK	Crimond, GB	100	68	98	71		50 -4-
81.0	FSK	London, GB	82	67	77	70		53 -2-
82.4	MORSE	Beograd, Yugoslavia			2	51		35
82.8	FSK	GYB (MKL) London, GB	98	67	95	62		48 -7-
84.3	DECCA	SW British, 1B	84	49	41	61		48 -7-
84.6	DECCA	N British, 3B	18	47	41	52	N	42
85.0	DECCA	English, 5B	5	46			S	
85.5	DECCA	Irish, 7D	100	57	80	57		46
87.2	FSK	Bonn, WG	63	56	30	56		47 -9-
90.7	CW				5	40		34
91.6	CW				2	40		34
93.4	CW				7	42		39
94.1	CW				5	47		45
94.5	CW				9	42		40
		----LORAN-C----						
110.6	FSK	DCF30, Bad Vilbel, WG	73	59	57	56		49 -6-
111.3	FSK	SOA211, Warsaw, Poland	2	46				
111.8	FSK/FAX	OLT21, Prague, Czech.	23	60	18	55		47 -9-
112.4	DECCA	SW British, 1B	12	46	18	56	N	50 -4-
112.6	DECCA	Northumbrian, 2A	93	50	23	51	N	45
112.9	DECCA	N British, 3B	8	46	16	51		42
113.3	DECCA	English, 5B	2	50	40	40	S	34
113.9	DECCA	Irish, 7D	100	61	95	71		61 -1-
115.2	DECCA	SW British, 1B	90	52	27	62		51 -3-
115.4	DECCA	Northumbrian, 2A	5	48	20	53		41
115.7	DECCA	N British, 3B	53	46	20	53		40
116.2	DECCA	English, 5B	3	47	9	44	S	32
116.8	DECCA	Irish,7D	97	60	30	59	N	46
117.4	FAX	DCF37, Mainflingen, WG	83	62	64	60		45
118.8	FSK	London, GB	23	55	32	47		30
119.2	MORSE	IDQ, Rome, Italy	23	50	5	56		39
119.7	FSK/FAX	SAY2, Nörrkoping, Sweden	28	50	18	47		29
120.9	FSK	GYA, London, GB	60	63	41	65		45
123.7	FSK	Mainflingen, WG	8	52	2	51		27
124.6	FAX	Olumouc, Czech.	15	56	2	54		29
126.4	DECCA	SW British, 1B	20	51	32	57		31
127.0	DECCA	N British, 3B	5	50			N	
127.5	DECCA	English, 5B	2	55	5	50	S	10
128.2	DECCA	Irish, 7D	67	56	20	62	N	21
129.1	CW				5	53		22
134.2	FAX	DCF54, Offenbach, WG	25	61	30	60		21
138.0	FSK		2	53	14	55		10
138.5	CW				2	56		11
139.0	FAX	DCF39, Frankfurt, WG	10	54	9	58		12
140.3	FSK	DCF60, Frankfurt, WG	2	50	7	51		4
142.3	FSK		3	53	7	51		0
145.2	FSK		2	54				

Types : TS=time signal, FSK=frequency-shift keyed, FAX=facsimile.
Countries : WG=West Germany, GB=Great Britain, Czech=Czechoslavakia.
LORAN-synchronous : *=UTC-locked, S=synchronous, N=near-synchronous.

Table 2 Summary of interfering signals: field strengths, percentages of readings which exceeded threshold values plus (for 8 'mobile' sites) weighted field strengths and worst potential interferers

100 kHz. Indeed, all the most prominent interferers lie within 22 kHz of the LORAN-C centre frequency.

Rank order	Freq. (kHz)	Type	Identity	Weighted dB/μV/m	% Readings	Sync (*/S/N)
1	113.9	DECCA	Irish 7D	61	95	
2	81.0	FSK	London, GB	53	77	
3	115.2	DECCA	SW British 1B	51	27	
4=	78.2	FSK	Crimond	50	98	
4=	112.4	DECCA	SW British 1B	50	18	N
6	110.6	FSK	DCF30, WG	49	57	
7=	82.8	FSK	GYB (MKL), UK	48	95	
7=	84.3	DECCA	SW British 1B	48	41	
9=	85.5	DECCA	Irish 7D	47	80	
9=	111.8	FSK/FAX	OLT21, Cz	47	18	

Table 3 Worst potential interferers encountered during mobile trials

Examining the data site by site shows that the prominent interferers fall into two clear groups:-

(a) Decca Navigator transmissions from local stations. The troublesome transmissions are those in the 6*f*, 8*f* and 8.2*f* Decca bands; that is, within approximately ±1% of the centre frequencies of 85.0, 113.3 and 116.2 kHz, respectively. Decca stations are relatively low-powered and their transmissions generally only feature among the most prominent interferers to LORAN-C at ranges up to 200 km over sea paths. However, since the separation between the master stations of adjacent Decca chains can be less than 200 km [10], moving a receiver quite a short distance can totally change the interfering Decca frequencies.

(b) Strong FSK, facsimile, time-signal, CW and Morse transmissions from distant stations. The strengths and probabilities of reception of these signals were broadly similar at all the sites visited. The pattern of interference which they cause is consistent over large areas.

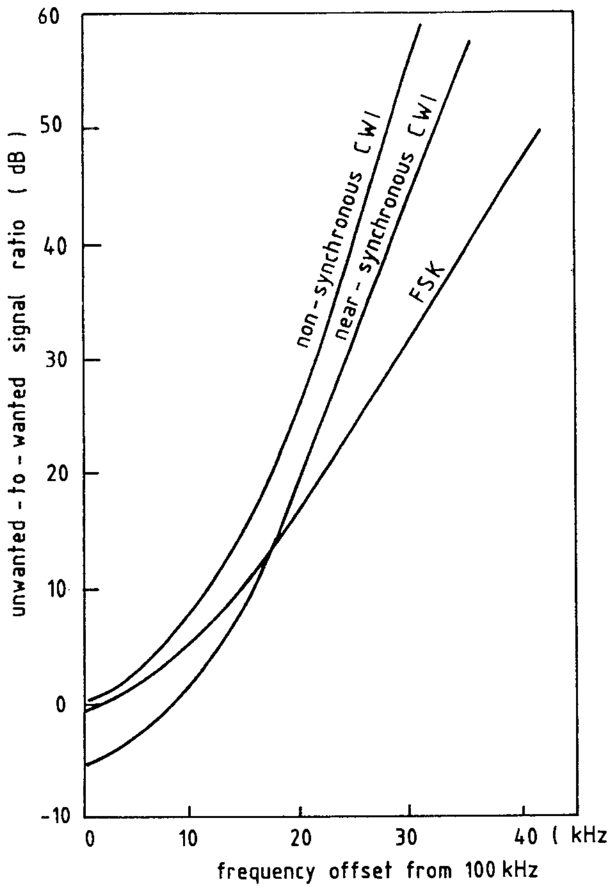


Fig. 6 Receiver weighting curves used to allow for receiver filtering (after TSC [9]).

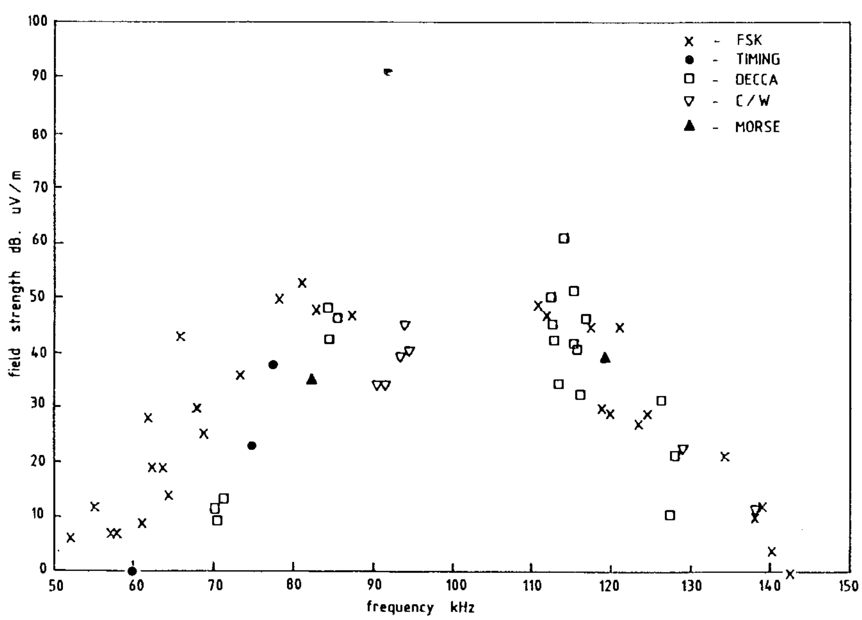


Fig. 7 Interfering signals at 8 'mobile'sites as in Fig 5, weighted to show effect of receiver filtering.

5.3 Notch filters

The interference data recorded can be used both to assess the efficacy of notch filter settings in existing receivers and as a basis for a strategy for setting notch filters for use in the trials area.

Two additional production LORAN-C receivers were installed in the mobile unit. One was equipped with 4 automatically-tuned notch filters whose settings were recorded each time readings were taken. This receiver invariably set its notches to two frequencies above, and two below, the LORAN-C band. The low-side frequencies most commonly selected appeared to correspond to the interferers on 81.0, 78.2 and 82.8 kHz which were ranked 2, 4 and 7= in Table 3. The Decca signals ranked 7= and 9= were occasionally selected. The high-side notches were most frequently both set to Decca interferers in the 113.3 or 116.2 kHz bands. Unfortunately, the precision with which this receiver displayed its settings was insufficient to permit identification of the exact Decca frequencies which it chose. While the settings chosen appear reasonable, the number of filters is clearly inadequate.

The second receiver was a European version of a popular US aeronautical model fitted with 8 pre-tuned notch filters. Table 4 compares the frequencies to which the manufacturer had set the filters with the interferers encountered during the trials. It can be seen that 6 of the notches were set to known interferers. However, only three of the worst 10 interferers of the trials area, those ranking 2, 6 and 9, were notched. Two notches, at 106.386 and 106.429 kHz, appeared to be aimed at interferers within the 90-110 kHz LORAN-C band which were never observed. These were probably two strong Czechoslovakian meteorological transmissions which used to be received there. This receiver may well have had sufficient filters, but they were not set to best advantage. Subsequent retuning of the notches to the 8 worst interferers allowed the receiver to demonstrate its excellent performance.

Notch filter setting (kHz)	Closest known interferer (kHz)	Position in weighted order
77.450	77.5	
81.240	81.0	2
106.386	None	
106.429	None	
110.667	110.6	6
111.911	111.8	9
117.323	117.4	
120.640	120.9	

Table 4 Receiver notch filter settings compared with frequencies and rank orders of actual interfering signals

These observations illustrate that manufacturers of LORAN-C receivers for use in North-West Europe face a number of difficulties which must be resolved before the new chains become operational:-

(a) There are many strong interfering signals, synchronous, near-synchronous and non-synchronous.

(b) There is a lack of knowledge of the frequencies and characteristics of these transmissions and of the geographical distributions of their effects.

(c) Manufacturers and service personnel concerned with receivers which employ fixed-frequency notch filters will need to develop strategies to guide them in setting frequencies. These will have to balance the conflicting claims of the high-powered interferers whose effects may cover substantial areas with those of the relatively localised Decca stations.

5.4 Cycle selection

In view of the high levels of carrier-wave interference experienced and of the inadequate filtering performance of the receivers employed, none of which was suitable as it stood for European operation, it is not surprising that cycle selection performance was poor. This was true even at sites which were shown by the USCG charts to be within the coverage limits of the chain selected (Fig. 1). It confirms the need for careful attention to the question of interference rejection.

6 Conclusions

The principal factors which control the signal-to-noise ratio of a received LORAN-C signal in North-West Europe are the field strengths of the signal, the atmospheric noise and carrier-wave interference.

The measurement programme has shown that signal strength can be estimated under the conditions described with an average error of 1.7 dB and a standard deviation of 2.8 dB. This uncertainty would be reduced by access to a more detailed and reliable database of ground conductivity values and by developing improved techniques for measuring low levels of field strength under conditions of high levels of carrier-wave interference.

The mean atmospheric noise level predicted was 49.3 dB/μV/m and the maximum 60.5 dB/μV/m. The average of the values measured at the 9 sites, using a technique of limited precision, was 41 dB/μV/m and the highest value 60 dB/μV/m. The measurements demonstrated, however, that in this region, atmospheric noise is rarely a significant factor in comparison with carrier-wave interference. Some 68 interfering signals were identified, of which at least 16 are believed to be either synchronous with, or to fall within 100 mHz of, a spectral line of one of the LORAN-C chains of interest. The worst-case predicted atmospheric noise was exceeded by 17 interferers. When a weighting function was applied which represented the filtering of a typical receiver, 18 interferers still exceeded the mean atmospheric noise.

The most significant interfering signals lay outside the notional LORAN-C frequency band of 90-110 kHz but not more than 22 kHz from the centre frequency of 100 kHz. The notch filters of the receivers employed were either insufficient in number, or set with inadequate precision, to deal with the interference experienced and cycle selection problems were common. The trials demonstrated the need for careful attention to the problem of carrier-wave interference: further study of the identities, frequencies and characteristics of the sources; reduction of the numbers and magnitudes of the signals where possible; improvement of the ability of receivers to reject interference; and operational strategies to minimise its effect tailored to specific areas of operation.

The trials have clearly demonstrated and confirmed the harshness of the LORAN-C environment in North-West Europe and the need to concentrate on solving the problems which it presents to the development and operation of an accurate and reliable LORAN-C navigation system. Given knowledge of the interfering signals and current developments in receiver design it should be possible to achieve satisfactory performance.

7 Acknowledgements

The work described in this paper was carried out under the aegis of the North-West Europe LORAN-C Technical Working Group. Calculations and measurements were performed by many colleagues from the French Direction des Constructions et Armes Navales, Brest, The Irish Lighthouse Service and Trinity House, England. The authors express their appreciation to their co-workers and acknowledge their friendly and efficient cooperation in this international programme.

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VERBAL PRESENTATION 31 OCTOBER 1989 HYANNIS, MA.

Thank you Chairman, Good morning ladies and gentlemen

It is clear from Mr. Stenseth's paper that there are big plans for the expansion of LORAN-C in Northwest Europe. There are also some big problems - not just the problems of getting a dozen or so independently-minded nations into bed together, not even the problems of sorting out who pays whom and for what - but above all the fundamental problems of actually making the system work properly.

When the technical studies started to get serious, the views of many of the participants and on-lookers appeared to fall almost entirely into two groups:- the faint-hearts and the ostriches. The faint-hearts said that it just couldn't be done. The LORAN environment in Europe was too severe. There was too much interference and the receivers wouldn't work. There was also too much land and the ASFs would be truly awesome. It was all very sad but there it was.

The ostriches, in contrast, simply didn't want to know about the problems. They went on ignoring all the bad news. They predicted LORAN coverage by assuming that all signal paths lay over sea water and, since therefore Europe clearly contained no land whatsoever, it couldn't have any interfering transmitters, so they ignored those too. The resulting predicted coverage was exceedingly impressive.

The wise men of the Northwest Europe Technical Working Group, however, sought facts, rather than hopes and fears. Noting the severe scarcity of reliable published information on LORAN performance in Europe, they set out to make measurements, using the existing LORAN transmissions. They measured times of arrival using differential GPS and time difference using LORAN receivers. They checked ASF and ECD values and observed receiver locking performance under European conditions. And within the context of those trials came the measurements which are the subject of our paper:- the fundamental parameters of field strength, noise and carrier-wave interference.

* Field strength
* Atmospheric noise
* Carrier-wave interference

We wanted to answer simple but vital questions:

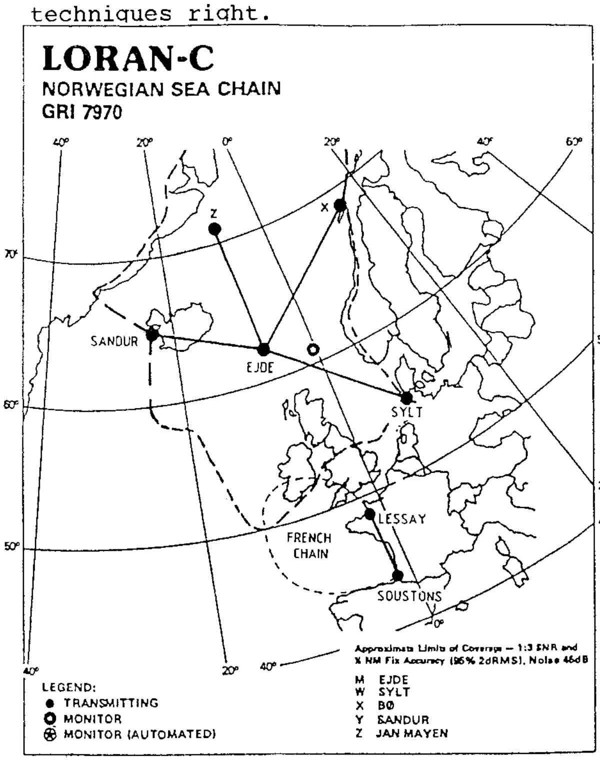
- can we predict field strength with confidence
- are the levels of atmospheric noise used in our coverage predictions realistic

and - how do these atmospheric nose levels compare with those of carrier-wave interference.

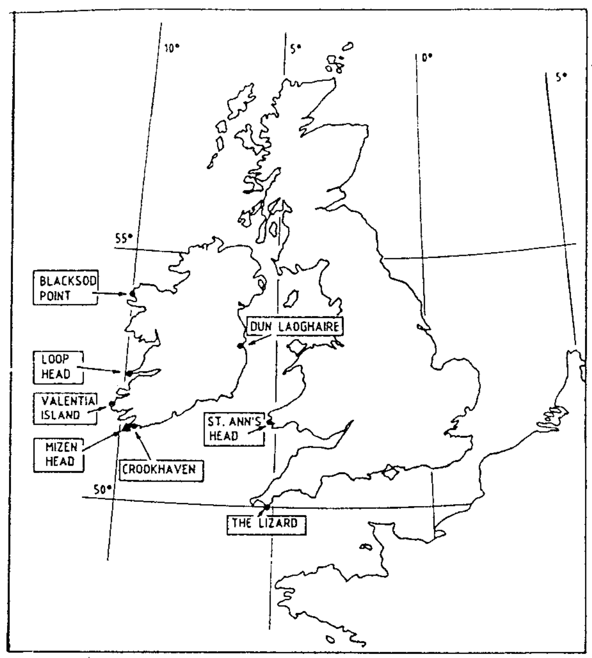
Let's look at how these tests were organized.

First you should be familiar with the LORAN stations in Northwest Europe. We used three from the Norwegian Sea chain: Sandur in Iceland, Ejde in the Faroes and Sylt in North Germany plus the two stations of the French rho-rho chain - Lessay in the north and Soustons in the South.

The area of the trials was Ireland and the Southwest of the United Kingdom. We chose sites which let us sample a variety of transmission paths - short sea paths, long sea paths, and a range of land paths. We also checked out a number of candidate sites for the proposed LORAN station in Southwest Ireland. And these were the prototype for a series of tests to be conducted throughout Europe in which we took a first look at conditions and got the measurement techniques right.



Let's look at the sites.



This is for those of you who aren't already totally familiar with the geography of Ireland - there can't be many, judging from the list of distinguished delegates here: we've got a McGann, Feeney, Cassidy, Doyle, Quinn and one or two other possible like Moroney and Callanan!

The key site is Mizen Head - that's simply the first place east of Cape Cod here. We put a team there to observe conditions for a month. Our second team started there, cross-checking readings with the Mizen Head people, then they spent two or three days at each of the other sites - Crookhaven on the South coast, then Valentia Island, Loop Head and Blacksod Point (with long, but progressively shorter, sea paths down from Sandur), Dun Laoghaire in the East of Ireland, and finally The Lizard in Southwest England (with its short sea path from Lessay) and St. Ann's Head in South Wales (where the Lessay signals must cross a peninsula.

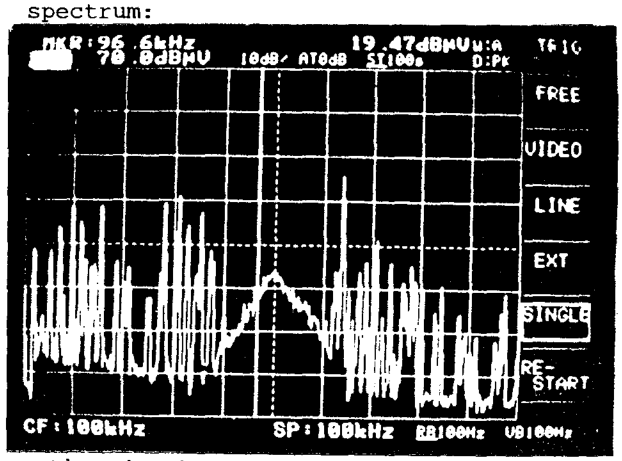
When it came to field strengths, we wanted to predict values, measure them accurately and compare our predictions and measurements. That sounds easy, but it's not. We all predict the field strengths of Loran signals using the US Coast Guard technique which employs Millington's method to deal with paths which have sessions of different ground conductivities. That's fine, except that in Europe there is no single, accurate, detailed database of ground conductivity values. Each country compiles its own and some are pretty tacky. There are even marked changes in ground conductivity at national boundaries, which maybe shows that out frontiers are put where the good Lord intended. We're trying at present to gather the best data together to improve coverage prediction accuracy, since conductivity affects not only field strength prediction, but also ASF and ECD modelling.

Measuring Loran field strength is also tricky. You'd think that you just needed to read the numbers from the Loran receiver, but it's not like that. First, you question whether the site is typical: signals suffer field perturbations when they cross coastlines and all our sites were coastal. Several of them were at light-houses-convenient for power supplies and cups of tea - but built on cliff tops and festooned with overhead cables. Then the signal voltages from short whip antennas turn out to be a function of antenna location, ground arrangements and cable positioning. And most Loran receivers don't tell you what they are measuring: is it the top of the pulse or the sampling point; is it a peak or an rms voltage. All these things matter.

We minimized the uncertainties this way: we calibrated the receivers carefully in the lab so that we understand how their readings related to Loran signal strength at the antenna terminal. Then we calibrated them at each site for field strength against a reference loop antenna and field-strength meter, using strong, ground-wave signals. Finally we compared the strengths of the Loran stations to this reference.

The readings we got tied in reasonably well with our predictions. There was an average discrepancy of 1.7 dB, and a standard deviation of 2.8 dB. We'd like to improve on this but it's certainly good enough to give us broad confirmation of our field strength predictions.

The Mizen Head and the mobile survey teams also sampled atmospheric noise and carrier-wave interference. They took readings simultaneously three times a day. In fact, to avoid always sampling at the same clock times and missing something interesting in between, their samples were spaced eight and one-third hours. So we have readings at 20-minute intervals around the clock. The teams recorded the spectrum from 50-150 kHz. If you haven't seen one before, here's a typical European off-air Loran-band spectrum:



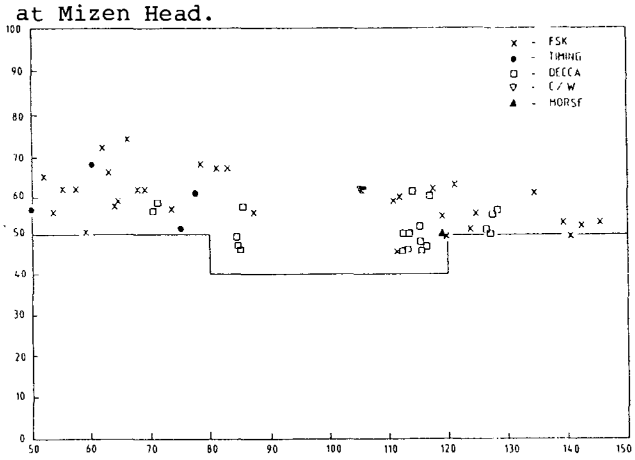
There's the Loran signals cowering around 100 kHz. The picture is dominated by carrier-wave interference. But we also wanted to measure atmospheric noise and you can see the noise of you peer into the bottoms of the occasional holes among the wall-to-wall transmissions.

Now let's be realistic here: to get reliable figures of atmospheric noise at a site takes at least a year's work. That's how they got the data in CCIR Report 322 which we all use for Loran coverage predicting. We aimed simply to sample the noise and check the reasonableness of the figures people were using for system planning. We dug down into the holes with the spectrum analyzer set to 100 Hz bandwidth. We had to move at least 30 kHz out from 100 kHz before the Loran spectral components fell below the noise. There was a reliably clear slot around 135 kHz where we read the noise level, then corrected it for the way atmospheric noise varies with frequency and calculated from it the field strength of the atmospheric noise in the bandwidth of a Loran receiver. You will see from the published paper that the readings we got fell within the range predicted for the area and time of year.

This noise measuring method is elementary and its accuracy is limited. But when you look at the spectrum you wonder not whether the noise readings are spot on - but why we bother to make them at all! Yet people go on predicting European Loran coverage using signal-to -atmospheric noise ratio as the range-limiting criterion. It's clearly carrier-wave interference we should be analyzing here.

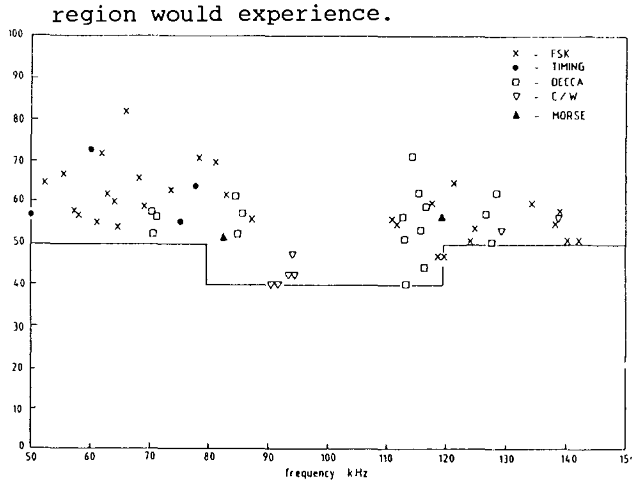
We measured this interference carefully, every time at every site. We wanted not merely to get an overall picture like this one but to identify the individual interferers and learn about their habits. The operators tuned the ban manually recording the centre frequency of each signal with 100 Hz resolution and identifying what kind of beast it was: FSK, FAX, a time signal or a Decca Navigator transmission.

Here are the interference recorded at Mizen Head.



This plots field strength vertically, frequency horizontally. We ignored anything below the line - that's weaker than 50 dB/ V/m, except within 20 kHz of the Loran centre frequency where we dropped the limit by 10 dB. This took us down to approximately the level of the atmospheric noise in the Loran bandwidth. We found 57 interferences: 32 assorted FSK or FAX, 20 Decca, 4 time signals and one lone Morse code operator!

We combined the results from all the other sites together to give a picture of the interference which a mobile Loran receiver operating in this region would experience.



The results are remarkably similar to those at Mizen Head. Certainly we see some extra Decca signals since the sites spanned several Decca coverage areas. And one or two signals transmitted from the UK and France got stronger as we came closer. But the general pattern is unchanged.

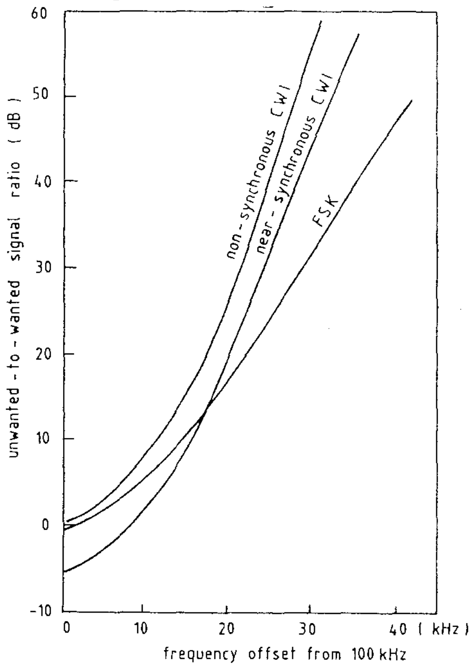
We identified most of these signals and you'll see the results in the big table in the printed paper; it's too detailed to show it all as a slide, but here's a sample.

-------Mobile------- (kHz)			%	Max	%	Max	Sync	Weighted
110.6	FSK	DCF30, Bad Vilbel, WG	73	59	57	56		49 -6-
111.3	FSK	SOA211, Warsaw, Poland	2	46				
111.8	FSK/FAX	OLT21, Prague, Czech.	23	60	18	55		47 -9-
112.4	DECCA	SW British, 1B	12	46	18	56	N	50 -4-
112.6	DECCA	Northumbrian, 2A	93	50	23	51	N	45
112.9	DECCA	N British, 3B	8	46	16	51		42
113.3	DECCA	English, 5B	2	50	40	40	S	34
113.9	DECCA	Irish, 7D	100	61	95	71		61 -1-
115.2	DECCA	SW British, 1B	90	52	27	62		51 -3-
115.4	DECCA	Northumbrian, 2A	5	48	20	53		41
115.7	DECCA	N British, 3B	53	46	20	53		40
116.2	DECCA	English, 5B	3	47	9	44	S	32
116.8	DECCA	Irish,7D	97	60	30	59	N	46
117.4	FAX	DCF37, Mainflingen, WG	83	62	64	60		45

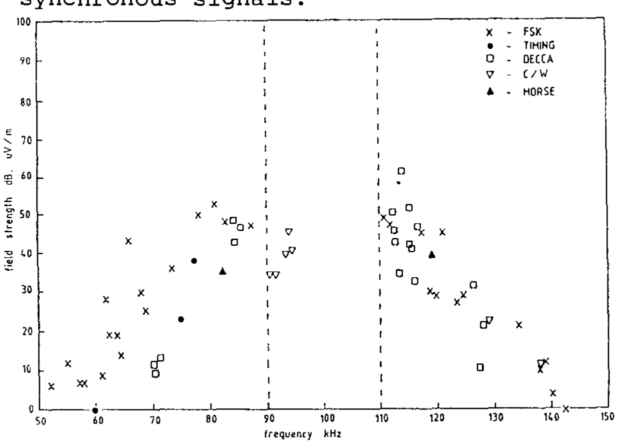
It's a frequency list of stations: the type and identity of each one, the maximum recorded field strength and also the percentage of occasions on which it was detected (some signals are always there, others are fleeting).

When you study the data you find that most of the interference is received via long paths from all around Europe which is why the pattern is essentially the same at all sites over a wide area. Almost the only local sources of interference are the Decca Navigator stations which are prominent interferers for a radius of a couple of hundred kilometers.

Now the magnitude of an interfering signal is one thing; its effect on a Loran receiver is quite another. We need to weight the interferers to allow for the bandpass filtering of the receiver. We must also recognize that interferers which are synchronous, or nearly-synchronous, with spectral lines of the Loran signal have especially insidious effects. Almost a quarter of our interferers lay within 100 mHz of a Loran spectral line.



We used these Transportation Systems Center curves to weight the interferers recorded by our mobile team. They effectively reduced strength with frequency offset from 100 kHz and they also distinguish between synchronous and non-synchronous signals.



Here is the result: weighing has a profound effect - and it shows up the real villains. For instance, the previous strongest signal, down near 65 kHz, falls by some 40 dB. Weighing also greatly favors any interferers in the notional Loran frequency band of 90-110 kHz. Despite this you can see that interference inside the band really isn't a big problem. We only ever heard 5 fairly weak carriers, in a month of round-the-clock listening at 8 sites. The big interferers are all outside this frequency band.

We've identified the 10 most prominent weighted interferers. Here's a league table of them:

Rank order	Freq. (kHz)	Type	Identity	Weighted dB/μV/m	% Readings	Sync (*/S/N)
1	113.9	DECCA	Irish 7D	61	95	
2	81.0	FSK	London, GB	53	77	
3	115.2	DECCA	SW British 1B	51	27	
4=	78.2	FSK	Crimond	50	98	
4=	112.4	DECCA	SW British 1B	50	18	N
6	110.6	FSK	DCF30, WG	49	57	
7=	82.8	FSK	GYB (MKL), UK	48	95	
7=	84.3	DECCA	SW British 1B	48	41	
9=	85.5	DECCA	Irish 7D	47	80	
9=	111.8	FSK/FAX	OLT21, Cz	47	18	

Let's see what this teaches us about the characteristics of European interferers. First, they all lie more than 10 kHz, but less than 22 kHz, from the Loran centre frequency. Then, they are fairly equally divided into two groups: the long-range signals which are broadly the same at each individual site; and the local interferers, mostly Decca, which vary quite significantly from site to site. And, incidentally, none of these 10 is known to be truly Loran-synchronous; only the one marked "N", for 'near-synchronous' definitely lies close to a spectral line. And perhaps the most important lesson of all: after weighing there are still 18 interferers which are stronger than the average atmospheric noise. It's interference which we need to deal with in Europe - not noise.

Now most Loran-C receivers, of course, reduce strong interfering signals by means of notch filters and the measurements we made let us get a feel of the effectiveness this approach. At the mobile sites we operated two Loran receivers: one with 4 automatically-tuned notches and one with pre-tuned notches. We recorded the settings selected by the automatic receiver. It always put 2 notches below the Loran band and 2 above. Generally its selections were sensible: it chose 81.0, 78.2 and 82.8 kHz on the low side most times and on the high side it almost always went for Decca signals in their bands around 113 and 117 kHz. But whilst the settings appear sensible, the number of filters is inadequate. If you notch out the worst 4 interferers you are left with lots of others which are almost as strong; this lists has 9 signals within a narrow 6 dB range of field strengths.

The other receiver was a popular US General Aviation receiver. The makers supplied the European version. This one is much more promising: it has 8 notch filters.

Notch filter setting (kHz)	Closest known interferer (kHz)	Position in weighted order
77.450	77.5	
81.240	81.0	2
106.386	None	
106.429	None	
110.667	110.6	6
111.911	111.8	9
117.323	117.4	
120.640	120.9	

The left hand column here shows the frequencies to which the manufacturer had set them - based on the best advice available. The centre column shows which interferer each notch attacks. Six notches were tuned to identifiable signals. The other 2 were set close to 106 kHz where we never detected any interferers. They were probably meant to zap a strong Czechoslovak MET station which appears to have been moved, possibly by persuasion from their neighbors further East. And only 3 of our worse 10 interferers were notched. This demonstrates clearly that manufacturers and service personnel badly need up-to-date information of the kind we had been recording to make the best use of receivers with fixed notch filters.

And in case 1 sound too miserable 1 should say that on retuning the notches to the 8 worst interfering signals, the receiver performed very satisfactorily.

Ladies and gentlemen, our survey has shown the importance of carrier-wave interference for planning European Loran operations. We have seen that we can predict field strength with acceptable accuracy, although we clearly need more reliable and complete ground conductivity data. We've also shown that we're using realistic values of atmospheric noise. But the key distinguishing feature between European and US Loran operation is carrier-wave interference. We believe that the factors which control European Loran-C coverage are the field strengths of the wanted Loran signals, those of the carrier-wave interference and the ability of receivers to deal with that interference.

Now I wouldn't want you to go to your coffee break feeling unnecessarily gloomy - so let me mention finally a little of the good news. Significant advances are being made in the ways in which Loran receivers process signals and reject interference and there are plenty of opportunities for further improvement. By the time the proposed European system comes on the air we may well be looking back on notch filters as neanderthal technology. Almost certainly our receivers will use both cross-chain and master-independent operation which will significantly reduce the need to receive distant weaker stations. None of these developments need increase receiver production cost unreasonably. And if Loran goes ahead, many Decca stations will be taken off the air, so the number of interferers will fall significantly.

What we will not be able to do is to import unmodified, low-cost US receivers into the tougher European Loran arena. But equally, there is no reason why, recognizing and dealing with the problems, we should not be able to achieve throughout Northwest Europe a Loran system using the best and latest transmitting equipment - a system of excellent performance which might even be good enough to impress wild geese flying in from the US.

Thank you.

EUROFIX: DIFFERENTIAL HYBRIDIZED INTEGRATED NAVIGATION

Durk van Willigen

Delft University of Technology
The Netherlands

Abstract

The proposed Eurofix differential, hybridized and integrated navigation system uses the Loran-C navigation transmissions for transferring differential and Navstar-GPS integrity data to the user. The Loran-C bursts are thereto time modulated yielding a 2.5..6 bps data transfer rate. The inherent message delay of 80..200 seconds is anticipated by using Loran-C as an extrapolator from the last derived differential GPS position up to the present position. Integrating the positions and hybridizing all Navstar-GPS and Loran-C pseudo ranges yield autonomous integrity checking, and increased reliability and accuracy. For improved short-term tracking and data transfer performance the Loran-C signals are tracked closer than normal to the peak of the burst giving an additional 12 dB rise in SNR. The plain data-modulation scheme yields a sufficient low BER, a simple detection algorithm and minimal Loran-C accuracy degradation.

1 - INTRODUCTION

Large parts of the United States, the Soviet Union, the People's Republic, the Middle East and Europe will soon have two main navigation systems available: space-based Navstar-GPS and terrestrial-based Loran-C. The Soviet Union operates Glonass, comparable to but not compatible with Navstar-GPS, and Chayka which is identical to Loran-C. Both, the space-based and the terrestrial system, have widely published unique properties in respect of attainable accuracy or cost effectiveness. However, we should also face some of the drawbacks.

Navstar-GPS almost completely lacks integrity, and the potential high accuracy will deliberately be degraded by selective availability when the system becomes fully operational. Unfortunately, neither the probability-density function of the error amplitude, nor the power spectral-density function of the selective availability is known. This makes Navstar-GPS in the Standard Position Service mode less suited as a sole-means precise and reliable navigational aid for high-risk transports. An effective way to circumvent the selective availability problem is the application of Differential Navstar-GPS, DGPS [1]. Differential information from a reference station is distributed either by public-domain short-range LF beacon transmitters or by privately owned long-range LF or HF stations. It is the author's opinion that safety is best served by supplying at least two basically different general-purpose radio navigation systems. Such public-domain systems should be accessible free of charge. Unfortunately, this view contradicts with the intention of some private companies to commercialize the DGPS data.
Further, the higher cost of the rather complex structure of the receiver must be mentioned.

Loran-C receivers have with their lower radio frequencies interesting cost aspects. Unfortunately, low-frequency propagation anomalies often cause insufficient absolute positioning accuracy. Compensation with ASF correction data improves the accuracy at sea significantly. However, it is known that such procedures are complex if high absolute accuracy in urban areas is needed. The lower information bandwidth of Loran-C and the CWI problem must also be considered.

Numerous discussions, especially in Europe, are carrying on whether Loran-C or Navstar-GPS should be the system to embrace. To the author's opinion this discussion should not focus on the preference of either system. Both systems will take considerable market shares. It is much more worthwhile to investigate the potential synergism of integrating the satellite and the terrestrial system. Integration and hybridization may offer significant improvements in accuracy, reliability and (autonomous) integrity over either of the systems separately. This gives new perspectives to all those users which are not satisfied with the integrity of GPS, it's navigation performance in troublesome-propagation areas or with the susceptibility of Loran-C signals to ground-conductivity variations and all kind of interferences. There is a widely experienced uneasiness, especially outside the USA, of not having any control over the exclusively US-military operated Navstar-GPS system. This, and the not yet clearly specified selective-availability procedures are good reasons to look for a more precise and reliable navigation system. The basic elements of such a system are Navstar-GPS and Loran-C.

Integration of the position data obtained from Navstar-GPS and Loran-C in a software filter gives some improvement in accuracy and reliability. It will, however, not cure the selective-availability problem nor will it improve the integrity sufficiently.

So, the three most important problems which this new system, called EUROFIX, primarily should solve are:

- selective availability
- low integrity of Navstar-GPS
- biases of the Loran-C fixes.

2 - EUROFIX

The first key elements in this problem-solving process is the narrow-bandwidth communication capability of Loran-C. The second element is it's excellent short-term, small-area positioning performance. Experiments and studies from Feldman/Letts/Wenzel [2], Forssell [3] and Enge/Bregstone [4,5] made clear that the Loran-C system has perfect potentials for narrow-band communication while maintaining the basic navigation accuracy. A transfer rate of 2.5..6 bps with low error probability can be achieved over ranges up to 1000 km.

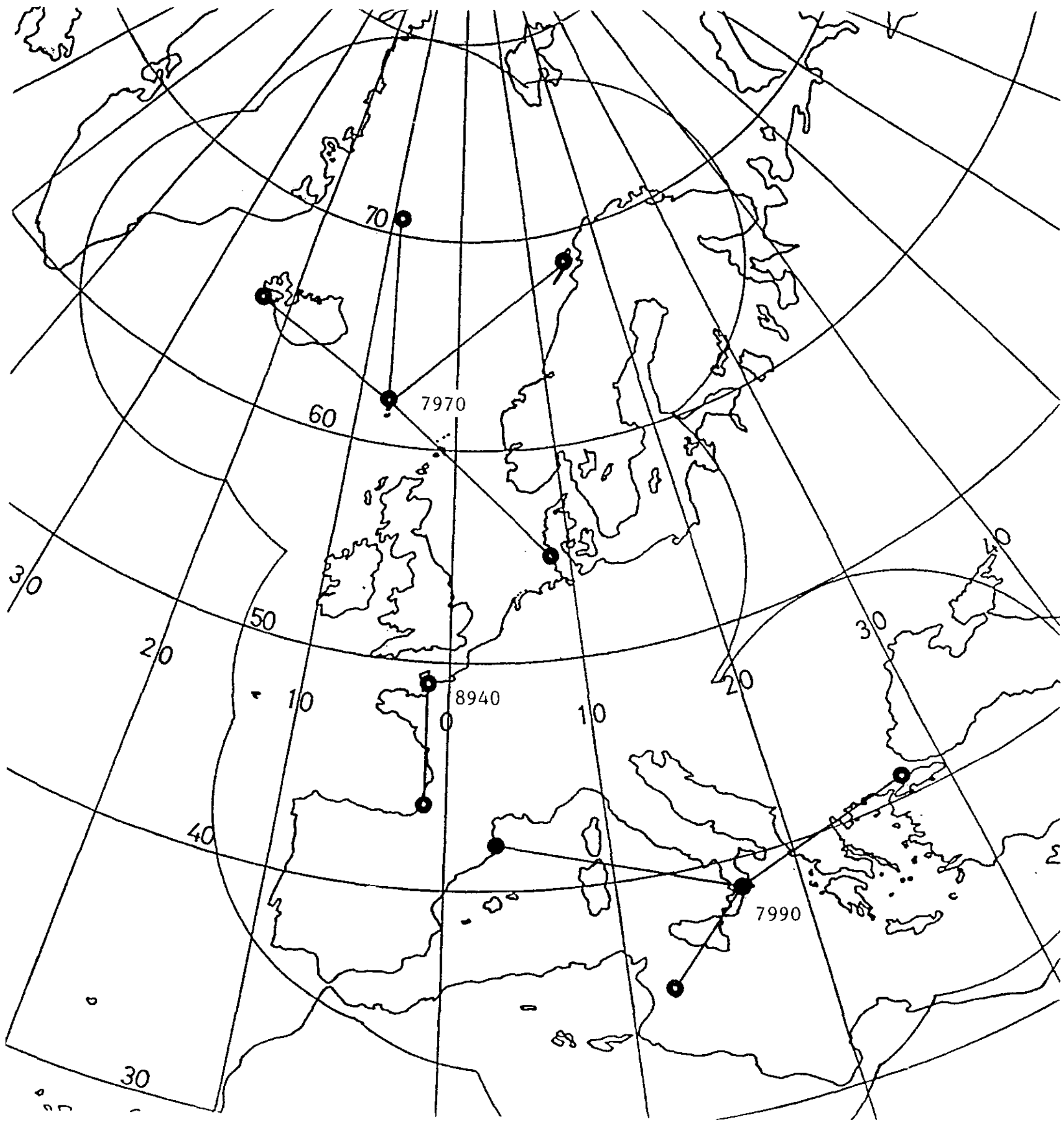


Fig. 1 Coverage area of the proposed EUROFIX differential integrated/hybridized navigation system. Any position in this area is within 1000 km from at least one operational Loran-C transmitter of the Norwegian Sea, the French SNRLC or the Mediterranean chain.

This communication channel opens interesting possibilities for transmitting Navstar-GPS differential and integrity data. In areas with good Navstar-GPS error correlation, the GPS-position can then accurately be estimated and the result may additionally be used for calibration of the Loran-C fixes.
It is suggested that each Loran-C station supplies differential data valid for the area around the station. The full European continent can be covered with differential Navstar-GPS data if the communication range of each station is 1000 km (see fig. 1). Comparative results may be expected in other Loran-C covered areas.

The low transmission bandwidth of the differential data introduces a rather long message delay of about 80..200 seconds (see section 2.2). The elapsed time since the last corrected GPS position update may grow up to 160..400 seconds. Although adequate for static positioning, dynamic users need intermediate updating. This is established by using Loran-C as an extrapolating device for finding the present position based on the last updated Navstar-GPS position. To obtain high-quality tracking performance, the Loran-C signal is sampled about four cycles later than at the standard sampling point position. This gives after the band-pass filter a gain in the SNR of about 12 dB. The possibly introduced sky wave interference is adequately phase-stable during these 160..400 second intervals. The four-cycles delayed phase tracking gives a reduction in the deviation of the phase tracking data (see section 2.3) and decreases the bit error rate (BER) to an acceptable level.

The suggested *EUROFIX* concept is based on the following items:

- Navstar-GPS reference receivers
- Loran-C communication link
- Mobile Eurofix Loran-C receiver
- Mobile Navstar-GPS receiver
- Eurofix concept
- Public-domain access to all transmitted correction data

The following paragraphs explain the mentioned items more in detail.

2.1 - NAVSTAR-GPS REFERENCE RECEIVERS

It is expected, at least in Europe, that Loran-C timing control is going to change from SAM to master-only or full TOT control. Most likely, Loran-C timing will then become synchronized with Navstar-GPS time. The Loran-C stations need then to be equipped with high-grade Navstar-GPS receivers to control the atomic time standards. The same equipment can be used for the error determination in the pseudo ranges to all satellites in view. Enge, Kalafus & Ruane [1] suggest to provide the user with correction data for the pseudo ranges and the range rates. However, this data set should preferably be expanded with satellite health or integrity status. The health status determined at the reference station is generally different from the status as received from the satellites itself.

2.2 - LORAN-C COMMUNICATION LINK

The next phase is to send the computed differential data to the user via the Loran-C navigation signals. Thereto, the timing of the Loran-C bursts can be modulated with time advances and delays of about 1 μs relative to the nominal time value. Conventional Loran-C receivers will hardly notice this modulation if the number of phase advances equals the number of phase delays. So, averaging the sampled phase data will suppress the applied modulation. This modulation process is e.g. used in the Clarinet Pilgrim Loran-C Communication System. Enge [5] suggests further refinements of this modulation method to minimize the remaining small navigation errors.

To keep the hardware and the software complexity of the Eurofix Loran-C receiver low, a very simple to decode, yet efficient coding scheme should be chosen. Further, the applied modulation method must show very low disturbances in the relatively fast navigation phase-tracking loop. And finally, the BER must be sufficiently low so that for normally encountered SNR's at ranges up to 1000 km, only very few differential messages are damaged. Finally, the fastest possible transmission rate should be strived for.

The Loran-C receiver is also used as a positioning device between subsequent Navstar-GPS updates. So, an adequately fast second-order phase-tracking loop with low tracking noise should be incorporated. This can be accomplished with an adequately high SNR and a perfectly balanced phase coding. Using a phase sampling point 40 μs closer to the peak of the Loran-C burst than normally practized increases the apparent SNR by 12 dB (see section 2.3). The short integration time of the phase samples encountered in vehicle navigation makes that the modulation code must also be balanced for short time intervals. To prevent dead zones in the phase-tracking loop with high SNR values, the first two bursts of every GRI are not modulated.

A simple, yet useful code with a code rate of 1/12 is depicted in table 1. The basic data transfer rate equals 1/2GRI or 5..12 bps.

Binary value	Modulation pattern	
	GRI-a	GRI-b
1	0 0 + - + - + -	0 0 - + - + - +
0	0 0 - + - + - +	0 0 + - + - + -

Table 1 Modulation pattern for code rate = 1/12, 0 = no time shift, + = advance, - = delay.

The code balance is maximized for the shortest possible integration time. Note that the coding is different for the a and the b parts of the GRI. The receiver has only to test for two alternatives in every set of 12 bursts in 2 successive GRI's. The decoding is simple, as the code is fully synchronous with the GRI-a and GRI-b frames.
It is interesting to investigate the BER of such a simple coding method. At the 40 μs delayed sampling point the Soustons transmitter gives in The Netherlands a +6 dB post-bandpass-filter SNR. The

range to the transmitter is around 1000 km. At a 1 μs distance from the zero crossing the SNR amounts now about +4.4 dB. Assuming a hard-limiter-type receiver and Gaussian noise, the polarity observation reliability - p_{obs} - then equals 0.9515. It is further assumed that the mean-zero-crossing is perfectly tracked. The 12 detected polarities during GRI-a and GRI-b are after being demodulated integrated in an up-down counter. After having collected the 12 demodulated code-polarity samples of a single code bit, the counter position N ($-6 < N < 6$) tells us whether a logical zero or a logical one is received. $N >= 1$ indicates a logical one while $N <= -1$ means a logical zero. From the binomial distribution function an erroneous decision probability - q_{dec} - of 9.3•E-6 for a single code bit is found. It takes 2 GRI periods, equivalent to 80..200 ms, to transfer a single data bit. The question now arises how long it takes to transmit the complete message. The information per message to be transferred can e.g. be as follow:

Per message:	
preamble	8 bit
GPS Z-count of data set	10 bit
# of satellite data sets	4 bit
station health	2 bit
parity	6 bit +
	30 bit
Per satellite data set:	
SV identifier	5 bit
pseudo range correction	16 bit
range rate correction	8 bit
age of data	8 bit
satellite integrity	3 bit
parity	6 bit +
	46 bit

So, the transmission of differential data for 10 satellites then takes 490 data bits. For a code rate of 1/12, it requires 980 GRI's (39..98 seconds) to transfer the data to the receiver. The probability that one bit of the 490 message bits is damaged then equals 9.3•E-6•490 = 0.0046; on the average 4..10 times per 24 hours.
This figure can be improved by reducing the code rate from 1/12 to 1/24. It takes then 4 GRI's to transmit a single message bit resulting in 2.5..6 bps. The receiver may detect the correctness of the 4-GRI frame synchronization by shifting this frame by 2 GRI. The frame with the highest correlation between two sets of 2 GRI's indicates the correct synchronization.

The message bit error rate for a SNR of +4.4 dB now equals 7.1•E-9. The penalty is an increase of the message time from 39..98 seconds to 78..196 seconds. However, it is expected that a message failure will now happen about once per year. Although correct for Gaussian noise, this optimistic figure will differ for atmospheric noise and high-level interference. However, the structure of the GRI frames assures a reasonable interleaving.

It should be remarked that no forward-error-correction coding is used. Parity bits are only added to prevent erroneous differential corrections. More sophisticated coding may improve the data transmission reliability at even higher transmission rates [4,5]. Unfortunately, it will also reduce the receiver's decoding-algorithm simplicity.

2.3 - MOBILE EUROFIX LORAN-C RECEIVER

The Eurofix Loran-C receiver performs three tasks. First, it is used as a standard receiver in all situations where satellite signals are not received or where the received signals are disqualified. The receiver tracks the Loran-C burst at the standard sampling point. Second, the receiver decodes the phase-modulated data bits from the Loran-C transmitter.
And third, Loran-C tracking is used to estimate the present position. This estimation is based on the last differential GPS update and the incremental Loran-C position since that update. This procedure is necessary to anticipate the differential-data message delay caused by the low 2.5..6 bps throughput. This is much lower than the 50 bps data link which RTCM Special Committee 104 prescribes for differential Navstar-GPS.

Shifting the sampling-point position four cycles towards the peak, from 55 μs to 95 μs, yields about 12 dB gain in SNR for standard Loran-C band pass filters. This value depends on the type and the bandwidth of the band-pass filter. The plot in fig. 2 shows the input and the output Loran-C signals of a 22 kHz wide Seiko SH-C35 band-pass filter. At this delayed tracking position in the burst, the sky-wave signal may already intrude the ground wave. At the standard 55 μs zero-crossing used for normal Loran-C navigation, a 37.5 μs/+12 dB sky wave interference introduces a 25 ns tracking error. This error increases to 1.1 μs at the 95 μs zero-crossing. Fig. 3 demonstrates the real-life improvement in tracking performance. The experienced influence of sky-wave instability during the 30 minutes recording reduces the expected 12 dB gain in tracking performance to just 7 dB. Fortunately, observations indicated that the sky-wave induced phase error varies slowly. This keeps the tracking stable enough to extrapolate the present position from the last updated differential position.

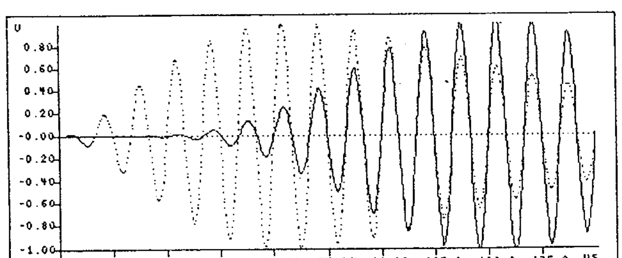


Fig. 2 Amplitude response of a Seiko SH-C35 22 kHz band-pass filter. The dashed line is the input Loran-C signal, while the solid line depicts the output signal. The envelope delay is about 50 μs. The envelope amplitude difference between the 55 and the 95 μs positions equals about 12 dB.

In this delayed tracking mode no ASF data are used or needed. The Loran-C position is at least once per 7 minutes calibrated with differential GPS. So, Loran-C positioning is now actually used as an incremental navigation system.

2.4 - MOBILE NAVSTAR-GPS RECEIVER

There are no special requirements for the used Navstar-GPS receivers. The receiver should preferably output pseudo ranges and the carrier-derived range rates of all satellites in view. These basic data are further to be processed in the EUROFIX software package.

2.5 - EUROFIX CONCEPT

The recovered 'tiny' differential data stream together with the GPS and Loran-C measured pseudo-ranges must now be converted to an optimal estimation of the present position. Fig. 4 shows a block diagram of the complete EUROFIX setup.
Assuming that the Loran-C time will be synchronized with GPS time, hybridizing the various pseudo ranges looks promising. A number of possible navigation modes is listed in table 2. The actual selected mode depends highly on the number of satellites in view and on the number of Loran-C stations within range. The navigation software

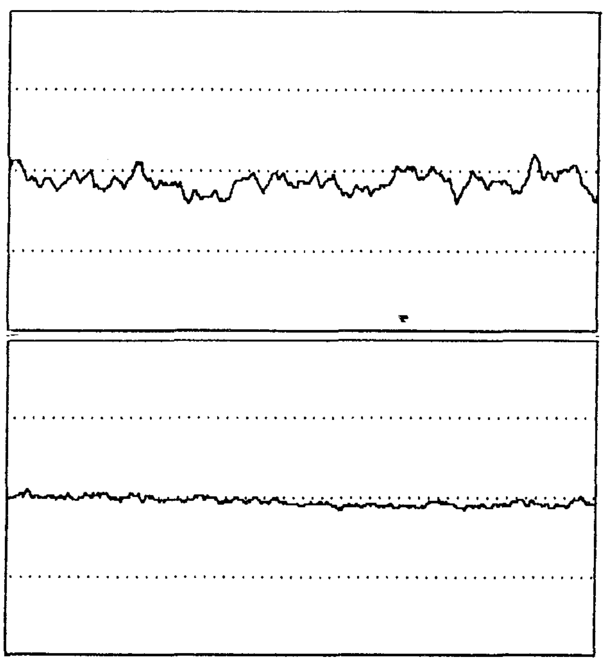


Fig. 3 450 TD-measurements during 30-minutes in The Netherlands of the 8940 250 kW transmitters at Lessay (550 km) and at Soustons (1000 km) in France. In the upper plot the signal is tracked at the standard sampling point, while in the lower plot the signal is sampled 40 μs later. The standard deviation is reduced from 117 ns to 51 ns. The vertical scale is 1 μs per division.

should continuously search for the optimum performance in respect of accuracy and integrity. The table shows that after full deployment of Navstar-GPS, EUROFIX provides highly accurate positioning with integrity checking adequate for most purposes. The rather low-bandwidth Loran-C communication link is sufficiently fast for low-dynamic shipping applications. In the Loran-C coverage area, high accuracy can be achieved for medium-dynamic users.

To get the benefits of the time synchronization between the Navstar-GPS and the Loran-C systems, it is advantageous to use also a single clock for both receivers.
In table 2 it is assumed that Navstar-GPS is used in the three-dimensional mode. This is correct for aeronautical and mountainous applications. At sea, the height is rather accurately known. This makes high accuracy EUROFIX differential Navstar-GPS navigation feasible with three or more satellites. The table may change also if dual-rated Loran-C is applied. Dual-rated three-station operation becomes an interesting option, the inter-chain calibration is now performed by differential Navstar-GPS.

2.6 - PUBLIC-DOMAIN ACCESS TO ALL TRANSMITTED CORRECTION DATA

Accurate and reliable navigation may help to increase safety at sea, especially in endangered ares. The author therefore favors free-of-charge and full public-domain access to the EUROFIX data as transmitted by the Loran-C stations. This approach makes the management and the financing of the system an international affair, and it keeps the cost per user relatively low. The importance of secure navigation makes also that the management of EUROFIX-ed Loran-C chains may probably best be effectuated by governmental agencies, like e.g. the national telecom companies. Such companies have an enormous international cooperation experience and may hopefully diminish the barriers between marine, air and land users of radio navigation.

3 - CONCLUSIONS

The proposed EUROFIX configuration provides an accurate public-domain-access positioning system with potential integrity checking. EUROFIX effectively diminishes the announced selective availability effects of Navstar-GPS and the propagation anomalies of Loran-C signals. Only minor changes in the Loran-C transmissions are necessary, and no additional communication system is required. This saves the already heavily loaded LF spectrum. The required additional technical effort in EUROFIX Loran-C receivers is expected to be very moderate. Conventional receivers are hardly influenced by the phase modulation of the Loran-C bursts for transmission of the EUROFIX information.
Although the name EUROFIX might indicate an exclusively European system, the system can be applied in all parts of the world where Loran-C or Chayka is operational. And finally, there are no basic limitations on applying the same system for the Soviet Union's Glonass navigation system.

Number of Loran-C stations	Number of SV's in view			
	> 4 SV's	4 SV's	3 SV's	2 SV's
Master + 2 slaves	123456789	1234567.9	.2.4..7.9	.2.4....9
Master + 1 slave	1..4.6789	1..4.67.9	...4..7.9	9
Master or 1 slave	1....6.89	1....6..9	9	9

1 - *Autonomous GPS navigation* (medium accuracy)
2 - *Autonomous Loran-C navigation* (medium accuracy)
3 - *Intĕgrated GPS/Loran-C navigation* (medium accuracy)
4 - *Hybridized GPS/Loran-C navigation* (medium accuracy)
5 - *EUROFIX differential-GPS/Loran-C navigation / medium dynamics*(high accuracy)
6 - *EUROFIX differential-GPS navigation / low dynamics* (high accuracy)
7 - *EUROFIX differential hybridized navigation* (medium accuracy)
8 - *Autonomous GPS integrity checking*
9 - *EUROFIX GPS integrity checking*

Table 2 Navigation mode as function of number of GPS space vehicles (SV's) in view and Loran-C transmitters in range.

4 - ACKNOWLEDGEMENTS

Mr. Bart C. Hoogenraad, a former student of the Delft University of Technology, focused his thesis work on different aspects of differential navigation and data communication via Loran-C transmissions. This resulted in constructive ideas and highly valued discussions with the author. The Norwegian Institute of Technology at Trondheim was so generous to give Mr. Hoogenraad all the required facilities to do his research. The stimulating guidance by prof.dr. Börje Forssell during his 6-month stay in Norway is gratefully acknowledged.
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Dr. Durk van Willigen (1934) heads as professor at the Delft University of Technology a group of students and staff working on various navigation systems. The main topics are system studies, software/hardware simulation and receiver design for Loran-C, Omega, Navstar-GPS and MLS. The group started 11 years ago with hard limiter studies.
Dr. van Willigen is also the president of Reelektronika bv, a consultant for radar and navigation. He is a member of the Advisory Board of the Netherlands Institute of Navigation, the Wild Goose Association, the Institute of Navigation (USA) and the Royal Institute of Navigation (UK).

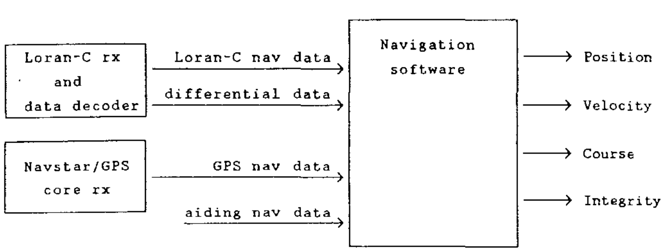


Fig. 4 Block diagram of the EUROFIX differential integrated hybridized positioning system.

Author's address:

Prof.dr. Durk van Willigen
Delft University of Technology
Faculty of Electrical Engineering
Mekelweg 4
2628 CD Delft
The Netherlands
tel +31-15-786186
fax +31-15-781774

The Wild Goose Association - Meeting the Challenge of Worldwide Loran-C Expansion

John M. Beukers

Beukers Technologies, Inc.
St. James, New York

Abstract

After a quarter of a century of development and implementation, Loran-C is now a mature system with a user base approaching one million. With the maturing process comes a shift in emphasis from government-funded development to private sector manufacturing and support. Several countries are currently installing Loran-C transmitters, and others are contemplating adoption of Loran-C but without the technological base and experience that the United States generated during the years in which the system was being developed. This paper explores the role that the Wild Goose Association can play in maintaining a forum, a source of talent and information relating to Loran-C technology as government support dwindles, so that we can move "Boldly into the 90's." Additionally, the paper analyzes the requirements for the Association's internal structure to support such a role.

Biography

Mr. Beukers graduated from London University in 1954 with a degree in Electronics and Telecommunications. In 1957 he immigrated to the United States taking a position with the Avionics division of IT&T. In 1960 he joined Servo Corporation of America where he developed Doppler direction finders and was responsible for the development of the Doppler VOR.

In 1963 he formed his own company, Beukers Laboratories, Inc. and became dedicated to Loran-C and Omega technology. He pioneered the navaid retransmission technology which has been applied to a wide range of applications, in particular, meteorological systems for monitoring the atmosphere.

Following the sale of his company in 1984 to the VIZ Manufacturing Company of Philadelphia and a subsequent 3 year contract, he formed Beukers Technologies and is currently devoting his time to the administration and expansion initiative of the Wild Goose Association.

Mr. Beukers is a past President of the WGA (77,78), past Secretary (75, 76) and present Secretary. He is editor of the Directors' Newsletter and Journal. Mr. Beukers is a senior member of the IEEE, a member of the Institute of Navigation, the Royal Institute of Navigation, the International Omega Association and the American Meteorological Society.

Author's Note .....

Although the author is a WGA Board Member and the current Secretary of the Association, the material presented in this paper and the views expressed are his and do not necessarily reflect those of a consensus of the Board of Directors.

I. Introduction:

To quote from Volume 1, number 1, of the Goose Gazette published in February of 1973:

"The WGA was organized at a meeting held at the Officer's Club, Governors Island, New York on 16 May 1972. This meeting was the result of a letter from Mr. Lloyd D. Higginbotham, Loran Program Office, Electronics Systems Division on 25 April 1972.

In the letter, Mr. Higginbotham expressed his desire to give the Loran community some recognition similar to that given to the people working in the Electronic Warfare Field, where they have for some years enjoyed the comraderie and fellowship of the "Old Crows" organization. After discussing this subject with many of his colleagues, they all agreed he should do something about it, therefore the letter.

The name Wild Goose was suggested by Vern Johnson of IT&T. He indicated that "Wild Goose" would be an appropriate name because of its precise navigation capabilities."

The paper is introduced with this quotation as a reminder that the founding members of our Association envisaged the WGA as a club with "Recognition and Comraderie" as the objective. In the formulation of the Charter, the scope was broadened with the words "Foster and Preserve the Art of Loran" and "Promote the exchange of ideas and information in the field of Loran".

During the intervening years and by following this charter, members of the WGA have made significant technical, political and administrative contributions which have helped guide the Loran-C system to its present mature operational status.

Today the radionavigation environment is quite different and the WGA Board and members must consider the Association's future. Are we to revert back to the original vision or continue to follow the charter into new uncharted territory? This paper presents a case for the latter based upon the unprecedented growth of loran and the technical-operational vacuum that is being created.

The subject of the future of the WGA and the role the Association should take in the 90's has been the topic of discussion at numerous Board Meetings. The concept of expansion of the Association is generally accepted, however, the strategy, tactics and timetable are still the subject of debate. An aim of this paper is to assist in defining the future of the Association and to get member input into this process by means of a questionnaire.

Questionnaire. - A simple questionnaire asking for the attendees' opinions regarding the WGA's future is being passed around as this introduction is being presented. The questions correspond to sections of the paper and should be answered during presentation of the relevant paragraphs. A blank form of the Questionnaire is included with this paper. The completed questionnaires will be collected at the end of the presentation. The results will be tabulated and the collective responses will be made known during the general assembly.

II. Radionavigation Policy and the WGA

In order to discuss the role of the WGA in the 1990's, it is necessary to take out the crystal ball again to see what long range radiolocation systems will be operating during the next decade and their likely status. The promise of the Global Positioning System (GPS) and other satellite systems as a "sole means" to navigation in the civilian theater remains in contention. The threat of service termination of Loran-C and Omega in favor of satellites has moved into the 21st century and is retreating. To provide the required redundancy and signal availability, radionavigation policy is shifting towards interoperabilty of systems, rather than dependence on any one system.

No attempt is made in this paper to second guess the outcome of proposals as to how to employ a Department of Defence controlled system in a civilian community or to resolve the dilemma of selective availability. However for the paper to be meaningful, a premise must be established.

Loran-C has upward of a million users and the number of new installations of receivers each year is estimated to be in excess of 70,000 but probably under 100,000. Due to the better than 99.8% signal availability in the service area and the system maturity, there is an established and fairly well constructed market and distribution system. The market is grossly lacking in training and is way ahead of itself as users attempt to integrate into classic navigational scenarios. Regulatory agencies are underfunded and wrestling with users' new found positioning capability and freedom.

Skirting the no-win debatable issues of accuracy, cost, and the DOD involvement in the Global Positioning System, the GPS system will most likely start to mature around 1995. Any significant market development will have to wait for published and frozen specifications, signal coverage in a service area comparable to that of Loran-C or Omega, and competitive receiver pricing.

Interoperability between systems will become important for redundancy and for those requiring a position of greater accuracy than Omega or for operating outside a Loran-C service area. The combined GPS/Loran, GPS/Omega will become attractive to a mass market if the price can be made competitive.

Based on these observations in the crystal ball, the premise for the paper is that we will see continued expansion of Loran-C world wide during the next decade with an estimated user population in excess of 3 million by the turn of the century. Combined Loran/GPS receivers will capture a significant amount of the market starting in the mid 90's. GPS and other satellite systems alone will have to wait until the latter part of the decade before enjoying significant market penetration.

What is your opinion? You are invited to register it by answering the questions.

Interoperability of Loran-C with GPS and other navaids raises a fundamental question for the WGA. Should the Association embrace other navaids when there is a combining of systems and technologies? It is the opinion of the author that the WGA must broaden its outlook while maintaining an advocacy position for the Loran-C system. As an Association we should go out of our way to make it known that we endorse a radionavigation mix as the only real solution to meet the positioning and navigation requirements of the 90's and beyond, (e.g. the national airspace) for redundancy and reliability. The Interoperability session at this convention is an indication of this policy at work.

Do you concur that the WGA should embrace more than just the Loran-C System?

III. Loran-C is a "Mature" System

1974 was a significant year for loran. The signature of the Secretary of Transportation adopting Loran-C for the United States Coastal Confluence in 1974 marked the start of the maturing process for the system. Prior to this, the system specification was a free for all and the design was a dream playground for engineers. The generation of a system specification, for which the WGA took the initiative, and the formalization of the system by publication in the Federal Register heralded an era of stability for Loran-C. This encouraged manufacturers to allocate resources for receiver development and manufacture and for users to purchase with confidence. At last there was a market. System commercialization in the true sense of the word commenced leading to an extensive and fast growing user population.

It is ironic that while maturity of the system builds a market, this stability creates severe financial burdens on the agencies struggling with unfinished loran business. Support for the WGA from government and industry has shown a significant drop. The impression in Congress of "Complete and Operational", added to publicity of "GPS Sole Means Coming Soon", and the very real budget limitations have all but eliminated serious money being allocated to the system.

There are some important observations to be made. A system will not mature until system specifications are frozen, at which time a market develops. When this happens, development money dries up. In this environment the WGA, and other similar organizations, must redirect their priorities to serving the end user. The organizations must become service and product oriented to disseminate their knowledge and experience to a large and technically unsophisticated user base. They must also become an interface between government and user.

Do you consider Loran-C to be a mature system with these implications? Do you think the WGA should become more user oriented?

IV. Government to User ...... and Back?

What is the Government/User relationship with regard to the Loran-C signal in space? Figure 1 is a graphic description of this relationship. With funding provided by the government, the Coast Guard has the responsibility of maintaining Loran-C service in authorized areas and of providing timely information on the system status. The loran signal in space is available to all who wish to receive and utilize position information. The process is formal and covered by regulations promulgated by the Department of Transportation.

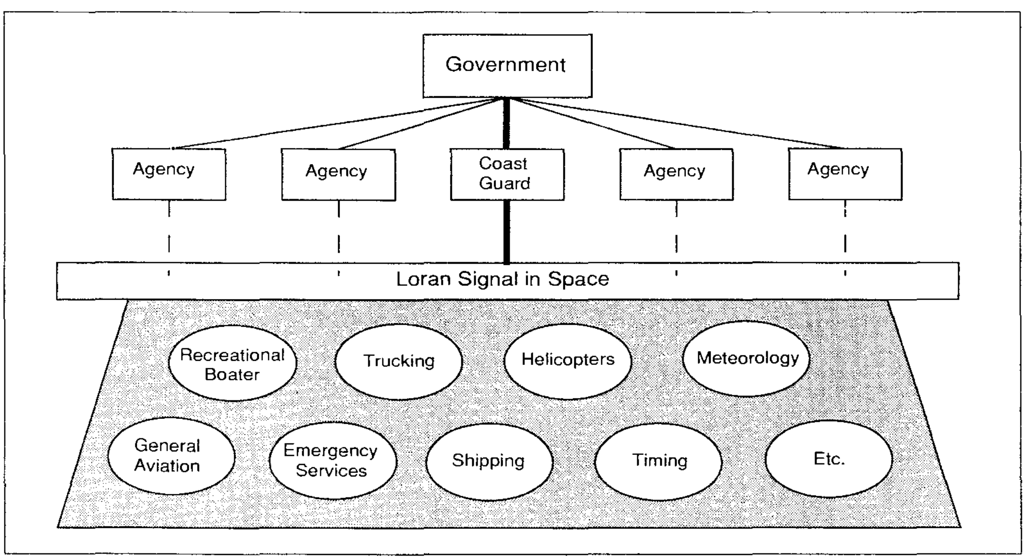
Other agencies of the government have regulatory and operational user interest, such as the FAA, and may influence the technical specifications of the signal to meet specific operational criteria but not without public notice and rulemaking.

The government/inter-agency organization is formal, slow moving yet relatively stable. It is handicapped by severe funding restrictions to react to the current demands of the end user.

By contrast, on the receiving end, there is virtually no coordination, interaction or feedback. Each group of users is a self contained microcosm as illustrated in figure 2. Specific manufacturers sell their products through dedicated dealer networks or catalogs. The groups have their own trade and professional associations. Books and

Figure 1.

Government to User and User to User Relationship



magazines are directed towards a specific readership - flying has little in common with fishing, and neither is relevant to trucking across the country. There is a insufficient technical information in the public domain and the lack of training in the skills of navigation is only too apparent.

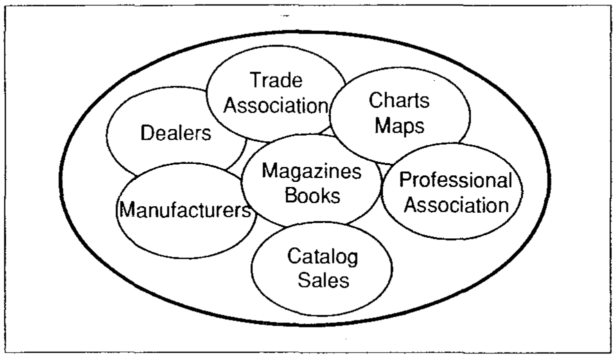


Figure 2. User Microcosm

A characteristic of this large diversified user population is the absence of inter-communication and a unified voice to communicate with the government. What are a million people doing with their little black boxes, and what new initiatives should the government and its agencies be undertaking to serve the user?

The WGA can perform an important function by being the focal point for users, a communicator between groups of users and agencies, and to represent user views and concerns to Congress.

Do you agree or have comments?

V. Future of the WGA

A. Membership

For the past several years, membership in the WGA has hovered around the 500 mark. Each year approximately 10% drop their membership to be replaced with new members. The membership profile tends to be a cross section of government agencies, manufacturers and individuals having specific interests in the loran system. Of late there has been an interest from the user community but representation remains a minority. There is a central core of charter and members of long standing who represents the Who's Who of loran. WGA members, as a group, represent substantial technical breadth covering all aspects of Loran-C technology. Membership is open to individuals and organizations expressing an interest in loran.

B. Manufacturers' Card Program

This is the 18th Annual Convention of the WGA and for 18 years there has been discussion at the Board of Directors' meetings as to how best we can attract users into the Association to broaden the membership base and interests. A few years ago it was suggested that we ask manufacturers of Loran-C receivers to include a card with each unit shipped that would provide a lead for the end user to the Association. A year ago such a card was generated, figure 3, and a few manufacturers offered to include them with their products. The card is returnable to the WGA Boston address and provides space for the sender to identify its referral source, (dealer, manufacturer, friend etc.). Upon receipt of the completed returned card, the WGA fact sheet is mailed together with a letter and a membership application form.

The pilot project has been running for just under a year. Approximately 3000 cards have been issued to four manufacturers. Although the sample is statistically small, a trend has developed which indicates that about 15% of the cards sent to users are returned and of the returned

Congratulations ! on your purchase of Loran-C receiving equipment. You've joined the rapidly expanding group of users of the world's most economical and precise navigational aid in operation today. Now we can introduce you to the world of Loran-C and a unique Association of Loran-C experts and enthusiasts.

We will keep you informed on:

- System improvements
- Charts
- New equipment and techniques
- Tips on installation and use

Keep in touch with other users and the loran engineering profession. And there's an annual technical conference with published proceedings, quarterly newsletters and more - all to help you get the maximum benefit from your investment.

We are the **Wild Goose Association** and welcome you to the world of loran.

For more information, please return this card.

Name __________
Address __________
City, State, Zip __________
Referred by __________

Figure 3. Manufacturers' Card

cards approximately 10% of the users sending in cards join the Association. These percentages are significant and indicate a desire by the end user for more information and to become a part of the system in which they have invested.

Perhaps of equal significance is the benefit the user community will derive from a rapidly expanding mailing list of Loran-C users, should the WGA take the initiative to formulate user wishes and concerns. This information could provide the basis for an active interface with national governments. The probability of making radionavigation policy blunders due to misinformation and the absence of user feedback could thereby be reduced.

There is every indication that the Manufacturers' Card program is achieving its objective. We should now expand the program by increasing the number of participating manufacturers and extending it to dealers. One manufacturer suggested that the WGA use its manufacturer's warranty card returns and supplied a listing to the WGA to add to the mailing list. This has been done and other manufacturers are encouraged to do the same.

The questionnaire provides an opportunity to offer suggestions and, if you are a manufacturer, to become an active participant in the program.

C. Volunteers or Central Staff?

There is a pleasant informality belonging to an organization of just a few tens of individuals. What work that has to be done can be easily managed by a member or two, who develop their own methods of execution. As the organization grows, the workload expands to fill all the available volunteer time and the amount that gets done is entirely up to the individual and not necessarily what should be done. With a membership of a few hundred, the jobs get more complex, demanding formality and continuity. At this point and as new members take over jobs, continuity is often lost. Files may not get transferred and tasks have to be redefined. The net result is an organization that ebbs and flows in accordance with individuals' dedication, the time that they are able to donate and the longevity of their term of office.

This is a difficult stage in evolution. Growing means losing the informality and club-like atmosphere. Growing means professional staff, budgets and all the trimmings of a formal organization. But it is the author's opinion that *grow we must* for maintaining a status quo is not an option. To reduce the Association to a manageable number will render it unable to meet its objective and charter. It will not be able to move ***Boldly into the 90's.***

Why does the WGA find itself in this dilemma? Until the Loran-C system matured, companies that were being funded by government agencies found that their management tolerated or even encouraged involvement in the Loran professional society of the WGA. Secretaries' time, engineers' time, travel, printing and other services were donated and buried in project costs and overhead (we see this taking place on a large scale now with the GPS community). With the maturing process, funding dried up, many of the larger companies left the loran business and this "taken for granted" support vanished. Volunteers stepped in to take up the slack but it became evident that the work required was inconsistent with the time available. This was brought dramatically into focus in 1988 with the almost simultaneous resignation of the WGA Secretary, the one man editor and producer of the Journal, and the Membership Chairman, due to other demands upon their time.

Administration of the WGA is becoming more centralized. Work is currently being done at a central office on a donated basis with the objective of making the effort self supporting by the end of 1990. Several options will then be available: (a) to run the WGA from within using a paid staff, (b) to co-locate and share administration costs with another professional organization, or (c) to contract out to an administrative professional service.

What is your opinion on how the WGA should be run as we move ***Boldly into the 90's***?

D. Infrastructure

Since its inception the WGA has been made up of a Board of Directors, Committee Chairmen (usually Board members), Committee members, and members at large. The framework for the infrastructure to tie the Association together lies in the Constitution and By-Laws. In practice the modus operandi has been informal and the dedication to task has yielded mixed results. This is not a criticism but a fact of life not uncommon to volunteer organizations. For the WGA to move forward and address the challenge of the 90's, a more formal administrative operation is essential, but it must be established in such a way as not to deter creative thought and initiatives.

The central administrative staff is one important part of the infrastructure. This is necessary to provide a permanent office for a phone and files and a staff to provide continuity of operation.

The annual convention is a good example for the requirement of these facilities. Each year a new Convention Chairman is volunteered from the membership. The absence of files, directions and prior experience from previous conventions places an added burden on the Convention Committee who essentially has to start from scratch. Mailing of Calendar Listing material and press releases, printing and mailing of the Call for Papers, printing and mailing of the programs and registration forms, printing of the Technical Proceedings are all tasks that are common to each convention and need not occupy the time of the Convention Committee. These functions should be handled by the central office and, as an added benefit, would ensure consistency and quality of products from year to year. The Convention location and arrangements plus the technical program content are the variables and these should be the primary responsibility of the Convention Committee.

The infrastructure has to include the membership as an active party. This is possibly the most difficult to achieve. Requests for inputs from members for the Newsletters, for example, do not yield bags of mail! Requests for written contributions to the Journal get little or no response. It has to be recognized that membership in an Association such as the WGA is essentially passive, if judgement is to be made on the basis of response. But response may be the wrong criteria to use. Whether a member is a recreational boater, a flyer, an engineer or government employee, the individual has expressed an interest in loran and is probably active in some aspect of the system. By communicating to the membership through newsletters, the Journal of Loran Navigation and other products and services, the WGA can be effective in raising the level of understanding of loran and related issues. This makes for an active membership that can be rallied to the cause when the need arises.

An infrastructure for effective communications is a necessity. Publication of the Journal is a good example. In the past the Journal has been the labor of a dedicated individual or two backed by the individual's organization. The last Journal to be published was in 1986 which covered two years. The editor of 1985/86 issue and previous issues found that, without the support of his organization, it was no longer possible to publish the Journal. The author of this paper took on the responsibility for the continued publication of the Journal and was immediately faced with the absence of files and information on past issues and the lack of a personnel structure through which to get material for publication. While this situation is currently being rectified, it emphasizes the need to establish an infrastructure for continuity.

E. Board of Directors

The WGA Constitution and By-Laws are explicit in respect of the elected President, the elected and appointed Directors and the appointment of Officers (Vice President, Treasurer and Secretary) and the Board has been rigorous in adhering to these formalities. Since its inception in 1972, there have been 152 terms of office open to members to fill. A count of the number of individuals filling these posts currently stands at 43 representing a turnover of just 28%. This is not uncommon with associations that have no limit to the terms of office that individuals can hold. It is indicative of the fact that incumbents are usually returned and new names do not collect votes.

For an Association that is looking to the user community for support, the static and rather limited board membership can be viewed as inconsistent with the WGA objectives. With the risk of offending some of my long time friends, it is the author's suggestion that it is time we reexamine our Constitution and By-Laws in respect of board membership. Some options are (a) to expand the board, (b) to introduce an Emeritus classification for those Old Timers whose knowledge and wisdom are invaluable, or (c) to limit the term of office to say, three years, with a forced one year sabbatical before an individual can run again. In addition there might be a regional representation requirement as well as an overseas position or two.

As we move forward ***Boldly into the 90's***, the somewhat sensitive subject of directors' disposition towards a full engagement with their elected position must be raised. An individual may not give sufficient thought as to whether he or she has the time, travel money and sponsor support before giving a willing "yes" to be placed on the ballot. When the WGA was smaller, it was of little consequence whether there was a full active Board. Today, however, attendance at board meetings and execution of responsibilities must be considered mandatory if the WGA is to meet its objectives. If time is a problem, then the individual should not be balloted. If funds are a problem, then the WGA should consider a travel allowance being placed in the budget. What must be considered here is the effect on the WGA Association and its membership of a seat(s) on the Board being filled by non or only partially active Board member(s). It should be noted that these comments are made to set the stage for the future and are in no way intended to condemn past practices.

The make up of the Board of Directors is an issue on which the membership should be heard and therefore the questionnaire asks for your views and suggestions.

F. Products and Services

What motivates an individual or an organization to join the WGA? First there are those who have been associated with loran and the Association for many years. They have built up professional and personal relationships within the WGA and wish to maintain this comraderie. Then there are those who have a technical/operational interest and wish to make and maintain contacts and keep current by attending the convention. These two groups form the backbone of the Association. But the real potential for membership lies in the several hundred thousand users of loran.

The motivation for an individual in this large population to join the WGA is to obtain benefits in relation to the dues paid and price paid for products and services. This directs us to consider the products and services provided by the WGA to its membership. Today these are minimal and must be improved if members are to be retained and the growth goals achieved.

The WGA is in a unique position to offer substantial benefits to its membership and the loran community. To realize this potential, current individual members and organizational members of the WGA must be prepared to contribute some of their energy to get the ball rolling. Products and services currently provided together with some suggestions of the author follow in alphabetical order. The questionnaire lists these and asks for them to be rated for importance. Additional suggestions are solicited.

1. **Annual Convention**
   Admission to members at a reduced price.
2. **Electronic Bulletin Board**
   Set up and run a loran bulletin board on Compuserve (for example) for use by members and non-members.
3. **Journal**
   Spasmodic publication to be restored to annual and then quarterly. Publish user articles and letters.
4. **Library**
   To include back issues of proceedings, papers, newsletters. Loran bibliographies. Loran books. Chart availability and source information. Video rental: training, installation, technical.
5. **Newsletter, Goose Gazette**
   Published quarterly. Increase frequency to bi-monthly then monthly. Communication through letters to the editor.
6. **Political Action**
   Collective clout in Congress to maintain and improve service. Vehicle for getting action on user concerns and requirements.
7. **Proceedings**
   Available to members not attending convention at reduced price.
8. **Shop by Mail**
   WGA specialty items.
9. **Speakers' Bureau**
   Access to loran experts for speaking engagements.
10. **Technical Service**
    Access to loran technical panel to answer user questions.
11. **Technical Initiatives**
    Introduce and participate in initiatives to improve or secure service.

VI. Financial Considerations

The WGA is a non-profit organization. The Association has been granted tax exempt status by the Internal Revenue Service under section 501(c)(6) of the IRS code. There has been some confusion as to exactly what this means in terms of the financial and member activities that are permitted under this section of the code without jeopardizing the tax exempt status. The code is quite explicit and is well summarized in a booklet published by the U.S. Chamber of Commerce entitled "Association Legal Checklist" (See reference 1), and "Financial Management Handbook for Associations", (reference 2).

Three points are worth mentioning since they have been the subject of deliberations of the Board from time to time: (a) The Association can earn a "profit" so long as its main purpose is not to earn a profit, (b) Section 501(c)(6) imposes no limit on the permissible size of the Association's reserve (bank balance), and (c) there are no restrictions on the amount of lobbying which may be carried on by 501(c)(6) organizations in the common business interests of their members. There are of course many restrictions but the code provides the necessary freedom for the WGA to move ***Boldly into the 90's*** without the fear of losing its tax exempt status. It is the author's personal observation that the Board may have been too timid in its financial administration of the Association and that it is now time to move forward with confidence.

If you are interested in learning more about a 501(c)(6) organization and other management subjects pertinent to running an association such as the WGA, the reading list at the end of this paper is recommended.

A. Budget

Budget preparation has not been a regular activity of the WGA administration. As the Association grows the budgeting process becomes essential and must be made the first order of business of those responsible for the financial and administrative functions. Last year a strawman budget for a five year plan was generated in considerable detail and is currently waiting to be addressed. This was based upon growing the Association from its present size of 500-600 members to a membership of 10,000 worldwide. The budget provides for an income from basic membership dues, however, the main source of revenue is from the Association's products and services that can be provided to members and non-members. (Note that the 501(c)(6) organization is permitted reasonable price differentials between members and non-members). The budget also provides for a paid central staff to handle general administration while assuming a level of volunteer activity for specific initiatives. For example, as previously discussed, to organize a convention such as this, general administrative tasks such as printing and mailing notices and programs, registration, attendance lists, printing and mailing of the proceedings, would be handled by the central staff allowing a volunteer team to concentrate on facility selection, convention planning, speakers and technical papers and sessions.

It is essential in the budgeting process to recognize hidden elements of potential cost. The small all volunteer organization that has most of its material costs underwritten by members' employers must be analyzed on the basis of total labor, overhead and materials input. Once this is done, it is a relatively simple step to segregate that which is to be donated and what must go into the budget to be supported by revenue.

B. Financial Viability

There is no basic difference between the WGA Association non-profit organization and a classic business. Total revenue must exceed the running costs and there must be sufficient working capital to enable the WGA initiatives, products and services to be executed without restraint. From a marketing standpoint, products and services must be desirable and of high quality to attract members and priced at a level to generate revenue. Membership dues must be consistent with the products and services offered but sufficiently high to defray the direct costs of the services provided. This may all sound rather basic but without rigorous attention to budgeting and tracking income/expenditure, establishing membership dues and pricing products becomes guesswork and financial viability cannot be assured.

The booklets put out by the U.S. Department of Commerce are very explicit on all aspects of budgeting and financial control for Associations such as the WGA. They would be well placed on the reading list of those seeking election and especially for those who are appointed officers of the Association.

VII. Conclusion and Actions

The purpose of this paper has been to focus on where the WGA stands today in an environment radically different from that which existed at its inception. It is the author's opinion that the WGA is uniquely poised to serve an expanding loran community, but, to do this, it must rethink its infrastructure and organize to address a diverse user population in addition to its traditional technical membership.

Specifically the author suggests:

(a) A change in the constitution of the Board of Directors and of their terms of office.
(b) Setting up guidelines for the involvement expected of elected and appointed directors and officers.
(c) A professional paid central staff for WGA administration.
(d) Continuation and expansion of the manufacturers' card program.
(e) Raising the standards and increasing the products and services offered by the WGA.
(f) Pricing of Member dues, products and services to be consistent with revenue requirements and market acceptance.
(g) Adoption of a rigorous budgeting process.

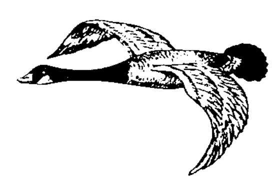
The Board of Directors' deliberations on these and other matters discussed in this paper will be greatly assisted by member comments and suggestions. Completion of the questionnaire would be an effective method of communication and is a requested action.

VIII. References and for further reading.

The following are published and available from:

The Association Department
United States Chamber of Commerce
1615 H Street N.W.
Washington D.C. 20062

1. Association Legal Checklist.
2. Financial Management Handbook for Associations.
3. Federal Tax Treatment of Unrelated Business Income.
3. A Guide to Association Committees.
4. Associations and Lobbying Regulation.
6. Guidelines for an Association Seeking a Chief Staff Executive.



WGA Participant Questionnaire

II. Radionavigation Policy

What dates do you consider to be realistic?

Loran-C termination	2000	2020	Later
Omega termination	2000	2020	Later
GPS approval for use in US airspace			
Sole Means	1995	2000	never
Interoperable	1995	2000	never
GPS user base of more than 100,000			
Sole Means	1995	2000	2010
Interoperable	1995	2000	2010

Should the WGA embrace other Navaids to cover Loran-C Interoperability? Yes-No

III. Loran-C Maturity

Do you consider Loran-C to be a mature system? Yes-No
Should the End User be the WGA's priority? Yes-No

IV. Government to User ......and Back

Do you think that the WGA can serve as an effective communicator between users and government? Yes-No

V. Future of the WGA

B. Manufacturers' Card Program

If you are a manufacturer and would be willing to become part of this program, please check the box and put your name and phone # below. Suggestions to make the program more effective would be welcome. ☐

C. Volunteers or Central Staff?

What is your opinion on how best to run the WGA as we move ***Boldly into the 90's***? Please check your preference.

(a) From within using a paid staff.
(b) Co-locate and share administration with another professional organization.
(c) Contract to a professional administrative service.
(d) Other, please suggest.

E. Board of Directors

Which alternatives do you favor for expanding the WGA Board of Directors? Please check your choice(s):

(a) Change the Constitution to add more Directors.
(b) Introduce an Emeritus classification.
(c) Limit the term of office by introducing a sabbatical.
(d) A combination of the above.
(e) Add Regional and International seats.
(f) Leave things as they are.

F. Products and Services

Please rate the importance of this list of products and services and add any that you would like to see offered by the WGA. 1- high, 2- useful , 3- low priority.

1. **Annual Convention** .... •
   Admission to members at a reduced price.
2. **Electronic Bulletin Board** .... •
   Set up and run a loran bulletin board on Compuserve (for example) for use by members and non-members.
3. **Journal** .... •
   Spasmodic publication to be restored to annual and then quarterly. Publish user articles and letters.
4. **Library** .... •
   To include back issues of proceedings, papers, newsletters. Loran bibliographies. Loran books. Chart availability and source information. Video rental: training, installation, technical.
5. **Newsletter, Goose Gazette** .... •
   Published quarterly. Increase frequency to bimonthly then monthly. Communication through letters to the editor.
6. **Political Action** .... •
   Collective clout in Congress to maintain and improve service. Vehicle for getting action on user concerns and requirements.
7. **Proceedings** .... •
   Available to members not attending convention at a reduced price.
8. **Shop by Mail** .... •
   WGA specialty items.
9. **Speakers' Bureau** .... •
   Access to loran experts for speaking engagements.
10. **Technical Service** .... •
    Access to loran technical panel to answer user questions.
11. **Technical Initiatives** .... •
    Introduce and participate in initiatives to improve or secure service.

Name:
Phone:

Please use the reverse side of this sheet for comments and suggestions. You have the right to remain anonymous!

Results of Convention Questionnaire

Participants provide useful information with some surprises.

During the presentation of the paper entitled "The Wild Goose Association - Meeting the Challenge of Worldwide Loran-C Expansion", given by John Beukers, a questionnaire was handed to the session participants. The results of 89 completed responses have been tabulated and are presented graphically below and provide some food for thought.

The Vertical axis on each graph represents the number of respondents. The Horizontal axis on the graph showing the Product and Service priorities is a percentage derived from the Importance categories 1 to 3.

Many respondents changed the question relating to End User Priority to "a" priority rather than "the" priority. A number of respondents added further categories of phase-in/phase-out years for the various navaid systems. The results have been prepared to reflect this.

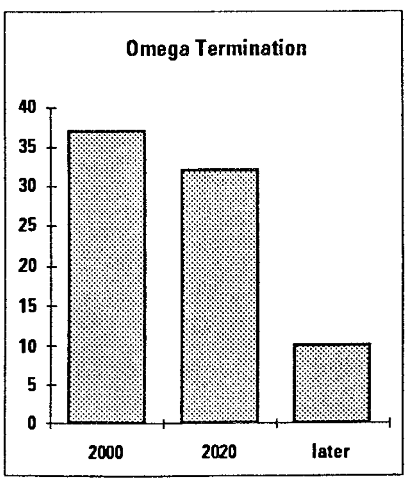
Perhaps the biggest surprise is the priority that the membership puts on the WGA's political activity. This, along with the almost unanimous positive response to the Effective Communicator question, is regarded as a clear signal that the WGA has an important role to play in influencing Radionavigation policy.

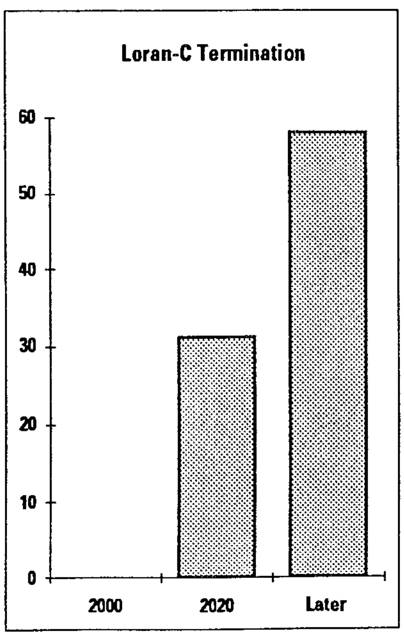
This information, along with the many comments and observations written on the questionnaires, will be useful to the Board of Directors in their deliberations formulating strategy for the 90's. Respondents are to be thanked and congratulated for an effective response.

II. Radionavigation Policy

(a) Termination Dates for Loran-C and Omega

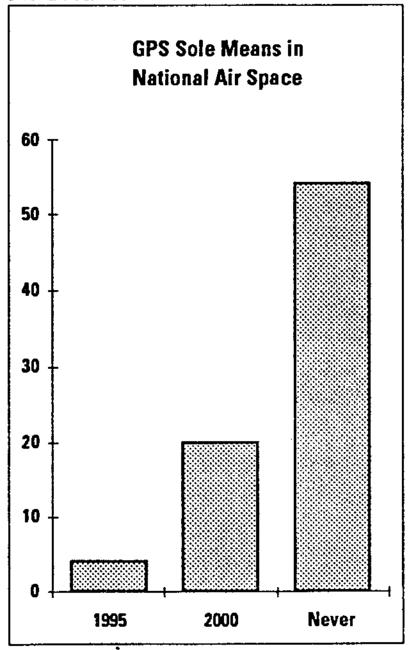
The prognosis for loran is a long and healthy life and one would trust that the government is listening. The WGA might indulge in some long range planning to be consistent with this thinking. On the other hand it would appear that our sister organization, the International Omega Association, has some PR work to do. Perhaps it is not generally known just how much Omega is used worldwide.

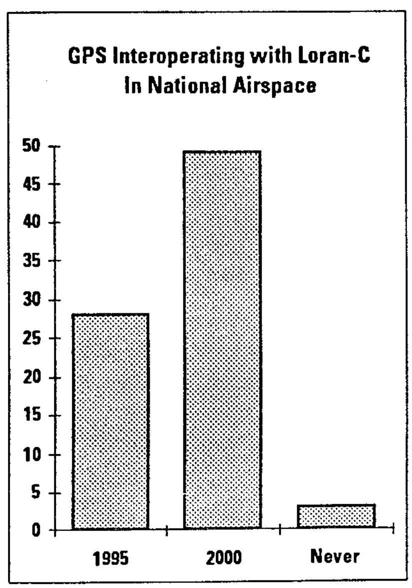




(b) GPS Approval for Use in National Airspace

Perhaps it is no surprise to find that the majority do not consider that GPS alone will satisfy the requrements for the U.S. air space. Technical analysis would appear to confirm this and official pronouncements are tending to support the position. Most respondents, however, consider a combination of Loran-C with GPS will provide a satisfactory navigation mix, but not until the latter part of the decade.





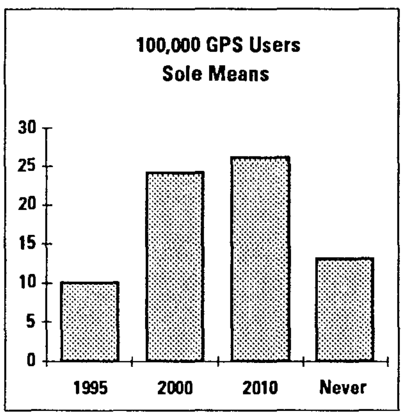
(c) GPS User Base of More Than 100,000

The wide disparity of answers to these questions probably reflect the uncertainty of DoD policy to the civil use of GPS and the delays associated with the program. The consensus is that interoperability will speed up the introduction of GPS although not until the latter part of the decade.

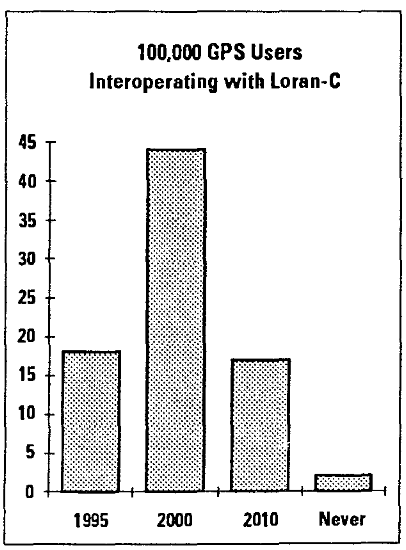
A conclusion could be drawn that to predict a market for GPS as a sole means of navigation could be hazardous!

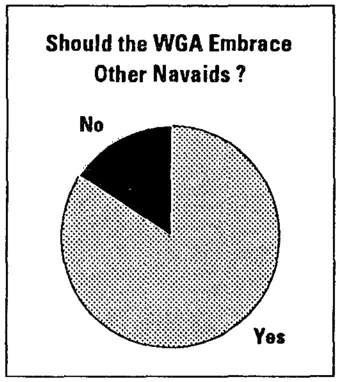
An overwhelming majority of participants recommend embracing other navaids - ***if in conjunction with Loran.***

(i) Sole Means



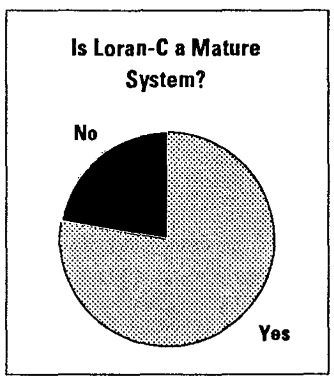
(ii) Interoperable

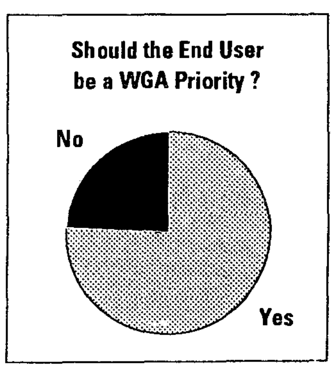




III Loran-C Maturity

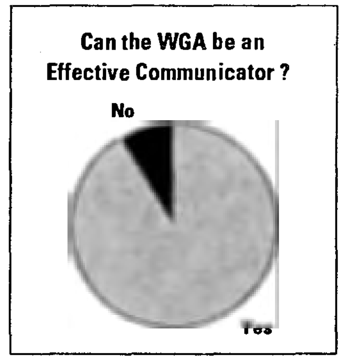
A surprising number of respondents indicated that Loran-C was not a mature system and added by comment that there was much room for improvement. Quite a few made the point that the WGA should not abandon technical issues in favor of an End User priority.





IV Government to User and Back

While a majority indicated that the WGA can be an effective communicator between user and government and visa versa, several respondents qualified their replies with the observation that the Association's name was a negative factor.

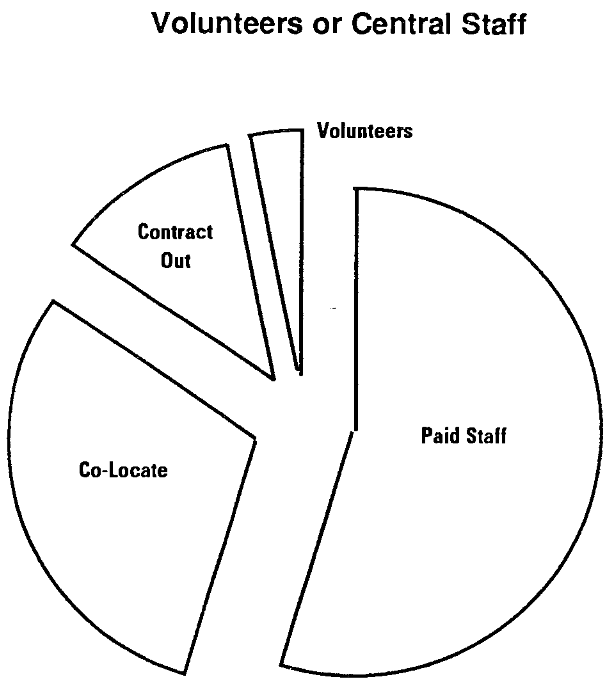


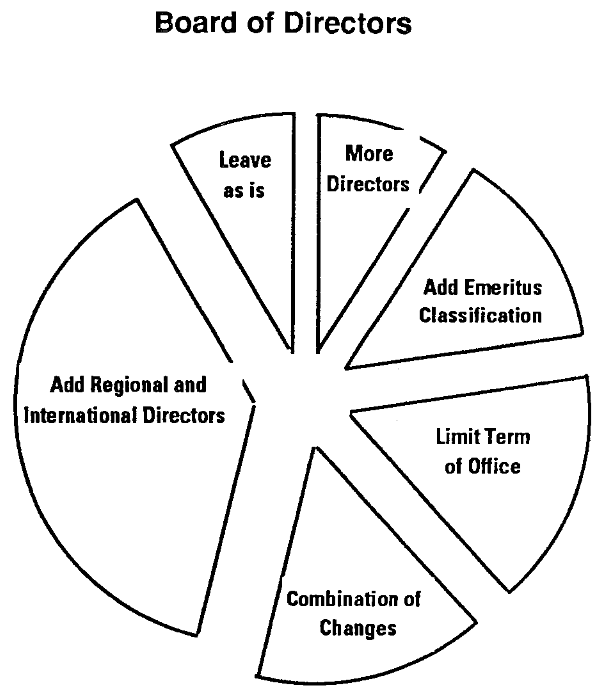
V Future of the WGA

One of the key issues to be resolved by the Board of Directors is the design of the Association's infrastructure to satisfy the world-wide interest in loran. The replies to questions, along with modifying comments, provide a good indication of the thoughts of the membership. This input is invaluable to formulating new directions consistent with the wishes of the membership.

(c) Volunteers or Central Staff

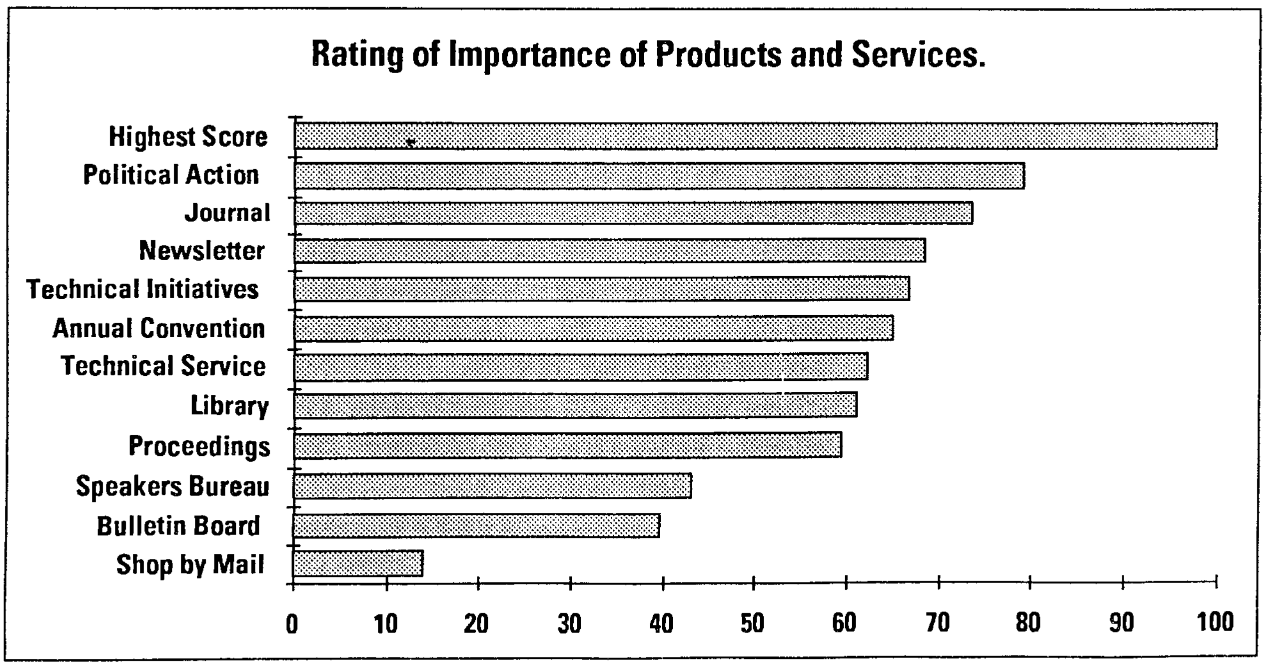
Administration of the Association is key to its on-going success. Few suggested that the WGA continue on a volunteer basis, but the responses were divided as to how to go about this. A majority indicated that a paid staff was the route to take with some reservations noted relating to dues structure and the ability to finance a central staff. A number of possible organizations with which to co-locate were mentioned. The results are shown on the following page





F. Products and Services

Using the ratings of 1 for high importance, 2 - useful and 3 - low priority, respondents' answers were summed and converted to a percentage. This provides an indication of the overall priorities that the Association might place on the various products and services offered to satisfy the wishes of the membership. No additional suggestions were made.



LORAN-C IN INDIA AND HER NEIGHBORHOOD

MR. B.S. SRIVATHSAN

Honorary Member, International Association
of Lighthouse Authorities & formerly Director General,
Indian Lighthouse Service

Mr. Chairman, Ladies and Gentlemen,

It is indeed my privilege to participate in this Symposium and present a few thoughts on the developmental trends in the field of Hyperbolic systems of Aids to Navigation happening in India and her neighborhood for the consideration of you all.

2. Scenario since '60s

2.1. After the Second World War, when hyperbolic systems of Aids to Navigation came to be introduced for civilian use, India's choice, for historical reasons and based on her closer maritime trade links with Great Britain, fell naturally upon the Decca Navigator system. Accordingly, 2 Decca Chains operating on the 'Mark-5' system and each comprising a 4-station configuration were set up in the '60s to serve the ports of Bombay and Calcutta and their approaches. While the 'day-light' service of these Chains was satisfactory, mariners were not quite happy about the night coverages because of 'Lane-slip' and other causes attributed to the high level of radio noise in the tropics and the proximity of the transmitters to the magnetic equator. With a view to overcoming these problems, the 2 Chains were updated in mid-'70s to the 'Mark-10' system, which basically involved 'Multipulse' transmission, i.e., 5 spot frequencies from each station in a cycle pattern in addition to the simple 'Lane Indent' format of transmissions employed earlier. The improvement in service, as a result, was no doubt significant. Based on this experience, a third Decca chain ('Salaya Chain') was set up in 1977 to provide adequate coverage in the Gulf of Kutch where Very Large Crude Carriers (VLCCs) had to negotiate through a 70-mile long narrow channel with quite a few sharp bends and constrictions. This Chain, also a 4-station configuration, has relatively shorter base-line lengths as compared to the Bombay and Calcutta Chains and is providing good service coverage on a round-the-clock basis.

2.2. As the transmitters employed in the Bombay and Calcutta Chain stations belonged to the 1st generation and started displaying signs of outliving their useful 'life', fresh proposals were mooted in 1985 to replace these by solid-state Decca transmitters. When the detailed estimates were about to be approved by the Government, it became known that the operations and management of similar Decca Chains established in Great Britain were to be taken over by the Trinity House since the equipment manufacturers who had been shouldering these responsibilities for nearly 3 decades suddenly notified for reasons, which you are well aware of, that they would no longer be in a position to continue to do so. Fortunately, the International Association of Lighthouse Authorities stepped in and after a careful and exhaustive study of the situation, recommended in May 1987 a set of guidelines indicating the possible future trends in the field of terrestrially based Aids to Navigation. As a result, India was perhaps the first country to re-cast her plans and decide, in principle, that the existing Bombay and Calcutta Decca Chains shall be replaced by the Loran-C system.

3. Proposed Loran-C coverage

3.1. First phase: In the first phase, the 4 Decca transmitters each in the Bombay and Calcutta Chains are proposed to be replaced by 3 Loran-C transmitters as follows:

	Master	Secondary 1	Secondary 2
Bombay Chain	Dhrangadhra 23° 00' 14" N 71° 01' 39" E	Billimora 20° 45' 40" N 73° 02' 17" E	Veraval 20° 57' 07" N 70° 20' 13" E
No. of Txs.	4 HCG	4 HCG	4 HCG
Power	11 kW	11 kW	11 kW
Calcutta Chain	Balasore 21° 29' 08" N 86° 55' 18" E	Patpur 20° 26' 48" N 85° 49' 47" E	Diamond Harbour 22° 10' 18" N 88° 12' 25" E
No. of Txs.	4 HCG	4 HCG	4 HCG
Power	*43 kW	11 kW	11 kW

(*Using a 350 ft. high Aerial Mast)

3.2. Second phase: In the second phase (mid-'90s), when the existing Salaya Chain transmitters are exposed to reach the end of their useful 'life', these are also proposed to be replaced by the Loran-C system. However, advantage is intended to be taken of its contiguity to the Bombay Chain so that 2 stations of the latter, viz. Dhrangadhra and Veraval will be common to both the Chains and will be operated in two rates, one for Bombay Chain and another for Salaya Chain. In addition, the Salaya Chain will have another Secondary station at Naliya (23° 15' 04" N; 48° 46' 04" E).

3.3. Perhaps fpr the first time, existing Decca Chains are yielding place to the Loran-C system and it can therefore well be said that India is taking the lead in providing the much needed visibility and acceptability of the Loran-C system in this part of the world, thanks to IALA's timely and well-defined futuristic guidelines.

4. Scenario in India's neighborhood

4.1. As you are aware, Saudi Arabia has 7 Loran-C transmitters in operation covering the land mass of Saudi Arabia, the entire Red Sea and the Persian Gulf. The Suez Canal has also been functioning with a VTS comprising the Loran-C system which has proved to be highly satisfactory. The People's Republic of China has 3 Loran-C transmitters and is considering the proposal to set up 6 additional transmitters in the very near future.

4.2. Bangladesh is perhaps the only other country in India's neighborhood operating a Decca Chain with 4 stations. While these transmitters are also due for replacement, it is reported that the proposal is held up due to delays in the allocation of funds on account of other high priority projects. It is very likely that when India sets up the Calcutta Loran-C Chain, Bangladesh will also hasten up the conversion of her Decca Chain to the Loran-C system.

4.3. A few countries in South East Asia, e.g., Malaysia, Indonesia, etc., which have close working arrangements with Japan in the field of Aids to Navigation are still having an open mind and some special efforts are needed to give the Loran-C system a break-through in this region.

5. Some concerns and solutions

5.1.1 The main concerns facing several Administrations while considering proposals for the establishment of Loran-C system can be broadly summarized as follows:

5.1.1. Future of Terrestrial system: In the expectancy of availability of the GPS on a global basis for civilian users in the near future, there is a natural tendency for Administrations to defer heavy capital investments on any terrestrially based hyperbolic system. To meet this situation, not only the preeminence and reliability of the Loran-C system by way of its several advantages to users have to be highlighted adequately but also the statement of IALA that "..on a global basis the future is likely to lie with the Loran-C system as the primary wide area radio aid to marine navigation until well after the turn of the century" needs to be brought to the notice of all concerned with due emphasis. At the same time, it is worth considering whether the several limitations of the GPS, viz. realistic time schedules, period of availability, receiver cost, etc., can be made known in a manner that is not objectionable.

5.1.2. Superiority of Loran-C over other terrestrial systems: Some Administrations are reported to have an incorrect notion that in so far as marine navigation is concerned, they can afford to cut down the capital costs drastically by choosing less expensive systems (say, Differential Omega) rather than the Loran-C system. Such a line of thinking can be attributed only to the lack of awareness on their part and steps therefore need to be taken to remove such misconceptions. A comprehensive study of the merits and de-merits of the various systems by a reputed, preferably independent, R&D Establihment which can publish the results of their studies for the benefit of all concerned is therefore recommended.

5.1.3. Receiver cost: While owners of foreign-going ships may not mind investing say $2,000 on a Loran-C receiver, a majority of the smaller category vessels such as fishing boats, barges, coastal vessels, etc., may hesitate to go in for a receiver even of the simpler version, say @ $500. As the users in such categories are in very large numbers, efforts should be made to examine ways and means of marketing a low-cost Loran-C receiver by maximizing the application of the latest production technologies.

6. New Applications

6.1.1 Apart from the presently accepted usage as an aid to marine/air navigation, the applicability of the Loran-C system in other fields has to be brought to the notice of Administrations. Some examples are indicated below: -

6.1.1. Sea-bed Explorations: In view of the expanded limits of economic zones as now permitted under International Laws, many Administrations are eager to set up schemes for commercial exploitation of mineral wealth from the ocean beds. The utility of Loran-C system in such mining operations can be high-lighted.

6.1.2. Homing Devices for Traffic Control/Security: The need for an accurate homing device in heavily congested traffic zones in metropolitan cities needs hardly to be emphasized. The Loran-C system appears to be ideally suited to meet such requirements. Also, such homing devices may be called for in highway patrols and to combat problems of law and order. The capability of Loran-C system to meet such situations can well be brought about.

7. Conclusion

7.1. While it is accepted that the Loran-C system has made great strides in the last 2/3 decades in the developed countries, it has to be acknowledged that there is a lack of awareness in the developing/underdeveloped countries of its multifarious utility and its technical pre-eminence as compared to other terrestrially based systems. I therefore sincerely hope that the professional experts as well as the representatives of manufacturers of Loran-C transmitters/receivers present here will be able to find out ways and means to render the system more economically viable without sacrificing quality or performance thereby widening its acceptance on a global basis thus paving the way for a bright future for the system in the '90s.

Thank you.

Presented on behalf of Mr. Srivathsan by Mr. Edward L. McGann

SESSION 4

LORAN-C TECHNOLOGIES

Technical Co-Chairman Francis S. Cassidy of Datamarine (top right) breakfasts with participants in this Wednesday morning session: (left to right) Gary L. Noseworthy and David H. Amos of Synetics, Paul R. Johannessen of Megapulse and (second row, left to right) Martin Beckman of the Delft University of Technology in the Netherlands, Gerard Lachapelle of the University of Calgary in Canada, Henry J. Wychorski of Northeastern University in Boston and David H. Gray of the Canadian Hydrographic Service in Ottawa.

PERFORMANCE OF LORAN-C ON THE CANADIAN WEST COAST

G. Lachapelle
T. Speakman
B. Townsend

Department of Surveying Engineering
The University of Calgary
2500 University Dr, N.W.
Calgary, T2N 1N4
Canada

ABSTRACT

Under a project sponsored by the *Transportation Development Centre, Transport Canada*, the diurnal and seasonal stability of Loran-C in the Coastal Mountains of British Columbia was investigated by continuously monitoring the Canadian West Coast Chain (#5990) signals over a four month period (May - August 1989) at Pemberton Airport (Latitude = 50° 18', longitude = 122° 31' W, Elevation = 200 m), some 90 km North of Vancouver. Data collected by Megapulse, Inc, at the same site during May - June 1987 was also available to study the long term stability of Loran-C. Some ten other sites in an area within 80 km from Pemberton Airport were also occupied for a shorter period to study the effect of the topography on Loran-C positioning and ascertain that differential Loran-C is not a viable option to improve accuracy in the mountainous part of Southwestern British Columbia. An analysis of the signal-to-noise ratio (SNR) data reveals a good stability of the Loran-C signals over the periods investigated for all transmitting stations except Shoal Cove which is located at some 800 km North from Pemberton. The SNR of Shoal Cove is above -10dB for only part of the time and is a function of the level of ionospheric activity. The absolute accuracy of Loran-C, which is affected by conductivity and topography, is of the order of several hundred metres. The differential Loran-C test revealed that DLC does not result in any major improvement due to the effect of the topography, which can amount to several hundred metres. An analysis of the Loran-C derived positions at the Airport Site reveals a diurnal stability of 5 m in each of the two horizontal coordinates, a corresponding seasonal stability of 20 m and a long term stability of 25 m. An en-route calibration method using differential GPS is proposed to calibrate the effect of conductivity and topography on Loran-C signals and investigate further the stability of Loran-C. An accuracy of 50 m, which would meet the requirement of a large number of land users, may thus be within reach with Loran-C. The use of similar airborne calibration methods at different altitudes to analyse and calibrate the spatial variation of the secondary phase lag is also discussed.

INTRODUCTION

Loran-C was adopted by Canada in the 1970's as the primary radionavigation system for the Great Lakes and the contiguous waters off the the East and West Coasts. The land part of the country which is covered by Loran-C include the Maritimes, southern Quebec, southern Ontario and the southwestern part of British Columbia. This latter part, which is covered by the Canadian West Coast Chain (No. 5990) as shown in Figure 1, includes a rugged part of British Columbia with heights varying between 0 and 3,000 m. The U.S. mid-continent expansion will provide coverage in the southern part of the Prairies (e.g., Heyes 1988). Loran-C will therefore be available along most of the Canadian east-west road transportation system. Loran-C is expected to be a strong competitor to provide the navigation component required for many classes of land navigation users provided specific accuracy and reliability requirements are met (e.g., Rostenne & Myers 1989). In recent years, many technical investigations were also conducted related to the extension of the Loran-C coverage in Canada (Transport Canada 1986, RTAC 1987). The possibility of using Loran-C for air navigation has also been considered.

Both accuracy and reliability are of fundamental importance when assessing the suitability of Loran-C for specific navigation tasks. On land, these parameters are relatively difficult to quantify due to ground conductivity variations. In mountainous areas, the situation is further complicated by the effect of the topography which can cause variations of up to several hundred metres over relatively short distances (e.g., Johler & Cook 1984). In Canada, the most difficult land area will therefore be that covered by the Canadian West Coast Chain as shown in Figure 1. An analysis of the ground conductivity within the coverage of that chain was conducted in 1988 using a series of flights along selected routes and concluded that the conductivity was poorer than previously anticipated (Dean 1988).

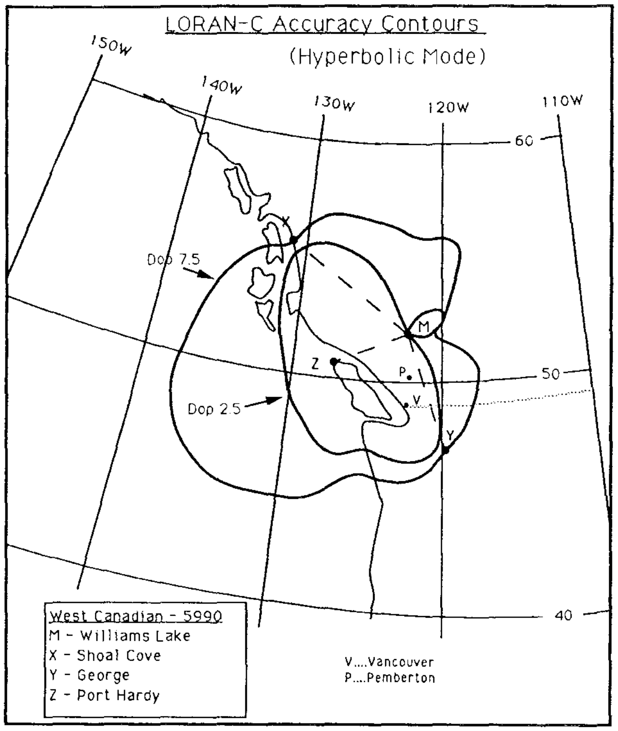


Figure 1: Estimated Coverage of Loran-C Canadian West Coast Chain

In order to analyse the accuracy and reliability of Loran-C in the southwestern part of B.C., a monitoring station established at Pemberton Airport, located some 90 km North from Vancouver, has been used to collect data from time to time over the past few years. During the period May-June 1987, data has been collected and made available by Megapulse, Inc., of Bedford, Mass. Under the current project, data has been collected on a continuous basis since May 1989 by the Department of Surveying Engineering, The University of Calgary. Under the same project, differential Loran-C has been tested by occupying some 10 sites for periods of 24 hours with a second receiver during the second half of June 1989. The specific objectives of the current experiment are as follows:

- Stability of Loran-C
  - Diurnal
  - Seasonal
  - Long term (multi-year)
  - SNR characteristics
- Absolute Accuracy (with respect to WGS72)
- Differential Loran-C performance in the mountainous part of southerwestern British Columbia

FIELD MEASUREMENTS

The location of the Pemberton Airport site with respect to the Canadian West Coast Chain is shown in Figure 1. The WGS72 coordinates of the transmitting stations and observation site are listed in Table 1. The distances to the transmitting stations are as follows:

M (Williams Lake - 400 kW) 186 km
X (Shoal Cove, Alaska - 400 kW) 808 km
Y (George, Wash. - 1,200 kW) 422 km
Z (Port Hardy - 400 kW) 329 km

Table 1: Absolute (WGS72) Coordinates of Loran-C Canadian West Coast Chain Transmitters and Test Sites Used in the Pemberton Area.

STATION	LATITUDE	LONGITUDE	HEIGHT
Grand	N49 19 17.294	W123 03 28.654	114.5
Pemberton	N50 18 13.114	W122 44 27.132	194.9
Hollandia	N50 29 40.018	W122 58 32.114	224.7
NDB #2	N50 13 52.739	W122 28 38.843	207.3
Bridge	N50 05 28.740	W122 32 10.441	190.9
School	N50 07 00.248	W122 57 27.476	663.7
Tisdall	N50 16 04.541	W122 52 12.336	369.9
Back Az	N50 18 24.326	W122 33 48.058	787.4
Eldridge	N50 23 33.706	W122 52 18.936	209.2
Phare	N50 28 28.142	W122 37 28.659	470.4
D'Arcy	N50 33 12.544	W122 28 36.549	254.7
Birkenhead	N50 33 54.407	W122 39 38.551	646.2
Bralorne	N50 46 37.695	W122 49 09.345	997.9
Transmitters			
Williams L.	N51 57 58.780	W122 22 03.240	
Shoal Cove	N55 26 20.851	W131 15 19.648	
George	N47 03 47.990	W119 44 39.530	
Port Hardy	N50 36 29.731	W127 21 29.043	

Since May 1989, Loran-C data from M, Y and Z has been collected on a continuous basis (90 second interval) using an Accufix 500 receiver provided by Megapulse, Inc. Data from X has also been collected from the later part of August onwards. The receiver performed satisfactorily and only a few hours of data was lost on a few occasion. The data collected consisted of M-X, M-Y and M-Z Time Differences (TD's) and associated signal-to-noise ratio (SNR) data. Similar data collected with the same type of receiver was collected at the same site during the period May-June 1987 by Megapulse (Lecaroz 1988). This data was made available to the investigators to analyse the long term stability of Loran-C.

Some 11 stations within a radius of 80 km from Pemberton Airport were also selected to perform Loran-C measurements with a second receiver. The location of these stations are shown in Figure 2. The WGS72 coordinates of the

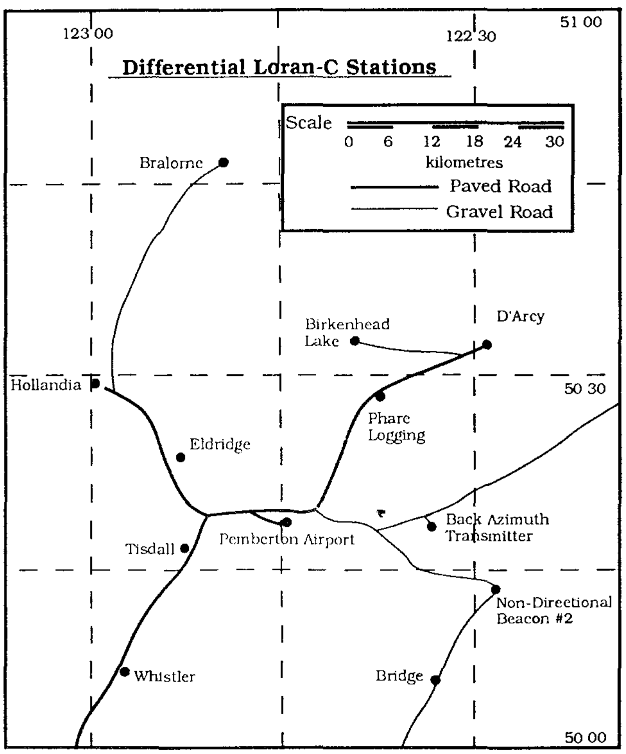
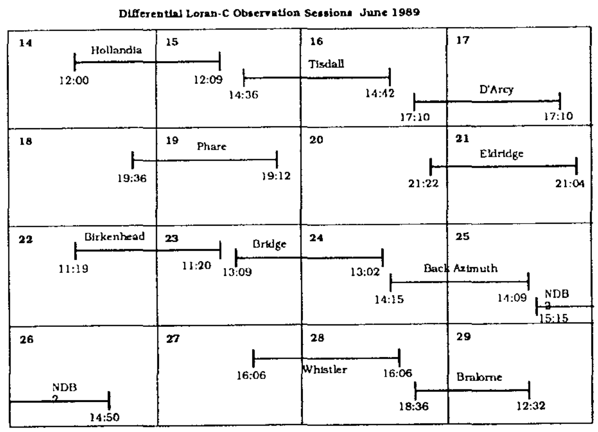


Figure 2: Sites Used for Differential Loran-C Experiment in Pemberton Area

stations are given in Table 1. The height of the stations varies from approximately 200 to 1,000 m. Surrounding mountains reach an elevation of approximately 3,000 m. Each station was occupied for a 24-hour period. TD data from transmitting stations M, Y and Z were used. The sequence of the measurements during the latter part of June is shown in Table 2. A R15 Loran-C receiver provided by ARNAV Systems, Inc., was satisfactorily used for the field measurements. One station, Phare Logging, was deliberately selected near a hydroelectric transmission line to confirm the interference caused by such a carrier. The data was indeed corrupted by signal interference and no further attempt was made to use data from this station in the sequel.

Table 2: Observation Schedule of Differential Loran-C Test Sites in Pemberton Area



The WGS72 coordinates of the Pemberton Airport site and of all surrounding stations were determined using a differential GPS survey based on L1 carrier phase data observed over periods of approximately one hour. This local GPS survey was tied to a local geodetic station known in NAD27. Proper datum transformations lead to the determination of the WGS72 coordinates of all stations with an estimated accuracy of one to 2 m. The relative accuracy of the WGS72 coordinates of all 12 sites is estimated at 50 cm or better.

The weather conditions along the transmitted signal paths during the May-August period were relatively stable with ranges estimated at 5^{o} C to 25^{o} C for temperature, 950 and 1150 mbars for atmospheric pressure and 5 and 20 mbars for partial water vapor. The ionospheric activity for the 1987 and 1989 observation periods reported herein is shown in Figure 3 for the auroral and sub-auroral zone in Canada. The Earth's magnetic field variation is given in nanoteslas as a function of time. One nanotesla is equivalent to one Newton per Ampere-metre. This data was obtained from the Geomagnetic Service of the Geological Survey of Canada and is based on observations obtained at some 13 magnetic observatories located in Canada.

DATA REDUCTION AND ANALYSIS

The TD measurements described in the previous Section were converted into WGS72 latitude and longitude coordinates using a standard least-squares solution. The hyperbolic mode is therefore implied. The WGS72 coordinates of the Loran-C transmitters given in (WGA 1984) were used. As only two TD's were usually available (M-Y and M-Z), no redundant observations were available which resulted in a trivial least-squares case. The primary phase lag was calculated by using an index of refraction with the following standard parameters:

- $T = 20^{o}$ C
- $P = 1013.25$ mbar
- $e = 16$ mbar

No secondary phase lag or terrain correction were applied as one of the objectives was to evaluate the effect of conductivity and topographic variations on Loran-C performance.

Long Term Monitoring - Pemberton Airport Site

During the four months covered by this paper, the SNR measured by the Accufix 500 receiver from Stations M, Y and Z at the Airport Site was stable with a regular diurnal variation of up to 11 dB. The SNR for the above three transmitters for the month of June 1989 is shown in Figure 4. The SNR for M (Williams Lake), which is at a distance of 186 km, varies between 9 and 11 dB while that for Y (George - 422 km) varies between -3 and 8 dB. Corresponding values for Z (Port Hardy - 329 km) are 0 to 10 dB. The signal-to-noise ratio at Pemberton for anyone of these three transmitters is therefore constantly better than 1/2, which is considered fully satisfactory. The SNR for the other months was similar to that for June.

The SNR from X (Shoal Cove - 808 km) for May 1987 and August 20 - September 22 1989 is shown in Figure 5. During May 1987, the SNR was above -10 dB over 50% of the time. The

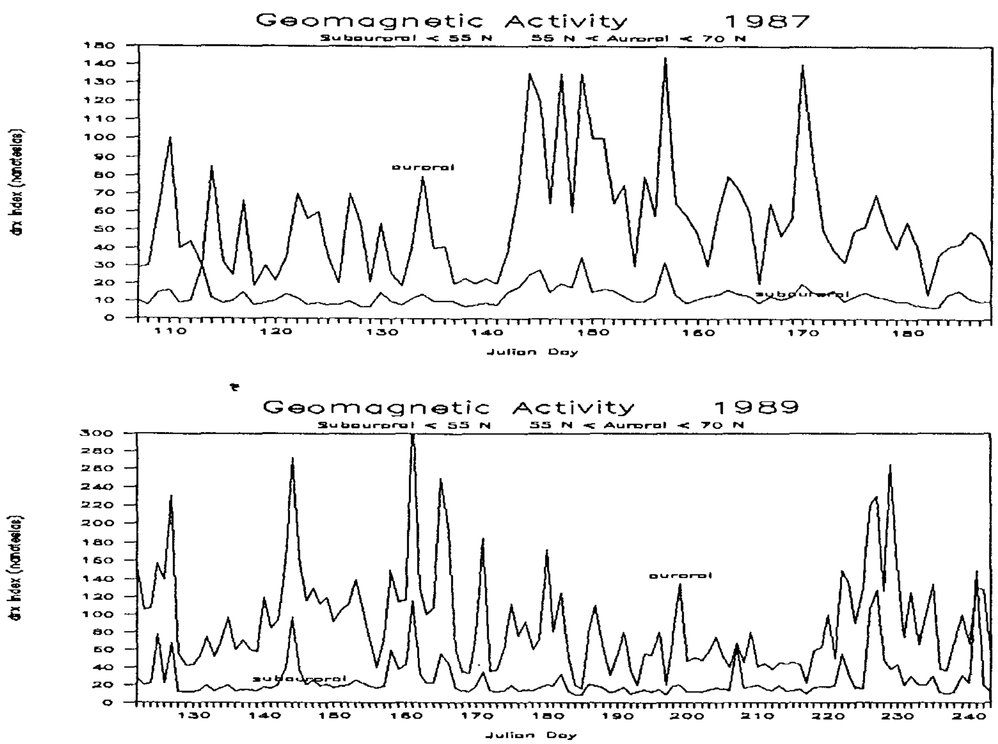


Figure 3: Geomagnetic Activity in Canada during Parts of 1987 and 1989

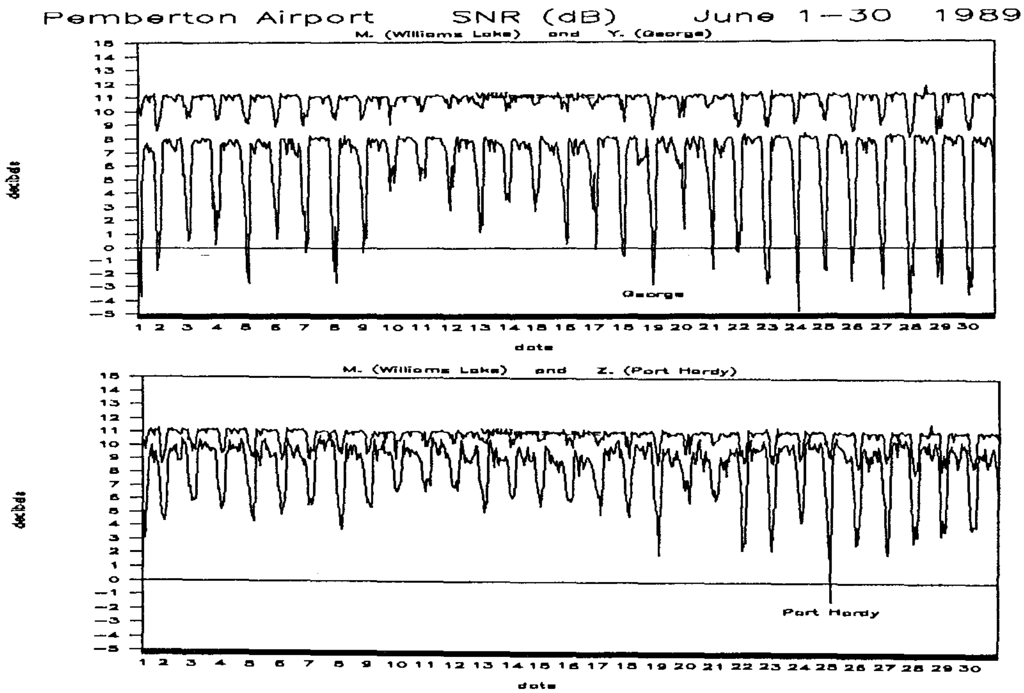


Figure 4: June 1989 SNR Time Series Observed at Pemberton from Williams Lake (M), George (Y) and Port Hardy (Z)

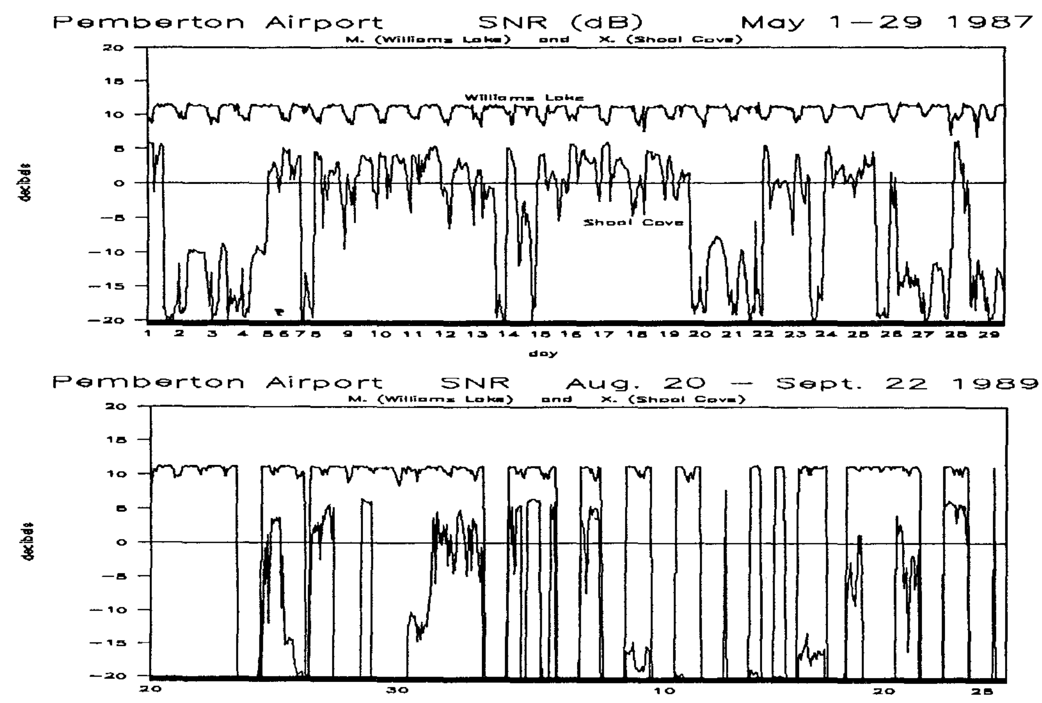


Figure 5: May 1987 and Aug-Sept 1989 SNR Time Series Observed at Pemberton from Shoal Cove (X)

strongest signals occur at nightime. A cursory analysis of the TD's indicates that the skywave was likely tracked most of the time when the signal strength is above 0 dB. The ground wave seems to have been tracked when the signal strength was between - 20 dB and 0 dB. A comparison of the SNR data with the level of ionospheric activity during the same period (Figure 3a) shows a clear correlation, a relatively high level of ionospheric activity coinciding with a lower signal strength, often below the -10 dB threshold. During the 1989 period, the receiver occasionally lost lock on all stations; the percentage of the time the SNR from Shoal Cove was above -10 dB was about 10%. The correlation of the SNR with the level of ionospheric activity during the same period (Figure 3b) is also fairly evident. Over relatively large distances, the effect of ionospheric activity on Loran-C signal strength obviously becomes important and will result in a lower reliability of the signal. Yet, according to the coverage prediction for Southern British Columbia made by RTAC (1987), Pemberton is well within the coverage of Shoal Cove. It was however pointed out by Dean (1988) that the conductivity in B.C., based on field measurements conducted in 1988, is poorer than originally estimated. More data will be collected from Shoal Cove during the period September 89 - March 90 and a more thorough analysis will be reported in (Lachapelle et al. 1990).

The absolute accuracy of Loran-C at the Airport Site for the period May - August 1989 is shown in Figure 6 for both the Northing and the Easting components. For each coordinate, the results are further broken down into daytime and nightime components. The differences between daytime and nightime are well below 5 m for either coordinate. The stability of either coordinate over the above four month period is of the order of 20 m. The absolute differences between Loran-C and GPS-derived WGS72 coordinates are of the order of 275 m in Northing and -185 m in Easting. These large differences are expected in view of the combined effect of the secondary phase lag and the topography.

The long term stability of Loran-C was analysed by comparing the May-June 1989 results with corresponding results obtained by Megapulse, Inc., during the same period in 1987 (Lecaroz 1988). The 1987 and 1989 time series analyses are shown in Figure 7. The smooth curve fittings represented by x's and o's are the result of a Fourier analysis made on the data to remove the

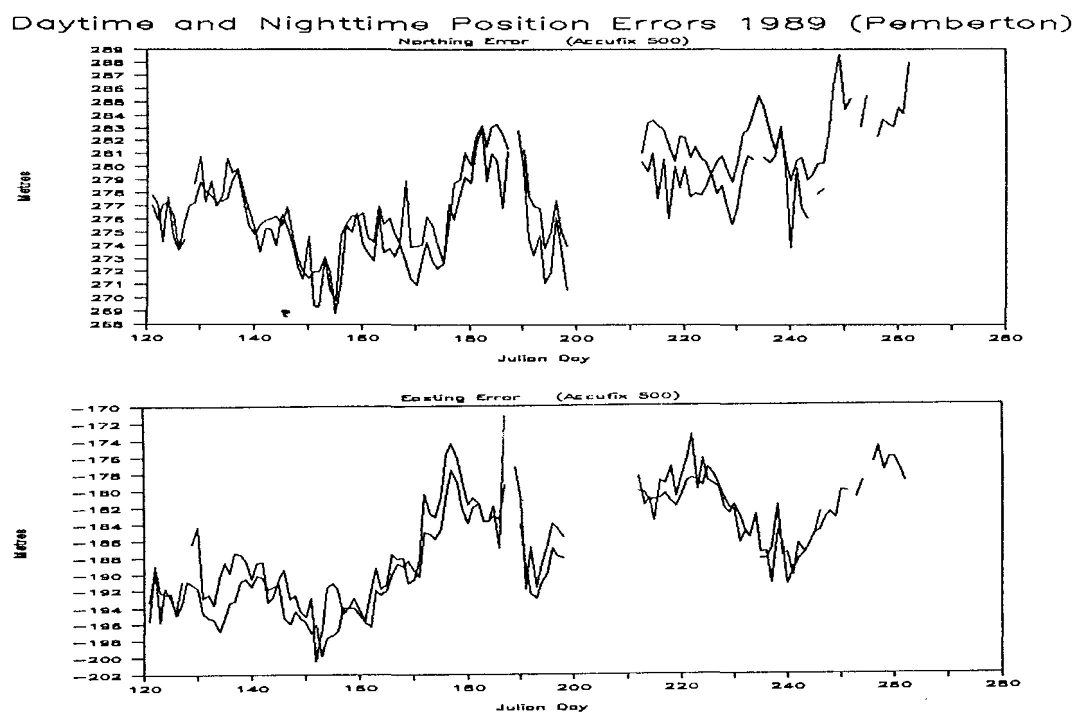


Figure 6: Seasonal Stability of Daytime and Nightime Loran-C Positions at Pemberton During May - August 1989.

high frequencies. The stability of Loran-C during the May-June 1987 period was similar to that of May - June 1989, namely 20 m. The differences between the two periods are practically constant at 5 m in Northing and 25 m in Easting. This is within the relative error estimated for clock synchronization of the transmitters.

Differential Loran-C Experiment

The absolute results of the Loran-C measurements performed at the 10 stations surrounding the Airport Site are summarized in Figure 8 which show the Northing and Easting differences between Loran-C and GPS-derived WGS72 coordinates for each stations. The variations in the Northing component range from -46 m for Back Azimuth to 412 m for Bralone while those in the Easting component range from -816 m for Tisdall to 302 m for Bridge. Back Azimuth and Bralone are separated by some 60 km while Tisdall and Bridge are separated by some 40 km. Such large distortions in mountainous areas are to be expected as discussed by several authors in the past (e.g., Johler & Cook 1984).

Evidently, the use of differential Loran-C in this area will not improve results substantially due to the effect of the topography. This is illustrated in Figure 9 which shows the differences between differentially corrected and GPS-derived WGS72

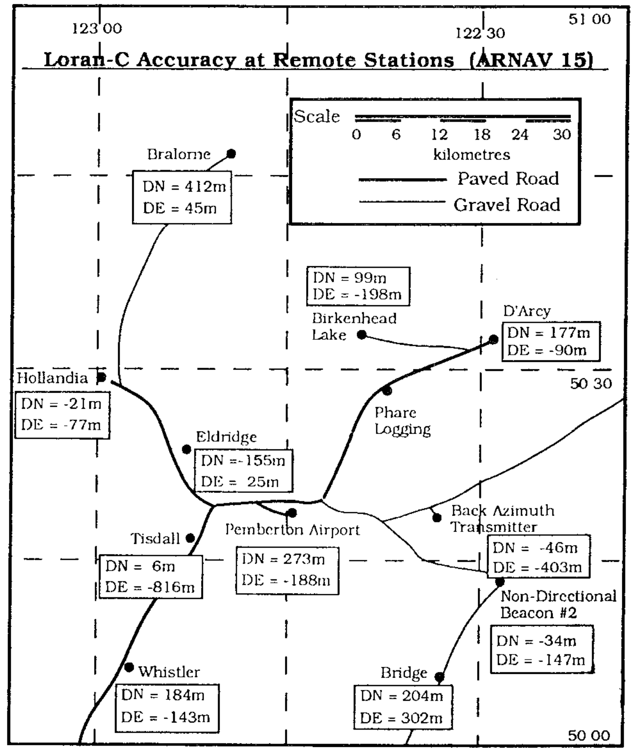


Figure 8: Errors in Absolute (WGS72) Loran-C Positions at Selected Sites in the Pemberton Area - June 1989

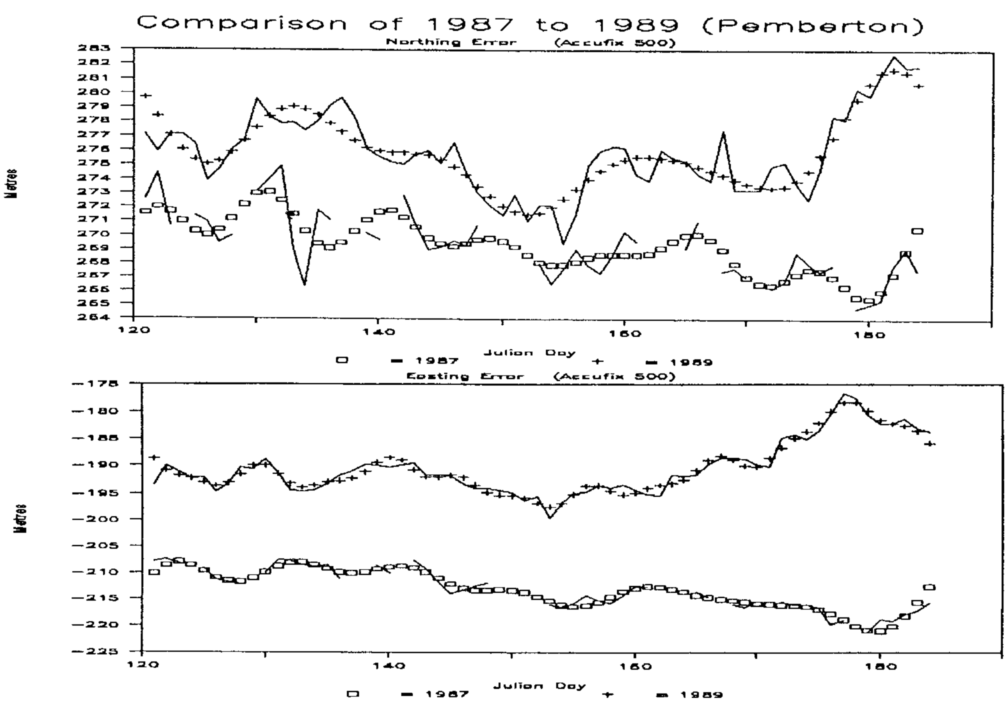


Figure 7: Errors in Absolute Loran-C Positions at Pemberton: 1987 Versus 1989

coordinates at the same 10 sites. The differentially corrected positions were obtained by applying the position differences (Loran-C - GPS) obtained at the Airport Site to all stations. This is why the values for the Airport Site are 0 in Figure 9.

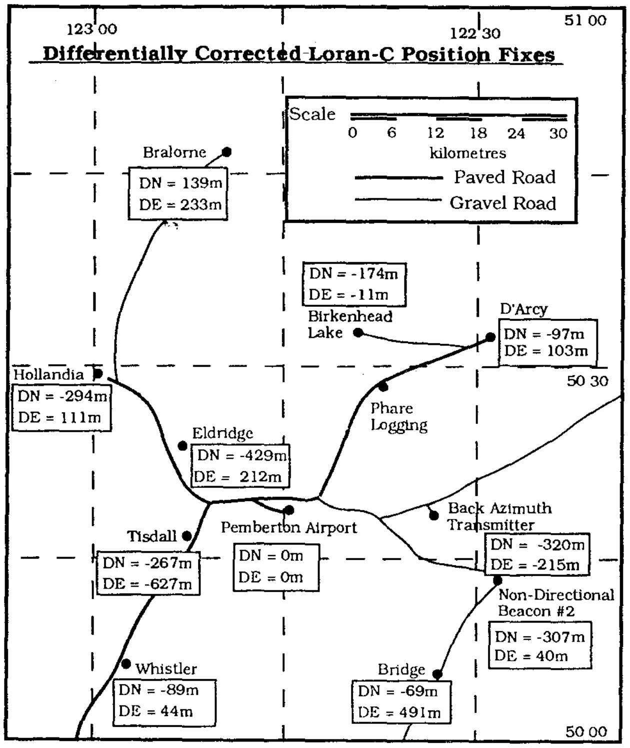


Figure 9: Remaining Errors in Differentially Corrected Loran-C Positions at Selected Sites in the Pemberton Area - June 1989

CONCLUSIONS AND RECOMMENDATIONS

The analysis conducted herein demonstrates a Loran-C position diurnal stability of 5 m and a seasonal and long term stability of 25 m at Pemberton Airport, a location surrounded by rugged topography. The absolute accuracy of Loran-C was found to be within expected bounds for such a mountainous area, namely of the order of several hundred metres. The effect of topography causes relative distortions of several hundred metres over short distances (< 80 km) but this effect is expected to be practically constant over time. An analysis of the signal-to-noise ratio (SNR) data reveals a good stability of the Loran-C signals over the periods investigated for all transmitting stations except Shoal Cove which is located at some 800 km North from Pemberton. In this latter case, the SNR dips below -10 dB for significant periods of the time. Such occurences generally correspond to a relatively higher level of ionospheric activity.

The data used herein was collected during Spring and Summer 1987 and 1989. The investigators intend to collect data at the Pemberton Airport Site on an uninterrupted basis throughout the Fall and Winter 1989-90 to analyse the effect of Winter conditions on the stability of Loran-C. A more detailed investigation of the effect of ionospheric activity on the Loran-C signals being received from Shoal cove is also being conducted. Further results will be reported in (Lachapelle et al. 1990).

The level of repeatable accuracy reported above, namely 25 m, is sufficient to meet a large percentage of land user's requirements, and confirms the competitiveness of Loran-C for many applications, even in mountainous areas (e.g., Lachapelle & Townsend 1989). Further tests are obviously required over a larger area and during all seasons to determine if the above stability level can be maintained throughout a large area. The use of an en-route Loran-C calibration method with differential GPS is being investigated by the authors. The accuracy of DGPS is well within 5 m. Such a method would be sufficiently accurate and cost effective to calibrate Loran-C for the effect of conductivity and topography along selected roads and study in more detail the stability of the system under a variety of conditions. An overall repeatable accuracy of 50 m may be attainable with calibrated Loran-C, especially if monthly average or on-line weather data is used to take weather effects into account.

Another related experiment being investigated is the spatial analysis and calibration of Loran-C using airborne DGPS at different altitudes over calibrated land routes. The secondary phase lage is known to decrease from the ground upward to an altitude of 5 λ, i.e., 15,000 m at Loran-C frequency. A series of precise spatial profiles over mountainous areas would provide the data required for an accurate analysis of the complex relationship between secondary phase lag, conductivity, topography and altitude. The findings of such an analysis would contribute to assessing the suitability of Loran-C for area navigation and non-precision approaches in mountainous areas.

ACKNOWLEDGEMENTS

This work was conducted under a project sponsored by the Transportation Development Centre, Transport Canada. The support of Megapulse, Inc., in providing Loran-C data collected at Pemberton in 1987 and an Accufix 500 receiver for the 1989 campaign reported herein is acknowledged. The support of ARNAV Systems, Inc., in providing a R15 receiver for the differential Loran-C conducted in June 1989 is also acknowledged.

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CONSTRUCTION OF SEASONAL LORAN TIME DIFFERENCE USING A TEMPERATURE MODEL

HENRY J. WYCHORSKI JR.

LORAN DATA SUPPORT

ABSTRACT

It takes three years of Loran data to characterize the seasonal variation of time differences. This paper will show how a historical temperature data base reduces the quantity of required data. Previous authors have identified the correlation between Loran time difference variations and the seasonal temperature change. This paper explains an unconventional procedure of substituting a years worth of temperature data (January to December 1988), for position location data, from six weather stations near Loran monitor sites within the Northeast Chain, MWX triad. The procedure uses a time difference prediction algorithm developed at the Transportation Systems Center. The prediction algorithm resulted from a study that used multiple regression analyses of the geographical location of transmitters, monitors, data collection sites, and several years of time difference variations from each site. The result of the study is the prediction algorithm of three independent variables. This dissertation compares the prediction capability of the algorithm when one exchanges monthly averaged temperature data for the latitudes of the monitor sites. Successful application of this technique reduces the required data collection period by a third.

BACKGROUND

Radionavigation is required to support movement of resources, raw materials, manufactured goods, and people in the processes of economy and trade, and to insure safety of life and property in commercial land, sea, and air transportation systems. The Department of Transportation is the primary Government provider of aids to navigation used by the civil community. The Research and Special Programs Administration (RSPA) sponsored flight tests that determined that the marine Loran (LOng RANge navigation) system was suitable for en route, terminal navigation and nonprecision approaches at small airports.

In 1977 the Vermont Department of Aeronautics requested RSPA to provide assistance in improving air access to the State's low altitude airspace and airports. The influx of new businesses to Vermont communities was creating a demand for improved airline, air taxi, and business aircraft services which could not fully and efficiently be met in view of limitations in navigation and approach aids. At that time there were two manufacturers of Loran avionics and less than 100 users. The two main airborne users were spotters for the fishing fleets and personnel and equipment carriers for the oil platforms in the Gulf of Mexico.

Now, there are more than 70,000 Loran receivers in aircraft and 22 manufacturers. Two thirds of the contiguous United States and one half of Alaska have Loran signal coverage. There are more than 16,500 landing areas in the contiguous United States and Alaska. Approximately one third of these have navigation aids.

The Federal Aviation Administration (FAA), responding to user demand for approval of the use of Loran for IFR (instrument flight rules) nonprecision landings, included the system in the National Airspace System plan.

Currently the Transportation System Center (TSC) maintains a ten-unit Loran signal monitor network that supports the landings into fifteen airports in the United States. This program gives the FAA operational experience with Loran navigation.

The FAA is installing 196 signal monitors and four more transmitters to insure Loran signal integrity throughout the United States. In a new technical service order, the FAA, pronounced that the basic Loran avionics would calculate the conversion between latitude and longitude coordinates and time difference (TD) values assuming salt water propagation paths. The FAA would provide correction factors to be added periodically to the avionics to correct both for the propagation path and the seasonal variations. An algorithm developed at TSC calculates these correction factors.

The TSC correction algorithm (Equation 1) estimates the monthly average TD value for locations, which have no historical record. This algorithm must have as an input at least two years of historical TD data from four different monitor locations for each Loran baseline. The multiple regression analysis performed on this input data creates, for each month, the four coefficients of the algorithm. The independent variables are latitude, range to the secondary transmitter, and the double range difference of the prediction point. The output of the algorithm is a monthly index for the location. This index, when multiplied by the long term (yearly average) TD value, produces the expected monthly average TD value. The difference between the expected value and the measured value is less than 200 nanoseconds.

Equations (distances in kilometers, time differences in microseconds)

(1) Seasonal index = C0 + (C1 · LAT) + (C2 · RGSEC) + (C3 · DRD · LAT)

Where:

LAT	=	Site latitude (decimal degrees)
RGSEC	=	Range from site to secondary transmitter
DRD	=	Double range difference
C0,C1,C2,C3	=	Four coefficients calculated for each month

(2) $$\text{Scale Temp}_n = \frac{\text{TEMPMONTH}_n - \text{MINTEMP}}{\text{MAXTEMP} - \text{MINTEMP}}(\text{MINTD} - \text{MAXTD}) + \text{MINTD}$$

Where:

TEMPMONTH_n	=	Average temperature for month n (F°)
MAXTEMP	=	Maximum average monthly temperature (F°)
MINTEMP	=	Minimum average monthly temperature (F°)
MAXTD	=	Maximum average monthly time difference
MINTD	=	Minimum average monthly time difference

(3) Double Range Difference = (R1 - R2) - (R3 - R4)

Where:

R1 = Range from site to secondary station
R2 = Range form site to master station
R3 = Range from service area monitor to secondary station
R4 = Range from service area monitor to master station

(4) Seasonal index = C0 + (C1 · TEMP) + (C2 · RGSEC) + (C3 · DRD · TEMP)

Where:

TEMP	=	Average monthly temperature
RGSEC	=	Range from site to secondary station
DRD	=	Double range difference
C0,C1,C2,C3	=	Four coefficients calculated for each month

(5) $$\text{Seasonal index} = \frac{\text{TD average for month}}{\text{Moving average TD for months n-5 to n+6}}$$

As mentioned above, Loran TD values vary with the propagation path and climatic changes. The propagation path effect is constant and is measured on site. Temperature variations have both a periodic and a random influence on TD variation. Averaging over a period of a month removes the effect of random fluctuations. Several published papers have explored the causal factor relationship between TD fluctuations and temperature changes. A correlation study conducted in preparation for this paper verified this relationship.

Weather stations in the United States have been recording temperature data for over a century. There are three times more weather stations than proposed sites for the FAA Loran operational monitors. If temperature data can be successfully substituted for the TD data used in the prediction algorithm then the period of TD data collection can be shortened, or even eliminated.

INTRODUCTION

In preparation for this paper the technical literature was searched for articles on Loran propagation characteristics. The temperature and TD correlation effects are well documented. The application of temperature records for the purpose described by this paper is original research. The New England area was chosen by the FAA for examining the interdependence of distance and local TD migration; several years of TD data from five monitor units are available for use. The US Coast Guard (USCG) collects TD monitor data from twenty four sites in the Northeast Chain (9960). We chose this chain for the study, specifically the MW or whiskey baseline. In recapitulation, this particular baseline was selected because of the availability of Loran TD data from USCG Harbor Entrance Project Monitor Sites. We selected seven of the twenty four TD monitor sites in the 9960 chain (Figure 1), namely Cape Elizabeth, ME, Massena, NY, Burlington, VT, Rutland, VT, Newport, VT, Sandy Hook, NJ, and Groton, CT. We sought temperature data from National Oceanic and Atmospheric Administration (NOAA) climatological data gathering sites. NOAA weather monitoring sites co-located with Loran monitoring sites are preferred.

Temperature records are available from the National Climatic Data Center, Asheville NC. We requested records from weather stations for each of the monitor sites.

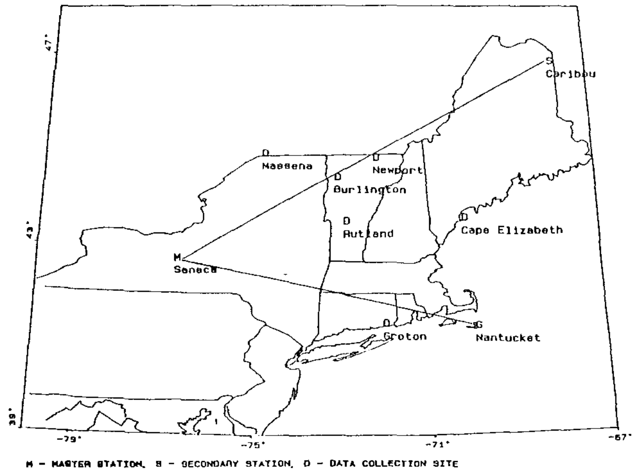

FIGURE 1 DATA COLLECTION SITES

METHOD

The first step in the analysis is to prepare the data by removing short term or high frequency temperature variations. Monthly averaging does this and creates a single value that is the mean temperature for the month. Much of the high frequency TD data is removed by the USCG during processing. Their daily data records were aggregated into monthly averages. We attempted a visual or graphical correlation of the temperature and TD data. The best graphical correlation is achieved by scaling the monthly average temperature with the monthly average TD value, see Equation 2 for the scaling and Figure 2 for the results. The mathematical correlation is illustrated in Figure 3. The next step was a mathematical regression of the data to search for outliers and errors in the data. A regression of monthly average TD and temperature data was correlated at the ninety five percent level, Table 1. Table 1 indicates that the data set is of high quality with few outliers. Examination of the yearly mean and standard deviations of the temperature and the TDs as a function of the relative latitude of the weather site and monitor locations showed a smooth transition from south to north. The more northerly sites had lower mean temperatures and larger standard deviations as expected. This activity confirmed the quality of the data and indicated the direction of the next step.

The TSC prediction algorithm (Equation 1) has three independent variables: latitude, range to the secondary transmitter, and double range difference. The first two variables are self explanatory. The third may not be. The equation for the double range difference is Equation 3. The USCG developed this concept to model the leverage effect, on other sites, of USCG TD control at the service area monitor. There are numerous versions of this concept; the one used by the TSC is Modification 1, of the original form.

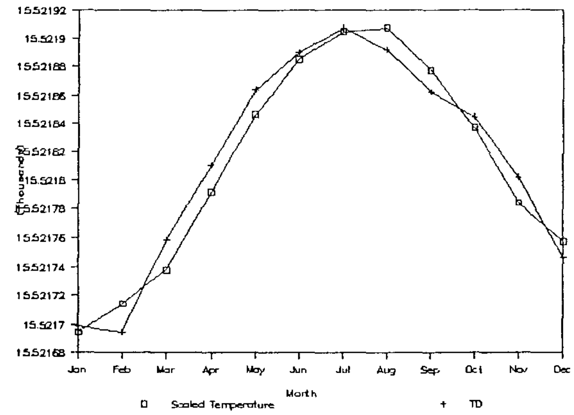

FIGURE 2 GRAPHICAL CORRELATION OF TEMPERATURE AND TIME DIFFERENCE DATA FOR SANDY HOOK, NJ.

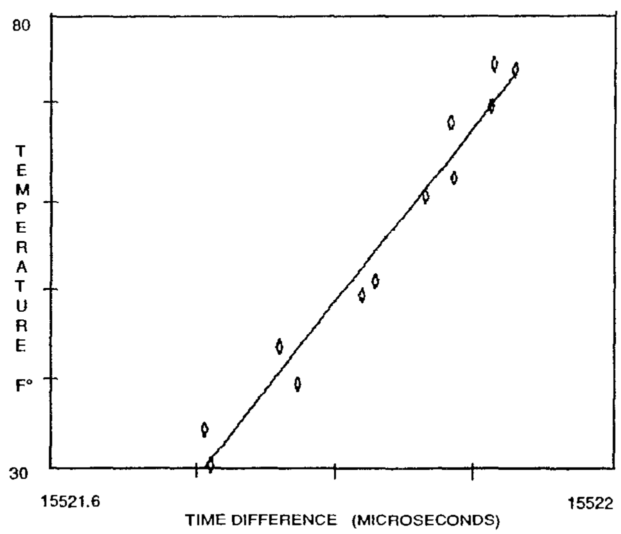

FIGURE 3 CORRELATION OF TIME DIFFERENCE AND TEMPERATURE DATA FOR SANDY HOOK, NJ

TABLE 1 RESULTS OF THE TEMPERATURE, TIME DIFFERENCE CORRELATION

SITE	Corr. Coeff	Mean temp.	Mean TD	σ temp.	σ TD
Massena, NY	0.984	43.2	14721.67	18.7	0.10
Newport, VT	0.949	43.4	13643.27	18.0	0.07
Burlington, VT	0.973	44.9	14221.67	18.1	0.19
Rutland, VT	0.971	46.7	14494.34	16.7	0.15
Groton, CT	0.954	50.7	14700.07	14.7	0.09
Sandy Hook, NJ	0.981	55.3	15521.81	15.0	0.07

The seasonal index in this paper (Equation 4) is similar to one at TSC developed in the range of validity study. In the TSC algorithm the seasonal index is computed using a twelve month sliding average and two years of TD data. Using a sliding average removed any erratic fluctuations while preserving the low frequency or slowly changing seasonal trends. The seasonal index for each month when multiplied by the TD long term average results in a predicted TD value for that month.

For Equation 1, at least four monitors sites, with at least two years of data must be available. A seasonal index from the sliding average is set equal to the equation and a multiple regression is executed for each month, to derive the four coefficients. There is a different set of coefficients for each month. The product of the site latitude and the double range difference in the equation removes the effects of regulation of the TD received at the service area monitors. Latitude is included in the equation to account for the larger amplitude of TD fluctuations at higher latitudes.

The seasonal index equation developed by this study replaces both the terms which include latitude with monthly average temperature data. See Equation 4.

The coefficients C0, C1, C2, and C3 are computed for each month, using TD and temperature data from Cape Elizabeth ME, Massena NY, Rutland VT, Sandy Hook NJ, and Groton CT. The computed coefficients are based upon three years of data from each site. The seasonal index for these sites were calculated using a sliding average, Equation 5. A file for each month also is created by the program. These files contained the seasonal indices, double range difference, range to secondary, and monthly average temperature for each site. The multiple regression, routine necessary to calculate the four coefficients from the above files and was performed with a program called Math CAD. Then these coefficients are used to compute the indices for sites which were not used in the regression. The only data necessary for these sites are the monthly average temperature, double range difference, and range to secondary. After calculating the seasonal indices using Equation 4 for the five sites listed above, the seasonal indices for each site are multiplied by the site's TD long term average. This furnished the site TD prediction for each month. These results were compared graphically with the measured TD data, see Figures 4,5. Measured TD data was also available for sites which were not used in the computation of the coefficients.

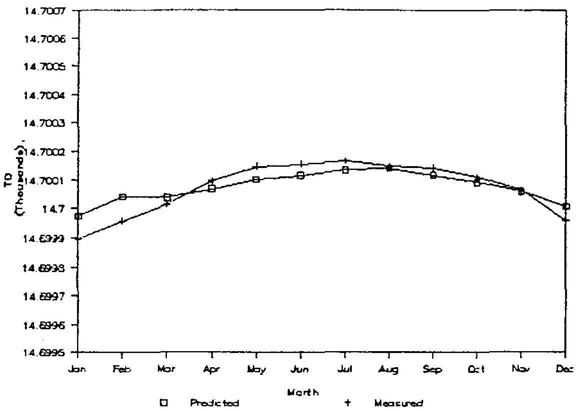

FIGURE 4 RESULTS OF THE SEASONAL INDEX EQUATION, AND ACTUAL MEASURED DATA FOR GROTON, CT.

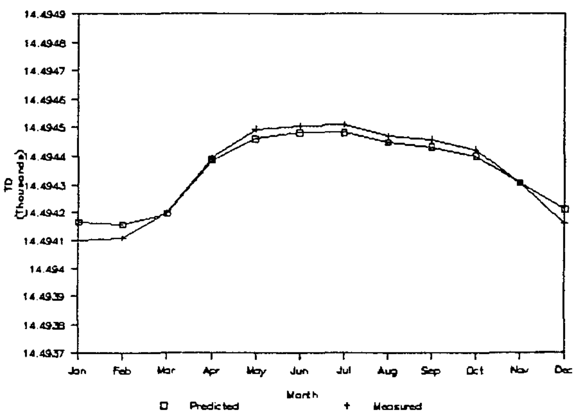

FIGURE 5 RESULTS OF THE SEASONAL INDEX EQUATION, AND ACTUAL MEASURED DATA FOR RUTLAND, VT.

Seasonal indices and TD predictions were calculated for these sites and results are compared graphically, with their measured TD data. See Figure 6 for one example of this comparison.

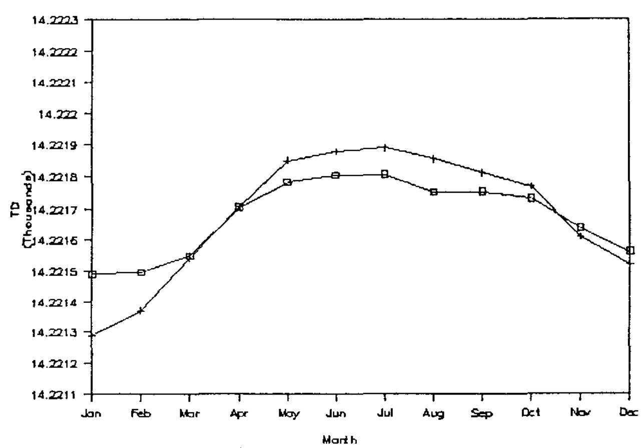

FIGURE 6 RESULTS OF THE SEASONAL INDEX EQUATION, AND ACTUAL MEASURED FOR BURLINGTON, VT.

CONCLUSION

The comparison of the predicted TD and the actual measured values show that the seasonal index developed by this report is a practical means for developing a seasonal TD model. Figures 4, and 5 show a difference in the worst month by 80 nanoseconds. Figure 6 for ten months predicts a value which is less than 100 nanoseconds, the other two months are less than 200 nanoseconds. The success of this research encourages the replacement of historical TD records with temperature data.

RECOMMENDATIONS

The next obvious step is to remove the need for twelve sets of coefficients for a base line. A multiple regression will be done on all the twelve months of data for the four sites on each baseline. One set of coefficients will be developed. With fixed site parameters and an average monthly temperature a monthly index is calculated. This in turn produces the expected TD value for that month. The next recommendation is to develop the correlation between the TD indices and the temperature indices.

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SELECTING GROUP REPETITION INTERVALS FOR EUROPEAN CHAINS

M. Beckmann and H.J. Lincklaen Arriëns
Delft University of Technology
The Netherlands

Abstract

Plans are currently being developed for the expansion of Loran-C coverage in Western and Northern Europe.
One of the proposals implies the creation of a new chain around the UK, a mini chain around the Skagerrak and a reconfiguration of both the existing Norwegian Sea and the SNRLC Chains.
Upon a request of Rijkswaterstaat, the Netherlands, the authors investigated the selection of Group Repetition Intervals for the UK and SNRLC chains. The goal was to find GRI's that keep Cross Rate Interference as well as Continuous Wave Interference at a minimum.
The results of the study are presented in this paper.

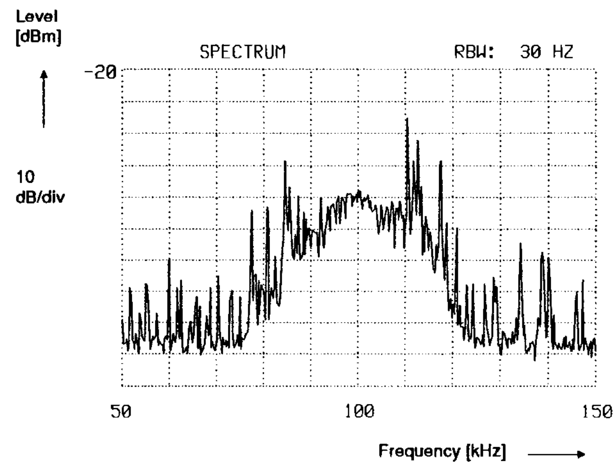

Fig. 1 *typical spectrum after bandpass filtering as received at Delft, the Netherlands.*

1. INTRODUCTION

In the past years possibilities for expanding the Loran-C system in Northern and Western Europe have been investigated.
Mr. Stenseth [1] reported last year's status. Currently, the dominant idea is to install a new chain (the UK Chain) and to reconfigure the existing Norwegian Sea (GRI 7970) and the French SNRLC Chains (currently 8940).
In Europe, the spectrum at both sides of the Loran-C band is crowded with interfering signals (Fig. 1), most of which originate from stations inside or close to the operational areas of the Loran-C chains.
The Group Repetition Interval (GRI) of a chain determines how many of these interferers will be a-synchronous, near-synchronous or synchronous. As the last two severely affect the tracking process of a receiver, their number should be as small as possible.
Mutual interference will be unavoidable, because current plans imply the positioning of a number of Loran-C transmitters in a relatively small area. Also the degree of Cross Rate Interference (CRI) is determined by the GRI values.
Upon a request of Rijkswaterstaat in The Netherlands (contract number MD 223), the authors had to find proper GRI's for the new UK Chain, and for the reconfigured SNRLC Chain (see Fig. 2). These GRI's had to guarantee the best possible operation with respect to interference rejection within the new areas.
In the following sections the methods that were used to analyze Cross Rate and Continuous Wave Interference (CWI) will be explained.
Then, the resulting GRI's will be described, together with some general guidelines that could be deduced from the analysis.

2. STRATEGY

Any GRI has to meet the specifications set up by the U.S. Coast Guard in [2].
Traditionally GRI's have been selected to be multiples of 100 µs. This was also chosen as the starting-point for the new-to-find ones.
In principle, all values between 4000 and 9990 can be used.

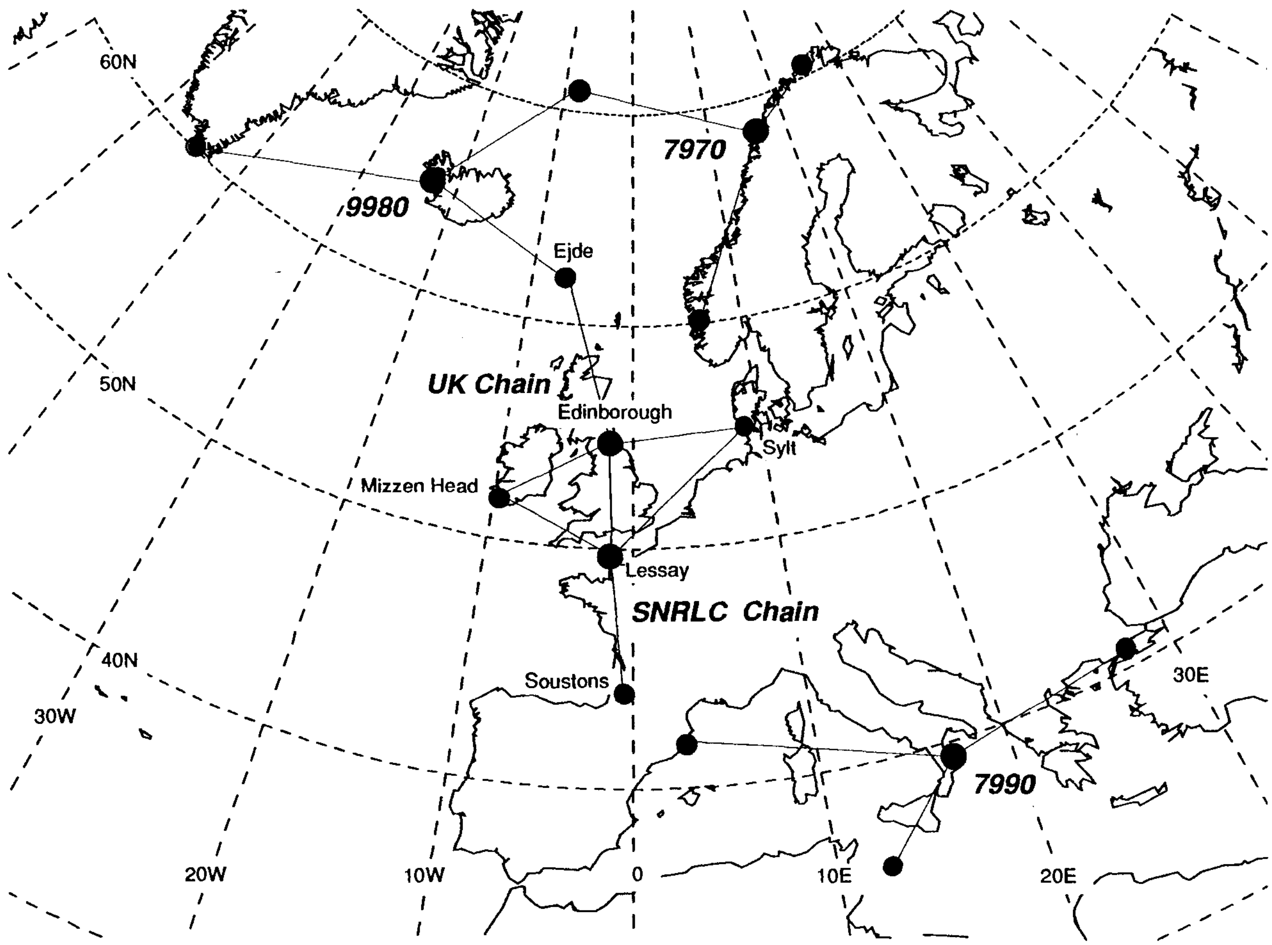

Fig.2 *Map of Europe showing the configurations of the analyzed UK Chain (Master near Edinborough and secondaries near Mizzen Head, Lessay, Sylt and Ejde) and SNRLC Chain (Master near Lessay, secondaries near Mizzen Head, Soustons and Sylt).*

The constraints for the assignment of Emission Delays [2], however, determine the smallest allowable GRI. This sets the lower bound for the GRI's to be analyzed.

The remaining GRI's can be tested on their CWI and CRI sensitivity. As CWI and CRI result in different tracking error patterns [3], their influences should be analyzed seperately.

The priority order of the evaluation depends on the impact each one is expected to have. For Europe, it will be useless to investigate CWI sensitive GRI's on their CRI sensitivity. In this case an evaluation of CWI, followed by CRI sensitivity seems to be the evident procedure. For areas with far fewer CWI sources the order should be reversed, of course.

It will be neccessary to specify beforehand an imaginary reference receiver. Its specifications should not favor particular operation-principles, for it is the aim to obtain GRI's that are optimal for all kinds of receivers.

From now on, this 'standard' receiver is assumed to have the following properties:

1. The receiver is an ideal linear type, without any non-linear processing in the front-end.
2. The step response time of the phase tracking loop is only 6 seconds. This value has been chosen to enable land-based and aeronautical operation. Slower reacting receivers with their inherently smaller tracking loops generally show a better interference rejection. GRI's that are optimal for fast receivers are therefore expected to be satisfactory for slower ones.
3. In the sampling process, one sample per burst is processed, using standard phase coding patterns. Using non-standard patterns would limit the usefulness of the analysis to receivers using such patterns. Since it is believed that the

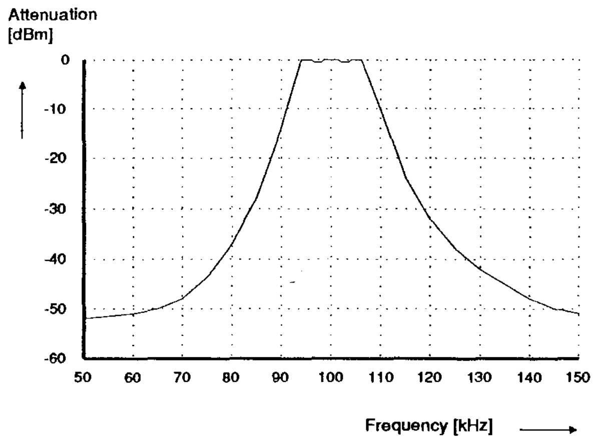

Fig. 3 *Transfer function of the 'standard' bandpass filter*

majority of receivers uses standard patterns, this will not be acceptable.

4. In the calculations, data about the attenuation of the rf bandpass filter in the front-end will be needed. For the filter characteristic (Fig. 3) a function without attenuation zeros was deliberately chosen, because notches would favor some frequencies too much.

3. MINIMAL GROUP REPETITION INTERVAL

The first step will be to calculate the smallest possible GRI that meets the U.S. Coast Guard specifications described in [2]. The criteria for the GRI and timing of Master and Slave Pulse Groups are stated there as follows:

Permissable GRI's are multiples of 10 µs from 40000 to 99990 µs, while anywhere within the coverage area of a chain the time differences of the received signal

- between master and first secondary should be greater than 10.900 µs,
- between any two consecutive secondaries should be greater than 9.900 µs, and
- between master and last secondary should be less than (GRI – 9.900) µs.

These criteria are visualized in Fig. 4.

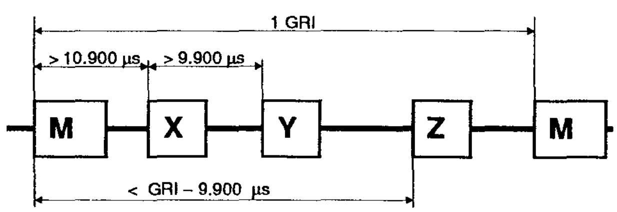

Fig. 4 *Constraints for assignment of Emission Delays.*

The smallest time difference ($\Delta t_{n,n+1}$) between the signals of two consecutively transmitting stations n and n+1 can be found at the position of transmitter n+1 itself. Hence the following condition should be satisfied:

$$\Delta t_{n,n+1} = T_{n,n+1} - \frac{dist_{n,n+1}}{v_{prop}} \geq Tmin_{n,n+1}$$

where

- $T_{n,n+1}$ is the difference in emission delay of the transmissions between stations n and n+1,
- $dist_{n,n+1}$ equals the length of the signal path between stations n and n+1,
- v_{prop} equals the propagation velocity for Loran-C radio waves (the propagation velocity over land has been used here to obtain worst case Δt's), and
- $Tmin_{n,n+1}$ is one of the values mentioned above:
  If we define n = 0 to identify the master, and $n \geq 1$ for secondaries, then $Tmin_{0,1} = 10.9$ µs,
  $Tmin_{n,n+1} = 9.9$ µs , and $Tmin_{N,0} = 9.9$ µs,
  where N is the total number of secondaries (N+1 = 0).

The minimum allowable GRImin can now be found from:

$$GRImin = \sum_{0}^{N} \left(Tmin_{n,n+1} + \frac{dist_{n,n+1}}{v_{prop}} \right)$$

GRImin obviously depends on the geographical position of the different stations and on the sequence in which they transmit. It has been assumed that the master was already assigned (Edinborough for the UK- and Lessay for the SNRLC-Chain), while the sequence of the secondaries could be chosen freely. From the N! possible sequences of secondaries the lowest value of GRImin can be selected.

The GRI's to be used in practice have to exceed these minimal values with a certain safety factor. There are, however, two reasons for selecting a GRI as low as possible :

- the number of samples per unit of time increases with decreasing GRI, which can speed up a receiver's response time.
- as will be explained in section 7, low GRI's generally are less sensitive to (near-)synchronous CW-interference.

4. CROSS-RATE INTERFERENCE

The analysis of Cross-Rate signals has been based on a method described by Feldman et al. [4]. A calculation model of this method is shown in Fig. 5. In words, the following computations have to be performed:

1. Given the Loran-C burst waveform, the GRI and the phase code of the transmitted signal, the Loran-C transmission

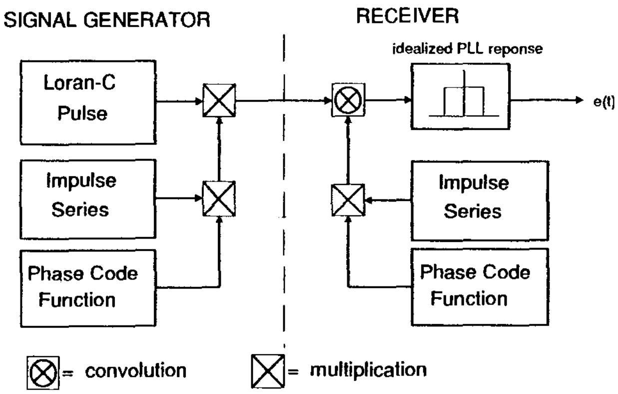

Fig. 5 *Calculation model to describe Cross-Rate Interference in the frequency domain*

spectrum can be calculated. This spectrum is centered around 100 kHz (Fig. 6a) and consists of spectral lines at 1 / 2 GRI Hz apart from each other.
Spectra for both the wanted and the Cross Rate GRI have to be calculated.

2. Similarly, the Fourier transform of the receiver sampling function can be calculated with the GRI and the phase-code used by the receiver. The resulting function - a line spectrum again - describes the sensitivity of the Loran-C receiver in the frequency domain and has, in theory at least, an infinite width (Fig. 6b).
In practice, the inevitable rf bandpass filter of the receiver limits the effective frequency range. Nevertheless, it is the spectrum of the Loran-C burst, which is already decayed to -20 dB at 90 and 110 kHz, that fixes the active information bandwidth and thus the necessary calculation boundaries.
3. In the time domain, the incoming (transmitted) Loran-C signal is multiplied with the receiver sampling function and then fed into the tracking loop.
In the frequency domain this multiplication translates into a convolution of the incoming spectrum with the Fourier transform of the receiver sampling function: the frequency domain functions that have been calculated in the previous steps.
The result of this convolution is then multiplied with the transfer function of the tracking loop and represents the spectrum of the output signal. Integration of this spectrum gives the power level of that GRI at the output of the tracking loop.
This convolution and integration has also to be performed separately for the wanted signal (with the GRI to be tracked) and for the Cross Rate signal.

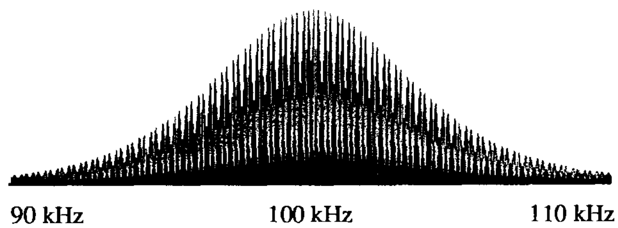

Fig. 6a *Power spectrum of Loran-C transmission*

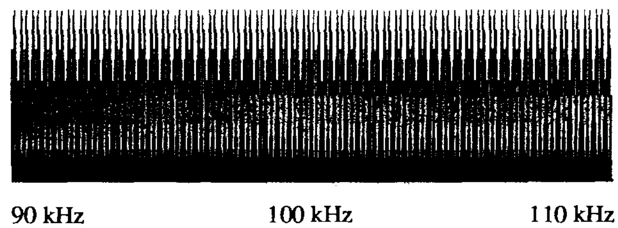

Fig. 6b *Fourier transform of receiver sampling function*

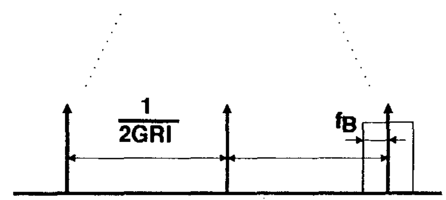

Fig. 6c *Distance between two spectral lines*

Finally, if both power levels are known, a Signal-to-Cross Rate Ratio (SCRR) for the GRI's can be calculated. Note that the value of this SCRR is based on equal signal levels of wanted and Cross Rate signals at the receiver's input.

SCRR's will be used to compare candidate GRI's on their CRI sensitivity: a higher SCRR indicates a better rejection of CRI.
In step 3 the transfer function of the tracking loop PLL will be needed. Feldman used a first-order PLL response function there. For comparing different GRI-combinations, if no particular receiver concepts are to be favored, a simple rectangular transfer function with bandwidth f_B would be appropriate.
Contrary to Feldman's approach, who searched for non-standard phase code patterns to eliminate CRI, only standard phase code patterns will be considered here for reasons mentioned before.

5. CONTINUOUS WAVE INTERFERENCE

First of all, data is needed about CWI transmitters in and around the operational areas. As a reference, the official ITU-list of all transmissions between 10 and 200 kHz [5] has been used. No attempt has been made to verify its data. It was assumed to be complete and reliable.

From the list a computer database was constructed, containing all transmitters in the 50 to 150 kHz spectrum with their frequencies, positions and radiated signal powers. Since the analysis was limited to Europe, only stations between 60 and -60 degrees longitude and 30 and 90 degrees latitude were included, which left a total of 898 potential interference sources. From these a large number belong to DECCA Navigation stations. Also the number of frequencies on exact multiples of 1 kHz was strikingly high.

As mentioned in section 2, all GRI's above GRImin are to be investigated on their CWI sensitivity. Only synchronous and near-synchronous interferences are considered here, since these cannot be kept outside the tracking loop and therefore are the most dangerous types.

The sensitivity to CW-Interference will be expressed as the total number of synchronous and near-synchronous interfering frequencies that could result in tracking errors exceeding 100 ns, anywhere in an operational area.

In fact, the number of notch-filters needed for that GRI corresponds exactly with this CWI-Sensitivity-Figure (CWISF).

All (near-)synchronous interferers for a particular GRI can be found by scanning the database for all transmitter frequencies f_{TX} that satisfy

$$\left| f_{TX} - \frac{N}{2\,GRI} \right| \leq f_B$$

where N is a positive integer.

In words, this Coast Guard definition [6] means a selection on signals that show a frequency difference with one of the receiver's spectral lines, less than or equal to the tracking bandwidth f_B. The tracking filter is thus assumed to be rectangularly shaped, and is in fact the same filter as the one to be used in the Cross Rate analysis.

The result will show all *potentially* dangerous frequencies.

Next, a more detailed selection can be made, accounting for the position and power of the interfering transmitters. This requires that an operational area should be established for the chain to be analyzed. Fig. 7a and b show practical, stylized operational areas for the UK and SNRLC Chains (it should be noted that the areas shown here are only meaningful for CW-interference analysis).

Interfering signals can now be divided into two categories, i.e. originating from transmitters located inside or outside the operational area.

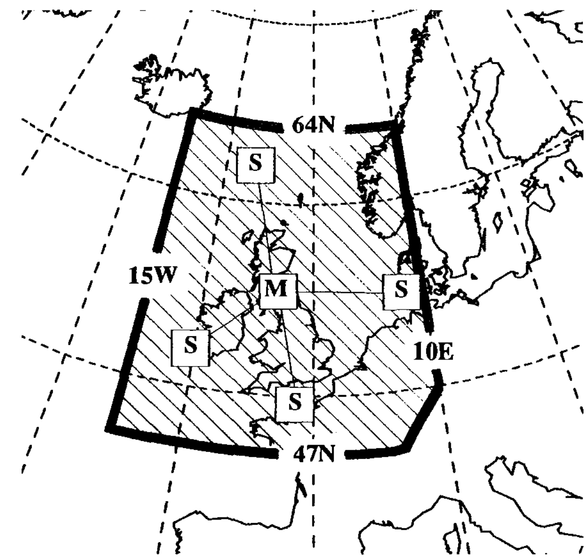

Fig. 7a *Stylized operational area for the UK Chain*

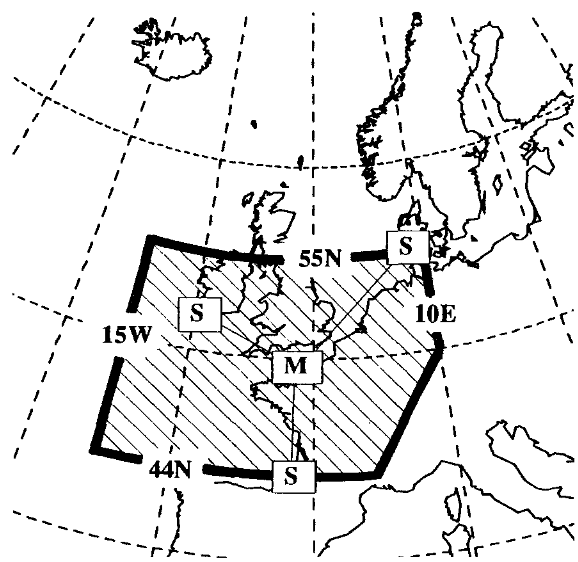

Fig. 7b *Stylized operational area for the SNRLC Chain*

Signals belonging to the first category affect a receiver's operation if not in the whole operational area, then at least in a part of it, and should always be counted.

For all signals of the second category the distance from transmitter to the nearest edge of the operational area is calculated. This distance is needed to estimate the field-strength at that location, using the curves of Fig. 8. These normalized curves are valid for an effective radiated power of 100 kW, and consequently readings have to be scaled with

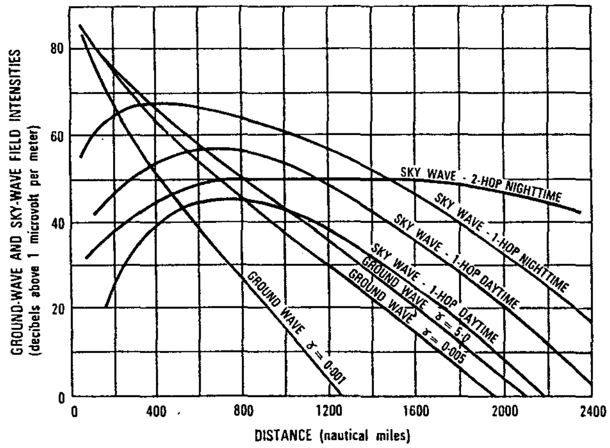

Fig. 8 *Variation of field-strength with distance to transmitter [7]*

the real power level of the transmitter as entered in the database. To obtain worst case values, data from first- or second-hop skywaves at nighttime is used.

From this field-strength at the antenna-input of the receiver, the signal level at the input of the tracking loop can be derived by accounting for the 'standard' bandpass filter function as defined before (Fig. 3). This will also be the interference level at the output of the loop, because of the rectangular shape of the tracking loop's transfer function.

The power levels of the Loran-transmitters were not known at the time of the analysis. A fixed value of 60 dB above 1 μV/m along the area's edges was therefore assumed for the Loran signal levels. Signal and interference can now be combined into a Signal-to-Interference Ratio (SIR) at the output of the tracking loop.

For this SIR the maximally resulting tracking error can be calculated with:

$$E = \frac{T_L}{2\pi} \arcsin\left(\frac{1}{SIR}\right) \quad [\text{ns}]$$

where T_L is the Loran-C carrier period of 10 μs. This can easily be derived from the formulae in [3].

Interferers resulting in errors larger than 100 ns are then counted to find the CWISF as defined above.

6. RESULTS

First the minimum allowable GRI's were established, starting from the presumption that Edinborough and Lessay were assigned masters.

Tables I and II show the configurations resulting in the smallest possible GRI's.

Table I (UK CHAIN)

Location	Status	Minimal Transmission Delay [ms]		
Edinborough	M	10.9 + 2.23	=	13.13
Mizzen Head	W	9.9 + 2.20	=	12.10
Lessay	X	9.9 + 3.07	=	12.97
Sylt	Y	9.9 + 4.06	=	13.96
Ejde	Z	9.9 + 2.47	=	12.37
				---------- +
		GRImin	=	64.54 ms

Table II (SNRLC CHAIN)

Location	Status	Minimal Transmission Delay [ms]		
Lessay	M	10.9 + 2.01	=	12.91
Soustons	X	9.9 + 3.60	=	13.50
Mizzen Head	Y	9.9 + 4.25	=	14.15
Sylt	Z	9.9 + 3.07	=	12.97
				---------- +
		GRImin	=	53.52 m

It will be clear that the same *GRImin* will be found if the order of the secondaries is reversed.

As explained in the Strategy-section, GRI's selection for European chains can be best done as a sequential evaluation of CWI and CRI sensitivity.

For both, the CWI and CRI, calculations, a value for the tracking bandwidth f_B has to be set. For the 'standard' receiver a response time of 6 sec was assumed: for a Type-I tracking loop, this response time corresponds with a -3 dB loop bandwidth of 0.1 Hz. An extra safety margin was included, resulting in an actual f_B of 0.25 Hz, because the filter used in the calculations was rectangularly shaped.

For all remaining candidate GRI's, (near-)synchronous interferers were filtered from the database. From them, those with the smallest CWI-Sensitivity Figures were used for further analysis on CRI sensitivity.

For the determination of the SCR-ratios, phase codes for Master tracking versus Master Cross Rate signals were used. Other combinations, such as Master-Slave phase codes, etc., indeed show other figures, but do not alter the judgement about a better or worse GRI-combination. Also, whether GRI_1 is used for tracking and GRI_2 for Cross Rate, or visa versa does not affect the conclusions.

For every GRI left, Signal-to-Cross Rate Ratios were calculated, with that GRI as wanted and the following 4 values as Cross Rate GRI's:

- 7970 - Norwegian Sea Chain
- 7990 - Mediterranean Sea Chain
- 8000 - Western USSR Tchaika Chain
- 9980 - Icelandic Chain

These SCRR's were summed and the candidate GRI with the highest SCRR sum and no single low SCRR, was considered best. Finally, simulation techniques as described in [8] were used to confirm the result.

A GRI of 7230 is found to be the best for the UK-chain, while for the SNRLC chain this should be 5770. Tables III and IV show the resulting CWI signals for both chains. Using the transmission sequences for the UK- and SNRLC-chains found in section 2, the following chain timing is now proposed:

Table V **UK CHAIN**

GRI	Location	Emission Delay
7230 - M	Edinborough	
7230 - W	Mizzen Head	15000
7230 - X	Lessay	29000
7230 - Y	Sylt	43000
7230 - Z	Ejde	58000

Table VI **SNRLC CHAIN**

GRI	Location	Emission Delay
5770 - M	Lessay	
5770 - X	Soustons	14000
5770 - Y	Mizzen Head	29000
5770 - Z	Sylt	44000

7. DISCUSSION

Tables III and IV both show a relatively large number of interferers with frequencies that are multiples of 5 kHz. It has been shown that the receiver has spectral sensitivity lines on frequencies

$$f_s = \frac{N}{2\,GRI}$$

where N is an arbitrary integer greater than 0.

For GRI's that are multiples of 100 μs, this can be rewritten as

$$f_s = \frac{10\,N}{2\,K}\ [\text{kHz}] = \frac{N}{K}\ 5\ [\text{kHz}]$$

where K = GRI [ms] / 10 and $400 \leq K \leq 999$.

For every K, considering a frequency range of e.g. 50 to 150 kHz, a number of N's can be found that are exact multiples of that K.

This means that every GRI that is a multiple of 100 μs, will be sensitive to synchronous interference on multiples of 5 kHz. Similarly, it can be proven that all GRI's being multiples of 200 μs or 500 μs, are sensitive to interference on multiples of 2.5, respectively 1 kHz. Unfortunately, many stations can be found on exactly such frequencies! These 200 and 500 μs GRI's do not have to be considered.

As a result, if a receiver is expected to behave properly in the European areas, it should be equipped with a fairly large number of (stable) notches. For newer equipment, a sampling algorithm using an alternative phase code could be considered.

Theoretically, best results would be achieved by altering transmitted phase code patterns, although this will not be realizable.

The next best remedy would be to use GRI's that are multiples of 10 μs. This is not conflicting with the rules mentioned in [2], but it has not been used up to now. Although not examined extensively, GRI's of 6551 (UK) and 5777 (SNRLC) can be mentioned as examples showing only 10, respectively 2 interferers.

The formulae for f_s also show the reason for opting for an as low as possible GRI. As said, the distance between spectral lines is 1 / 2 GRI. This means that the number of such lines falling in a specific frequency range decreases with decreasing GRI's. Assuming randomly distributed interference signals over this frequency range, the risk of encountering (near-) synchronous interference with lower GRI thus also decreases. This was apparent when a scan was made of the number of interferers for all GRI's between 4000 and 9999.

8. CONCLUSIONS

It has been shown that for the new European chains GRI's can be found that are expected to suffer the least from Continuous Wave and Cross Rate Interferences.

Even for these GRI's, selected on the lowest number of (near-) synchronous interferers, a large number of notch filters will still be needed. The main reason is the inability of the Loran system as is to reject frequencies on multiples of 5 kHz. In the European situation this directly results in some ten potential interferers.

Table III Synchronous and Near-Synchronous Interference sources for the UK Chain

f [kHz]	Transmitter location	Country	Remarks
50.000	Liblice	Poland	input bandpass filter should be sufficient
60.000	Rugby	UK	nearby reception needs notch
71.3625	Barra, Kentra Moss, Stornoway	UK	DECCA, notch needed locally
75.000	Geneve Prangins	Switzerland	notch needed at eastern boundary
85.000	Lewes, Norwich, Puckeridge, Warwick	UK	DECCA chain, notch needed
88.700	Kootwijk	Netherlands	notch needed
105.000	Koenigswustern	GDR	in band, should be switched off
113.3333	Lewes, Norwich, Puckeridge, Warwick	UK	DECCA chain, notch needed
115.000	Chatham, Rosyth	UK	notch needed
115.4218	Allerdean Greens, Burton Fleming, Peterhead, Stirling	UK	DECCA chain, notch needed
115.650	Karlsborg	Sweden	notch needed in north-eastern area only
120.000	Londonderry	Ireland	notch needed
123.700	Mainflingen	FRG	notch needed
125.000	Mainflingen	FRG	notch needed
145.000	Leningrad, Riga	USSR	input bandpass filter should be sufficient

Table IV Synchronous and Near-Synchronous Interference sources for the SNRLC Chain

f [kHz]	Transmitter location	Country	Remarks
50.000	Liblice	Poland	input bandpass filter should be sufficient
60.000	Rugby	UK	nearby reception needs notch
70.5375	Clanrolla, Kidsdale, Neston, Stirling	UK	DECCA chain, notch needed
75.000	Geneve Prangins	Switzerland	notch needed at eastern boundary
85.000	Lewes, Norwich, Puckeridge, Warwick	UK	DECCA chain, notch needed
88.700	Kootwijk	Netherlands	notch needed
105.000	Koenigswustern	GDR	in band, should be switched off
113.3333	Lewes, Norwich, Puckeridge, Warwick	UK	DECCA chain, notch needed
115.000	Chatham, Rosyth	UK	notch needed
115.650	Karlsborg	Sweden	notch needed in north-eastern area only
120.000	Londonderry	Ireland	notch needed
123.700	Mainflingen	FRG	notch needed
125.000	Mainflingen	FRG	notch needed
140.000	Toulon	France	in southern part only, input bandpass filter should be sufficient
145.000	Leningrad, Riga	USSR	input bandpass filter should be sufficient

The best way to lower the number of interferers will be to use GRI's on multiples of 10 instead of on 100 μs.
Much of the remaining interference originates from DECCA stations, which often are situated inside the coverage areas. Nearby such stations, navigation with Loran-C becomes troublesome, if not impossible. If these chains are phazed out of operation, as is announced for the nineties, an improvement in Loran-C signal quality can be expected. In fact, should Loran-C be really accepted in Europe, DECCA should be abandoned as soon as possible.
Finally, the ITU-list [5] shows a lot of frequencies inside the Loran-C band claimed for purposes other than Loran-C or radio-navigation in general. Though these frequencies did not seem to be used at the time of the analysis, the fact that they are claimed still leaves an uneasy feeling.

9. ACKNOWLEDGMENTS

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About the authors

Martin Beckmann was born in 1964. He studied Electrical Engineering at the Delft University of Technology. He completed his masters thesis concerning software for an OMEGA navigation receiver in 1987, and is still with the Delft University, working on Loran-C receivers.

Huib J. Lincklaen Arriëns was born in 1947. He received his B.Sc. degree in electrical engineering in 1969, after which he joined the Department of Electrical Engineering of the Delft University of Technology. Since 1978 he is involved in radio-navigation projects associated with OMEGA and Loran-C systems.

A LEAST SQUARES APPROACH TO POSITION DETERMINATION AND ACCURACY ANALYSIS

David H. Gray
Canadian Hydrographic Service
Ottawa, Ontario, Canada

Abstract

The production of Loran-C receivers that maintain lock on more than two time differences (TD's) within the same Loran-C chain and those that are capable of simultaneously tracking time differences from more than two Loran-C chains would benefit from the generalized approach to the postion computation afforded by the observation equation method of least squares.

The benefit to using this method is not only the independence from two TD's in one chain type solution but also the analysis of the quality of the computed position derived from the inversion of the normal equations.

Introduction

At the 1988 Wild Goose Association Technical Symposium, one of the papers descibed the error analysis of Loran-C positioning as a function of a fixed traid of master/slave/slave. I suggest that a more general approach is possible by taking a more generalized approach afforded by Least Squares.

What is Least Squares? The least squares solution is based on the requirement that the sum of the squares of the weighted corrections to the observations is a minimum. With just two TD's there is only one realistic position, but with redundant observations, it is necessary to adjust the value of each of the observations so that there is a mathematical consistency among the observations. If the observations are normally distributed about their 'true' values (no biases), a least squares adjustment will give the most probable value of the observations.

Observation Equation Method

The observation equation (or variation of parameter) method is based on the principle that the observed value of an observation plus its correction must equal the computed value obtained from the parameters after they have been adjusted.

$$TDc = f(Lat_m, Long_m, Lat_s, Long_s, Lat_i, Long_i) \qquad (1)$$

where: TDc = the computed value from the adjusted value of the positions
Lat, Long = the adjusted value of the positions of master, slave and ship.

Since the position of the transmitters are well known:

$$TDc = f(Lat_i, Long_i) \qquad (2)$$

But $TDc = TDo + v. \qquad (3)$

where: TDo = the observed value.
v = the correction to that observation.

Thus

$$TDo + v = f(Lat + dLat\ ,\ Long + dLong). \qquad (4)$$

where: dLat = the correction to the initial latitude, and
dLong = the correction to the initial longitude.

Let TDcp = the computed TD at the preliminary position:

$$TDcp = f(Lat_i, Long_i) \qquad (5)$$

$$TDo + v = TDcp + \frac{\partial\, TDcp}{\partial\, Lat_i} dLat_i + \frac{\partial TDcp}{\partial Long_i} dLong_i \qquad (6)$$

or as the observation equation is normally written:

$$v = a_1 dLat_i + a_2 dLong_i - (TDo - TDcp) \qquad (7)$$

where: $a_1 = (-\cos(az_m) + \cos(az_s)) \times radius_M \times 0.5$

$a_2 = (\sin(az_m) - \sin(az_s)) \times radius_{PV} \times 0.5$

$\times \cos(Lat_i)$

az_m *= azimuth from i to master*

az_s = azimuth from i to slave

$radius_M$ = earth's radius in meridian

$radius_{PV}$ = earth's radius perpendicular to meridian

In matrix notation:

$$V = AX - L \tag{8}$$

where: V = matrix of corrections to observed TD's
A = matrix of the partial differentials
X = matrix of the corrections to the preliminary coordinates
L = matrix of differences between observed and computed TD's based on preliminary coordinates

For the Least Squares condition:

$V^T PV$ is a minimum

where: P = matrix of correlated weights of the observations

$$\begin{aligned} V^T PV &= (X^T A^T - L) P (AX-L) \\ &= X^T A^T PAX - X^T A^T PL - L^T PAX + L^T PL \end{aligned} \tag{9}$$

$$\frac{d(V^T PV)}{d\,X} = 2\,X^T A^T PA - 2\,L^T PA \tag{10}$$

For minimum: $\dfrac{d(V^T PV)}{d\,X} = 0$

Therefore: $X^T A^T PA - L^T PA = 0$

$$A^T PAX = A^T PL$$

$$X = (A^T PA)^{-1} A^T PL \tag{11}$$

then $$V = AX - L \tag{12}$$

The $(A^T PA)^{-1}$ matrix, often called the the inverse of the normal equations, has special properties because it is the variance / covariance matrix of the parameters; namely, of the latitude and longitude of the receiver.

$$B_v = \begin{bmatrix} var_{lat} & covar_{lat\,long} \\ covar_{lat\,long} & var_{long} \end{bmatrix} \tag{13}$$

The error ellipse is the equation:

$$S_F^2 = \frac{var_{long}\,x^2 - 2\,covar_{lat\,long}\,xy + var_{lat}\,y^2}{var_{lat}\,var_{long} - covar_{lat\,long}} \tag{14}$$

The semi-major, semi-minor axes and azimuth of the major axis of the error ellipse can be found from: rotation clockwize from the Y axis (North)

$$\tan(2\,Theta) = \frac{-2\,covar_{lat\,long}}{var_{lat} - var_{long}} \tag{15}$$

The semi-major and semi-minor axes are the roots of:

$$S_F^2 = var_{lat} \cos^2(alpha) - 2covar_{lat\,long} \cos(alpha)\sin(alpha) + var_{long} \sin^2(alpha) \tag{16}$$

with alpha = Theta and Theta + 90°

Multi-TD Solution

The advantage of using the Least Squares approach is that TD's do not have to be from a common master, that more than two TD's can be used for the solution and that an analysis of the position accuracy is possible with this method.

With more than two TD's, each observed TD gets a correction to its observed value. If the TD's are not compatible, the corrections will be large. If the systematic errors (e.g. ASF) are not properly accounted for, the corrections will also be significant. But if there are no blunders (e.g. wrong cycle) and an accurate ASF model, then the corrections to the TD's will be in the order of the noise of Loran-C (about 0.1 - 0.2 microsec.).

Here is an example in Lake Erie that I personally observed:

Rate	TD	Correction	Rate	TD	Correction
8970W	16635.13	0.099	9960W	16463.17	0.013
8970X	29781.63	0.021	9960X	28924.47	0.133
8970Y	49797.73	0.175	9960Y	44563.30	0.112
			9960Z	58542.50	-0.006

The adjusted position is:
42° 39′ 43.63″ N
80° 10′ 15.83″ W

The error ellipse is:
semi-major axis = 34 m.
semi-minor axis = 20 m.
azimuth of major axis = 160°

Normally with only the two best TD's the semi-major axis is about 60 m.

Also, a second example, this time on Georges Bank:

Rate	TD	Correction	Rate	TD	Correction
5930X	12153.2	0.00	9960W	12900.5	-0.22
5930Y	30946.5	0.14	9960X	25095.2	-0.02
			9960Y	43777.7	-0.28

The adjusted position is:
41° 48′ 25.00″ N
66° 49′ 39.70″ W

The error ellipse is:
semi-major axis = 47 m
semi-minor axis = 26 m
azimuth of major axis = 313°

The semi-major axis of the error ellipse from the best pair of TD's (5930XY) is 62 metres.

Coverage Diagrams

Since the variance-covariance matrix is independent of the actual observed values and only dependent on the geometry of the selected TD's, then it is possible to calculate the error ellipse at pre-determined locations without knowing the observed values. If a computer program is designed to evaluate the error ellipses from various combinations of TD's and to rank them in ascending order of semi-major axis, one can then make up coverage diagrams and contours of repeatability based on the error ellipses, see figure 1. Since this method does not require master/slave/slave limitations, any combination of TD's is possible, see figure 2. There are definite improvements in certain localities. And since one is not limited to only two TD's, one can analyze the effect of multi-TD combinations, as in figure 3.

Conclusions

The use of a Least Squares approach to solving for the position determination relieves the user from the master/slave/slave restraint and allows the user the capability of a multiple TD solution, the use of TD's from more than one chain, the verification of mathematically consistent data, and the analysis of the repeatability of the position from the error ellipse data.

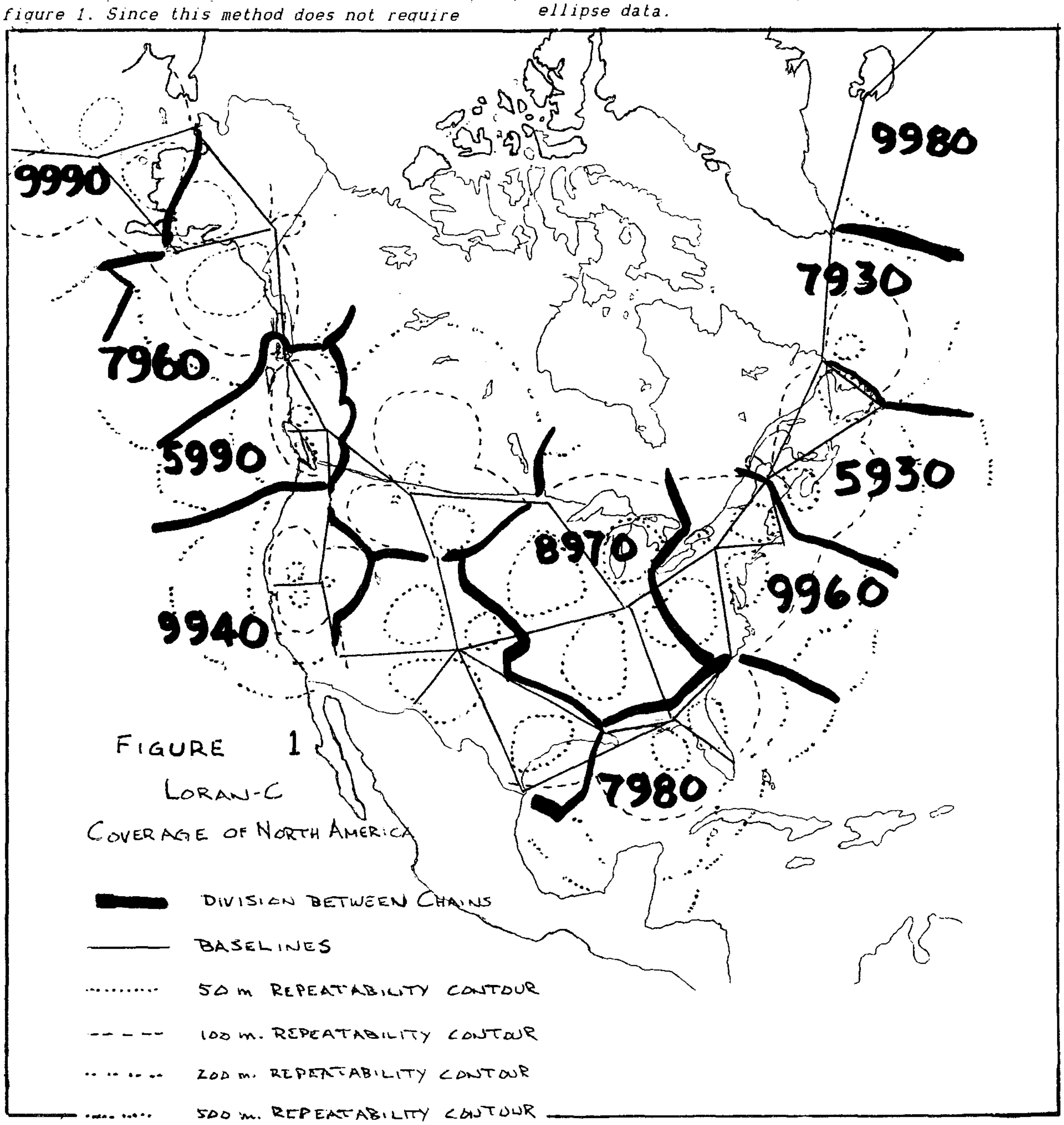


FIGURE 1
LORAN-C
COVERAGE OF NORTH AMERICA

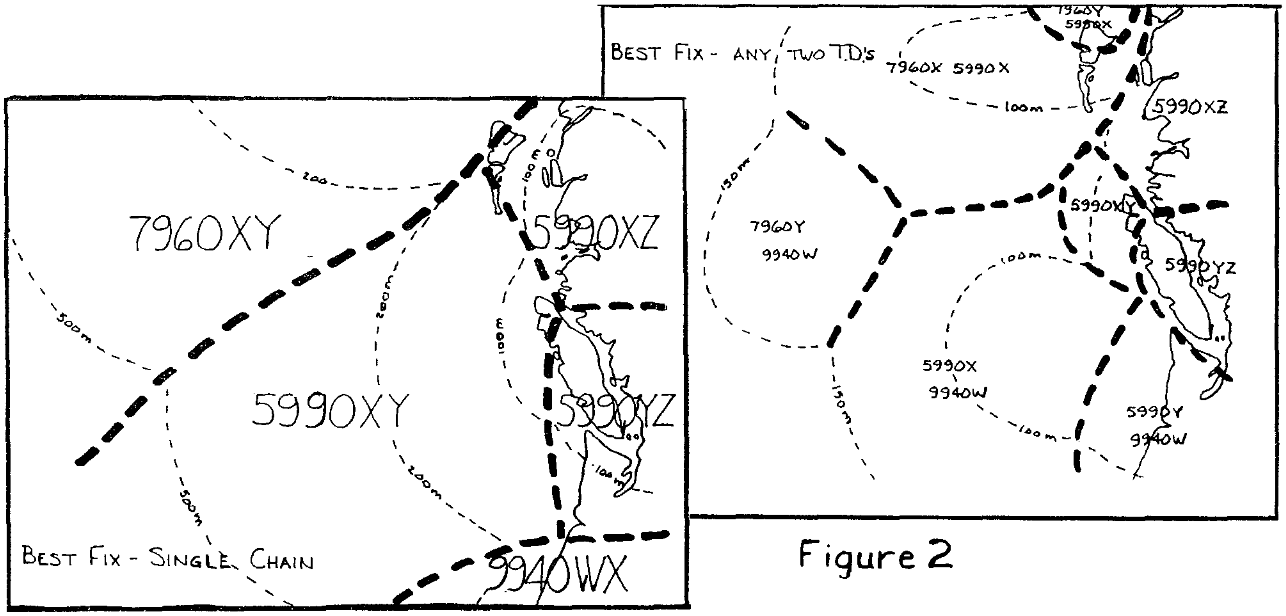
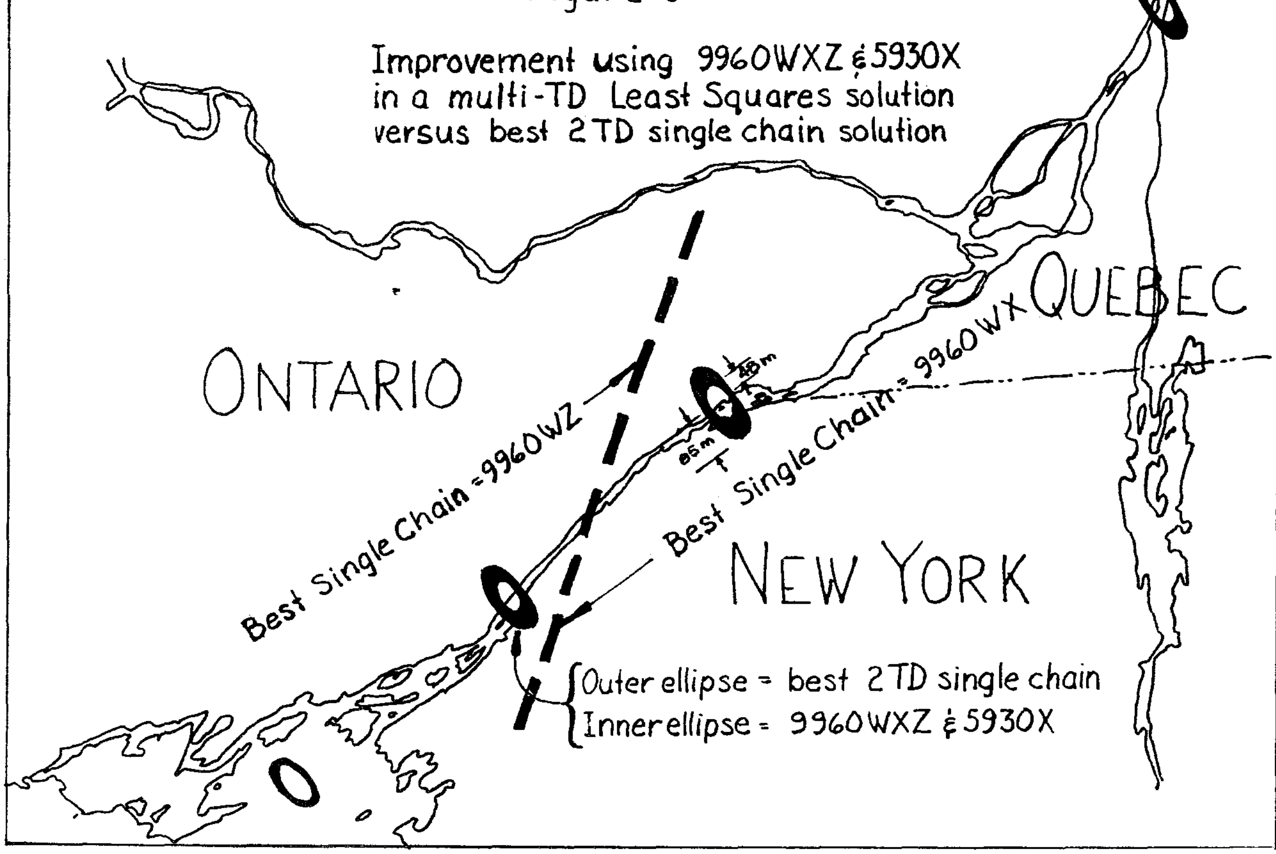


Figure 2

Figure 3



MATCHING ANTENNA PARAMETERS TO THE SOLID-STATE TRANSMITTER

Paul R. Johannessen

Megapulse, Inc.

ABSTRACT

The design study of top-loaded monopole antennas as presented in Reference 1 concludes that optimum bandwidth-efficiency product is obtained when the projected length of the top-hat radials is 0.7 of tower height or 0.8 for maximum power-bandwidth product. To minimize antenna cost, 24 radials should be used in the top-hat, anchored at a distance from the base equal to the tower height.

For antennas above 600 feet in height, such a top-hat causes the antenna resonance frequency to be below 100 kHz. For Loran-C application, therefore, the top-hat must be reduced such that the antenna resonance frequency is above 100 kHz. In the past, Loran-C antennas have been designed with the largest possible top-hat within the limit restriction imposed by the antenna resonance frequency.

In this paper, the antenna top-hat parameters are determined by maximizing the radiated peak power when the antenna is driven by the solid-state transmitter. It is shown that the optimum ratio of the projected length of the top-hat radials to the tower height is dependent on tower height. For antennas below 600 feet, this optimum ratio is 0.7 and decreases for antennas higher than 600 feet. For the 1350 foot antenna, the optimum ratio is 0.2. This lower optimum ratio still results in an antenna resonance frequency above 100 kHz for antenna in the height range of 600 feet to approximately 1,200 feet. For antennas above approximately 1,200 feet, the optimum ratio can be achieved within the antenna resonance frequency restriction.

1.0 INTRODUCTION

To determine the optimum antenna parameters, the peak radiated power is calculated as a function of antenna height h, and ratio of the projected length of the top-hat radials to the tower height, h′/h. In the following sections, the peak radiated power is calculated using a low-pass equivalent model of the antenna/transmitter configuration.

2.0 EQUIVALENT REPRESENTATION

A simplified circuit diagram of the solid-state transmitter and the antenna is shown in Figure 1. The low-pass equivalent circuit is shown in Figure 2. The unit impulse response

$$\frac{1}{N} i_T(t) = u_1(t) \tag{1}$$

becomes

$$i(t) = \frac{1}{LC\beta} e^{-\alpha t} \sin \beta t \tag{2}$$

where

$$\alpha = \frac{R}{2L}$$

$$\beta = \sqrt{\frac{1}{LC} - \left(\frac{R}{2L}\right)^2}$$

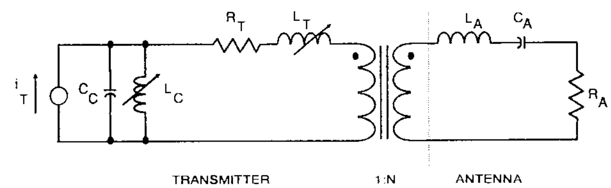


Figure 1. Simplified Circuit Diagram of Transmitter and Antenna

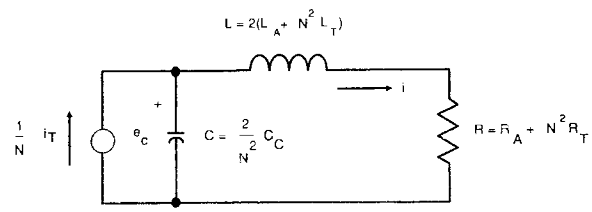


Figure 2. Low-pass Equivalent Circuit

Reference 1. Low Frequency Top Loaded Antennas by T. E. Devaney, R. F. Hall, and W. E. Gustafson, NEL/Report 1381, June 22, 1966.

This unit impulse response is plotted in Figure 3. For a high Q circuit, the response is oscillatory as shown in Figure 3(a). The coupling capacitor voltage, as shown by the dotted curve, goes to zero shortly after the peak of the antenna current, shown as t_c in Figure 3(a). To eliminate the oscillatory tail, a switch connected across the coupling capacitor is closed at time t_c, thus generating an exponential tail as shown by the dotted line in Figure 3(a). A more detailed discussion of the switch is presented in Section 8. For a low Q circuit, the response tends to be more exponential as shown in Figure 3(b).

In the Megapulse solid-state Loran-C transmitter, the total transmitter energy is delivered to the coupling network during the first two cycles of the RF carrier. This energy is delivered in the form of four half-cycle current pulses. In the low-pass equivalent circuit, these current pulses are represented by four current impulses occurring at the peak of the half-cycle currents, as shown in Figure 4. For the case of equal current pulses, the antenna current can be calculated by means of superposition as shown in Figure 5. As shown in the figure, the peak of the sum current occurs 10 μsec later than for a single current impulse occurring at time t = 0.

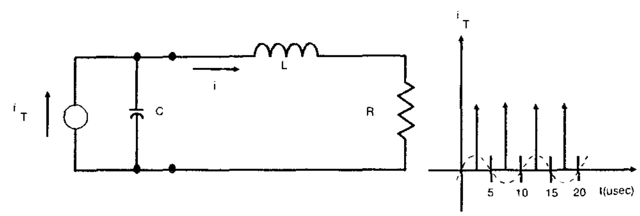


Figure 4.
Equivalent Representation of Transmitter Half-Cycle Current Drive

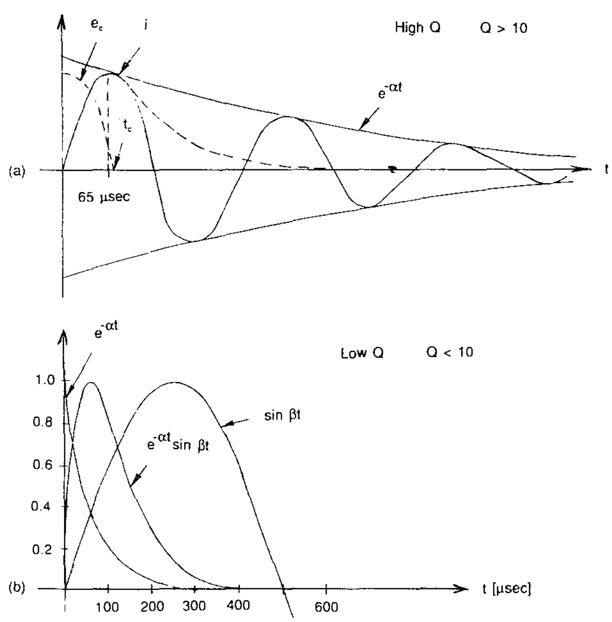


Figure 3. Unit Impulse Response of Low-pass Equivalent Circuit

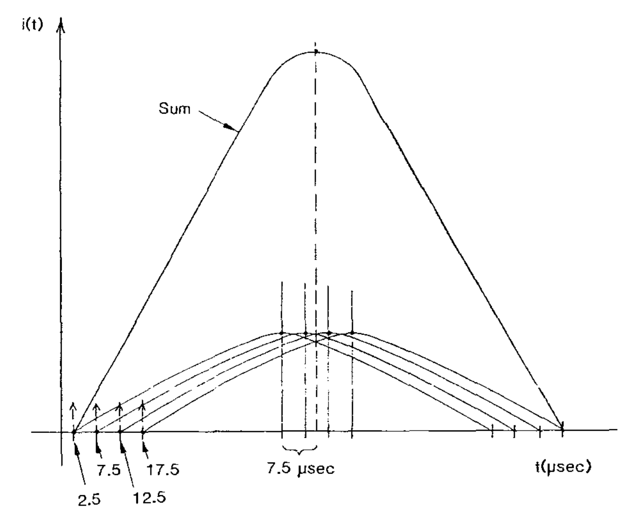


Figure 5. Antenna Current Resulting from Four Current Impulses

3.0 ENVELOPE TIME-TO-PEAK

For a single impulse of current excitation occurring at time t = 0, the antenna current envelope is given by Equation (2). The time-to-peak is given by

$$\frac{di(t_p)}{dt} = 0 \tag{3}$$

Therefore

$$\beta e^{-\alpha t_p} \cos \beta t_p - \alpha e^{-\alpha t_p} \sin \beta t_p = 0 \tag{4}$$

which gives

$$\tan \beta t_p = \frac{\beta}{\alpha} \tag{5}$$

or

$$t_p = \frac{1}{\beta} \tan^{-1} \frac{\beta}{\alpha} \tag{6}$$

When the coupling network is excited by four impulses as shown in Figure 4, the time-to-peak becomes

$$T_p = \frac{1}{\beta} \tan^{-1} \frac{\beta}{\alpha} + 10 \times 10^{-6} [\text{sec}] \tag{7}$$

As an example, consider an antenna having the following parameter values which are typical for a 625 foot antenna.

$$\left.\begin{aligned} L_A + N^2 L_T &= 255\ \mu H \\ C_A &= .01\ \mu F \\ R = R_A + N^2 R_T &= 2.5 + 3 = 5.5 \Omega \end{aligned}\right\} \tag{8}$$

and the desired time-to-peak

$$T_p = 62.5\ \mu\text{sec} \tag{9}$$

Using these values we obtain

$$\alpha = \frac{R}{4L_A} = \frac{5.5}{1020} \times 10^6 = 5{,}392 \tag{10}$$

$$\beta = \sqrt{\frac{980}{C_C} - 5.392^2} \times 10^3 \tag{11}$$

where the unit for C_C is in μF.

Combining Equations (7), (9), (10) and (11) yields

$$\frac{1 \times 10^{-3}}{\sqrt{\frac{980}{C_C} - 29.07}} \tan^{-1} \frac{\sqrt{\frac{980}{C_C} - 29.07}}{5{,}392} = 52.5 \times 10^{-6} \tag{12}$$

Solving this equation for C_C gives

$$\left.\begin{aligned} & C_C = 1.4\ \mu F \\ \text{and} \quad & \beta = 25{,}902 \end{aligned}\right\} \tag{13}$$

4.0 THE COUPLING CAPACITOR VOLTAGE

The coupling capacitor voltage is obtained as follows

$$e_C(t) = E(0) \left[1 - \frac{1}{C} \int_0^t i(t)\, dt \right] \tag{14}$$

Substituting Equation (2) in (14) and integrating yields

$$e_C(t) = E(0) \frac{(\alpha^2 + \beta^2)^{1/2}}{\beta} e^{-\alpha t} \sin(\beta t + \psi) \tag{15}$$

where

$$\psi = \tan^{-1} \frac{\beta}{\alpha} \tag{16}$$

The envelope waveforms of antenna current and coupling capacitor voltage, as given by Equations (2) and (15) are plotted in Figure 6. The current peak occurs at time t_p and the coupling capacitor voltage goes through zero at time t_c. Note that t_c always occurs after t_p. For a lossless circuit t_p and t_c occur at the same time.

5.0 CALCULATION OF PEAK ANTENNA CURRENT

From Equation (6) the peak antenna current occurs at time

$$t_p = \frac{1}{\beta} \tan^{-1} \frac{\beta}{\alpha}$$

Substituting this value for t in Equation (3) yields

$$I_P = \frac{1}{\beta LC}\, e^{-\frac{\alpha}{\beta}\tan^{-1}\frac{\beta}{\alpha}} \sin(\tan^{-1}\frac{\beta}{\alpha}) \qquad (17)$$

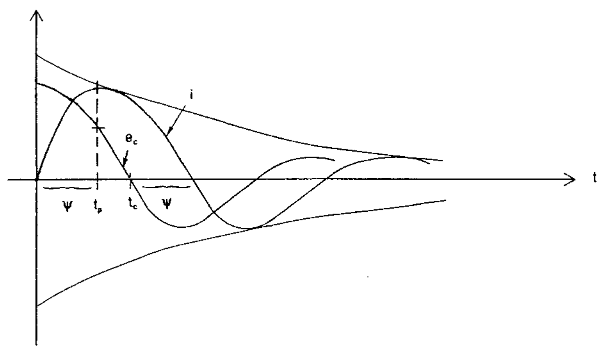


Figure 6. Voltage and Current Envelope Waveforms

Equation (17) is the peak current resulting from a unit current impulse response. For a current impulse of magnitude Q, the peak current becomes

$$I_P = \frac{E(0)}{\beta L}\, e^{-\frac{\alpha}{\beta}\tan^{-1}\frac{\beta}{\alpha}} \sin(\tan^{-1}\frac{\beta}{\alpha}) \qquad (18)$$

where

$$E(0) = \frac{Q}{C}$$

The initial coupling capacitor voltage, E(0), is determined by the total amount of energy delivered to the coupling network by the transmitter. The peak current generated by a 32 HCG transmitter in a dummy antenna having the parameter values of Equation (8) is typically

$$I_P = 690 \text{ amps} \qquad (19)$$

Substituting numerical values in Equation (18) yields

$$690 = \frac{E(0) \times 10^6}{25{,}902 \times 510}\, e^{-\frac{5{,}392}{25{,}902}\tan^{-1}\frac{25{,}902}{5{,}392}}$$

$$\sin(\tan^{-1}\frac{25{,}902}{5{,}392}) = .05573\ E(0)$$

therefore

$$E(0) = 12{,}372 \text{ volts} \qquad (20)$$

and the total energy delivered by the transmitter is

$$U_T = \frac{1}{2}\, C_C E(0)^2 = \frac{1}{2} \times 1.4 \times 10^{-6} \times (12{,}372)^2$$

$$= 107.15 \text{ joules} \qquad (21)$$

or an average of 3.35 joules/HCG.

6.0 MATCHING THE TRANSMITTER TO THE ANTENNA

In the Megapulse Transmitter there exists two matching problems. One is to match the output of the HCGs to the coupling network, and the other is to match the coupling network to the antenna. These two matching problems may be considered separately, because the amount of energy transferred to the antenna during the two first cycles is small compared to the total transferred energy. Typically, the peak antenna current in the fourth half-cycle is .15 I_P representing an energy of 6.25% of the peak energy in the antenna.

It has been determined theoretically and experimentally that maximum energy is transferred from the HCGs to the coupling network when the coupling network capacitance, C_C, is .092 μF/HCG. Each coupling capacitor consists of two parallel sections of .184 μF capacitance, capable of matching two HCGs.

The matching problem between the coupling network and the antenna is to insure that the antenna current peak occurs at approximately 65 μsec and that adequate control of the antenna current leading edge is obtained in order to adjust for the desired ECD. This problem was discussed in Section 3, and it was shown that by properly selecting the value of the coupling capacitor, the desired antenna current time-to-peak could be achieved. Since the value of the coupling capacitor is set by the number of HCGs, an RF transformer must be used between the coupling network and antenna to obtain the desired match, as shown in Figure 1.

The transmitter output inductance, L_T, is variable and is, by closed-loop feedback technique, adjusted such that

$$\sqrt{\frac{1}{(L_A + N^2L_T)C_A}} = .2\pi \times 10^6 \qquad (22)$$

The inductance L_C is manually adjusted so that

$$\sqrt{\frac{1}{L_CC_C}} = .2\pi \times 10^6 \qquad (23)$$

The low-pass equivalent circuit of Figure 6 is shown in Figure 7.

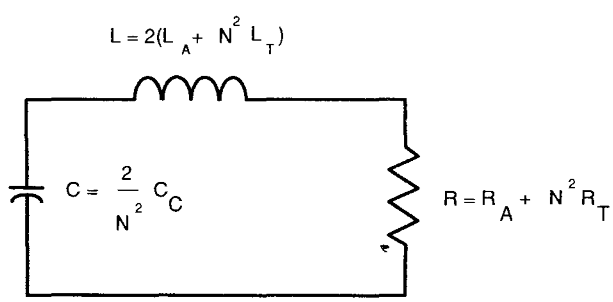


Figure 7. Low-pass Equivalent Circuit of Transmitter Output Circuit with Matching Transformer

To determine the value of N we use the equations

$$(6) \qquad t_p = \frac{1}{\beta}\tan^{-1}\frac{\beta}{\alpha}$$

$$\alpha = \frac{R_A + N^2R_T}{2 \times 2(L_A + N^2L_T)} \qquad (24)$$

$$\beta = \sqrt{\frac{1}{\frac{2}{N^2}\,C_C\,2(L_A + N^2L_T)} + \left[\frac{R_A + N^2R_T}{2 \times 2(L_A + N^2L_T)}\right]^2} \qquad (25)$$

7.0 DETERMINING THE VALUE OF R_T

During the leading edge of the antenna current, the coupling network voltage appears across all the HCG's output transformers and the RF antenna matching transformer. Since these transformers use ferrite as core material, substantial core losses, in addition to winding and capacitor losses, occur. In the equivalent circuit, these losses are taken into account by the series resistor R_T. The value of this resistor is obtained by measurements.

The dummy antenna current of a 32 HCG transmitter with the Tailbiter disengaged is shown in Figure 8. The dummy antenna is adjusted to represent a typical 625 foot antenna having the following parameter values

$$\left.\begin{aligned} C_A &= .01\ \mu F \\ L_A + N^2L_T &= 255\ \mu H \\ R_A &= 2.5\Omega \\ N &= \sqrt{2} \\ C_C &= 2.944\ \mu F \end{aligned}\right\} \qquad (26)$$

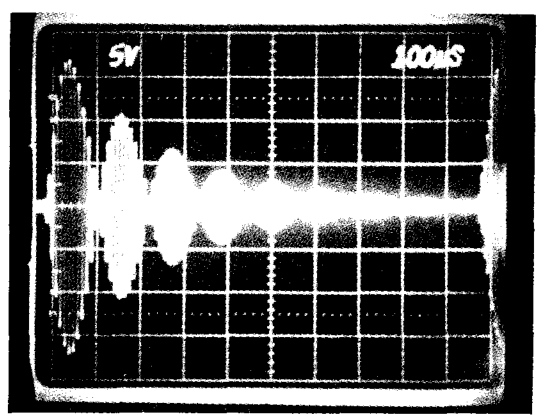


Figure 8. Dummy Antenna Current with Tailbiter Disengaged

The antenna current is given by

$$i_A(t) = I\, e^{-\alpha t} \sin \beta t$$

where

$$\alpha = \frac{2.5 + 2R_T}{255} \times 10^6 \qquad (27)$$

$$\beta = \sqrt{\frac{2 \times 10^{12}}{4 \times 255 \times 2.944} - \left[\frac{2.5 + 2R_T}{255} \times 10^6\right]^2} \qquad (28)$$

From Figure 8

$$\beta = \frac{\pi \times 10^6}{115} = 27{,}318 \qquad (29)$$

at $t = t_1 = 57.5\ \mu\text{sec}$, $I\, e^{-\alpha t_1} = 3.3$ (30)

at $t = t_2 = 230\ \mu\text{sec}$, $I\, e^{-\alpha t_2} = 1.3$ (31)

which gives

$$\alpha = 5{,}400 \qquad (32)$$

Thus we obtain

$$R = 2L\alpha = 1020 \times 5{,}400 \times 10^{-6} = 5.5\Omega \qquad (33)$$

therefore

$$R_T = \frac{1}{2}(R - R_A) = \frac{1}{2}(5.5 - 2.5) = 1.5\Omega \qquad (34)$$

8.0 SHAPING THE TAIL OF THE ANTENNA CURRENT

An oscillating antenna current pulse tail, as shown in Figure 8 is not acceptable. An exponentially decaying pulse tail as shown in Figure 9 is required. To obtain this desired pulse tail, a switch in series with a resistor is connected across the coupling network. This switch is referred to as the Tailbiter Switch. The low-pass equivalent circuit with the Tailbiter Switch is shown in Figure 10.

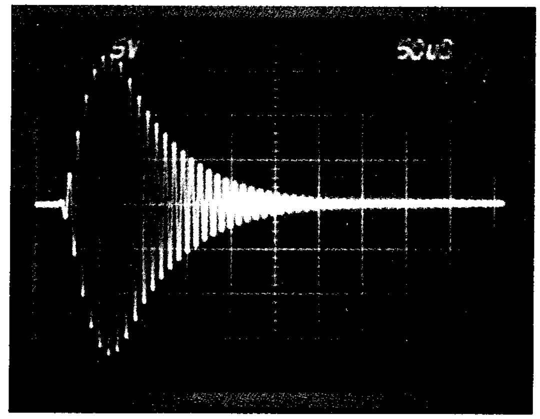


Figure 9. Dummy Antenna Current with Tailbiter Engaged

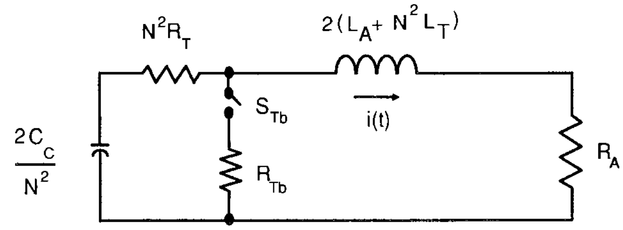


Figure 10. Low-pass Equivalent Circuit with Tailbiter

If we assume that R_{Tb} is small compared to N^2R_T and that the Tailbiter closes when the coupling capacitor voltage is zero (t_c in Figure 6), then for $t > t_c$, the antenna current decreases exponentially with time constant

$$\tau = \frac{2(L_A + N^2L_T)}{R_A + R_{Tb}} \qquad (35)$$

From Figure 9

$$\tau \cong 75\ \mu\text{sec} \qquad (36)$$

$$R_{Tb} = \frac{510 \times 10^{-6}}{75 \times 10^{-6}} - 2.5 = 4.3\Omega \qquad (37)$$

Unfortunately, the assumption initially made to arrive at the above value for R_{Tb} is not valid. In fact, R_{Tb} is slightly larger in value than $N^2R_T(3\Omega)$. To see the effect of the coupling capacitor and the transmitter resistance, we calculate the antenna current after the closing of the Tailbiter Switch. This calculation is straightforward and yields the following result

$$i(t) = I\left(1.08\, e^{-\frac{1}{70}t} - .08\, e^{-\frac{1}{11.5}t}\right) \qquad (38)$$

where t is in µsec. The second term in this expression is negligible so we are left with an exponential transient with a time-constant of 70 µsec, instead of the desired 75 µsec, which is quite acceptable.

9.0 IN-BAND VS OUT-OF-BAND ENERGY REQUIREMENT

Besides having the requirement of a certain envelope shape, as shown in Figure 9, the antenna current pulse must meet certain spectrum requirements. The requirement we are concerned with here is the in-band versus out-of-band energy requirement, because this requirement determines the minimum "length" of the pulse tail, or more precisely, the minimum time-constant of the tail. This energy requirement specifies that the energy in the pulse spectrum between 90 kHz and 110 kHz should be at least 99% of total pulse energy. From spectrum measurements we know that the pulse shown in Figure 9 just barely meets the in-band energy requirement.

In the 625 foot antenna, a considerable amount of energy is wasted in the Tailbiter resistance. If this energy could be used to increase the antenna current without affecting in-band energy requirement, considerably more peak power could be radiated.

10.0 ANALYSIS OF THE CHINESE LORAN-C TRANSMITTER/ANTENNA CONFIGURATION

The Chinese Loran-C stations use 64 HCG transmitters to drive a 810 foot top-loaded antenna. The antenna parameters are as follows:

$$\left.\begin{aligned} h &= 810 \text{ ft} \\ N &= 12 \\ \rho &= 1.73h \\ h'/h &= .34 \end{aligned}\right\} \qquad (39)$$

From Reference 1:

$$\left.\begin{aligned} C_0 &= .0028\ \mu F \\ R_0 &= 2.7\Omega \\ R_r/R_0 &= 2.1\ , \quad R_r = 5.67\Omega \\ C_A/C_0 &= 3\ , \quad C_A = .0084\ \mu F \end{aligned}\right\} \qquad (40)$$

The measured parameter values are

$$\left.\begin{aligned} R_A &= R_r + R_\ell = 6.68\Omega \\ C_A &= .00821\ \mu F \end{aligned}\right\} \qquad (41)$$

There is a small discrepancy (2.25%) between the calculated and measured antenna capacitance probably due to top-hat sag. To be conservative, we will reduce the radiation resistance by 10% due to top-hat sag, thus

$$R_r = 5.103\Omega \qquad (42)$$

The measured peak antenna current is

$$I_P = 780 \text{ amps} \qquad (43)$$

The peak radiated power becomes

$$P_r = \frac{1}{2} \times 5.103 \times 780^2 = 1{,}552{,}332 \text{ watts} \qquad (44)$$

To determine the antenna current and coupling capacitor voltage envelopes, we use the following measured parameter values

$$\begin{aligned} R_A &= R_r + R_\ell = 6.68\Omega \\ C_A &= .00821\ \mu F \\ C_C &= 5.888\ \mu F \\ N &= 2 \\ R_T &= .75\Omega \\ L_A &= 308.5\ \mu H \end{aligned} \qquad (45)$$

Using these numerical values we obtain

$$\alpha = \frac{R}{2L} = \frac{6.68 + 3}{2 \times (2 \times 308.5)} = 7{,}844 \qquad (46)$$

$$\beta = \sqrt{\frac{10^{12} \times 2^2}{2 \times 5.888 \times 2 \times 308.5} - 7{,}844^2} = 22{,}113 \qquad (47)$$

Time-to-peak becomes

$$t_P = \frac{1}{\beta} \tan^{-1} \frac{\beta}{\alpha} = \frac{1}{22{,}113} \tan^{-1} \frac{22{,}113}{7{,}844}$$

$$= 55.6\mu sec \qquad (48)$$

From the measured peak current of 780 amps, we can obtain the coupling capacitor voltage

$$I_P = \frac{E(0) \times 10^6}{22{,}113 \times 2 \times 308.5}$$

$$e^{-\frac{7{,}844}{22{,}113} \tan^{-1} \frac{22{,}113}{7{,}844}}$$

$$\sin(\tan^{-1} \frac{22{,}113}{7{,}844}) = .044635\ E(0) \qquad (49)$$

therefore

$$E(0) = \frac{780}{.044635} = 17{,}475 \text{ volts} \qquad (50)$$

The total coupling capacitor energy

$$U_T = \frac{1}{2} \times 2.944 \times 17{,}475^2 = 449.5 \text{ joules} \qquad (51)$$

$$U_{HCG} = \frac{449.5}{2 \times 64} = 3.5 \text{ joules} \qquad (52)$$

Antenna Q (including transmitter output resistance)

$$Q = \frac{\omega L_A}{R_A + R_T} = \frac{.2\pi \times 308.5}{9.68} = 20.02 \qquad (53)$$

Thus, the antenna current before the Tailbiter is engaged becomes

$$i_A(t) = 1280\ e^{-7{,}844t} \sin 22{,}113t \qquad (54)$$

and the coupling capacitor voltage

$$e_C(t) = 18{,}542\ e^{-7{,}844t} \sin(22{,}113t + 70.47°) \qquad (55)$$

The above envelope waveforms are plotted in Figure 11. As seen from this figure, the coupling capacitor voltage goes through zero at time 87 μsec from the start of the pulse and at this time the Tailbiter is engaged. If we use no resistance in the Tailbiter, the time-constant of the tail would be

$$\tau = \frac{L}{R_A} = \frac{2 \times 308.5}{6.68} = 92\ \mu sec \qquad (56)$$

The resulting tail is shown by the dashed curve in Figure 11. Superimposed on Figure 11 are a number of data points for other antenna current pulse shapes. By adding a little resistance in the Tailbiter, the Chinese antenna current tail will coincide very closely with the 625 feet and the standard $t^2\ e^{-2t/65}$ current tails. The 1350 foot antenna, however, has a slightly different tail shape as will be discussed in the next section.

11.0 ANALYSIS OF THE 1350 FOOT ANTENNA DRIVEN BY A 64 HCG TRANSMITTER

This analysis is directed toward the Icelandic Loran-C station in Sandur. Unfortunately at this time we are lacking data on the antenna input impedance at 100 kHz. However, we will use data from similar 1350 foot antennas.

The Sandur 1350 foot antenna parameters are

$$\left.\begin{aligned} h &= 1350 \text{ ft} \\ \rho &= h \\ h'/h &= .29 \\ N &= 6 \text{ (top-hat radials)} \end{aligned}\right\} \qquad (57)$$

From Reference 1 we obtain

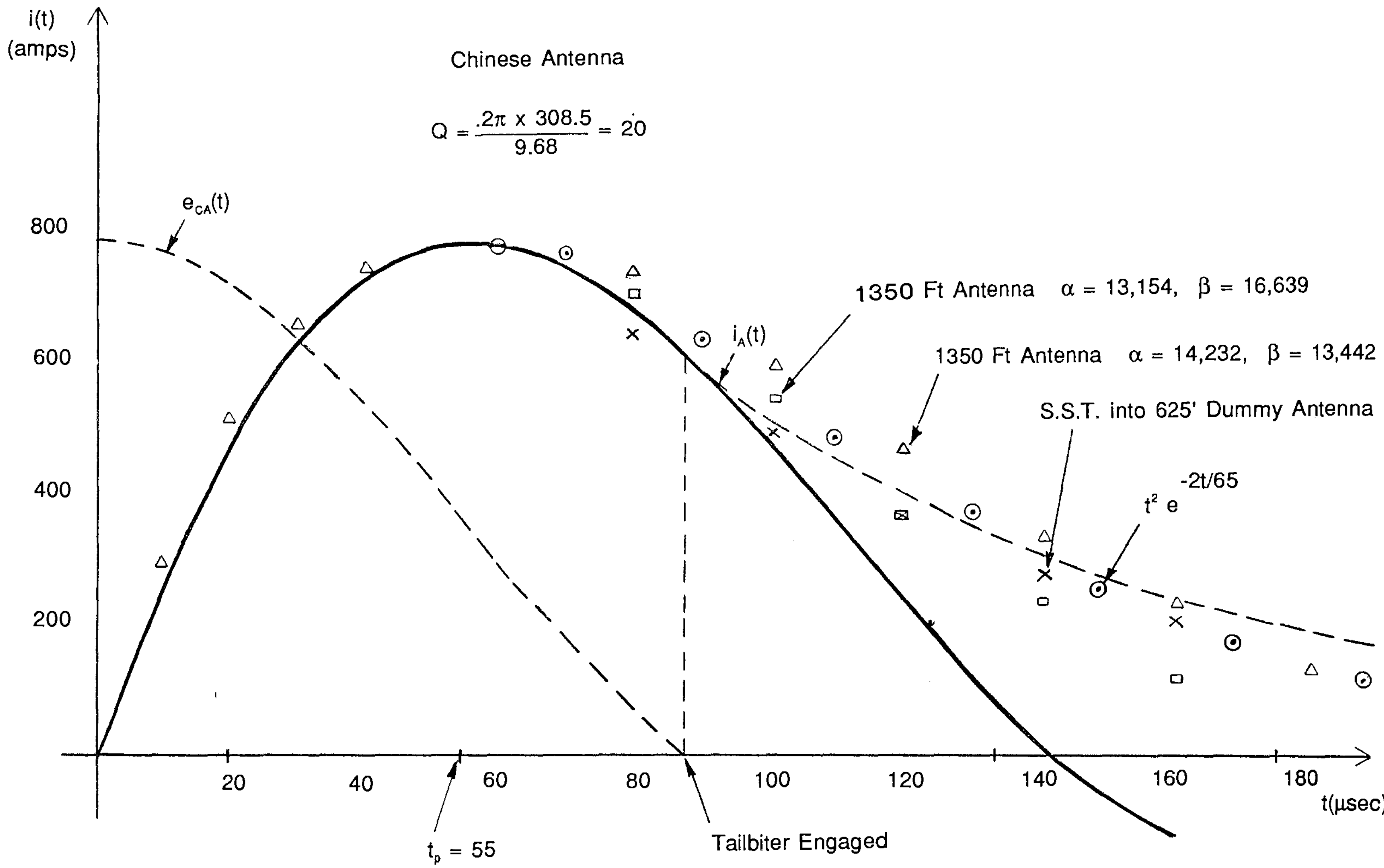


Figure 11. Envelope Shapes of Chinese Antenna Current and Coupling Capacitor Voltage

$$\left.\begin{aligned} C_A/C_0 &= 1.5 \\ C_0 &= .004725\ \mu F \\ C_A &= .00709\ \mu F \\ L_A &= 357\ \mu H \\ R_r/R_{r0} &= 1.67 \\ R_{r0} &= 7.29\Omega \\ R_r &= 12.17\Omega \end{aligned}\right\} \quad (58)$$

We have the following data on two 1350 foot antennas:

LORSTA Port Clarence: $R_A = 13\Omega$ (59)

LORSTA Iwo Jima: $R_A = 16\Omega$ (60)

Since the LORSTA Sandur has almost the same top-loading elements as Iwo Jima, we will use for Sandur

LORSTA Sandur: $R_A = 16\Omega$ (61)

To be conservative, we reduce the radiation resistance from 12.17Ω to 11Ω so that the antenna loss resistance becomes

$$R_{\ell} = 5\Omega \quad (62)$$

By trial-and-error, it is determined that an RF output transformer turns ratio of $1.2\sqrt{2}$ gives a time-to-peak of 60.05 μsec which is acceptable. Thus

$$N = 1.2 \times \sqrt{2} \quad (63)$$

$$N^2R_T = .75 \times 2 \times (1.2)^2 = 2.16\Omega \quad (64)$$

$$R_r + R_{\ell} + N^2R_T = 18.16\Omega \quad (65)$$

$$C = 2 \times \frac{5.888}{2 \times (1.2)^2} = 4.09\ \mu F \quad (66)$$

$$\alpha = \frac{18.16}{1428 \times 10^{-6}} = 12{,}717 \quad (67)$$

$$\beta = \sqrt{\frac{10^6}{4.09 \times .000714} - (12{,}717)^2} \quad (68)$$

$$t_P = \frac{1}{\beta} \tan^{-1} \frac{\beta}{\alpha} = 60.05\ \mu sec \quad (69)$$

Using 3.5 joules of energy per HCG gives the coupling capacitor voltage

$$E(0) = \sqrt{\frac{2 \times 2 \times 64 \times 3.5}{4.09}} \times 10^3 = 14{,}801 \text{ volts} \quad (70)$$

and the peak antenna current becomes

$$I_P = \frac{14{,}801 \times 10^6}{13{,}443 \times 714}\, e^{-\frac{12{,}717}{13{,}443} \tan^{-1} \frac{13{,}443}{12{,}717}} \sin\left(\tan^{-1} \frac{13{,}443}{12{,}717}\right) = 522 \text{ amps} \quad (71)$$

and the peak radiated power

$$P_r = \frac{1}{2} \times 11 \times 522^2 = 1{,}499{,}000 \text{ watts} \quad (72)$$

The antenna current and coupling capacitor voltage envelopes are plotted in Figure 12.

For purposes of comparison, Figure 12 also shows the antenna current envelope which results when a solid-state transmitter drives a 625 foot antenna.

12.0 STEP RESPONSE CALCULATION

In the previous section we have represented the four drive half-cycles of current as impulses occurring at the midpoint of the half-cycle, or simply as an impulse occurring at time zero. In this section we use a rectangular current pulse representation of the drive half-cycles of current as shown in Figure 13.

The Laplace transform of the antenna current becomes

$$I(s) = \frac{1 - e^{-as}}{LCs[(\delta + \alpha)^2 + \beta]}\, I_T \quad (73)$$

and the time function becomes

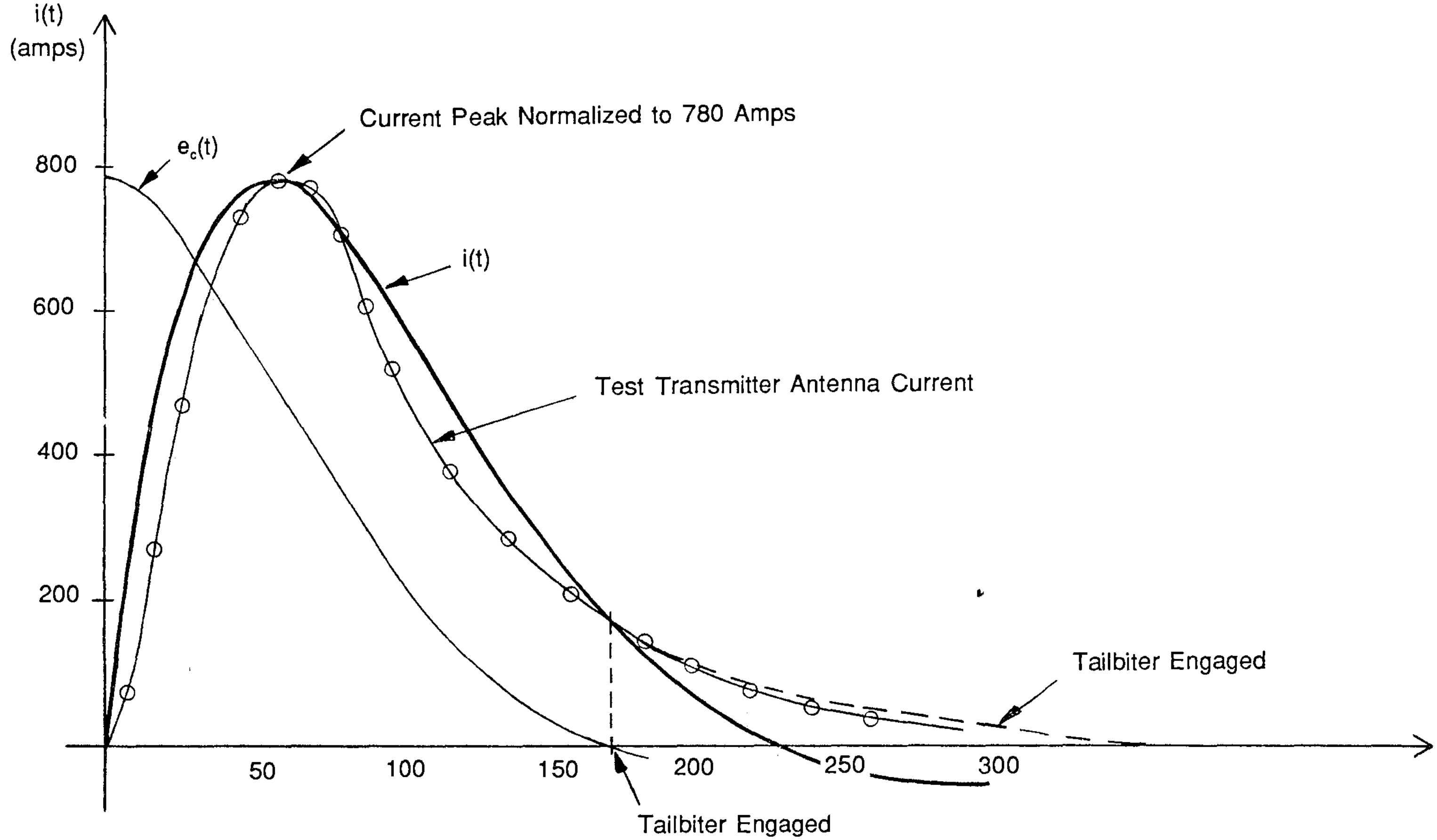


Figure 12. Envelope Shapes of 1350 Foot Antenna Current and Coupling Capacitor Voltage

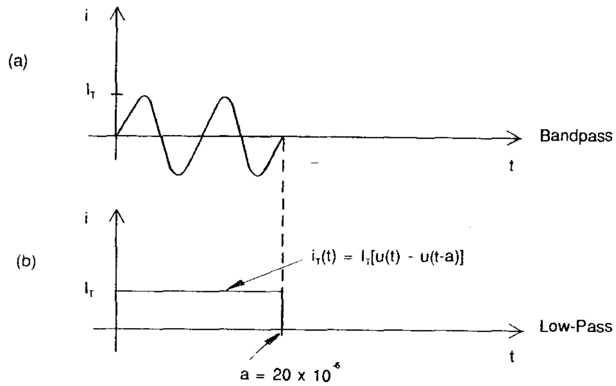


Figure 13. Rectangular Step Approximation to Drive Half-Cycle Current

$$i(t) = \left[\frac{1}{\alpha^2 + \beta^2} + \frac{1}{\sqrt{\alpha^2 + \beta^2}\,\beta}\, e^{-\alpha t} \sin(\beta t - \psi)\right] \frac{I_T}{LC} u(t)$$

$$- \left[\frac{1}{\alpha^2 + \beta^2} + \frac{1}{\sqrt{\alpha^2 + \beta^2}\,\beta}\, e^{-\alpha(t-a)} \sin(\beta t - \beta a - \psi)\right] \frac{I_T}{LC} u(t-a) \quad (74)$$

where

$$\psi = \tan^{-1} \frac{\beta}{-\alpha}$$

To determine the magnitude of the step current, I_T, we again assume that each HCG delivers 3.5 joules of energy to the coupling network. At time t(a) we can write the energy equation:

$$\frac{1}{2} Li^2(a) + \int_0^a (R_A + N^2 R_T) i^2(t)\, dt + \frac{1}{2} \frac{N^2}{2C_c} \left\{\int_0^a [I_T - i(t)]\, dt\right\}^2 = 448 \text{ joules} \quad (75)$$

To solve this equation we use iterative techniques. The two first terms in Equation (75) are small compared to the third term, and $i(t) << I_T$ so to a first approximation we obtain

$$\frac{N^2}{4C_c} \left[\int_0^a I_T\, dt\right]^2 = 448 \quad (76)$$

Using the numerical values from Equations (63) and (66) we obtain

$$I'_T = \frac{1}{20 \times 10^{-6}} \sqrt{448 \times 8.18} \times 10^{-3}$$

$$= 3{,}027 \text{ amps} \quad (77)$$

The antenna current envelope waveform of Equation (74) is plotted in Figure 14 for the case where

$$\left.\begin{aligned} N &= 1.2\sqrt{2} \\ \alpha &= 14{,}232 \\ \beta &= 13{,}442 \end{aligned}\right\} \quad (78)$$

and the peak antenna current normalized to 780 amps. Using the value of I_T given by Equation (77) yields

$$\text{At} \quad t = t_P = 70\ \mu\text{sec} \quad (79)$$

$$I_P = .452 \times 10^{-9} \frac{I_T}{LC}$$

$$= .452 \times 10^{-9} \frac{3{,}027 \times 10^{12}}{2 \times 319 \times 4.09} = 524 \text{ amps} \quad (80)$$

and the peak radiated power

$$P_r = \frac{1}{2} \times 11 \times (524)^2 = 1{,}510{,}168 \text{ watts} \quad (81)$$

Using the data presented in Figure 14 and Equation (80), we obtain

$$i(a) = \frac{.16}{.452} \times 524 = 185 \text{ amps} \quad (82)$$

The first term in Equation (75) becomes

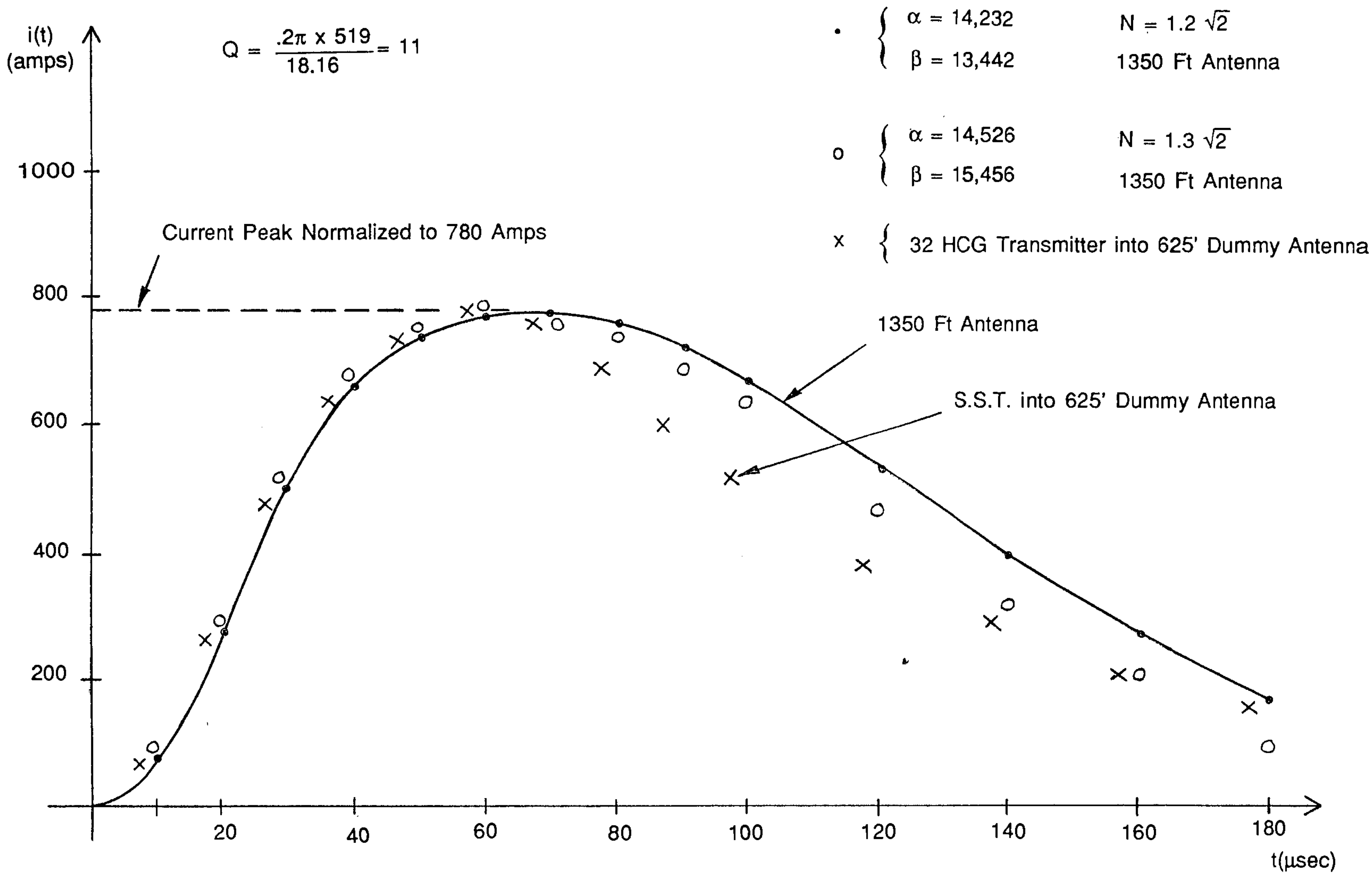


Figure 14. Antenna Current Envelope Shape with Rectangular Current Pulse Excitation

$$\frac{1}{2} Li^2(a) = \frac{1}{2} \times 2 \times 319 \times 10^{-6} \times 185^2$$

$$= 10.92 \text{ joules} \quad (83)$$

To calculate the second term in Equation (75) we have to find an analytic expression for i(t), $0 < t < 20$ µsec. From Figure 14 it is evident that a second order polynomial is a good approximation to i(t) in this time-interval, thus let

$$i(t) = a_1 t + a_2 t^2 \quad 0 < t < 20 \ \mu\text{sec} \quad (84)$$

From Figure 14:

$$t = 20 \ \mu\text{sec}, \quad i = 276 \times \frac{524}{780} = 185 \text{ amps}$$

$$t = 10 \ \mu\text{sec}, \quad i = 79 \times \frac{524}{780} = 53 \text{ amps} \quad (85)$$

Substituting the numerical values of (85) in (84) yields

$$i(t) = 1.35 \times 10^6 t + .395 \times 10^{12} t^2 \quad (86)$$

Substituting (86) in the second and third terms of (75) yields

$$\int_0^{20 \times 10^{-6}} 18.16(1.35 \times 10^6 t + .395 \times 10^{12} t^2)^2 \, dt$$

$$= 19.45 \text{ joules} \quad (87)$$

$$\frac{1}{2} \frac{10^6}{4.09} \times 10^{-12}(20 \, I_T - 1323)^2$$

$$= 48.9(I^2_T - 132.3 \, I_T + 4376) \times 10^{-6} \quad (88)$$

Combining Equations (75), (83), (87) and (88) yields

$$I^2_T - 132.3 \, I_T - 8.5361 \times 10^6 = 0 \quad (89)$$

therefore

$$I_T = \frac{132.3}{2} + \sqrt{\left(\frac{132.3}{2}\right)^2 + 8.5361 \times 10^6}$$

$$= 2988.6 \text{ amps} \quad (90)$$

The peak antenna current becomes

$$I_P = \frac{2988.6}{3027} 524 = 517 \text{ amps} \quad (91)$$

and the peak radiated power

$$P_r = \frac{1}{2} \times 11 \times (516)^2 = 1{,}472{,}055 \text{ watts} \quad (92)$$

The change in antenna current obtained after one iteration is only 1.3%. Thus, no further iterations are necessary.

From Figure 14 we observe that the antenna current envelope is wider than required and the antenna current peak occurs at 70 µsec instead of 65 µsec. By changing the RF output transformer turns ratio to

$$N = 1.3 \sqrt{2} \quad (93)$$

we can obtain higher output power and a time-to-peak of 65 µsec. The resultant waveform is shown by the "circles" in Figure 14. The peak antenna current and peak radiated power are

$$I_P = 545 \text{ amps} \quad (94)$$

$$P_r = 1{,}592{,}000 \text{ watts} \quad (95)$$

As demonstrated in the foregoing analysis, impulse approximation or rectangular current approximation of the transmitter current results in, for all practical purposes, the same antenna current. In the remainder of this report, only the impulse approximation is used.

13.0 THE OPTIMUM h′/h

The Megapulse solid-state transmitter is designed to operate into a high Q load. The transmitter operates efficiently and can generate the desired Loran-C pulse for all antennas having a Q greater than 10. If the Q falls below 10, the peak output power decreases, and the pulse increases in length thereby wasting unnecessary power.

To study the effect of the parameter h′/h on the peak radiated power, three typical Loran-C antennas are analyzed--the 720 foot, the 1000 foot, and the 1350 foot top-hat monopole antennas.

13.1 The 720 Foot Antenna

The antenna parameters selected are:

$$\rho = 1.36h\ , \qquad N = 18$$

and the peak radiated power is calculated for the following h′/h values:

$$h'/h = 0.4,\ 0.5,\ 0.6,\ 0.7,\ \text{and } 0.8$$

Typical antenna loss resistance is one ohm for the 720 foot antenna. Thus

$$R_{\ell} = 1\Omega$$

(1) $h'/h = 0.4$

Select RF transformer turns-ratio

$$N = 2$$

From Reference 1, the radiation resistance becomes

$$R_r = R_{r0} \times 1.9 = 2.1 \times 1.9 = 3.99\Omega$$

This radiation resistance is reduced by 5% due to top-hat sag, thus

$$R_r = \frac{3.99}{1.05} = 3.8\Omega$$

The antenna capacitance

$$C_A = C_{A0} \times 3.2 = .008\ \mu F$$

$$L_A = 317\ \mu H$$

These numerical values yield

$$R = R_r + R_{\ell} + N^2R_R = 3.8 + 1 + 4 \times .75 = 7.8\Omega$$

$$C = \frac{2}{N^2} C_C = \frac{2}{4} \times 5{,}888 = 2.944\ \mu F$$

$$L = 2L_A = 634\ \mu H$$

$$\alpha = \frac{R}{2L} = \frac{7.8}{2 \times 634} = 6{,}151$$

$$\beta = \sqrt{\frac{10^6}{2.944 \times .000634} - (6{,}151)^2} = 22{,}314$$

Time-to-peak becomes

$$t_P = \frac{1}{\beta} \tan^{-1} \frac{\beta}{\alpha} = 58.3\ \mu\text{sec}$$

Each half-cycle generator delivers on an average 3.5 joules to the coupling network. For a 64 HCG transmitter, the initial coupling capacitor voltage becomes

$$E(0) = \sqrt{\frac{2 \times 2 \times 3.5 \times 64}{2.944}} \times 10^3 = 17{,}446 \text{ volts}$$

and the peak antenna current becomes

$$I_P = \frac{17{,}446 \times 10^6}{22{,}314}\ e^{-\alpha t_P} \sin \beta t_P = 830 \text{ amps}$$

Peak radiated power

$$P_r = \frac{1}{2} \times 3.8 \times 830^2 = 1{,}333{,}350 \text{ watts}$$

and

$$Q = 27$$

Similarly:

(2) $h'/h = .5$,
$I_P = 910$ amps, $\quad Q = 22$
$P_r = 1{,}406{,}202$ watts,

(3) $h'/h = .6$,
$I_P = 1{,}000$ amps, $\quad Q = 21$
$P_r = 1{,}427{,}500$ watts,

(4) $h'/h = .7$,
$I_P = 1{,}079$ amps, $\quad Q = 20$
$P_r = 1{,}455{,}301$ watts,

(5) $h'/h = .8$,
$I_P = 1{,}180$ amps, $\quad Q = 19$
$P_r = 1{,}392{,}024$ watts,

13.2 The 1,000 Foot Antenna

The antenna parameters selected are

$$\rho = 1h\ , \quad N = 12\ , \quad R_{\ell} = 4\Omega$$

$$h'/h = 0.2,\ 0.3,\ 0.4,\ 0.5,\ \text{and } 0.6$$

The results are:

(1) $h'/h = 0.2$,
$I_A = 634$ amps, $Q = 23$
$P_r = 1{,}316{,}400$ watts,

(2) $h'/h = 0.3$,
$I_A = 678$ amps, $Q = 18$
$P_r = 1{,}608{,}900$ watts,

(3) $h'/h = 0.4$,
$I_A = 707$ amps, $Q = 16$
$P_r = 1{,}674{,}500$ watts,

(4) $h'/h = 0.2$,
$I_A = 748$ amps, $Q = 14$
$P_r = 1{,}706{,}500$ watts,

(5) $h'/h = 0.2$,
$I_A = 781$ amps, $Q = 13$
$P_r = 1{,}646{,}900$ watts,

13.3 The 1,350 Foot Antenna

The antenna parameters selected are

$$\delta = 1h\ ,\quad N = 12\ ,\quad R_\chi = 4\Omega$$

$$h'/h = 0,\ 0.1,\ 0.2,\ 0.36,\ 0.5$$

The results are

(1) $h'/h = 1$,
$I_A = 600$ amps, $Q = 19$
$P_r = 1{,}312{,}200$ watts,

(2) $h'/h = 0.1$,
$I_A = 574$ amps, $Q = 16$
$P_r = 1{,}647{,}400$ watts,

(3) $h'/h = 0.2$,
$I_A = 560$ amps, $Q = 14$
$P_r = 1{,}724{,}800$ watts,

(4) $h'/h = 0.36$,
$I_A = 532$ amps, $Q = 11$
$P_r = 1{,}698{,}100$ watts,

(5) $h'/h = 0.5$,
$I_A = 553$ amps, $Q = 10$
$P_r = 1{,}682{,}000$ watts,

The above data is plotted in Figure 15. As can be seen from this plot, the peak radiated power occurs when $h'/h \cong 0.2$ for the 1350 foot antenna, $h'/h \cong 0.5$ for the 1000 foot antenna, and $h'/h \cong 0.7$ for the 720 foot antenna. Also plotted in Figure 15 is the 100 kHz tower resonance frequency limit. The value of 0.7 for the ratio h'/h also maximizes the bandwidth-efficiency product of the antenna.

For a high-Q antenna, the peak of the antenna current occurs just before the coupling capacitor voltage goes to zero. At time t_p, therefore, the transmitter delivered energy has been partly dissipated and radiated in the antenna/transmitter combination and stored in the series inductance of antenna/transmitter. This relation is expressed as follows

$$U_T = U_D + U_S$$

If the front part of the pulse is approximated by a one quarter sinewave of 55 μsec duration, then

$$U_D = \frac{1}{4} R I_A^2 \times 55 \times 10^6$$

and

$$U_S = \frac{1}{2} L I_A^2$$

From these equations the peak radiated power is obtained

$$P_r = \left(\frac{\omega U_T}{\frac{17.28}{Q} + 1} \right) (R_r\ \omega C_A)$$

For the high-Q antennas, this expression is a maximum when the product $R_r\ \omega C_A$ is a maximum. This product is precisely the bandwidth-efficiency product (BW_p), and, as shown in Reference 1, is a maximum when $h'/h = 0.7$.

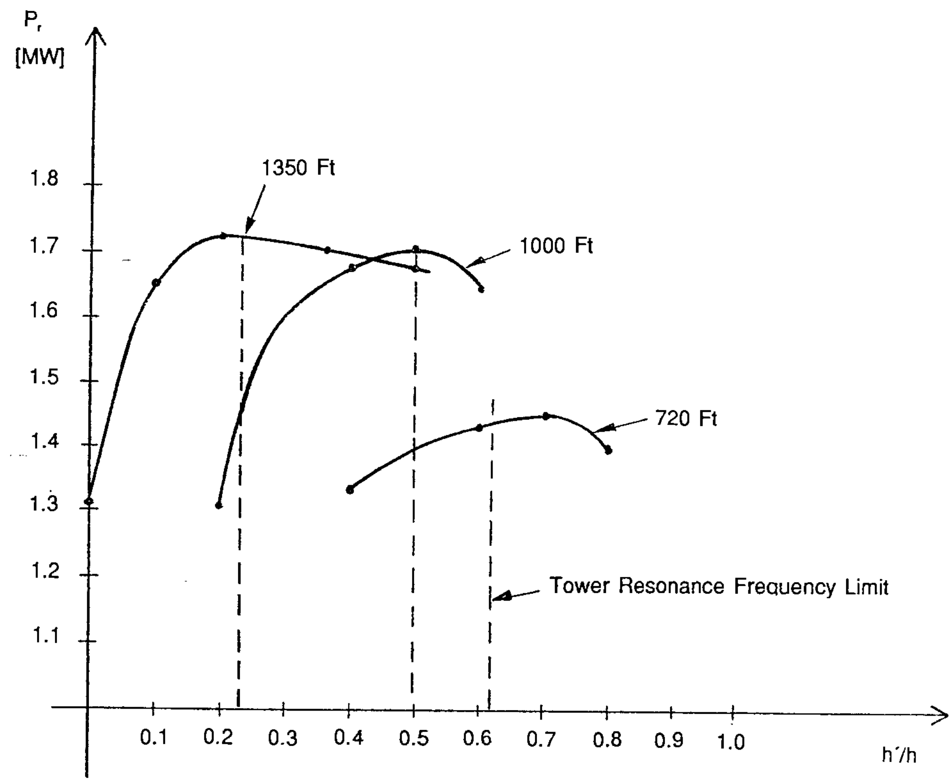


Figure 15. Radiated Power as a Function of h′/h

BIOGRAPHY

Dr. Johannessen received an Engineering degree from Schou's Institute of Technology, Oslo, Norway, in 1949. In 1953 and 1958, respectively, he earned S.M. and Sc.D. degrees in Electrical Engineering from Massachusetts Institute of Technology.

In 1970, Dr. Johannessen founded Megapulse, Incorporated. Primary programs at Megapulse have included development and manufacture of megawatt solid-state Loran-C transmitter systems for commercial and military use under the trade name Accufix®. Accufix® equipment is now in use world-wide by government and by the leading survey companies.

Dr. Johannessen is a member of Sigma Xi and Eta Kappa Nu, and a senior member of the IEEE.

He holds many patents in the fields of control circuitry and nonlinear magnetics and has published numerous papers.

LORAN-C SYSTEM REPEATABILITY UNDER TIME OF EMISSION CONTROL

David H. Amos, Jeffrey D. Catlin, Richard W. Heldt

SYNETICS, Inc., Wakefield, MA

AUTHORS

Mr. Amos is Director, Navigation Systems for SYNETICS, Inc. in Wakefield, MA. This group is heavily involved in analysis, system engineering, and development of software products for a wide variety of radionavigation systems and applications, and in the development of tactical shipboard systems. Mr. Amos joined SYNETICS after completing a 23-year career in the U.S. Coast Guard, where he was heavily involved in the Loran-C program in operational, engineering, and management roles. He directed the U.S. Air Force Tactical Loran C/D Program from 1979-1983, including the Commando Lion and European Loran C/D chain deployments. He has extensive experience and background in communications and in the design, construction, and implementation of major communications facilities and antenna systems. Mr. Amos is a 1965 graduate of the U.S. Coast Guard Academy and received his MSEE (with distinction) from the U.S. Air Force Institute of technology in 1970.

Mr. Catlin has been involved in several different areas of radionavigation over the past two years. He was the principle engineer in the development of an automated Loran-C coverage diagram generator, which is to be used to produce diagrams for publication by the Coast Guard or can function as a chain design tool. Prior to that, he was involved in the development of a model which was used to predict conductivities for the state of Alaska. Currently, he is involved in a project to update and modify the program used to synchronize the Omega system. Mr. Catlin received a bachelor's degree in Systems Engineering from the University of Massachusetts in 1987.

Mr. Heldt is a Senior Engineer at SYNETICS involved in developing software for the acquisition and analysis of data from terrestrial navigation systems, including Loran-C and GPS. He has also participated in a variety of projects involving space navigation, inertial navigation of ballistic missiles, and other forms of re-entry vehicle navigation. His software interests and centered about the design and implementation of efficient computation schemes in small- and medium-size computers. Mr. Held is a 1967 graduate of MIT in Aeronautics and Astronautics. He received a master's degree in 1969, also from MIT.

ABSTRACT

Public Law 100-223, the Airport and Airway Safety and Capacity Act of 1987, requires an analysis and report to Congress on the impact to current users of synchronizing loran-C secondary stations to within 100 nanoseconds (ns) of Universal Coordinated Time (UTC), and the methods and impact of coordinating the time references of the loran-C and GPS systems to within 30 ns of each other. The report from which this paper is drawn fulfills the requirements of the law. The impact on repeatable accuracy of the five loran-C chains covering the United States (excluding Alaska and Hawaii) is analyzed using the Double Range Difference (DRD) model. The model is modified to predict system repeatability in the UTC synchronized environment, when the control strategy excludes use of a System Area Monitor (SAM). Charts showing the loran system repeatable accuracy under SAM control, and under control regimes synchronizing master and secondary stations to within 0 ns (perfect time-of-emission control), 30 ns (1σ), and 100 ns (1σ) of UTC are shown. A discussion of the Double Range Difference model, and its conversion to the Single Range Difference (SRD) covariance analysis software is presented. The impact of the various control strategies on coverage is discussed.

INTRODUCTION

Loran System Area Monitors (SAMs) provide a method for observing the timing performance of the loran system and making changes to the time of transmission of the secondary necessitated by propagation variations and by the small but significant frequency and phase offsets between the cesium standards at master and secondary stations. It is the SAM's job to measure the time difference (TD) between the master and a specific secondary, and compare this TD with the Controlling Standard Time Difference (CSTD) established for the specified master-secondary pair. The SAM then inputs a local phase adjustment (LPA) to keep the TD at CSTD. The effect of an LPA is to change emission delay (ED) of a baseline, that is, the actual time between the master and secondary station transmissions. One result of this control process is a stabilization of the loran grid at and near SAM. For this reason, SAMs are typically located in the area of major user concentration. Historically, loran users have been the marine community, and therefore, SAMs are concentrated along the coastline and in major harbor areas. A user located near SAM will obtain the grid stability offered by the SAM control process. However, the portion of the LPA made by SAM, attributable to propagation changes, will not be valid for users much more than 90-100 nautical miles away from SAM, and in some cases the distance is actually less. The term "correlation distance" is used to describe the effective radius of the SAM-introduced grid changes. For the distant users, the impact of changes in the emission delay is a contributing factor, along with propagation variation, in the total systematic error seen by a user. One potential method to be considered for reducing this contribution is a process of synchronizing transmission of the master and secondary transmitting stations to some common, available and precise time reference such as Universal Coordinated Time (UTC). Such a scheme might increase the utility of loran-C to the aviation community and other non-marine user groups.

The current set of loran-C chains provides coast-wise coverage of the Atlantic, Gulf of Mexico, and Pacific coasts of the United States, as well as a good portion of the land mass. There is, however, a large expanse of the middle parts of the United States which is not covered by loran-C. This area has been termed the "mid-continent gap," and new chain construction is underway to fill the gap. Once the mid-continent chains are complete, the entire United States and southern Canada will have loran-C hyperbolic navigation coverage available for any user.

Diagrams are published by the U.S. Coast Guard that depict the geographic area served by the loran system. It is necessary to clearly understand several concepts that relate directly to these coverage diagrams. The coverage contours define the geographic limits at which a receiver with a 20 KHz bandwidth will acquire and track a master and two secondary stations, each having a signal-to-noise ratio (SNR) better than -10 dB, and provide a fix uncertainty smaller than 1/4 nautical mile 95 percent of the time. This specification is typically expressed as 0.25 nm 2 drms repeatability.

The difference between acquisition of the signal by the receiver and tracking of the signal is important. Acquisition is the more difficult process for the receiver, and is the limiting factor in receiver performance. A receiver will always be able to track a signal it has previously acquired, under the same SNR environment. Moreover, a receiver will continue to track a loran signal at a much poorer SNR than that which it will acquire the signal. Coverage area must therefore be defined in terms of acquisition, as that process defines the operational limits at which a navigation solution can be initiated. SNR is the major factor in determining a receiver's ability to acquire the loran signal. Noise in this coverage analysis context is generally assumed to be atmospheric noise as defined in CCIR-322 (Reference 1). It has been a long-standing practice in the generation of loran-C coverage diagrams to assume that the process of estimating the loran TD by the receiver is normally distributed and has a standard deviation of 100 ns. The 100 ns figure is used as a lumped parameter throughout the chain service area and has proven to be satisfactory in the past. It is an approximation of the real world and is intended to represent the total system variance resulting from four general categories of processes contributing to the total systematic error of the loran-C system. These four processes can be categorized as noise-induced, equipment-induced, process-induced, and propagation-induced.

<u>Noise-induced errors</u> result from atmospheric and manmade noise coupled into the receiver phase-lock loop circuits through the antenna and receiver front end. Added to these is receiver internal noise. These processes tend to average out to zero over a moderately short-term, but do produce instantaneous errors in the navigation solution. Severe noise conditions can adversely affect signal acquisition.

<u>Equipment-induced errors</u> include phase modulation of the transmitted signal, error inherent in the conversion of TDs to coordinates of latitude and longitude, and errors induced by multi-pulse averaging of TD information inside the receiver.

<u>Process-induced errors</u> relate to the fact that the SAM does not always hold the system TDs at SAM to CSTD. In order to avoid what could be nearly continuous timing changes, procedures have been established which dictate when to insert an LPA and how much of a change to make in baseline timing. The result is a small but measurable technical control error budget associated with the SAM control process.

<u>Propagation-induced errors</u> result from signal phase modulation and the variance in velocity of propagation of the loran signal along the infinite number of paths between the transmitter stations and all possible system users, as compared to the velocity of propagation along the two paths from the master and secondary transmit-

ting stations to the SAM. Even for one user, the velocity of propagation from the transmitting stations to the user and to SAM are neither equal nor constant. The result of this is that the SAM does not perfectly remove grid variations induced by the spatially and temporally varying velocity of propagation of the loran signal over the service area. The SAM does the best job for users within the local area around the SAM.

There are two definable groups of propagation variations affecting the loran system, diurnal and seasonal. Diurnal variations occur, as the name implies, on a daily basis. Diurnal changes in propagation occur primarily as a result of local weather anomalies which affect the velocity of propagation of the loran signal for a short period of time, or as a result of changes in ionospheric height between day and night. This latter phenomenon results in movements of the loran-C skywave relative to the groundwave, and is most notable at day/night transition along the baseline, and on very long paths to the user. Seasonal propagation variations on the other hand, are long-term and have been shown to be yearly cyclic. Seasonal propagation variation can result in a peak-to-peak excursion in the TD measured at a user point of up to several hundred nanoseconds. The primary cause of seasonal variation are periodic changes in the lapse rate of index of refraction of the atmosphere.

The predominant components of the loran-C error budget are generally considered to be the noise-induced and propagation-induced components. The St. Mary's River Stability Study Report (Reference 2) documented that the SAM technical control error (or process error) has a standard deviation of 13 ns; a good qualitative estimate of equipment induced error would be of the same magnitude. Thus, virtually all of the 100 ns standard deviation in the receiver's TD estimate assumed by most coverage diagram generator programs are preserved as an approximation of the expectable variance contributed by noise and propagation effects. This is probably a valid assumption for producing coverage diagrams intended to depict system accuracy on a short-term (days to weeks) basis. It is generally not a good assumption if the coverage diagram is interpreted to predict accuracy season-to-season. It is important to note here that coverage diagrams are indicative of repeatable accuracy, the repeatability, of the loran-C system.

Another approach to estimating loran-C repeatability limits was made in the USCG office of Research and Development project 2100. The various loran-C signal stability studies done under this project employed a large number of Harbor Monitor System (HMS) sites recording time difference data four times a day, over periods of one to three years. These time-series data were used to estimate the statistics of the total loran-C systematic error. These statistics, taken from real-world data, are representative of the equipment, noise, propagation, and process induced components of the error budget. These data and this approach will be used in this study to predict the changes in loran system performance, and thus the impact to current users, of proposed changes in the method of operation of the loran-C system.

USER METHODOLOGY

It is important to clearly understand the navigation grid available from the loran-C system. While modern loran receivers produce a latitude and longitude readout, and in many cases contain correction tables in memory to make the navigation solution as accurate as possible with relation to the geodetic grid, the solution is not a precise geodetic solution. Warping of the hyperbolic LOPs due to terrain, variation in velocity of signal propagation, and computational limits of coordinate conversion contribute to the error budget of the indicated position. There exists an offset of the loran latitude/longitude grid from the geodetic grid. This offset is, however, measurable and precise.

On the other hand, the loran system repeatability is excellent over the terms of days to weeks or longer. This means that, once the location of the reference point or waypoint is known in the loran frame of reference, a navigator can return to that point with very high precision. The frame of reference can be either in TD or loran latitude/longitude coordinates. Repeatability is the strength of the loran-C system for the majority of uses. Repeatability declines as the period of time between measurement of the reference point location and return to that point increases, due to seasonal effects on loran signal propagation. If a plot of time difference or loran latitude/longitude is made for a fixed user location over a period of several years, a definite periodicity in the data are clearly seen. The data will have a sinusoidal pattern with a period of one year, and are generally repeatable year-to-year.

The mission profile of the vast majority of users spans periods of hours, not days, weeks, or seasons. Within this time frame, the repeatability of the loran navigation solution is very high, approaching that available from differential loran techniques. For a user leaving and returning to the same harbor or airport, a precise navigation grid is available. For the user moving from airport-to-airport or seaport-to-seaport, the repeatability of the loran-C system is such that low data rate corrections, even "yesterday's" correction (Reference 2), result in precision that meets the needs of the most demanding user. Table 1 synopsizes the user requirements developed during the process of the study.

TABLE 1

REQUIREMENTS OF LORAN-C USERS

USER GROUP	PRIMARY METHOD OF USE	PERIOD OF CONTINUOUS USE	REQUIRED ACCURACIES
Marine Recreational	Repeatable Navigation	2 days or less	50-60 ft
Marine Commercial	Repeatable Navigation and Time	Less than one week	250m to 2 Nm
Merchant Marine	Repeatable Navigation	Greater than one week	≈1 Nm
Vehicle Position Monitoring	Geodetic Navigation	1 to 5 days	10m - 10 Nm
Mapping and Geodetic Control	Geodetic Positioning	?	1.1m ± 0.9m
Dredging and Seismic Surveys	Geodetic Positioning	?	1.1m ± 0.9m
Civil Aviation	Geodetic Navigation	<1 day	0.3 Nm to 2.5 Nm

ALTERNATIVE METHODS OF ACHIEVING UTC SYNCHRONIZATION

The word synchronization implies a coincidence in time of two or more events. In the context of loran-C synchronization to Universal Coordinated Time (UTC), this coincidence is defined as occurring between the UT second and the start of the first master station pulse. The time at which this occurs is called Time of Coincidence (TOC).

Public Law 100-223 requires examination of two levels of synchronization of the loran system to UTC. The first level is synchronization of the master stations, a replication of current operational practice, but to a higher degree of accuracy and precision. The second level would require synchronization of the secondary stations. This added level will require the definition of an additional set of time of coincidence, secondary TOCs. Therefore in the remainder of this discussion, the term TOC will imply both master TOC (MTOC) as defined earlier, and secondary TOC (STOC), which will have the same properties as MTOC, except that it will apply to the secondary station transmissions.

Achieving synchronization of the loran-C system to UTC requires knowledge of the UT second, knowledge of the time at which TOC should occur, and the ability to make a measurement at TOC relating the UT second to the start of the first pulse of the loran station transmission in the A group of the PCI. This measurement relates the time offset Δt between the two points at TOC, and also relates the rate of change in time offset $\Delta t/t$ between the two points. The latter quantity is directly related to the frequency offset between the USNO Master Clock which is keeping UTC (USNO) and the cesium frequency standard which is keeping local station loran time.

There are two alternatives to achieving synchronization between the loran system and UTC (USNO). The first alternative is to physically maintain time synchronization at TOC to within some specified tolerance. This implies that the loran signal relationship to UTC (USNO) would be monitored and processed, perhaps using optimal filtering techniques, to accurately estimate the time and frequency performance of the local loran station frequency standards against UTC (USNO). Periodically, phase corrections would be entered into the loran stations phase microsteppers to maintain TOC synchronization. The second alternative would be to perform the same monitoring and processing of time and frequency offset, but to broadcast these offsets to users in a manner timely enough to allow the user to exploit the information.

The measurement of time offset and frequency offset in either of these two cases would essentially use the same process. One level of this measurement is currently being done: USNO estimates and publishes the time relationship between all US operated loran chain master stations and UTC. It is a policy of the U.S. Coast Guard to maintain this estimate of synchronization to within $\pm 2.5\ \mu s$. The USNO data are used by Chain Managers to calculate phase corrections to be applied to the master stations "operate" cesium frequency standard, with the goal of achieving a slow (1 cycle per year) walk of the synchronization offset between the high and low limits of tolerance. PL100-223 makes two major impacts on this policy. The first is that it requires a change in the tolerance of the master station synchronization to ± 100 ns and requires that change be implemented by the U.S. Coast Guard by September 1989. The second impact is that the law requires a study of the impact on current users of synchronizing the secondary station transmission to ± 100 ns of UTC. This would imply that at MTOC and STOC, if the synchronization were ever implemented, the measurements must allow either a broadcast to users of the time offset (and perhaps the frequency offset) of the stations transmissions against UTC, or the adjustment of the station time of transmission to meet the specified synchronization tolerance.

The U.S. Coast Guard is already conducting experiments with the 9960 (North-East United States) and 8970 (Great Lakes) chains to assess the current capability to achieve master station synchronization to the ± 100 ns specification of Public Law 100-223. This synchronization is being attempted in the 9960 chain by frequent phase changes to the master station operating frequency standard. For the 8970 chain, it is being attempted by frequent time step inputs to the entire chain. In both cases, the accuracy of this process is severely degraded since the propagation path to USNO from each master station is unmodelled.

Extension of the current practices to meet the ultimate requirements of PL100-223 can be functionally accomplished in several ways using either a time synchronization methodology, an offset broadcast methodology, or a combination of both. Table 2 shows these options:

TABLE 2
FUNCTIONAL OPTIONS FOR ACHIEVING SYNCHRONIZATION OF LORAN-C TO UTC

	METHODOLOGY	
OPTION	MASTER STATION	SECONDARY STATION
I	Time Synchronization	Time Synchronization
II	Broadcast Offset	Broadcast Offset
III	Time Synchronization	Broadcast Offset

A fourth option, the obverse of Option III, is unreasonable in the context of loran operations in general, as it would imply secondary stations fixed in time, with a "floating" master station timing.

Option I is the option most people think of first when the issue of loran system synchronization to UTC is discussed. This approach would require the measurement and control of time and frequency offset of both master and secondary stations against UTC. This option implies the implementation of Time-of-Emission (TOE) control of the loran-C system, with the attendant control of emission delay and concerns about changing the utility of the loran system to the current user community. For the Coast Guard, this option represents the most radical departure from current operational procedures and a requirement to implement new equipment procurements and system integration. Conversely, this option has the least impact on current user equipment. Users' equipment would be impacted only when a user needed to exploit the additional navigation capability afforded by the synchronization and even then, changes would be limited to processing changes within the users' software.

Option II is the second most often thought of approach to achieving loran-C system synchronization to UTC. This approach would require measurement of time and frequency offset of master and secondary stations time of transmission against UTC, but this option implies no necessary change to the current operational procedures implemented by the U.S. Coast Guard. On the contrary, operational procedures would remain nearly the same, removing the concern about impact of this approach to UTC synchronization to current users of the system. The option would require new equipment procurements and integration by the U.S. Coast Guard to measure and process the time and frequency offset information, and then to broadcast the data to users who desire it. On the users part, equipment changes will be more radical than under Option I, as the users equipment must receive and detect the transmitted offset information, either from an in-band signal (modulation of the loran-C signal itself, for example) or an out-of-band signal, and then process information from all loran stations, including the master. As in Option I, only those users requiring the additional navigational capability would realize an equipment impact as long as implementation of the broadcast method is carefully done. Unlike Option I, current system users would see no system impact.

Option III exploits current operational procedures and equipment in many cases, but requires equipment procurements and integrations as well. In this option, the master stations would be time synchronized to UTC but the secondary stations would broadcast their offset from UTC as in Option II. As in Option II, this approach has no impact on current system users and minor impact on chain operational procedures currently in place. Exploitation of the additional navigational capability afforded under this scheme would depend on the architecture of users' equipment. Current receiver equipment and users would see no impact. Users requiring the added capability would require the capability to detect and process offset information from the secondary stations only, since master stations would be synchronized to UTC to within specified tolerances. This option requires the development and integration of three sets of equipment by the U.S. Coast Guard: the measurement equipment for master station synchronization against UTC; the control equipment for master station timing; and the broadcast equipment for the secondary stations.

Table 3 presents these three options in terms of the operational and equipment impacts to the user and the U.S. Coast Guard.

REPEATABILITY ANALYSIS

As utilized in numerous loran studies, the term repeatability relates to a user's ability to return to a previously visited point using the same receiver as a navigation reference. This is equivalent to characterizing the distribution of loran position solutions obtained over a (suitability long) period of time by a fixed receiver. Since the indicated position can vary in either of two dimensions (e.g., north-south or east-west), it is possible to define two dimensional measures of repeatability. In this study, however, the two dimensions are combined into a single statistic, 2 drms, which is defined by the equation:

$$2\ \mathrm{DRMS} = 2\sqrt{\sigma_x^2 + \sigma_y^2}$$

where

σ_x^2 = variance of east-west distribution

σ_y^2 = variance of north-south distribution

TABLE 3
OPERATIONAL AND EQUIPMENT IMPACTS RESULTING FROM UTC SYNCHRONIZATION

	OPERATIONAL IMPACTS		EQUIPMENT IMPACTS	
OPTION	IMPACT TO CURRENT USERS (REPEATABILITY ACCURACY)	IMPACT TO USCG OPERATIONAL PROCEDURES	IMPACT TO MANUFACTURERS & USERS EQUIPMENT AND SUPPLIES	IMPACT TO USCG EQUIPMENT
I	Repeatability changes as discussed below	High - This option represents the change from SAM-based CSTD control to transmitter station-based time-of-emission control	Low - Current Users have no equipment impact. Software changes to implement receiver architecture to exploit TOE controlled system capabilities. Charts and tables unaffected if nominal ED is maintained	Low - Develop and integrate equipment to 1) measure and 2) control UTC synchronization; cancel development of new monitor receiver
II	None	Minimal - Maintain SAM-based CSTD control, Implement procedures to measure and broadcast time and frequent offset (MTOC and STOC)	Moderate - Hardware and software changes to detect and process broadcast offset data if required. current users have no equipment impact. No impact to manufacturers of current receivers. No impact to manufacturers or users of tables and charts	Moderate - Develop and integrate equipment to 1) measure and 2) broadcast offset of master and secondary station from UTC. SAM remains in the system, new monitor receiver development continues
III	None	Moderate - Maintain SAM-based CSTD control - Implement higher precision UTC synchronization control at master (MTOC). Implement procedures to measure and broadcast time and frequency offset of secondaries (STOC)	Moderate - Hardware and software changes to detect and process broadcast offset data if required. Current users have no equipment impact. No impact to manufacturers of current receivers. No impact to manufacturers or users of tables and charts	High - Develop and integrate equipment to 1) measure and 2) control and 3) broadcast master and secondary offsets with respect to UTC. SAM remains in the system, new monitor receiver development continues

If the 2-dimensional distribution of displacements is normal, it can be shown that a circle (centered at the reference point) whose radius equals the 2 DRMS value will enclose 95% (or more) of the position fixes. Although it cannot be proven that the position displacements have the required distribution, they (almost always) approximate it sufficiently well that the 95% circle and 2 DRMS statistic can be considered equivalent.

The repeatability of loran-C measurements varies with position for two distinct reasons. First, the "sensitivity" of the receiver's solution to a small shift in the time difference (TD) between receipt of master and secondary signals varies with its position. Moreover, the magnitudes of the TD shifts also vary over the coverage area.

In addition to the spatial factors, a second factor that impacts repeatability is the measurement time base. It is plausible to expect that a pair of measurements taken hours apart will show less variability than a pair taken a year or more apart. Most loran-C users are short duration users. During short intervals the TD changes are substantially smaller than the annualized time difference changes. Thus short duration users can expect a better repeatability than random annual users.

The major constituents of the loran-C TD variations are as follows:

a) Seasonal Component. This component, in most cases, is the largest contributor to the net error budget. It has a period of 1 year.

b) Medium-Term Component. Here we are talking about variations occurring over periods ranging from several days to several weeks. The variations are most significant in the winter months -extending from late October to late April in northern regions. They are minimal in the summer. In a statistical sense, these variations are found to follow the modified double range difference model very well.

c) Short-Term Component. These variations occur over periods ranging from several hours to a few days. It is noted, however, that significant variations over a period of several hours are rare occurrences. Moreover, the variations are smaller than the seasonal or medium term components.

d) Near-Instantaneous Variation Component. These are considered to by any variations which occur over the period of up to an hour or so. These variations, for practical purposes, are considered to be equipment-related and not associated with changes in single propagation characteristics. Examples can be seen when equipment is changed at transmitting stations, when corrections are made to chain timing by the control station, or when there are receiving equipment problems. These variations are small but cannot be considered negligible when considering the capability of loran-C for precise applications.

All of the repeatability estimates presented in this report are annual estimates that incorporate all of the above constituents.

The repeatability analysis performed in this study is based on techniques developed by the U.S. Coast Guard during the last decade (Reference 3). In examining field data acquired in the loran-C signal stability studies, patterns observed in the time sequence of loran observations from a number of monitor receivers have led to the formulation of a mathematical model with the power to attribute the observed variability of the loran-C signal to one of three sources:

1. Propagation effects intrinsic to the terrain over which the signal travels

2. Chain control effects resulting from the operation of the Station Area Monitor (SAM)

3. Local/unexplained effects.

This model has become known as the Double Range Difference (DRD) model. Application of the original DRD methodology to the data collected at a finite number of locations allows us to estimate the repeatability of the existing loran-C system at any point in the coverage area. Extending the methodology, one can predict loran-C repeatability for alternative control strategies on a consistent basis. The combination of the previous DRD model with the extension developed in this project will be called the DRD/SRD model. The SRD component of the acronym stands for "Single Range Difference."

Briefly, a repeatability analysis using the DRD model consists of the following steps:

1. By analyzing time-difference data from a set of monitor receivers, the factors affecting observed signal stability are apportioned into the three groups identified earlier - propagation, chain control, and residual (unexplained/unmodelled) effects.

2. By applying appropriate geometric corrections to the partitioned signal, estimates are made of the time differences expected at many locations distributed over the coverage area.

3. By applying a second set of equations, the time difference variations at each location are converted to the 2 DRMS repeatability at that location.

4. The array of 2 DRMS repeatability values is converted to a series of contours of equal repeatability, and plotted against a suitable background.

In the extended DRD/SRD analysis the same sequence of 4 steps is utilized, with the following change in Step 2:

2A. Propagation effects are converted to time difference according to a slightly different equation that accounts for the removal of the SAM.

Control effects derived in step 1 are replaced by new terms that account for the new control strategy.

Residuals (unknown/unmodelled effects) are assumed to contribute equally to signal variability under the old (SAM) or new

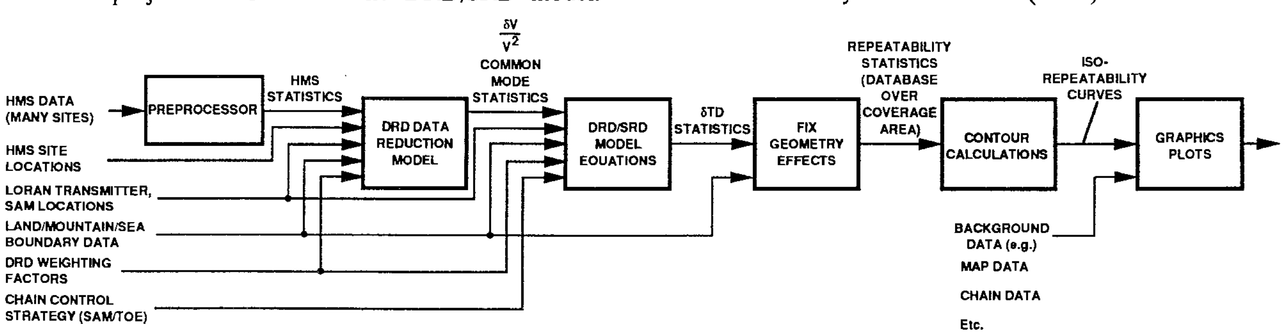


Figure 1 Data Flow Diagram

(TOE) control regime.

Figure 1 outlines this procedure in diagram form.

The data utilized in this study was acquired by U.S. Coast Guard personnel as part of the various loran-C signal stability studies. The objective of the project was to make direct measurements of loran-C repeatability at selected locations. This was accomplished by using a small computer to record the output of a stationary receiver, and then retrieving the data from the computer via phone link and/or magnetic media. The combination of receiver and computer is known as a Harbor Monitor System (HMS) set. Detailed descriptions of the various types of HMS sets are given in Reference 3.

The HMS final report (Reference 2) summarizes the signal stability monitoring activity by illustrating some 345 station-years of collected data. The subset of data considered in this study included all available data for calendar year 1984, except the analysis of GRI 8970 (Great Lakes) which was performed using 1986 data. This includes approximately 1/3 (114 station-years) of the data identified in Reference 2. In processing the HMS data files for this report, all previously-applied tests for data validity have been honored. Thus, any data rejected in previous signal stability studies is excluded from consideration here.

In addition to the actual HMS data files, there are several other data sources that should be documented here. Data files giving the loran-C transmitter locations and digitized map files giving both the political boundaries shown in the figures with maps and the boundaries between terrain types were provided by the U.S. Coast Guard R&D Center. Locations of the HMS monitors were obtained from Reference 2. The DRD methodology allows empirically-determined weigthing factors to be combined with the physical distances between transmitters and receivers to yield a "weighted," rather than "true" range for use in the model equations. In previous studies, (References 3,4) a specific set of weighting factors has been utilized for each region of the country, with a standard nomenclature (mod 1, mod 2, etc.) utilized to describe the corresponding set of factors. The plots have been labelled according to this same convention.

A brief description of the possible tests for correctness/consistency and their results is in order. There are three basic tests:

1) Do repeatability estimates for locations where repeatability has been directly measured agree with those measurements?

2) Are the residuals (unmodelled/unexplained) terms of credible magnitude, and do they agree with those reported in References 2 and 3?

3) Do the results given in this report for repeatability under the existing (SAM control) regime agree with those previously published in References 2 and 3?

The question posed by the first test was addressed by examining measured vs. model (predicted) repeatability at those HMS sites where the set monitored both legs of the triad. Inspection of the results showed qualitative agreement in all cases, and variations exceeding 100% in 7 out of 99 cases.

The disagreement between model and measurement is traceable to the residual at that particular point - whenever the residuals statistics match the level assumed in the model prediction, the model is guaranteed to match the measurement. Based on References 2 and 3, a residual level of 20 ns has been utilized throughout this study. The chain with the largest residuals is GRI 8970 (Great Lakes) indicating a need for further analysis of the HMS data from this region. It should also be noted that the Great Lakes loran-C chain also exhibited the greatest variability in the HMS measurements. Residuals for the northeast U.S. (GRI 9960) also fail to achieve the 20-25 ns level postulated in Reference 3.

The standard deviations of the raw (TD) data acquired by the HMS monitors are well examined. In spite of its inability to "explain" all of the signal variability measured by the HMS monitors, the power of the DRD method is significant. In nearly every case, the RMS residuals are less than half as large as the original standard deviations. It is also noteworthy that most of the HMS monitors experienced less than 100 ns of TD variability often assumed in parametric studies. On this basis, synchronizing the loran system to UTC with 100 ns (1 sigma) accuracy would result in poorer repeatability than currently experienced.

The third test of the results given in this report is the comparison between previously published 2 DRMS repeatability contours and those which result in our analysis. Again, qualitative but not quantitative agreement is obtained. Here, the probable explanation lies in differences between the number of stations incorporated in the analysis, coupled with differences between the meteorology enclosed by the years for which HMS data does overlap. An intermediate check, made by reducing the set of HMS sites in the solution, gave closer agreement than the full set of data employed in our analysis.

RESULTS OF THE ANALYSIS

In all of the analyses done for this report, results of the SAM control repeatability diagrams have been compared against results published by the U.S. Coast Guard in the various loran-C signal stability studies. This was done as a quality check on the software development and data processing and to insure consistency and integrity of analytic results. It must be noted that the DRD model software required for use in this study does not incorporate an SNR failure contour feature. The DRS/SRD AS would have to be integrated with features from other coverage diagram generator programs to calculate and plot SNR failure contours.

Table 1 showed that, by far, the majority of current and future users of the loran-C system have a mission profile that encompasses a period of time of hours to days, and are, therefore, subject only to diurnal variations in the repeatability of the loran navigation grid. A repeatability measure such as a coverage diagram, based on annualized repeatability, gives a conservative estimate of system capability. For those few users who require season-to-season repeatability, advertising repeatability coverage based on short-term data would give rise to unrealizable expectations. For these reasons, the analysis done in this project has been done using an annual repeatability approach. To reiterate briefly, the DRD/SRD AS was used to produce coverage diagrams for the five existing loran-C chains that provide coverage to the continental United States, excluding Alaska. Each chain was analyzed triad-by-triad, and a chain composite was produced using the best triad in each user area. Repeatability diagrams were produced showing the current repeatability under SAM control, and under a time-of-emission control scheme using a standard deviation for the TOE control process of 0 ns (perfect TOE control), 30 ns, and 100 ns. Table 4 describes the reasoning behind selection of these statistics. Subsequently, overlay repeatability diagrams were produced showing the geographic difference between the SAM and the various TOE control schemes.

TABLE 4

TOE CONTROL STATISTICS

If you want to see the loran system repeatability under the following conditions:	Then look at charts labeled:
68% of the samples of synchronization of loran against UTC fall within ±100 ns, that is, 100 ns is a 1σ specification on TOE control	100 ns TOE control
>99.75% of the samples of synchronization of loran against UTC fall within ±100 ns, that is, 100 ns is >3σ specification on TOE control	30 ns TOE control
Perfect TOE control	0 ns TOE control

7980 Chain Analysis

Figures 2 through 4 present the 7980 chain composite 2 drms repeatability plots for SAM, TOE (30 ns) and TOE (100 ns) control, respectively. Notice that on the whole, SAM control and TOE (30 ns) control produce repeatability plots which are somewhat equivalent. 30 ns TOE control repeatability is notably poorer in the southern Florida and the Florida keys, which have a large user population. One-quarter nautical mile coverage is slightly improved in the coastal areas of north Virginia, but this is an area better served by 9960 and probably approaching the SNR limits of the 7980 master. The 100 meter 2 drms accuracy coverage

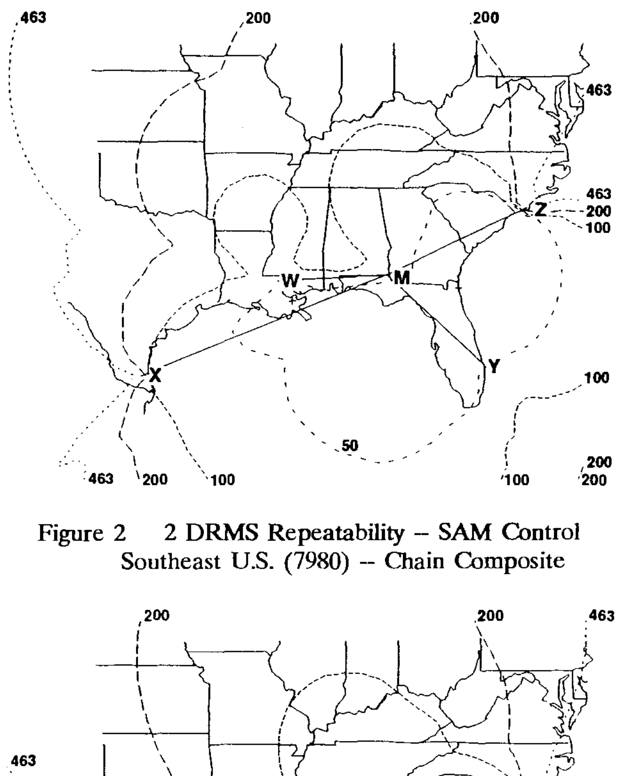


Figure 2 2 DRMS Repeatability – SAM Control Southeast U.S. (7980) – Chain Composite

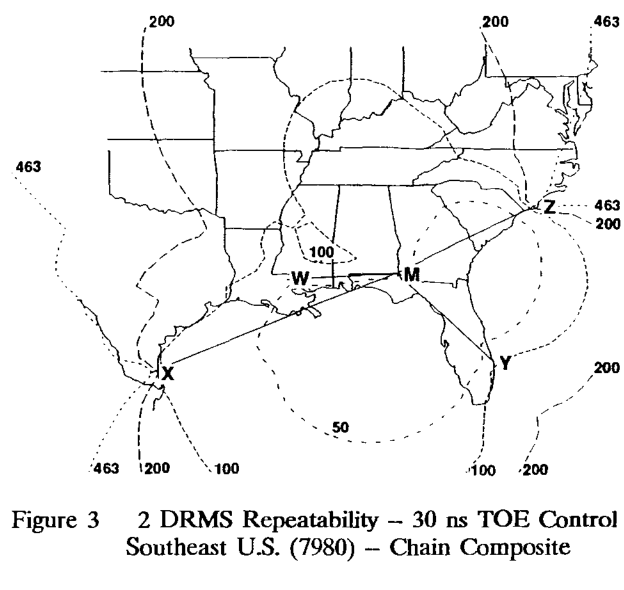


Figure 3 2 DRMS Repeatability – 30 ns TOE Control Southeast U.S. (7980) – Chain Composite

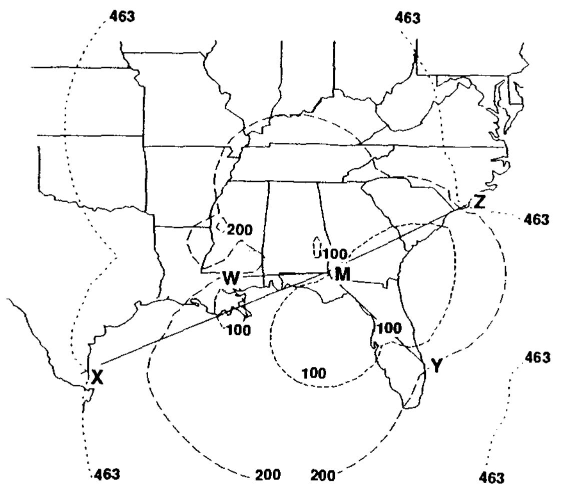


Figure 4 2 DRMS Repeatability -- 100 ns TOE Control
Southeast U.S. (7980) -- Chain Composite

area is lost seaward east of the Carolinas and Florida on both TOE control cases. At the 100 ns TOE control level, 50 meter 2 drms accuracy is not available to any 7980 user, and the 100 meter contour collapses. In general, repeatability in the service area, is impacted negatively by a factor of four.

In the 7980 chain, 100 ns TOE control is an unacceptable alternative for current users. 30 ns TOE control, while not as degrading to current users, still results in some loss of repeatable accuracy coverage.

9940 Chain Analysis

Figures 5 through 7 show the chain composite repeatability plots for the 9940 chain. SAM control is displayed in Figure 5, while TOE (30 ns) is shown in Figure 6. If these two figures are compared to one another, the most obvious difference is that repeatability along the western coastal regions is reduced slightly under TOE (30 ns) control to the point that 50 meter accuracy is denied to users, and 100 meter accuracy falls closer to the coast. This loss affects California and Oregon. The 50 meter contour actually expands inland under 30 ns TOE control over Nevada and Utah. Repeatability is decreased when TOE (100 ns) is used as shown in Figure 7. The degradation in service is so severe that the 50 meter repeatability contour vanishes entirely. Repeatability along the coast of California and southern Oregon degrades by a factor of four, and along the coast of Washington by a factor of more than two. Coverage inland degrades by a factor of two. The 1/4 nautical mile contour under 100 ns TOE control is similar to the 200 meter contour under SAM control over Idaho, Washington, Montana, Wyoming, Colorado, Utah and Arizona. Coastal southern California, with a huge user population, also suffers a repeatability degradation by a factor of two.

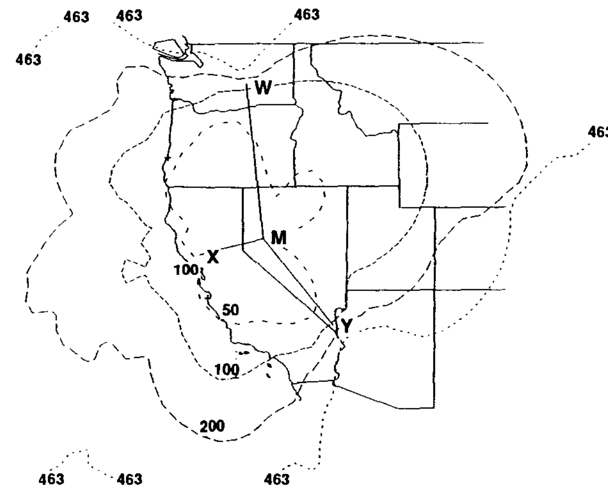


Figure 5 2 DRMS Repeatability -- SAM Control
U.S. West Coast (9940) -- Chain Composite

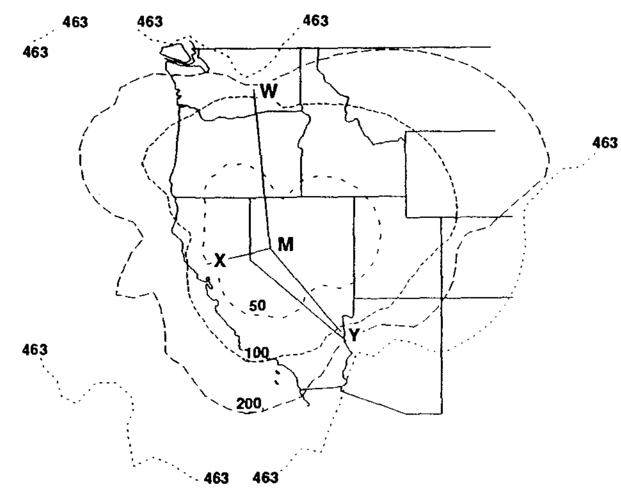


Figure 6 2 DRMS Repeatability -- 30 ns TOE Control
U.S. West Coast (9940) -- Chain Composite

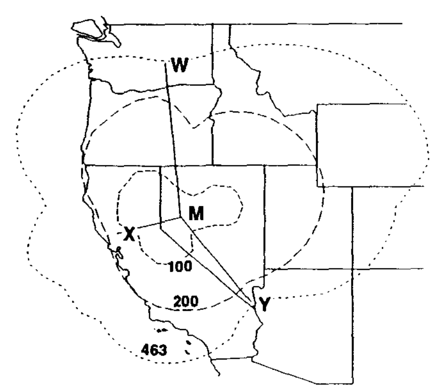


Figure 7 2 DRMS Repeatability -- 100 ns TOE Control
U.S. West Coast (9940) -- Chain Composite

For the 9940 chain, a switch to TOE control at either the 30 or 100 ns level results in a moderate to severe loss of accuracy for current users of the system.

8970 Chain Analysis

The repeatability plots for TOE control of this chain are inconsistent with those seen in the 7980 and 9940 chain. The TOE (100 ns) repeatability plot is slightly better than the SAM plot. It is strange that TOE (100 ns) control degrades performance so severely in all other chains and generally improves coverage in the Great lakes. We are not confident of these results and contend they should be discounted. The various modes of the DRD/SRD software have failed to effectively model this chain. Residuals are very large, and they are comparable between the various land/water weighting approaches of the model. The HMS input data have much larger variability than any other set. These observations have convinced us that the results reflect the severity of the chain environment, geography, geology and are a failure of the model. No further attempt will be made in this report to draw conclusions for the 8970 chain.

5990 Chain Analysis

Figures 8 through 10 show the repeatability contours for the 5990 chain. In this chain, the 30 ns TOE control process produces results nearly equivalent to the repeatability seen under the SAM environment, with the exception of a small area loss on the coast of Oregon, Washington, and British Columbia. If the control specification on TOE is 100 ns, significant degradation of coverage occurs. The 50 meter 2 drms contour is lost. Throughout the coverage area, a 3 to 1 degradation in repeatability is predicted.

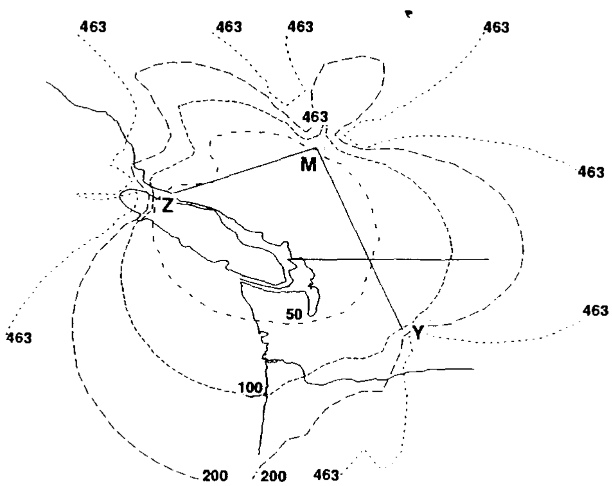


Figure 8 2 DRMS Repeatability -- SAM Control Canadian West Coast (5990) -- Chain Composite

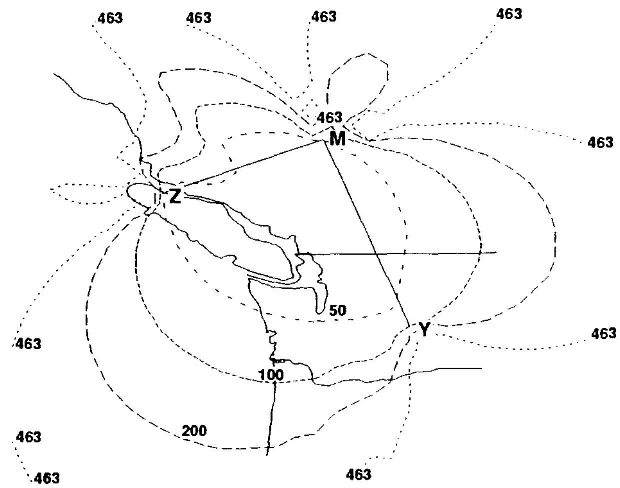


Figure 9 2 DRMS Repeatability -- 30 ns TOE Control Canadian West Coast (5990) -- Chain Composite

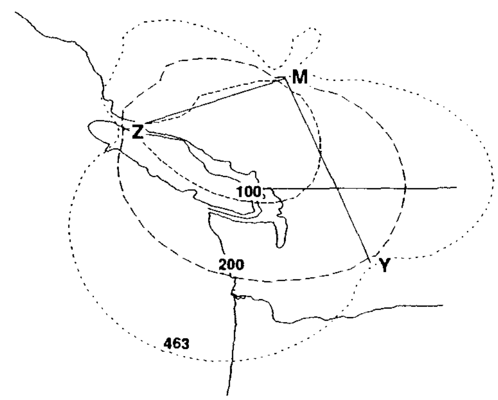


Figure 10 2 DRMS Repeatability -- 100 ns TOE Control Canadian West Coast (5990) -- Chain Composite

9960 Chain Analysis

Figures 11 through 13 show the chain composite repeatability contours for the 9960 chain. In this chain there is also a noteworthy difference between the TOE (30 ns) control and SAM control. The TOE (30 ns) control appears to give an increase in the 50m repeatability contour throughout parts of Pennsylvania, Ohio and West Virginia, but the price for the increase in 50 meter repeatability over land is a vast decrease (approximately 50%) in the 50 meter repeatability along the coastal regions of the northeast. Under 30 ns TOE control, 50 meter 2 drms coverage is lost to the coastal areas of Virginia, Delaware, and most of New Jersey, all of the Chesapeake Bay, and the offshore areas of Rhode Island, Massachusetts, New Hampshire, and Maine.

At 100 ns TOE control, 50 meter 2 drms repeatability is unavailable anywhere in the chain service area.

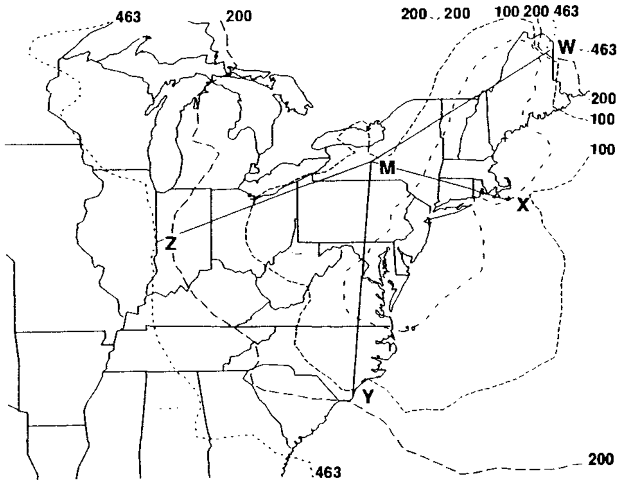


Figure 11 2 DRMS Repeatability -- SAM Control
Northeast U.S. (9960) -- Chain Composite

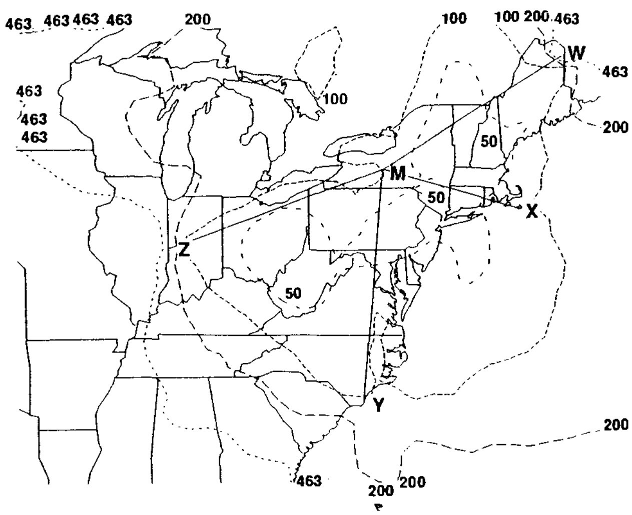


Figure 12 2 DRMS Repeatability -- 30 ns TOE Control
Northeast U.S. (9960) -- Chain Composite

Coastline coverage accuracy from Maine to South Carolina is degraded by 100%. 100 meter repeatability collapses from extensive coverage along the coast and far offshore from Maine through South Carolina, to a limited area along the coast from New Hampshire and a small section of Southern Maine to Cape May, N.J. and the Delaware Bay, and an inland area over parts of Pennsylvania, Ohio, West Virginia and Virginia.

In the 9960 chain service area, 100 ns TOE control severely impacts current loran system users. 30 ns TOE control also significantly degrades system repeatability for the current users. In 9960, TOE control is an unacceptable alternative.

At this point, conclusions can be drawn concerning

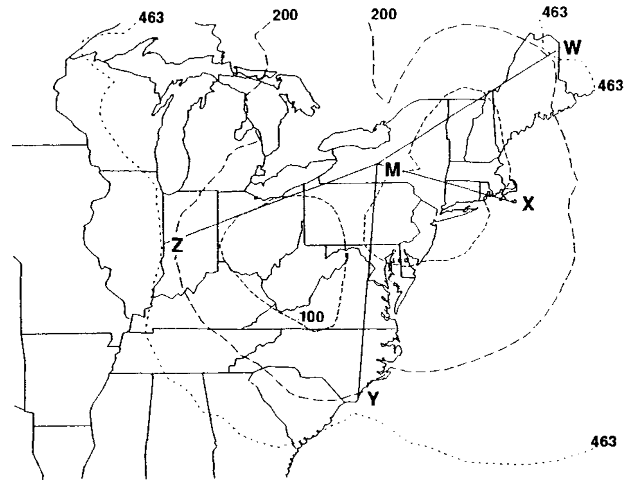


Figure 13 2 DRMS Repeatability -- 100 ns TOE Control
Northeast U.S. (9960) -- Chain Composite

the impact of TOE control to current and near future users of the loran system.

First, if the standard deviation of the TOE control method is specified as 30 ns, which would correlate to an assumed specification on the requirements in PL100-223 that there be better than a 99.75% confidence that all samples of loran-UTC(USNO) time fall within 100 ns, there is roughly equivalent repeatability in some parts of the service areas of the four loran chains which we analyzed to the current SAM mode of chain control.

However, the coastal and marine areas experience a decline in repeatable accuracy. This sacrifices service to those users for little improved coverage gain for the user in the inland areas.

Secondly, if the standard deviation of the TOE control method is specified as 100 ns, which would correlate to a 68% confidence that all samples of loran-UTC(USNO) time fall within 100 ns, the repeatability throughout the service areas universally and significantly deteriorates when compared against the current SAM control regime. Even this 100 ns synchronization specification is not being met by today's methods of synchronization monitoring and control.

Third, the correlation distance of SAM control actions has been shown to be 90-100 miles or less. The only reasons for inserting LPAs into secondary station timing are to support the high repeatability expectations of users within that vicinity of SAM, and to remove the effects of frequency standard offsets existing between the master and secondary stations. Implementation of TOE control would, of course, eliminate entry of LPAs. However, even if TOE synchronization of the loran system to UTC(USNO) is not done, relative inter-chain time transfer supporting high-precision frequency stabilization of the chain ensemble of frequency standards, through an optimal estimation process, could eliminate the need for LPA insertion and eliminate the need for real-time SAM control over chain timing. This would free SAM resources for casualty control, quality monitoring on chain timing, pulse shape monitoring, and control station administrative functions.

Fourth, the 30 ns TOE plots represent a lower bound on technical capability. Control within 30 ns of UTC is probably the best that could be hoped for, and even then would be difficult and expensive to achieve. This is driven by an expectation of approximately 20 ns uncertainty in time transfer combined with 20 ns granularity in timing control available from the loran system equipment. This being the case, TOE (30 ns) control would have to be much better than SAM control to justify a switch.

The full scope of our report (Reference 5), provides additional material for the following broad conclusions to be reached:

- Current users of the loran-C system will suffer a loss of repeatable accuracy over broad areas of current coverage if the loran secondary station transmissions are synchronized to Universal Coordinated Time (UTC) at a 30 ns (1σ) level. Users will suffer a severe loss of repeatable accuracy if the loran secondaries are synchronized to UTC at a 100 ns (1σ) level. These losses are suffered for little gain to the civil aviation community.

- Coordination of the time references of the loran-C and GPS systems to within 30 ns of each other is feasible and improves the availability, fault detection and fault isolation capability of a hybrid GPS/loran-C receiver markedly. Hybrid receivers operated in absence of time reference synchronization provide better service in these three areas than either system operated singly. Time synchronization will permit development of loran receiver architectures that are of value to the civil aviation community.

- Coordination of the loran system master stations to within 30 ns of UTC should be accomplished. SAM control should be retained for timing control of the secondaries.

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SESSION 5

LORAN & GPS INTEROPERABILITY

Participants in the final session included (left to right top) John C. Castonia of Illgen Simulation Technologies, session chairman Chick Longman of Air Navigation Consulting, Inc. Lt. Cdr Gary R. Westling, USCG and Frona B. Vicksell of Megapulse, Inc.

THE ADMINISTRATIVE SYNCHRONIZATION OF LORAN-C MASTER STATIONS TO COORDINATED UNIVERSAL TIME

G.R. Westling, M.D. Sakahara and C.J. Justice

United States Coast Guard
Washington, D.C.

ABSTRACT

In 1987 the Coast Guard, anticipating Public Law 100-223, began improving the synchronization of its Loran-C master stations. Two parallel approaches were begun. One was to develop a hardware addition to the master station's frequency standard rack to provide timing offsets and maintain synchronization with Coordinated Universal Time (UTC) using GPS timing receivers. The other was to examine administrative methods to improve the master station synchronization as reported by the U.S. Naval Observatory (USNO). Three such methods were studied: frequency control, time step control, and modified master station control. These methods were used at three Loran-C master stations: Seneca, NY, Dana, IN, and Malone, FL. All three methods achieved significant synchronization improvement. Key improvement factors were timely and precise time-difference offset reporting and no-notice timing corrections.

INTRODUCTION

The Coast Guard began improvements to the synchronization of its master stations in anticipation of Public Law 100-223 (Section 310)[1] being signed [1]. This law requires the Coast Guard to synchronize all Loran-C master stations in the United States to within approximately ±100 nanoseconds (ns) of Universal Time. An accurate method of time transfer from Coordinated Universal Time (UTC), as maintained by the USNO, to the Loran-C master station's time is one of the keys to successful compliance with the law [2]. In March 1987, the Coast Guard pursued two approaches to improve the synchronization of its Loran-C master stations:

The first approach was a study conducted by the Coast Guard Electronics Engineering Center, Wildwood, NJ, (EECEN). The EECEN was tasked to develop an addition to the frequency standard rack to provide precise time using the GPS system to transfer time between USNO and the Loran-C station (LORSTA). The EECEN would also study and evaluate methods of coordinating Loran-C time with GPS time to within ±30 ns. The equipment would monitor and steer the local cesium oscillators, keeping them synchronized to UTC.

The second approach was a series of experiments using administrative techniques to steer the master station's clocks. The Coast Guard believed that it could approach 200-ns synchronization using the administrative method and, possibly, 100-ns synchronization as the techniques were refined.

Results

The result of these two approaches is that Loran-C offsets have been held to within ±100 nanoseconds of UTC to confidence levels ranging from 61% to 78% for the four Loran-C chains in the lower 48 states (Northeast U.S. (NEUS), Southeast U.S. (SEUS), Great Lakes (GLAKES), and the U.S. West Coast (USWC)) since 1 May 1989. For the NEUS, SEUS, and GLAKES Chains, these offsets are daily averages of measurements comparing Loran-C signals received at USNO, Washington, D.C. with the USNO master clock. For the USWC chain, the signal is received at a USNO supported Precise Time Reference Station (PTRS) at the Naval Weapons Testing Center, China Lake, CA, and linked to the USNO master clock via GPS time transfer. These chains were chosen for their proximity to USNO monitoring facilities.

The remaining chains required by law to be synchronized to UTC are the Canadian East Coast (CEC) chain (master at Caribou, ME), the Gulf of Alaska (GOA) chain (master at Tok, AK), the Central Pacific (CENPAC) chain (master at Johnson Is., HI), the North Pacific (NORPAC) chain (master at St. Paul, AK), and the two midcontinent expansion project (MEP)

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1 Hereafter referred to as Public Law 100-223.

chains: the North Central U.S. (NOCUS) and South Central U.S. (SOCUS) chains. Synchronizing the master stations of these chains requires the addition or upgrading of USNO PTRS facilities. The Coast Guard's intention is to include the LABSEA chain (master at Fox Harbor, LAB) and the Canadian West Coast (CWC) chain (master at Williams Lake, BC), as well as the required CENPAC chain, with minimal equipment additions.

This report discusses the administrative efforts from the standpoints of performance, procedures and future recommendations.

IMPROVING THE SYNCHRONIZATION OF LORAN-C MASTER STATIONS BY ADMINISTRATIVE MEANS

Improving the synchronization of Loran-C master stations using administrative techniques was one of the least expensive alternatives the Coast Guard considered to improve Loran-C master synchronization. It could also be implemented quickly at selected chains.

The USNO proposed one method of improving Loran-C master station synchronization, and the Atlantic Area Regional Manager (responsible for the NEUS, SEUS, GLAKES, CEC and LABSEA Loran-C chains) proposed two methods.

USNO Proposal

The USNO proposed to develop a steering algorithm to steer the master operate oscillator. This technique uses frequency changes to maintain synchronization. It was tested at LORSTA Seneca, the master station of NEUS.

Atlantic Area Proposals

The first proposal from the Atlantic Area Regional Manager was to retain the current method of controlling master stations and to reduce the offset data averaging period from 30 days to 3. This involves making a combination of time steps and frequency adjustments to the master operate oscillator to maintain synchronization. It was decided to test this technique at LORSTA Malone, the master station of SEUS.

The second proposal from the Atlantic Area Regional Manager was to use daily time steps to "zero" the master station's daily offset. The record of offsets and subsequent corrections would then be used to calculate monthly frequency adjustments to reduce the magnitude and frequency of the time steps needed to maintain synchronization. This method is similar to the method the Coast Guard uses to maintain Loran-C secondary station synchronization. It was decided to test this technique at LORSTA Dana, the master station of GLAKES.

To maximize the performance of the new techniques, the Coast Guard suspended the requirement to issue prior user notification of timing corrections being made to the master stations. Normally, before a time step or frequency adjustment is made to the master operate oscillator, Loran-C users are given the opportunity to object. Maintaining this prior notification would delay corrections for one month, making it impossible to maintain 100-ns synchronization. The Atlantic Area Regional Manager solicited objections to removing the prior notification requirement and received no response. Therefore, the plan was implemented.

The key to the success of these administrative techniques is USNO's ability to precisely and frequently (at least daily with 10-ns resolution) report the master station offsets from UTC. If there is a significant delay between USNO's measuring and reporting the master station offsets, the ability to maintain synchronization of the master station is diminished. For the chains being tested, USNO reported daily master station offsets with 10-ns resolution.

GENERAL ASSESSMENT OF SUCCESS

The Frequency Control Method used at LORSTA Seneca

The USNO is responsible for reporting the timing offset of Loran-C master stations. To do this, USNO compares the arrival time of a Loran-C master signal to the station's time of coincidence (TOC)[2]. A modeled propagation time and equipment delay from the station to the monitor point is subtracted from the time difference, or offset, to move the time reference to the master station. The offset data are then averaged over a day.

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2 TOC occurs when a Loran-C station transmits at the same instant as the UTC second. By measuring the time between the expected Loran-C master signal and the UTC second at TOC, the master station offset may be determined.

The average offset is published daily in USNO's Series 5 report and biweekly in their Series 4 report[3]. This process is used to monitor all Loran-C master stations under the jurisdiction of the United States. The monitor used by USNO may not directly monitor the master signal, but, instead, it may monitor a secondary signal and perform a series of time transfers to arrive at the master station's offset. This is the case for the Alaskan and North Atlantic master stations. For LORSTA Seneca, USNO uses its PTRS in Washington, DC to directly monitor LORSTA Seneca's signal.

The USNO initially averaged LORSTA Seneca's offset data for 4 days and, based on the averaged data, recommended a frequency correction, if necessary. The correction was entered in a special Electronic Bulletin Board (EBB). At a predetermined time, the watchstander at LORSTA Seneca would call the EBB to obtain the day's correction. If a correction was recommended, the watchstander entered the correction and confirmed its entry with the EBB.

The performance of this method is shown in Figure 1. The improved synchronization experiment started on 03 May 1988. Performance statistics from USNO's steering method are listed in Table 1.

Improved Synchronization at NEUS			
From	To	Mean usec	Sigma usec
Jan. 1, 1988	May 25, 1988	−0.26	0.65
May 25, 1988	Oct. 14, 1988	−0.045	0.139
Oct. 14, 1988	Jan. 17, 1989	−0.109	0.130
Jan. 17, 1989	May 15, 1989	−0.023	0.160
May 15, 1989	Aug. 17, 1989	−0.031	0.061

Table 1. The Synchronization Performance of Loran-C Station Seneca.

The period from 01 January 1988, through 25 May 1988, is a "before" picture of the synchronization performance of LORSTA Seneca for comparison purposes. The USNO began calculating steering corrections on 03 May 1988. During the start-up period, LORSTA Seneca's offset was reduced approximately 5-fold, as shown in Figure 1. The improvement lessens during the winter of 1988, from 14 October 1988 through 17 January 1989. On 17 January 1989, USNO reduced the minimum time between corrections from four days to three, resulting in another improvement in LORSTA Seneca's synchronization with UTC. On 15 May 1989, USNO again decreased the minimum time between corrections from three days to one. The average offset improved somewhat as a result, and the standard deviation of the offset was more than halved. The Area Regional Manager noted that even though the corrections were calculated daily, corrections were actually required only about every three days. The effect of seasonal propagation changes on this method of control are to be determined.

The goal of this experiment, as with the others, was to attain a zero offset average and to minimize the standard deviation. As shown in Figure 2, about 84% (79 of the 94 offsets plotted) of the offsets from 15 May through 11 August exceeded the ±100-ns limit of the law.

This experiment, using the steering algorithms developed by USNO, has been successful in reducing the offset of LORSTA Seneca. The station went from a mean offset of -0.26 microseconds (usec) and a standard deviation of 0.65 usec before the synchronization improvement to a mean of 0.031 usec and a standard deviation of 0.061 usec after the minimum period between corrections was reduced to one day; this is more than a 10-fold improvement.

The Accelerated Coast Guard Master Control Method Used at LORSTA Malone

For the SEUS Loran-C chain (SEUS), the Coast Guard proposed to accelerate the current technique used to maintain master synchronization. Prior to this, daily offset data collected over a 30-day period were analyzed to determine if the station required a time step or frequency adjustment. This technique proved adequate for the previously required 2.5-usec tolerance of Loran-C master stations. This favored frequency corrections to maintain synchronization. The proposed technique would reduce the 30-day period to about 3 days. This experiment was coordinated by the Coordinator of Chain Operations (COCO) for the SEUS. The synchronization improvement project was implemented during the same time frame as the synchronization improvement project at NEUS.

[3] The Series 5 report is used for the data in gauging the success of the synchronization techniques discussed herein. The offset data base began on 01 Jan. 1988 and contains the offset data on all Loran-C master stations under United States jurisdiction.

This method provided a significant improvement in the synchronization of LORSTA Malone, as shown in Figure 3. When this method was first used, USNO discovered that the offset data from their PTRS in Richmond, FL, contained too much noise (source not determined) for 10-ns precision. By using the Richmond site, USNO could monitor LORSTA Malone's signals directly to improve the precision of the offset data. Then USNO opted to monitor LORSTA Carolina Beach (the Zulu secondary of SEUS) from Washington, DC, and work back to LORSTA Malone. Even though this also added noise and long propagation paths to LORSTA Malone's offset data, it was considered the lesser of the noise sources. The COCO SEUS also noticed that the offset drifts seemed to correlate with frontal systems passing between LORSTA Malone and the monitor point in Washington, DC.

Performance statistics of the technique used at LORSTA Malone are shown in Table 2.

Improved Synchronization at SEUS			
From	To	Mean usec	Sigma usec
Jan. 1, 1988	Oct. 14, 1988	−0.32	0.86
Oct. 24, 1988	Apr. 21, 1989	−0.029	0.188
Apr. 21, 1989	Aug. 17, 1989	−0.006	0.089

Table 2. The Synchronization Performance of Loran−C Station Malone.

The period from 01 January 1988 through 14 October 1988 provides a picture of the synchronization of LORSTA Malone before synchronization improvement. This includes the start-up period beginning on 03 May 1988. There is a significant improvement in the synchronization of LORSTA Malone. The average offset was reduced 15-fold, with a 4-fold reduction in the standard deviation. On 21 April 1989 LORSTA Malone's operate oscillator was replaced, resulting in an additional 50% reduction in both average offset and standard deviation. The overall performance is shown in Figure 4.

The limiting factors to improving synchronization are USNO's ability to model propagation changes between the master station and its monitor site and to precisely and frequently report offsets. The PTRS in Richmond, FL, will be upgraded to allow USNO to monitor LORSTA Malone transmissions directly, thus improving the precision and frequency of their ability to report LORSTA Malone's offset. This would be beneficial regardless of the final synchronization improvement technique that is implemented, because each synchronization technique relies on the ability to monitor the master station Loran-C signal closely.

The Time-Step Control Method Used at LORSTA Dana

The technique applied at LORSTA Dana used small time steps to maintain synchronization, with occasional frequency adjustments to reduce the number and magnitude of the time steps. The watchstander at LORSTA Dana called the USNO EBB and examined the Series 5 report for the day's offset. If the offset was greater than ±50 ns, then the offset was "zeroed" using 40-ns time steps. The time steps and offsets were plotted, and frequency adjustments were made, as needed, after 30-days of observation. This technique has the advantage of being able to collect long-term drift data that can be used to steer the cesium frequency standards.

Figure 5 is a plot of offsets for LORSTA Dana. The USNO and the Coast Guard were concerned over using time steps to control master synchronization. The Atlantic Area Regional Manager postponed implementing time-step control in order to first solicit objections from the user community. None were received, and the control method began on 12 February 1989. Synchronization improvement was almost immediate. Performance statistics of the system are shown in Table 3.

Improved Synchronization at GLKS			
From	To	Mean usec	Sigma usec
Jan. 1, 1988	Feb. 24, 1989	−0.08	0.64
Feb. 24, 1989	Aug. 17, 1989	−0.013	0.099

Table 3. The Synchronization Peformance of Loran−C Station Dana.

The period from 01 January 1988 through 24 February 1989 is the "before" picture of synchronization performance. After the start-up period from 12-24 February 1989, this technique produced the largest improvement in the shortest time, nearly an 8-fold decrease in the average offset and a 6-fold decrease in the standard deviation (See Figure 6 for synchronization performance). This technique relies on the USNO's ability to report LORSTA Dana's offset precisely each day. There is a gap[4] in the data every weekend, and this gives a periodic appearance to the offset plots.

Improving Synchronization at Other Loran-C Stations

After the Coast Guard observed the successes in the Atlantic Region, the Pacific Area Regional Manager (responsible for the USWC, the CWC, the GOA, the NORPAC, NWPAC, and the CENPAC Loran-C chains) implemented the time-step control technique. LORSTA Fallon, NV, the master station in the USWC chain, began the time-step control method -- as used at LORSTA Dana -- on 12 February 1989. The USNO was unable to furnish daily offset reports with 10-ns resolution (the resolution of the offset reports for NEUS, SEUS and GLAKES) until 17 April 1989.

The offset plot in Figure 7 shows the 100-ns resolution of the offset data used to maintain LORSTA Fallon's synchronization. Note the sinusoidal seasonal drift common to Loran-C in this plot. Once USNO increased the precision of the reported offset data to 10 ns, LORSTA Fallon settled within the $\pm$100-ns boundaries. Table 4 lists the progress of improving the synchronization of LORSTA Fallon.

Improved Synchronization at USWC			
From	To	Mean usec	Sigma usec
Jan. 1, 1988	Feb. 24, 1989	−0.151	0.61
Feb. 24, 1989	Apr. 27, 1989	−0.113	0.141
Apr. 17, 1989	Aug. 17, 1989	0.015	0.116

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

Synchronization improved from a mean offset of -151 ns to one of 15 ns with a 6-fold reduction in standard deviation. The short period between the beginning of the synchronization improvement project (24 February 1989) and when USNO was able to publish daily offset reports with 10-ns resolution (17 April 1989) is not considered significant, but the later synchronization improvements are. Figure 8 shows the performance of LORSTA Fallon from 17 April 1989 through 11 August 1989.

OVERALL PROGRESS AND RESULTS

As shown above, the three techniques (USNO's frequency control (NEUS), modified master control (SEUS) and time-step control (GLAKES, USWC) all provide significant reductions in the synchronization offsets as reported by USNO. Table 5 shows the

Improved Synchronization Performance May 1, 1989 through August 17, 1989				
Station	Mean	Sigma	% of Daily Averages	
			< 100 ns	< 200ns
Seneca	−0.050	0.076	73.5	96.3
Malone	−0.012	0.089	61.8	100.0
Dana	−0.007	0.073	78.4	100.0
Middletown	−0.020	0.116	75.5	89.8

Table 5. Overall Administrative Synchronization Performance.

overall performance of the four master stations involved in the preliminary effort to improve master synchronization with UTC using administrative control. All four improvement techniques resulted in synchronization offsets surpassing $\pm$100 ns at least 60% of the time. The data are from the summer of 1989. The effect of increases in propagation noise during the winter months is to be determined.

The Alaskan master stations are not monitored directly by USNO. The offsets measured by USNO go through several time transfers. Figures 9-12 show the synchronization performance of the GOA and NORPAC chains. The USNO proposes to install another PTRS near Fairbanks, AK, to increase the frequency and precision of reported offset data from the Alaskan Loran-C master stations as is required to meet the $\pm$100-ns mandate. The Pacific Area Regional Manager has directed the COCO of the GOA and NORPAC Loran-C chains to begin controling master synchronization to within $\pm$500 ns in anticipation of the new PTRS installation.

The synchronization of Loran-C master stations depends critically on the ability of USNO to measure and provide timely and precise time difference offsets. The temporary reporting delay USNO is experiencing with LORSTA Fallon shows this dependence. With only a few days delay, LORSTA Fallon's offset quickly drifts beyond the $\pm$100-ns threshold.

CONCLUSIONS

The administrative methods of improving master station synchronization evaluated herein have significantly improved the Loran-C master station synchronization as reported by USNO. They have reduced the offsets of the four experimental master stations to within $\pm$200 ns of UTC 97% of

4 USNO does not issue their Series 5 report on Saturday and Sunday.

the time[5]. Average offsets were reduced to near zero values and, more significantly, the standard deviations were reduced to near 100-ns.

The preferred method of maintaining synchronization is the frequency control method. Once station improvements are made to increase the stability of cesium standards and an adequate number of PTRS sites are implemented, little correction should be necessary to maintain Loran-C master station synchronization. The frequency-control method is also less sensitive to short-term loss of offset reports. The time-step control method has the advantage of quickly reducing the master station offset and providing long-term drift data for the frequency standards.

Stable cesium frequency standards and the ability to determine the master station's offset frequently (at least daily) and precisely (at least 10-ns resolution) are key factors in the synchronization of Loran-C master stations with UTC. USNO has made significant improvements in its ability to report Loran-C master station offsets. The offsets of all the master stations in the United States are reported within 48 hours. Most are reported daily with 10-ns resolution. More accurate means of time transfer are being investigated by the Coast Guard and the USNO to measure Loran-C master station offsets at the stations themselves.

The ability to make no-notice timing corrections is also needed to reduce master station offset. Since the timing correction may occur daily, there would be no time for user notifications before they are entered. Both the Atlantic and Pacific Area Regional Managers have solicited objections to the no-notice timing corrections. None have been received.

The Coast Guard will continue testing the three methods of improving the synchronization of Loran-C master stations. The administrative techniques will be refined, and further improvements are expected. This winter season should show the full capability of the methods, including their strengths and weaknesses.

LIMITATIONS OF THE ADMINISTRATIVE CONTROL METHODS

The synchronization improvements shown for the four chains tested are at the limit of feasibility, given the facilities available. Even these significant improvements should be viewed critically. The synchronization experiments run by the four chains were developed to determine the best methods of synchronization and to identify problems. They may have to be further refined to satisfy long-term operational requirements for using synchronized signals.

These results reflect the more quiet spring/summer propagation season and may hide the fact that synchronization accuracy is strongly dependent on the proximity of the PTRS to the master transmitter. Changes in overland propagation can be expected to contribute to errors in synchronization accuracy. These errors increase with distance from the transmitter. To minimize propagation error for reliable synchronization, a PTRS should be located in the service area of each Loran-C master station and, ideally, it should be relatively close to the master.

The receiver site at USNO is just marginally within the service area of the three chains discussed. However, it is not critical to locate the time reference point at the master station. While colocation removes the propagation path error from the transmitter to the time reference station, the error from modeling the propagaion path from the PTRS to the user remains. The best position for the PTRS from the user's standpoint is coincident with the user. Because the aviation user population is expected to be distributed throughout the service area, the best location for a PTRS is near the center of chain coverage. This not only places the PTRS central to most users, but also simplifies the user's propagation model for pseudorange determination.

RECOMMENDATIONS

Further improvement and inclusion of other chains cannot be expected without added facilities for time service monitoring and improvement of existing PTRSs and Loran-C station frequency standard systems. The USNO and the Coast Guard have identified an efficient technical approach to meet the remaining

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5 The combined offsets of LORSTAs Seneca, Malone, Dana and Fallon during the period beginning 01 May 1989 and ending 17 Aug. 1989.

requirements of the law.

This approach also recognizes the limitations arising from recent Department of Defense policy which has removed GPS as a practical and reliable method of synchronizing Loran-C to UTC. Under this policy, encrypted, precise-time GPS signals cannot be used to synchronize Loran-C. Un-encrypted signals are not accurate enough, and common-view techniques are not appropriate to operational demands. The two-way satellite time-transfer technique (TWSTT) can circumvent this limitation while offering the advantages of reliability, accuracy and integrity over GPS. The extent of further progress depends on which of the following conditions are met:

- The USNO could establish a few key long-distance links between USNO, its PTRSs and Loran-C chains, using TWSTT techniques. Instrumentation at PTRS for time transfer and Loran-C monitoring must be upgraded. The TWSTT is the most appropriate time transfer method for this operational requirement, based on past USNO experience.

- Time transfer facilities could be placed at USNO PTRS sites, as opposed to Loran-C stations or sites. The Coast Guard prefers this placement, since it reduces both electronic interference and the engineering, maintenance, and operational burden on minimally crewed Coast Guard facilities.

- Six TWSTT ground stations could be added at PTRS sites. This should provide adequate time service monitoring to accomplish 100-nanosecond master synchronization to better than the 95% confidence level. Existing TWSTT facilities are at Boulder, CO, Washington, D.C., and Richmond, FL (planned for October 1989). Proposed sites are at Fairbanks, AK, China Lake, NV, and in the states of Washington, Montana, Ohio and Massachusetts. No ground stations funded by this project are planned for Hawaii (present equipment should allow better than 300-nanosecond synchronization, and the chain is due to close in 1994). The intent is to include the monitoring of the LABSEA chain from facilities within the United States.

- The Coast Guard could improve the cesium frequency standard stability at the Loran-C master stations. This can be done by installing environmental chambers (high reliability medical incubators) to house the cesium standards and also by implementing a Loran-C "master station time scale" (the algorithmic combination of the three station cesiums, used to steer the operate phase microstepper). The USNO has determined that this combination should result in a significantly more stable master time reference and is testing environmental chambers and developing a Loran-C station time scale system.

- Both the Coast Guard and the USNO could upgrade the procedures for all chains, following successful pilot efforts in the U.S. East Coast Chain. The recommended improvements to cesium standard stability and the addition of time monitoring facilities near each master station should remove much of the short-term variations in synchronization. Filtering and control recommendations by USNO should remove the remaining synchronization drifts. If they do not, the present procedure for small, infrequent time steps and frequency adjustments can be refined.

SUMMARY

Significant improvements have already been made in Loran-C synchronization to USNO UTC using only administrative techniques. If the additional hardware techniques discussed herein are also used, it is highly probable that the requirements of Public Law 100-223 will be satisfied, independent of the final synchronization interpretation of that law.

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1. Public Law 100-223, "Airport and Airway Safety and Capacity Expansion Act of 1987."

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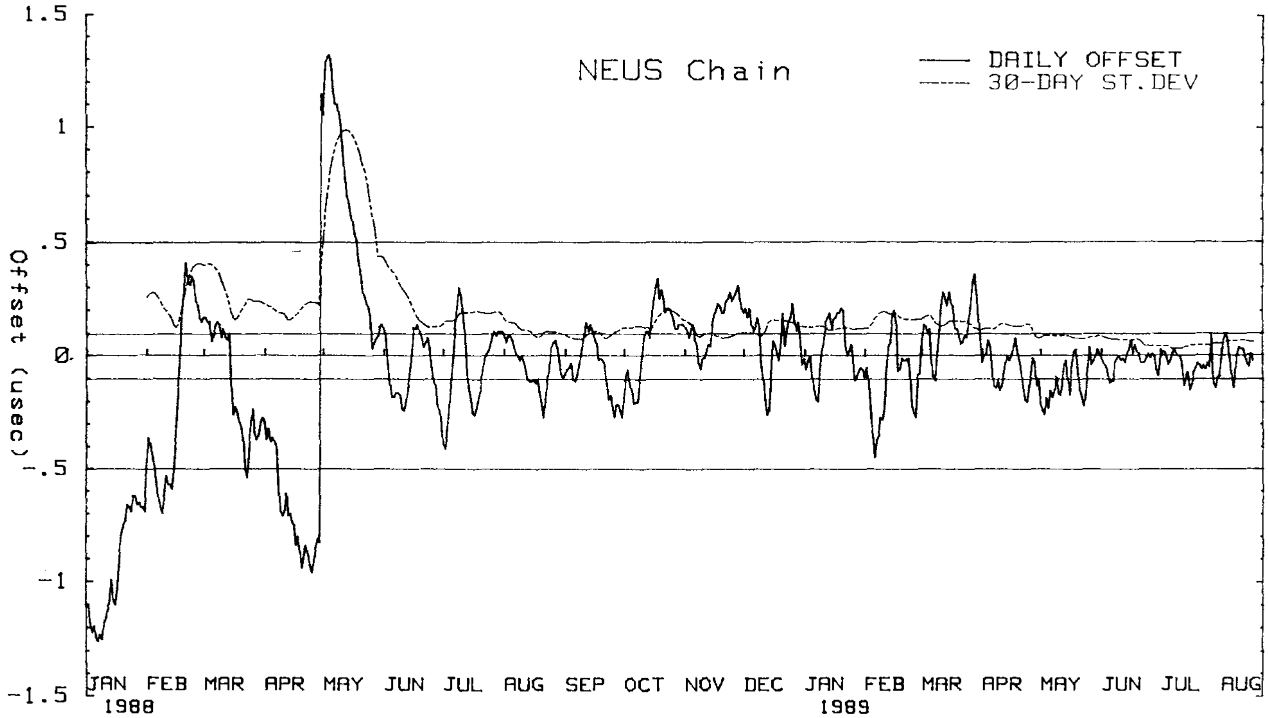

Figure 1. Offset Data for Loran-C Station Seneca, NY.

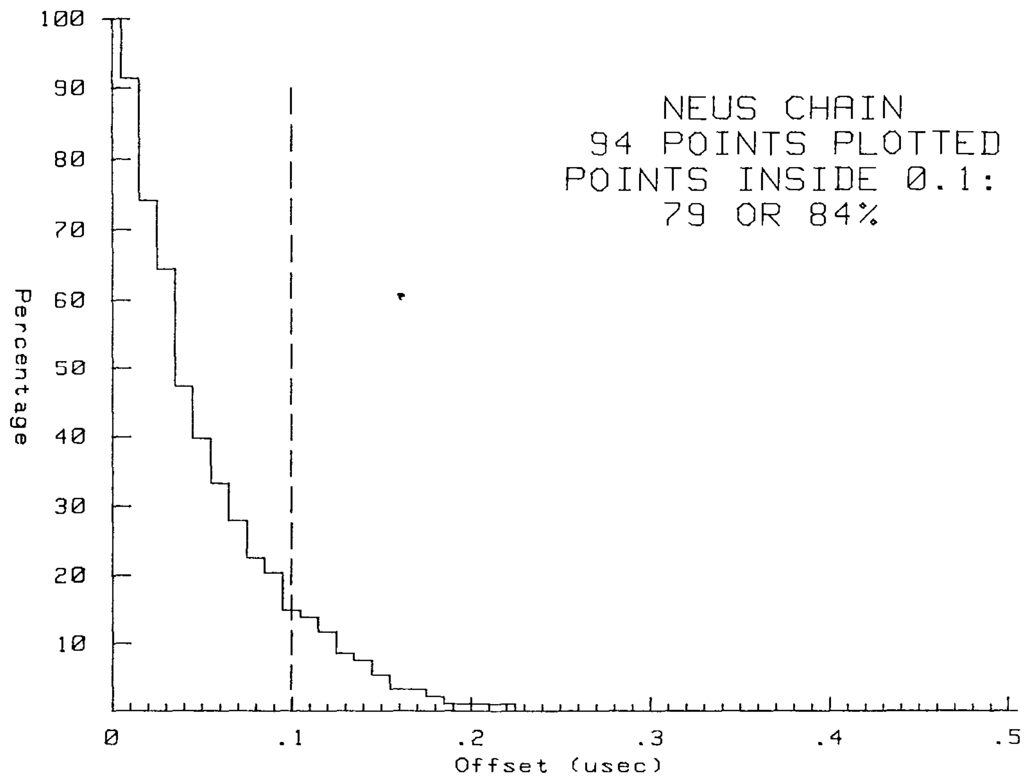

Figure 2. Percentage of Offsets Outside a Given Tolerance for LORSTA Seneca from May 15 , 1989 to August 17, 1989.

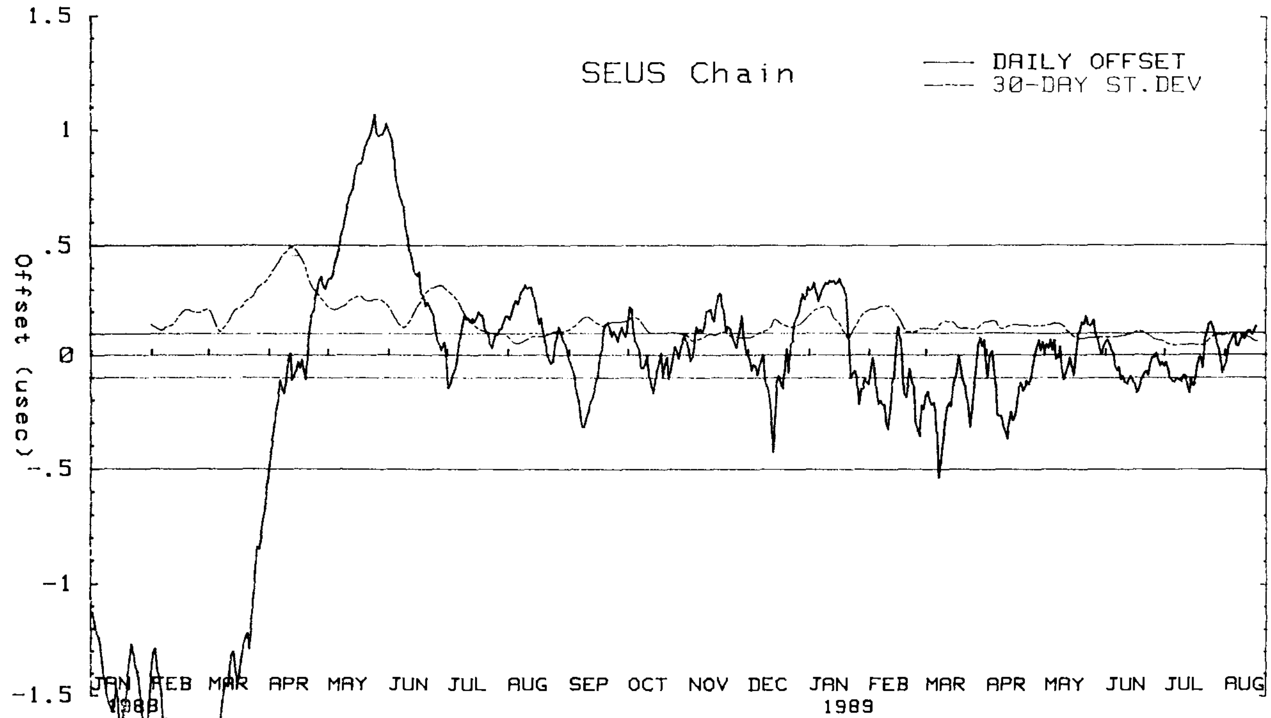

Figure 3. Offset Data for Loran-C Station Malone, FL.

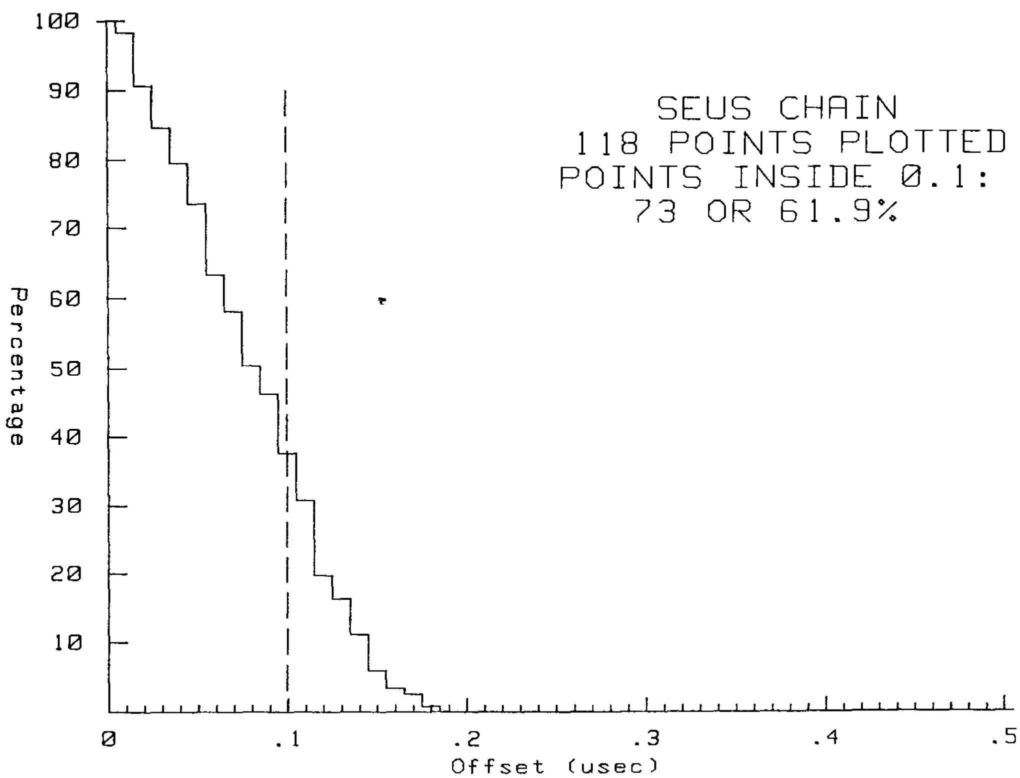

Figure 4. Percentage of Offsets Outside a Given Tolerance for LORSTA Malone from April 21 , 1989 to August 17, 1989.

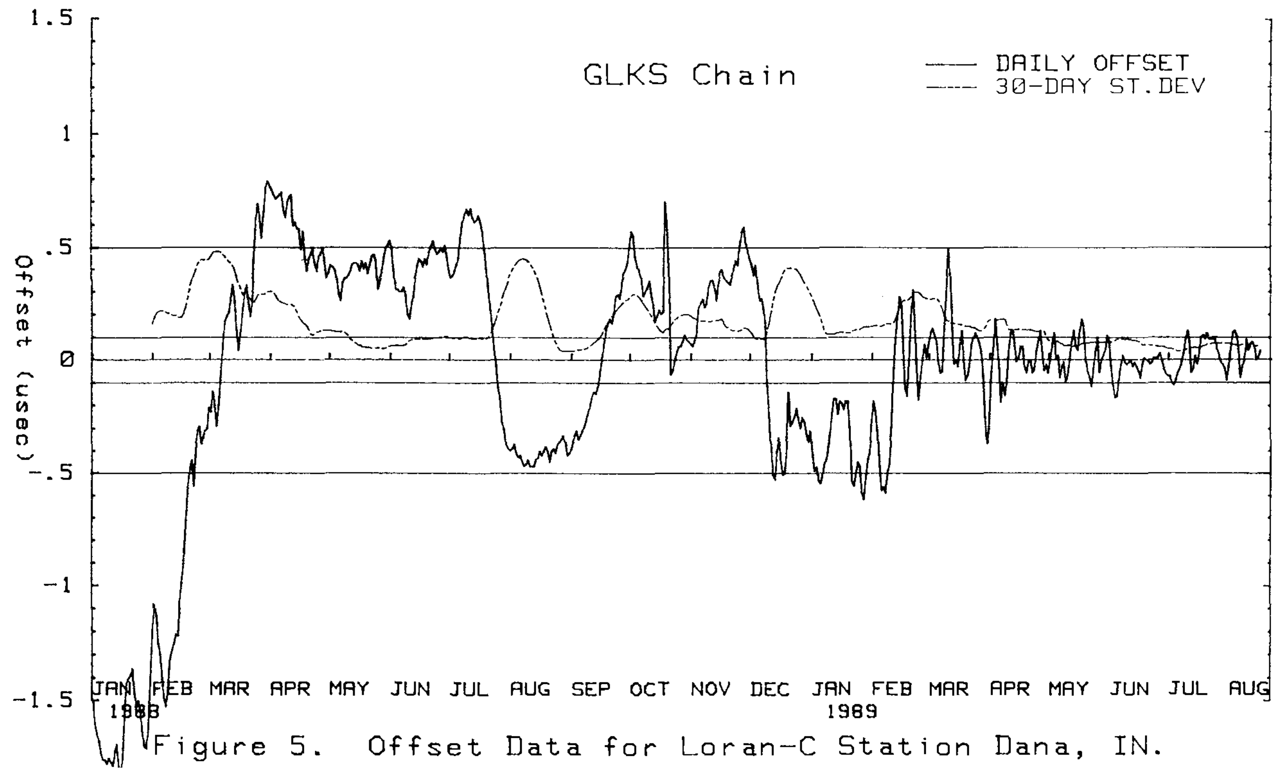

Figure 5. Offset Data for Loran-C Station Dana, IN.

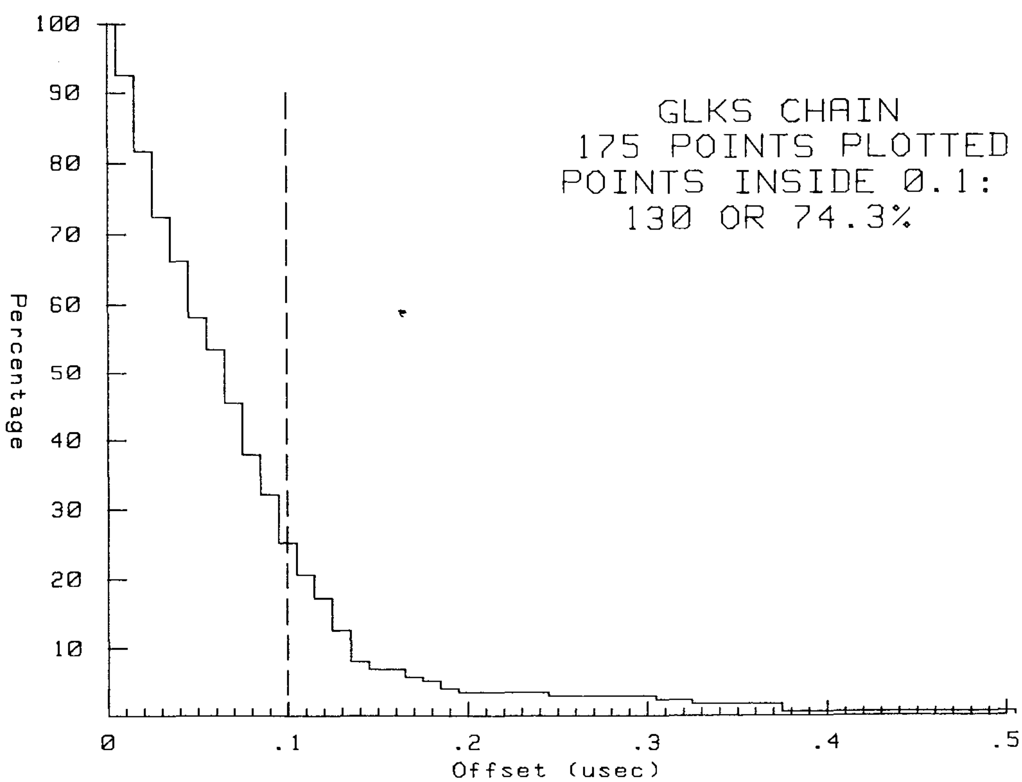

Figure 6. Percentage of Offsets Outside a Given Tolerance for LORSTA Dana from February 24 , 1989 to August 17, 1989.

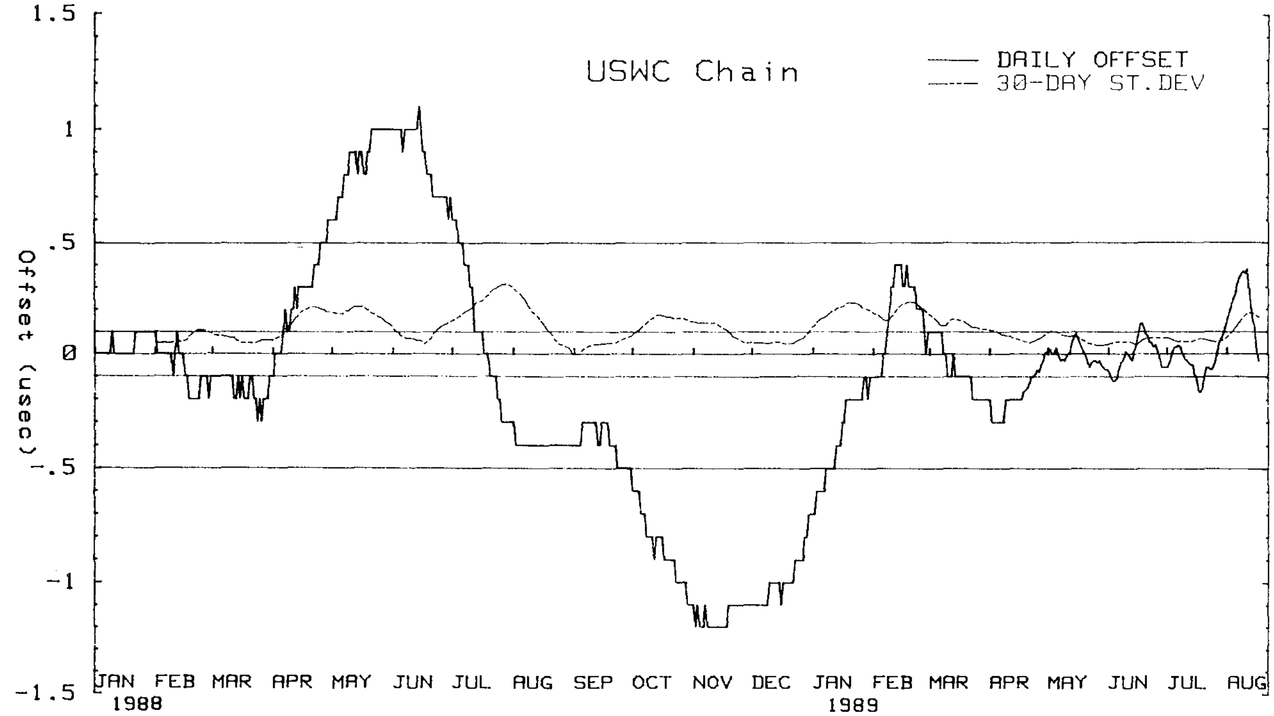

Figure 7. Offset Data for Loran-C Station Fallon, NV.

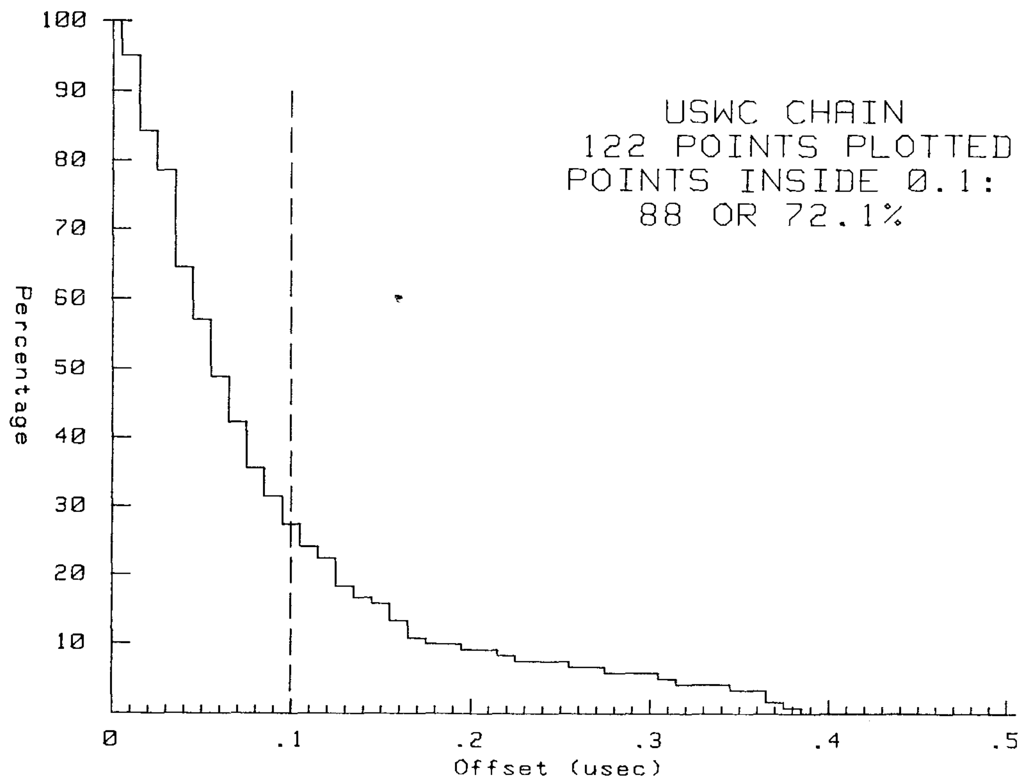

Figure 8. Percentage of Offsets Outside a Given Tolerance for LORSTA Fallon from April 17, 1989 to August 17, 1989.

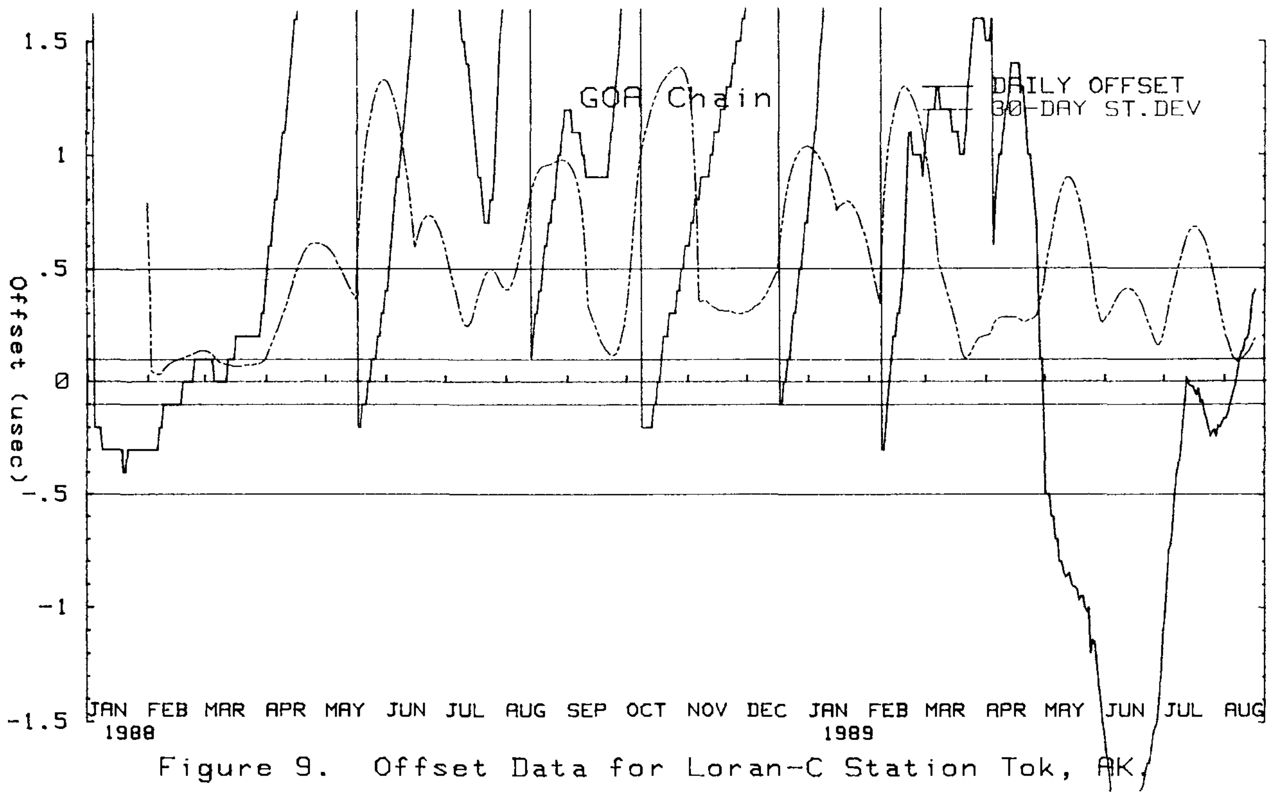

Figure 9. Offset Data for Loran-C Station Tok, AK.

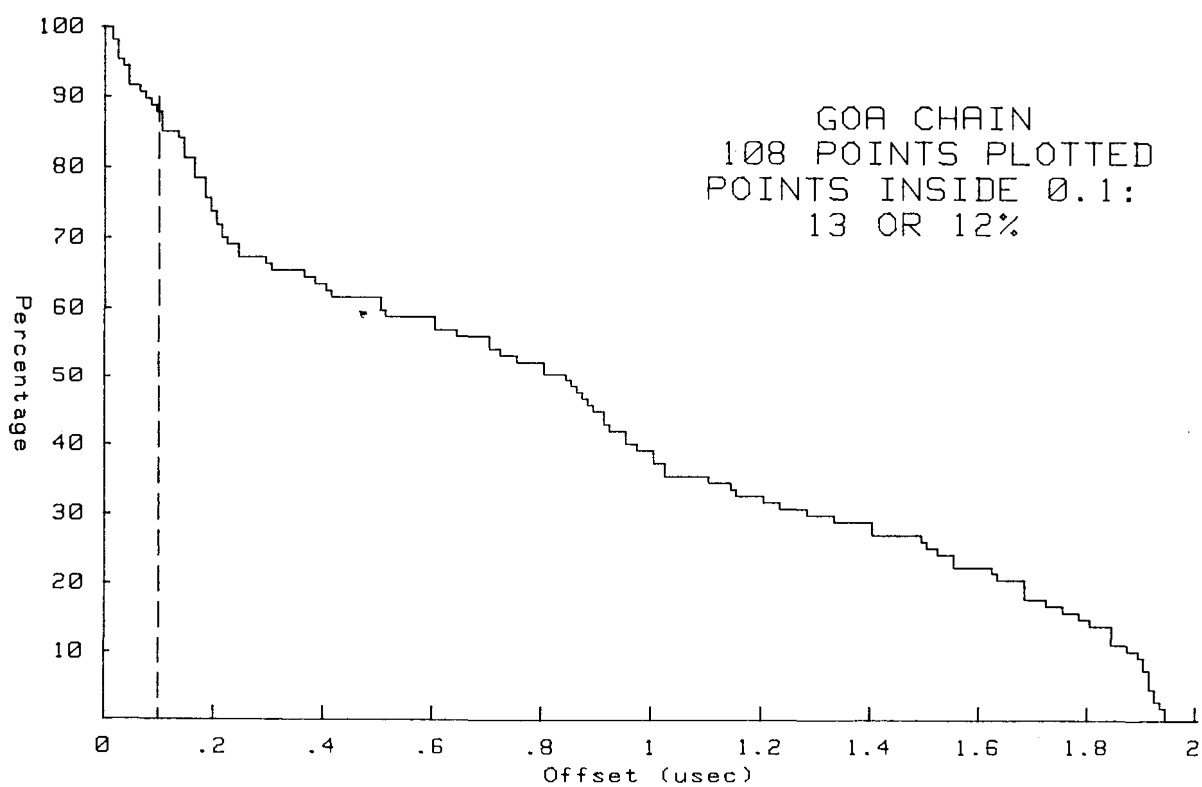

Figure 10. Percentage of Offsets Outside a Given Tolerance for LORSTA Tok from May 1 , 1989 to August 17, 1989.

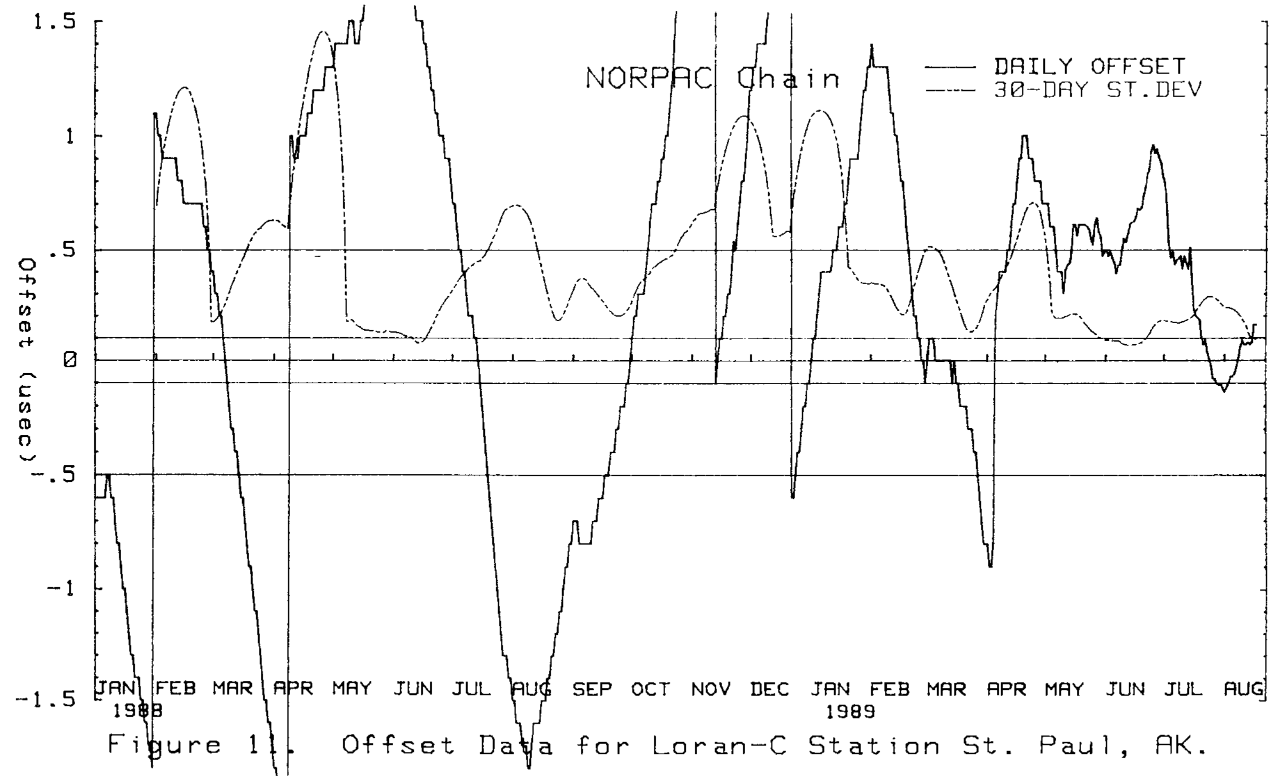

Figure 11. Offset Data for Loran-C Station St. Paul, AK.

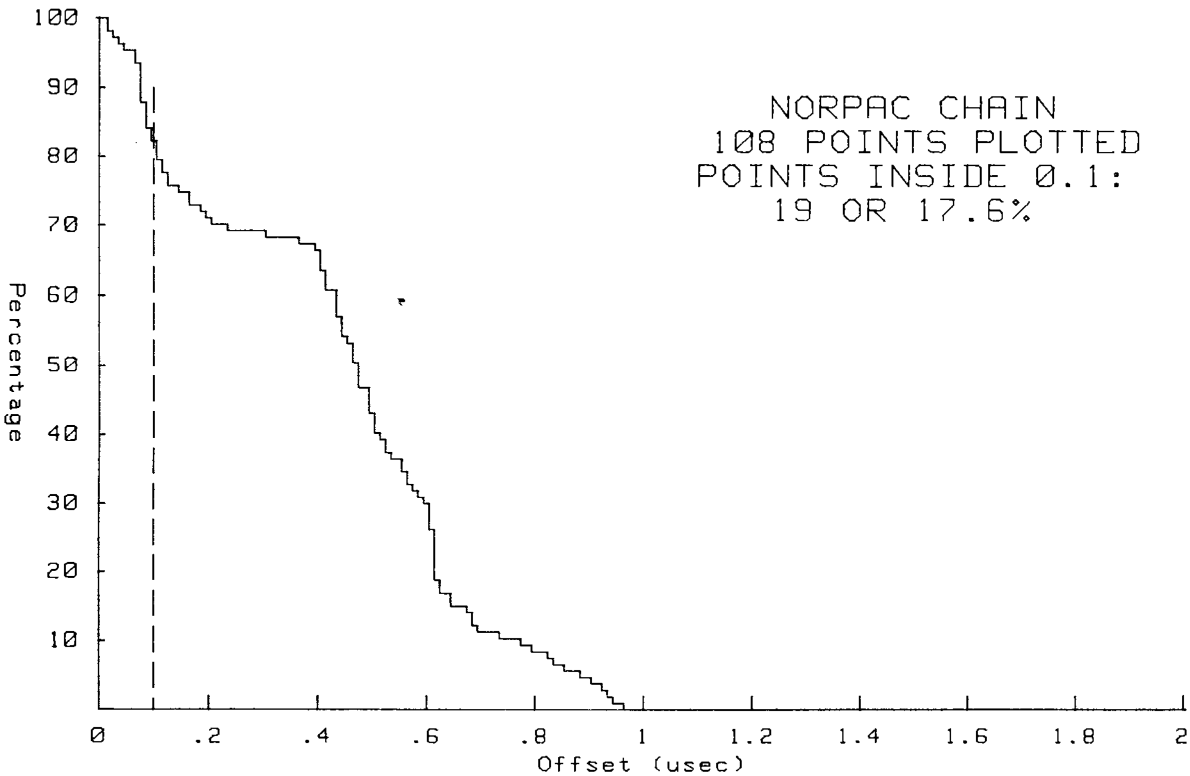

Figure 12. Percentage of Offsets Outside a Given Tolerance for LORSTA St. Paul from May 1, 1989 to August 17, 1989.

LORAN-C/GPS INTEROPERABLE COMPUTERIZED ALGORITHMS (LOGICAL)

John C. Castonia
Illgen Simulation Technologies, Inc.
351 S. Hitchcock Way, Ste. B230
Santa Barbara, CA 93105
(805) 563-0665

BIOGRAPHY

John C. Castonia is Vice President, Director of Technical Programs at Illgen Simulation Technologies, Inc. Mr. Castonia has been involved in navigation systems, simulation, integration, analysis and design work for mission applications relating to various platforms such as Unmanned Airborne Vehicles, the Precision Location Strike System, and Loran-C and GPS receiver design. He is a member of the WGA, ION, and IEEE. Mr. Castonia holds a B.S. Biomedical Engineering and has completed M.S.E.E. course requirements from the University of California, Santa Barbara.

ABSTRACT

This paper was prompted by Public Law 100-223, the Airport and Airway Safety and Capacity Expansion Act of 1987, which directs the synchronization of Loran-C master stations to within 100 nanoseconds of universal time, and solicited reports on the synchronization of Loran-C and GPS for the purpose of interchange of positioning data.

In response to this requirement, this paper presents a simulation architecture and preliminary results for the investigation and relative comparison of GPS/ Loran-C interoperable system architectures designed for the National Airspace (NAS). The LORAN-C/GPS Interoperable Computerized Algorithms (LOGICAL) have been integrated to predict the effects on accuracy of system error contributions and failure modes in user-defined scenarios as desired.

INTRODUCTION

The LOGICAL is a PC-based simulation, written in Turbo Pascal V5.0 (Borland International), that integrates navigation algorithms replicating the GPS and Loran-C navigation systems, a scenario generation function, and a graphics generation feature into an expandable, modular architecture.

The LOGICAL allows the user to input and configure a variety of GPS or Loran-C system elements into a particular analysis scenario. System elements could include GPS satellite constellation, Loran transmitters (LORSTA) configuration, control segment failures, or receiver characteristics. Accuracy values can be generated over a 24-hour period or for a single time and be compared with total system accuracy requirements for the enroute, terminal (SID/STAR), and non-precision (NPA) approach phases of flight and graphically presented to the user for screen or printer (hard copy) output display. The LOGICAL is based on verified methods for generating system accuracy values, and makes use of a third party program supplied by the GPS Program Office located at USAF Space Division, El Segundo, CA.

The LOGICAL is composed of four main processing functions. The overall architecture and the relationships between these processing functions are shown in Figure 1. Three of these functions, Scenario Generation (SG), Loran-C Processor, and GPS Processor, are controlled by the executive shell called "LOGICAL". LOGICAL oversees the operation of the three functions maintaining data integrity during handling and processing, and is responsible for graphics routines and post-processing data reduction routines.

The modularity of LOGICAL allows flexibility through multiple input scenario selection or rapid enhancements and updates as new interoperable architectures are identified.

LOGICAL DESCRIPTION

The LOGICAL is divided into three primary functions: scenario generation, analysis, and output processing and graphics generation. Each of these primary functions can be further characterized as Loran-C, GPS, or INTEROPERABLE. The following sections of this paper will present an overview of each of these functions.

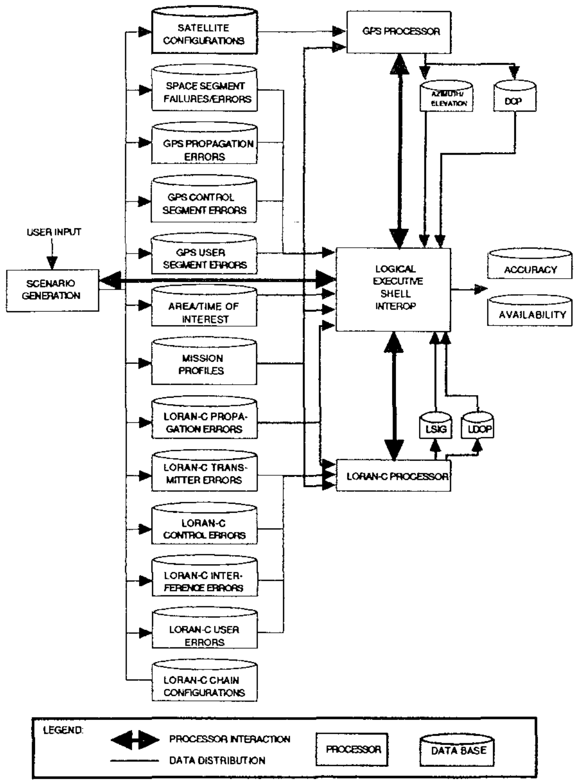

Figure 1. LOGICAL Architecture.

SCENARIO GENERATION FUNCTION

The Scenario Generation (SG) function offers the user an interactive, menu-driven capability that allows the definition of scenario analysis options. The SG function includes four primary input specification paths including:

- Area/Time of Mission (ATOM)
- GPS System Configuration
- Loran-C System Configuration
- Interoperable System.

By specifying each of these paths the user can configure mission location and time, GPS system, Loran-C system, navigation error contributions and magnitudes, and failure modes. For example, the user may assign a time (and duration) of failure to a Loran-C transmitter or control station, or may assign a particular GPS receiver error magnitude. The design intention of the SG is to pass the necessary input parameters to associated processors to provide comprehensive end-to-end analysis of various modes of operation of interoperable or individual GPS/Loran-C navigation systems.

While a complete listing of all the SG input options is beyond the scope of this paper, the primary features of the SG function are:

- entry and automatic routing of scenario data to GPS, Loran-C, or LOGICAL processing analyses

- definition of multitudes of scenarios including combinations of various transmitter (LORSTA or GPS SV) or mission waypoints for investigation

- definition of various navigation system failure modes by:

  - system
  - type (e.g., control monitor gone down)
  - magnitude of failure/error
  - time of failure
  - duration of failure
  - location of failure

The first three levels of the SG hierarchical structure are shown in Table 1. In total there are over fifty (50) menus representing approximately 100 input parameters or system status conditions that can be varied from run to run thus offering the user a high degree of analysis flexibility.

ANALYSIS FUNCTION: LORAN-C PROCESSOR

The Loran-C processor is designed to generate Loran-C performance estimates under a variety of operational scenarios and can be operated in two modes:

- as a stand-alone tool that can be used to generate accuracy values given the time and location of operation

- as a processor to supply inputs to the LOGICAL graphic processor or to the interoperable processing routines

The primary features of the Loran-C processor that support LOGICAL operation are:

- utilizes all Loran-C triads in the contiguous U.S encompassing the National Airspace including the Canadian East and West Coast chains and the planned mid-continent chains

- computes GDOP and necessary gradients on lines of position associated with master-secondary pairs to allow total error computation

- computes SNR values and compares to thresholds to determine signal availability

Table 1. LOGICAL SG Hierarchical Overview.

LOGICAL
Area/Time of Interest
Mission Area Selection
CONUS Region/State Terminal Area Point Analysis
Time/Date
GPS INPUT SPECIFICATION
Space Segment
Active Satellite Constellation Space Segment Error Contributions
Propagation Segment
Ionospheric/Tropospheric Multipath
Control Segment
System Status
User Segment
Receiver Error
LORAN-C INPUT SPECIFICATION
Transmitter (LORSTA) Segment
Active Chain/Station Selection LORSTA Error Magnitude
Propagation Segment
Temporal Variations Ground Conductivity
Interference Segment
Skywave Cross Rate
Control Segment
Control Station Status CM Status
User Segment
Receiver Specification
INTEROPERABLE INPUT SPECIFICATION
Lat/Long Comparison
Loran as GIC
GPS Pseudo/Loran Pseudo
GPS Pseudo/Loran TD
Direct Range Loran/GPS Time Transfer

• conducts automatic simulation runs of large numbers of waypoint locations and/or Lorsta combinations for:

- k-out-of-n transmitter failure mode analysis
- optimization studies
- accuracy studies

The Loran-C processor can exercise a variety of analysis operations by modifying the user-interactive menus and thus avoiding the requirement to recompile source code for every simulation.

ANALYSIS FUNCTION: GPS PROCESSOR

The GPS processor was incorporated to perform off-line processing of GPS performance analysis. The results of this off-line analysis are used as inputs to interactive LOGICAL operation.

The GPS processor is utilized in two modes:

• as a stand-alone tool that can be used to identify the windows of GPS availability and acceptable Geometric Dilution of Precision (GDOP)

• as a supplier of inputs to the LOGICAL main processor via ASCII text file transfer of DOP. These DOP values are used to compute total GPS navigation error using User Range Error (URE). (The GPS processor is a third party program supplied to ISTI by the GPS JPO in El Segundo, CA. This or any other program that provides ASCII text files in the same format (user can make his own DOP files) can be used as input to LOGICAL.)

The primary features of the GPS processor that directly support LOGICAL operation are:

• utilizes satellite vehicle (SV) combinations including Block I, Block II (Primary or Optimal), or the 18 + 3 constellation

• provides satellite orbit location predictions
• computes data required for GPS visibility
• computes GDOP, HDOP, and PDOP
• conducts automatic simulation runs of large numbers of waypoint locations and/or transmitter combinations for:

- k-out-of-n failure mode analysis
- optimization studies
- availability and accuracy studies

ANALYSIS FUNCTION: INTEROPERABLE PROCESSOR

To date at least five LORAN-C/GPS modes of interoperability have been identified as viable options (Reference 22). These five architectures are:

• Loran as the GPS Integrity Channel
• Latitude/Longitude Comparison
• GPS Pseudoranges with Loran-C Pseudoranges
• GPS Pseudoranges with Loran TDs
• Loran Direct Ranging Using GPS Time Transfer

A brief description of each of these interoperable modes is now presented:

Loran as GPS Integrity Channel: The Loran-C communications capability is used to transmit GPS health status to an aircraft; the aircraft uses GPS to perform navigation and the Loran-C message indicates whether or not GPS status is acceptable.

Latitude/Longitude Comparison: Both GPS and Loran-C position fixes are performed independently, and if their difference exceeds a certain threshold, a pilot integrity alarm is sounded.

GPS Pseudoranges with Loran-C Pseudo Ranges: A single receiver combines GPS and Loran-C pseudorange navigation data with reference to a common clock to produce latitude, longitude outputs.

GPS Pseudoranges with Loran-C TDs: A single receiver combines GPS pseudoranges with Loran-C TDs to produce latitude, longitude outputs.

Loran Direct Ranging Using GPS Time Transfer: GPS provides accurate clock timing which is used to synchronize the receiver clock to the Loran transmitter clock so that range can be measured directly from Loran-C signals.

The focus of the LOGICAL was to implement interoperable modes that are currently available and implemented in real receiver architectures, then add interoperable modes as desired. For this reason, Version 1.0 of the LOGICAL focuses on the Latitude/Longitude Comparison mode of interoperable operation (which is currently implemented in Trimble Navigation's GPX or 10X navigation receivers).

The Results section of this paper provides examples of the Lat/Long comparison mode of interoperability.

ANALYSIS CAPABILITY: FAILURE MODES

In order to adequately assess the failure modes and error factors that contribute to the operational performance of the GPS and LORAN-C navigation systems within the NAS, and incorporate these into the LOGICAL, error factors were characterized in terms of navigation system segments. The GPS error sources are described in terms of Space Segment, Control Segment, and User Segment. The Loran-C error sources are specified in terms of LORSTA, Propagation, Control Segment, Interference, and User Segment errors. These error sources were taken from an extensive library of navigation references located at ISTI and are listed as references to this report.

Table 2 lists the error sources that are incorporated in the LOGICAL. A detailed description of these errors and failure modes is given in Reference 23. Descriptions in the referenced document are given in terms of type of failure/error, detailed failure/error description, magnitude and time dependence (if any), special notes, and references. The failure modes and error sources can all be varied using the interactive SG function of the LOGICAL. Figure 2 gives some representative examples of user input menus that specify failure modes. These failure modes and error contributions are taken into account during LOGICAL run-time execution to calculate navigation performance.

OUTPUT DISPLAY DESCRIPTION

The LOGICAL presents results to the user in accordance with the type of analysis and tolerance levels specified by the user. Graphical and tabular outputs are provided for all analysis options. Graphical results are plotted with respect to sole means navigation criteria for total system accuracy* requirements cited in Reference 22 and repeated here:

Position Accuracy:

- =< 0.3 nm during NPA operations
- =< 1.7 nm during terminal area operations
- =< 2.8 nm during enroute operations

The user selects which mode of flight (tolerance) he is interested in and a comparison of the calculated navigation accuracies versus the requirements is performed at the points of interest previously specified by the user. Three situations are displayed to the user as follows:

1) If the navigation accuracy is better than the threshold specified then the area surrounding the point of interest on the map is colored solid.

2) If the navigation accuracy is marginal, then the surrounding map area is cross hatched.

3) Finally, if the navigation accuracy is worse than the threshold specified, then the area is left open on the display indicating a gap in adequate navigation accuracy.

In addition, tabular outputs are provided to the user during run time and are recorded to disk for post-simulation viewing and analysis.

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*does not include FTE.

Table 2. GPS/Loran-C Navigation Error Failure Modes and Error Contributions.

	GPS	LORAN-C
Space/LORSTA Segment	• Atomic clock drift/ relativistic frequency effects • SV group delay	• Cesium Frequency Standard Variations • Cycle compensation loop • Phase control • Pulse shape control • Timing circuit synchronization
Propagation Sources	• Ionospheric Noise • Tropospheric noise • Multipath	• Temporal variation • Diurnal variation • Ground conductivity
Control Segment	• SV clock and ephemeris drift due to missing an update from MS to SV • MCS/MS malfunction • Selective availability • MS failure	• Control station failure • CM failure
Interference Sources		• Skywave • Cross rate
User Segment	• Geometry • Code loop noise • Tracking error • Temporal noise • Dynamic limitations • Receiver clock error	• Geometry • Receiver limitations Hard limiter Linear Digital Signal Processor

```
GLOBAL POSITIONING SYSTEM CONFIGURATION MENU

        SP(A)CE SEGMENT
        (P)ROPAGATION SEGMENT
        (C)ONTROL SEGMENT
        (U)SER SEGMENT
        (S)AVE CHANGES AND EXIT TO SYSTEM
        (E)XIT TO SYSTEM

          Enter Option Selection:
```

Figure 2a.

```
     SPACE SEGMENT ERROR CONTRIBUTIONS MENU

(A)TOMIC CLOCK DRIFT/RELATIVISTIC FREQ EFFECTS
(S)ATELLITE VEHICLE GROUP DELAY
SV (P)ROFILES (id#, failure start time, duration)
RETURN TO SPACE SEGMENT (M)AIN MENU

       Enter Selection Option:
```

Figure 2b.

```
          7980 CHAIN TRANSMITTER MENU

TRANSMITTER (M) IS      OK FROM 00:00 TO 24:00
TRANSMITTER (W) IS FAILURE FROM 12:34 TO 15:46
TRANSMITTER (X) IS      OK FROM 00:00 TO 24:00
TRANSMITTER (Y) IS FAILURE FROM 03:45 TO 04:45
TRANSMITTER (Z) IS      OK FROM 00:00 TO 24:00
(R)ETURN TO MAIN MENU

   Enter Option Selection :
```

Figure 2c.

```
(1) 5990 AREA MONITOR #1 AT  (50.58,126.91) IS      OK FROM 00:00 TO 24:00
(2) 5990 AREA MONITOR #2 AT  (48.29,124.56) IS      OK FROM 00:00 TO 24:00
(3) 9940 AREA MONITOR #1 AT  (43.41,124.24) IS FAILURE FROM 10:23 TO 10:59
(4) 9940 AREA MONITOR #2 AT  (36.63,121.93) IS      OK FROM 00:00 TO 24:00
(5) 7980 AREA MONITOR #1 AT  (30.38, 81.42) IS      OK FROM 00:00 TO 24:00
(6) 7980 AREA MONITOR #2 AT  (30.58, 86.61) IS      OK FROM 00:00 TO 24:00
(7) 7980 AREA MONITOR #3 AT  (29.82, 90.02) IS FAILURE FROM 12:56 TO 13:45
(8) 9960 AREA MONITOR #1 AT  (43.56, 70.20) IS      OK FROM 00:00 TO 24:00
(9) 9960 AREA MONITOR #2 AT  (40.47, 74.03) IS      OK FROM 00:00 TO 24:00
(10) 9960 AREA MONITOR #3 AT (41.38, 82.66) IS      OK FROM 00:00 TO 24:00
(11) 9960 AREA MONITOR #4 AT (43.53, 86.48) IS      OK FROM 00:00 TO 24:00
(12) 8970 AREA MONITOR #1 AT (44.38, 82.66) IS      OK FROM 00:00 TO 24:00
(13) 8970 AREA MONITOR #2 AT (30.60, 86.61) IS      OK FROM 00:00 TO 24:00
(14) 8970 AREA MONITOR #3 AT (30.38, 81.42) IS FAILURE FROM 19:00 TO 21:00
(15) 5930 AREA MONITOR #1 AT (43.56, 70.20) IS      OK FROM 00:00 TO 24:00
RETURN TO CONTROL SEGMENT (M)ENU

Enter Option Selection :
```

Figure 2d.

Figure 2. Sample Configuration Menus.

RESULTS

Several examples will suffice to illustrate the utility of the LOGICAL.

Figure 3a shows an output map display of CONUS with 6 waypoints of interest shown on the map. Using the left/right arrow keys a user can select any of the waypoints. For this display, San Francisco (#6) has been chosen. The navigation system of interest is GPS, and the split screen display, which has been output to a EPSON-compatible printer, shows both graphical and tabular outputs which are updated as the user toggles through the waypoints. Figure 3b gives a summary of the total and individual error contributions in tabular format. The user can toggle between tabular data or map displays by using the up/down arrow keys. Figure 3c illustrates the effect of attaching the tolerance levels to the output map display, where all but two of the waypoints has met the sole means navigation accuracy criteria for enroute travel, one is marginal, and one is clearly unacceptable. Figure 3d shows one of the recorded output disk files available for post-simulation processing and review.

Figure 4a exhibits CONUS for the Loran-C system. Figure 4b shows a portion of the recorded disk file for one sample calculation out of a 24-hour period.

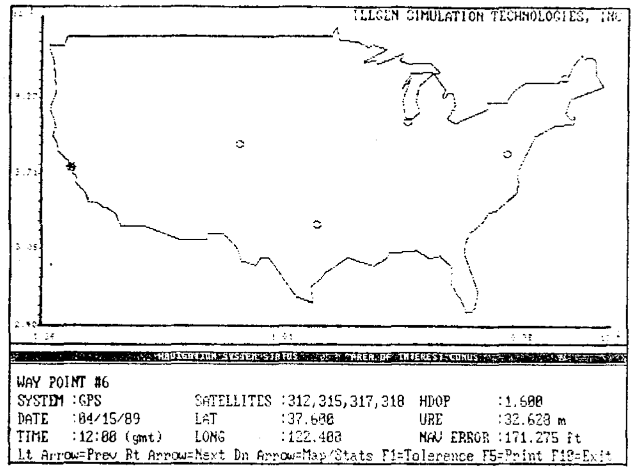

Figure 3a.

CONUS: 6 Waypoints.

```
FULL NAVIGATION STATUS DISPLAY  FOR WAY POINT #6

SYSTEM: GPS          DATE:04/15/89          TIME:12:00
LAT :37.600          LONG:122.400           SATELLITES:312,315,317,318
URE :32.628 m        HDOP:1.600             TOTAL NAV ERROR: 171.275 ft

—— ERROR CONTRIBUTIONS ——
SATELLITE VEHICLE GROUP DELAY: 1.000 m
SATELLITE ATMOSPHERIC NOISE  : 10.400 m
MULTIPATH ERROR              : 5.400 m
CONTROL FAILURE ERROR        : 4.900 m
SELECTIVE AVAILABILITY       :30.000 m
RECEIVER ERROR               : 1.500 m

Lt Arrow=Prev Rt Arrow=Next Dn Arrow=Map/Stats F1=Tolerence F5=Print F10=Exit
```

Figure 3b,

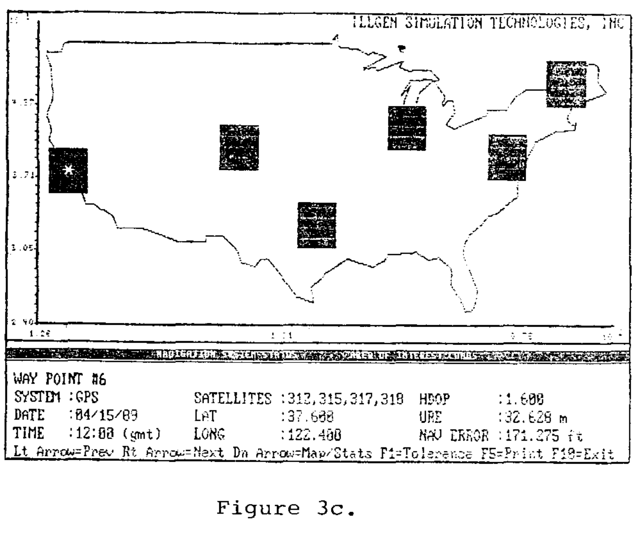

Figure 3c.

```
SYSTEM: GPS
DATE:04/15/89
TIME: 12:00
LAT: 45.500
LONG: 71.000
SATELLITES: 304,312,315,316
URE: 32.484 m
HDOP: 1.100
TOTAL NAV ERROR: 117.231 ft
--- ERROR CONTRIBUTIONS ---
SATELLITE VEHICLE GROUP DELAY:        1.000 m
SATELLITE ATMOSPHERIC NOISE:          9.938 m
MULTIPATH ERROR:                      5.400 m
CONTROL FAILURE ERROR:                4.900 m
SELECTIVE AVAILABILITY:              30.000 m
RECEIVER ERROR:                       1.500 m

***********************************************************
SYSTEM: GPS
DATE: 04/15/89
TIME: 12:00
LAT: 38.900
LONG: 77.000
SATELLITES: 312,315,316,319
URE: 32.628 m
HDOP: 1.200
TOTAL NAV ERROR: 128.457 ft
--- ERROR CONTRIBUTIONS ---
SATELLITE VEHICLE GROUP DELAY:        1.000 m
SATELLITE ATMOSPHERIC NOISE:         10.400 m
MULTIPATH ERROR:                      5.400 m
CONTROL FAILURE ERROR:                4.900 m
SELECTIVE AVAILABILITY:              30.000 m
RECEIVER ERROR:                       1.500 m

***********************************************************
SYSTEM: GPS
DATE: 04/15/89
TIME: 12:00
LAT: 41.600
LONG: 87.400
SATELLITES: 312,315,316,319
URE: 32.628 m
HDOP: 1.300
TOTAL NAV ERROR: 139.161 ft
--- ERROR CONTRIBUTIONS ---
SATELLITE VEHICLE GROUP DELAY:        1.000 m
SATELLITE ATMOSPHERIC NOISE:         10.400 m
MULTIPATH ERROR:                      5.400 m
CONTROL FAILURE ERROR:                4.900 m
SELECTIVE AVAILABILITY:              30.000 m
RECEIVER ERROR:                       1.500 m

***********************************************************
SYSTEM: GPS
DATE: 04/15/89
TIME: 12:00
LAT: 32.750
LONG: 96.750
SATELLITES: 312,315,316,318
URE: 32.628 m
HDOP: 1.400
TOTAL NAV ERROR: 149.866 ft
```

Figure 3d.

Figure 3.

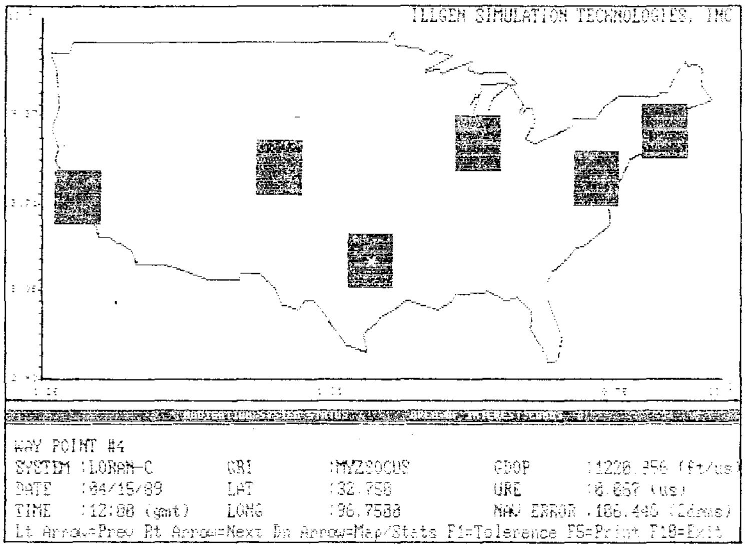

Figure 4a.

LORAN-C DATE: 04/15/89 TIME: 12:00
LAT: 42.500 LONG: 71.000 GRI: 9960 STATIONS: M,W,X
URE = 0.087(us) DOP=926.726(ft/us) TOTAL NAVIGATION ERROR = 80.790(ft)

MASTER SNR	=28.592(dB)		
SECONDARY #1 SNR	=22.987(dB)	GRADIENT W=596.390 (ft/us)	
SECONDARY #2 SNR	=38.304(dB)	GRADIENT X =550.368 (ft/us)	
CONTROL MONITOR DRIFT	=0.000(nsecs)	CONTROL STATION DRIFT	=0.000(nsecs)
TEMPORAL VARIATION	=0.000(us)	DIURNAL VARIATION	=0.050(us)
SKYWAVE ERROR	=0.000(us)	CROSS RATE INTERFERENCE	=0.050(us)
RECEIVER ERROR	=0.010(us)	LORSTA TIMING FLUXATION	=0.050(us)

****

LORAN-C DATE: 04/15/89 TIME: 12:00
LAT: 38.900 LONG: 77.000 GRI: 9960 STATIONS: M,X,Y
URE = 0.987(us) DOP = 1209.035(ft/us) TOTAL NAVIGATION ERROR = 105.401(ft)

MASTER SNR	=23.340(dB)		
SECONDARY #1 SNR	=11.143(dB)	GRADIENT X=951.127 (ft/us)	
SECONDARY #2 SNR	=17.386(dB)	GRADIENT Y=492.708 (ft/us)	
CONTROL MONITOR DRIFT	=0.000(nsecs)	CONTROL STATION DRIFT	=0.000(nsecs)
TEMPORAL VARIATION	=0.000(us)	DIURNAL VARIATION	=0.050(us)
SKYWAVE ERROR	=0.000(us)	CROSS RATE INTERFERENCE	=0.050(us)
RECEIVER ERROR	=0.010(us)	LORSTA TIMING FLUXATION	=0.050(us)

****

LORAN-C DATE: 04/15/89 TIME: 12:00
LAT: 41.600 LONG: 87.400 GRI: 8970 STATIONS: M,X,Y
URE = 0.133(us) DOP = 979.310(ft/us) TOTAL NAVIGATION ERROR = 129.920(ft)

MASTER SNR	=38.139(dB)		
SECONDARY #1 SNR	=17.902(dB)	GRADIENT X=624.991 (ft/us)	
SECONDARY #2 SNR	=13.397(dB)	GRADIENT Y=516.441 (ft/us)	
CONTROL MONITOR DRIFT	=0.000(nsecs)	CONTROL STATION DRIFT	=0.000(nsecs)
TEMPORAL VARIATION	=0.000(us)	DIURNAL VARIATION	=0.050(us)
SKYWAVE ERROR	=0.100(us)	CROSS RATE INTERFERENCE	=0.050(us)
RECEIVER ERROR	=0.010(us)	LORSTA TIMING FLUXATION	=0.050(us)

****

LORAN-C DATE: 04/15/89 TIME: 12:00
LAT: 32.750 LONG: 96.750 GRI: SOCUS STATIONS: M,X,Y
URE = 0.087(us) DOP = 1220.056(ft/us) TOTAL NAVIGATION ERROR = 106.448(ft)

MASTER SNR	=15.678(dB)		
SECONDARY #1 SNR	=11.632(dB)	GRADIENT X=596.388 (ft/us)	
SECONDARY #2 SNR	=17.145(dB)	GRADIENT Y=493.588 (ft/us)	
CONTROL MONITOR DRIFT	=0.000(nsecs)	CONTROL STATION DRIFT	=0.000(nsecs)
TEMPORAL VARIATION	=0.001(us)	DIURNAL VARIATION	=0.050(us)
SKYWAVE ERROR	=0.000(us)	CROSS RATE INTERFERENCE	=0.050(us)
RECEIVER ERROR	=0.010(us)	LORSTA TIMING FLUXATION	=0.050(us)

****

LORAN-C DATE: 04/15/89 TIME: 12:00
LAT: 39700 LONG: 104.750 GRI: SOCUS STATIONS: M,X,Y
URE = 0.133(us) DOP = 1097.609(ft/us) TOTAL NAVIGATION ERROR = 145.626(ft)

Figure 4b.

Figures 5a and 5b show examples of a regional area analysis applied to the State of New Mexico assuming the Loran-C mid-continent gap has been filled.

Figure 6a shows ten (10) waypoints of a potential landing pattern into San Francisco International Airport. Figure 6b displays results for a GPS alone analysis, Figure 6c for a Loran-C alone analysis, and Figures 6d and 6e for a lat/long comparison interoperable analysis.

SUMMARY

This paper has presented an overview of the architecture, capabilities, and preliminary results of Version 1.0 of the LOGICAL. The LOGICAL is a user-interactive simulation which provides navigation accuracy predictions of Loran-C or GPS or interoperable system performance within the NAS. A major feature of the LOGICAL is the capability to predict the effects on navigation performance of system error contributions and failure modes in user-defined scenarios as desired. Results presented included the analysis of Loran-C and GPS operating individually and interoperably in the latitude/longitude comparison mode. Results were presented for CONUS, regional, and terminal areas.

The LOGICAL can be used in various applications such as flight operations, mission planning, and assessment of navigation coverage. Additional potential applications include Air Traffic Control and Air Traffic Management.

ACKNOWLEDGEMENTS

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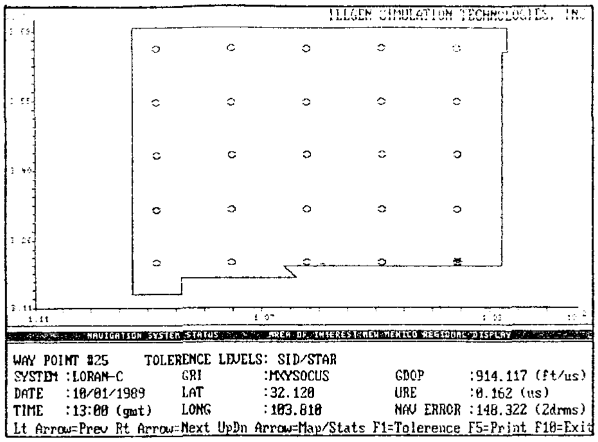
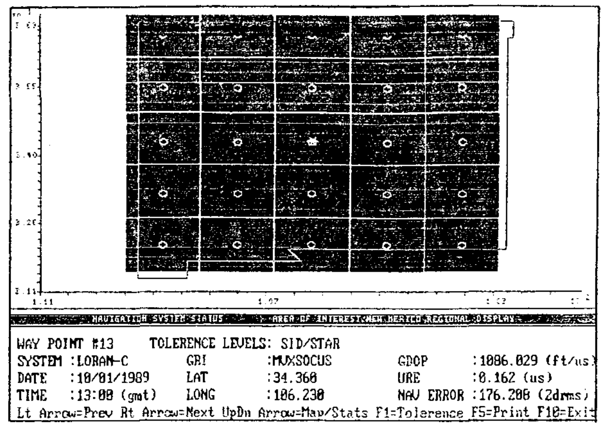


Figure 5a.



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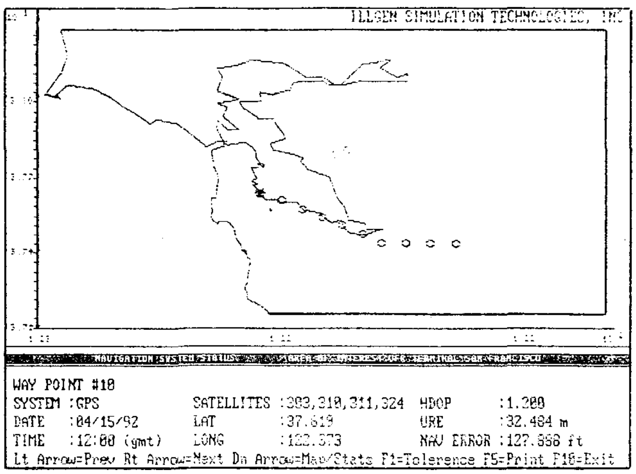
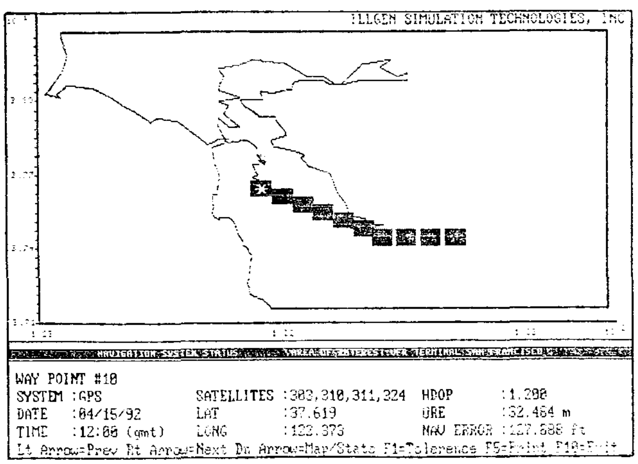


Figure 6a.



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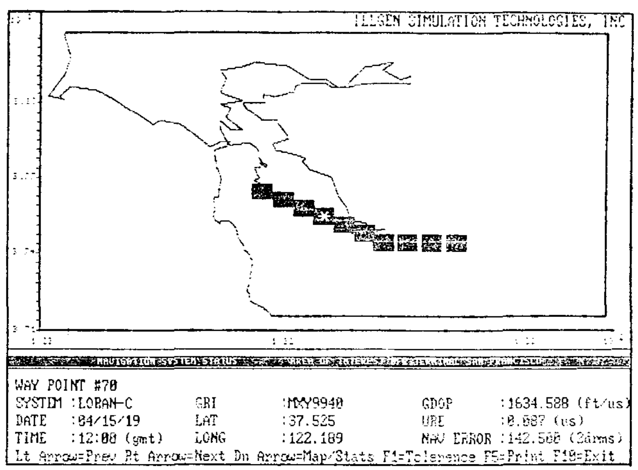

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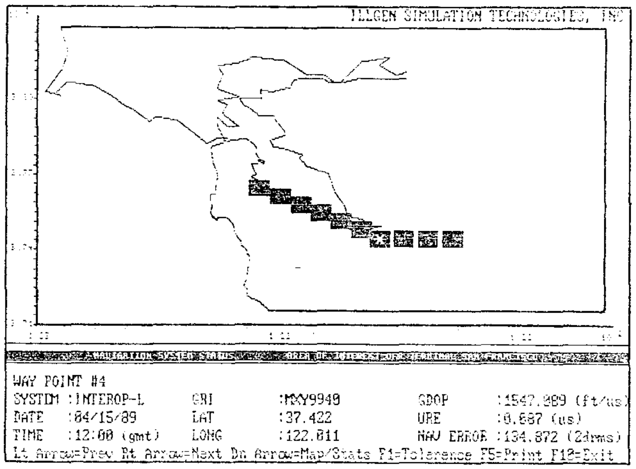

Figure 6d.

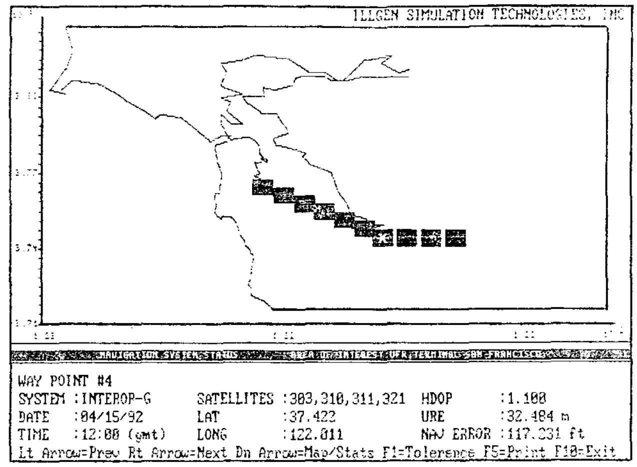

Figure 6e.

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ANALYSIS OF LORAN-C/GPS INTEROPERABILITY FOR AIR NAVIGATION

Frona B. Vicksell and Robert B. Goddard, Megapulse Inc.

Per K. Enge, Worcester Polytechnic Institute

Frank van Graas, Avionics Engineering Center, Ohio University

ABSTRACT

Computer runs show that it is likely that in the National Airspace System a hybrid of Loran-C and a 24-satellite Global Positioning System can meet aviation sole means requirements for availability of accuracy, and perhaps integrity as well. A hybrid GPS/Loran system reduces unavailability by a factor of 1000 compared to GPS alone.

The GPS and the Loran-C System signals are well suited for combination in a hybrid fix algorithm. Virtual synchronization of GPS and Loran clocks can be achieved by inclusion of each Loran transmitter's offset from Universal Time within the Loran signal. GPS failure rates and distributions of GPS Selective Availability errors are not yet known, nor are the characteristics of rare high levels of atmospheric noise affecting Loran measurements known; reasonable estimates were used. An integrity requirement specification should include both a maximum miss rate and a maximum alarm rate along with the radial protection limit. For integrity checking, both the maximum separation and least square residuals techniques were examined.

1. INTRODUCTION

This paper covers topics related to two reports on GPS/Loran Interoperability prepared for the Department of Transportation, Transportation Systems Center [1, 2]. Frank van Graas was the author of one of these reports, and Per Enge, Robert Goddard and Frona Vicksell were contributors to the other report, which was prepared under contract to NAVCOM Systems in response to the Airport and Airways Safety and Capacity Expansion Act of 1987.

We define availability of a navigation service at a particular location and time as whether or not predetermined requirements are met at that location and time -- yes or no. Availability over a region is what fraction of locations and times have yeses, that is, meet the requirements.

For the purposes of the NAVCOM report, sole means navigation demanded the very high availability of .999999975. That is the equivalent of an UNavailability of 25 cases per billion or roughly a 5 minute outage on some 30 square mile area out of the total National Air Space, once a day. Also, in the case of the NAVCOM report, the availability requirement was primarily for accuracy. At each place and time, the 2 drms position error had to be less than a specified maximum (for example, .3 nautical miles for nonprecision approach).

There can be other availability requirements such as continuity of service and integrity. Integrity is the system's ability to detect its own errors, particularly position error outside of some radial protection limit. A maximum time-till-alarm is usually specified. However it has not been made clear what probability of alarm assertion and what probability of error detection failure (at each NAS location and time) is acceptable. Specification of these two rates along with the protection limit is required before the operational availability of integrity can be determined.

Both the Navstar Global Positioning System and the Loran-C System have weak points which prevent either one alone from delivering service at the level of availability required for sole means navigation.

Many authors have studied and continue to study the problem of GPS integrity [3, 4]. In spite of the absence of a complete specification of the integrity requirements for sole means navigation, the consensus is that GPS alone, with its intentional Selective Availability errors, cannot meet the long term goal of a 100 meter protection limit for nonprecision approach. The addition of an independent GPS Integrity Channel and/or extra geostationary satellites sometime in the future would be expensive and still would probably not give sufficient availability unless local differential corrections were also supplied [5]. But the Loran system, already in existence in many areas around the world, is an excellent source of compatible navigation signals which, combined with GPS, will increase the availability of both accuracy and integrity.

This report briefly surveys ways in which Loran and GPS can be combined, and describes recent studies of accuracy and integrity in a GPS/Loran hybrid system over the National Air Space.

2. WAYS OF COMBINING GPS AND LORAN

Characteristics of GPS and Loran

Table 1 compares a few salient aspects of GPS and Loran.

Note that in part because of the different frequencies used and the different signal paths, the chief error sources for the two systems are non-overlapping and independent; therefore the two together, even without combining data, have a much smaller unavailability rate than either alone. One could use GPS when enough satellites are in view for integrity checking, and otherwise use Loran with its own integrity checks.

But in addition, the two systems are fundamentally the same mathematically speaking, so that even in some situations where neither system alone can obtain a fix, a hybrid system using essentially the same algorithm can obtain a fix, not only with accuracy, but also with the redundancy needed for an integrity check. Thus availability is still further increased. The next two sections review pseudoranging and related timing considerations.

The Pseudorange Fix Algorithm

Figure 1 shows the principle of pseudorange measurements. Only one signal source is shown. It could be either a GPS transmitter or a Loran transmitter. The receiver knows when the Time of Emission (TOE) is supposed to be, but does not have a good clock. It makes an arbitrary guess at setting its clock relative to Universal Time, and starts counting at the "proper" time (left side of the figure), introducing an unknown bias. In the mean time, the transmitter emits the signal. When the signal arrives at the receiver (TOA), the receiver stops counting. The interval counted by the receiver, multiplied by the speed of light, is called the pseudorange, "pseudo" because it contains the possibly large local clock offset.

The receiver also knows where the transmitter was (nominally) at the Time of Emission. The receiver has a model for estimating propagation times between two points, including ASF corrections or ionospheric corrections. The receiver's job is to find an x, y, z position and a clock bias b such that when you add up the bias and the model propagation time, it agrees with the observed pseudorange. Of course one measurement is not enough for a unique solution. Measurements from 4 transmitters in different directions all using the same bias allow the receiver to solve for the 4 unknowns. If altitude is already known, then only 3 signals are needed; this is the case with ordinary hyperbolic Loran. If a good clock is on board as in Loran range-range operations, then one less measurement is needed.

In practice, there are errors in the advertised TOEs and ephemeris and in models and measurements, so the solution also has error, as shown in Figure 1. Two ways to reduce the solution error are

a) select a combination of signals with a statistically small expected distance root mean square error (for example the Loran triad with best SNR, crossing angle, and gradient combination, or, the 4 satellites sufficiently above the horizon with best geometry),

or

b) combine more than the necessary number of measurements, in least square fashion. In this case, the solution chosen does not match any of the measurements exactly, but represents the most probable compromise.

If the least square approach involves Loran signals or involves satellites at very low elevation, it is best to use weighting because of the wide variation in the standard deviations of the pseudorange measurements. The Loran weights could for example be based on a combination of path length and observed signal-to-noise ratio. It is also possible to take into

	Transmitter Placement	Carrier Frequency	Chief Problems	Failure Indicators
Loran	Stationary on earth surface, selected areas only	.1 MHz	Variable propagation velocities, local noise, cycle slip	Signal/noise, blink, distance, path over land, bad geometry
GPS	In 12-hour orbits covering globe, altitude = 3 earth radii	1227.6 and 1575.42 MHz (center frequencies)	Coverage gaps, intentional errors, long time to repair	Health message (delayed), bad geometry, possible integrity channel

Table 1 - Comparison of Loran and GPS

Note: position determination in both systems is based on range differences.

```
TIME ---->

                        TOE(k)                                  TOA(k)
                          |              actual PT(k)             |
                          |~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~|
|_________________________|                                       |
|unknown receiver|                                                |
|clock bias      |                                                |
|                                                                 |
|_________________________________________________________________|
|                measured pseudorange(k) / c                      |
|                                                                 |
|____________________|____________________________________________|  / 4-signal
|         b          |         model PT(k, x, y, z)               |  \ fix
|                                                                 |
|________________|______________________________|ooooooooo|  / least-square
|        b       |     model PT(k, x, y, z)     |residual |  \ fix

TOE(k) = Time of Emission, kth signal          c          = speed of light
TOA(k) = Time of Arrival, kth signal           b, x, y, z = solution values for receiver
PT(k)  = Propagation time, kth signal                        clock bias and position
```

Figure 1 Pseudorange Timing Diagram

account correlation in the pseudorange errors, such as would occur in seasonal ASF variation.

Figure 1 shows a residual resulting from a least square solution. The sum of the squares of the weighted residuals is the quantity minimized in the fix process and also can serve as a measure of how consistent the pseudorange measurements are with each other. In other words, it provides an integrity check.

In summary, GPS and Loran measurements can be combined and used to check each other at the most basic level of the fix algorithm.

Later in the paper we shall present some results of computer simulations. Frank van Graas calculated hybrid accuracy availability estimates using option a). He also tested option b) without weights for convergence and simulated the use of residuals as an integrity criterion. A study at Megapulse estimated the availability of different drms error levels and integrity check capabilities using option b) with weighting.

Clock Considerations

In the description of pseudoranging above, there was only one clock unknown, the receiver's offset from UTC. It is possible to solve for additional clock unknowns, but each additional unknown requires one more signal source, with corresponding loss of redundancy. For the very best results, therefore, we would like to have

- o Times of Arrival all measured relative to a common receiver clock, and
- o Times of Emission relative to Universal Time (UTC) known to the receiver.

The current status of transmitter Time of Emission offsets is as follows:

GPS -- the offset of each GPS transmitter vs. UTC is included in the transmitted message, but may be intentionally in error because of Selective Availability. Differential GPS can help here.

Loran -- U. S. Loran masters are to be synchronized within 100 nsec. to UTC, but secondaries may be off by more. Secondaries could be controlled more closely, but that would entail abandoning the SAM method of control.

Regardless of the Loran control method, two ways for the receiver to determine Loran transmitter offsets are

- o Solving for extra unknowns in the hybrid receiver during periods when GPS is self sufficient. This is of limited usefulness because the results will remain valid only over short time periods, whereas GPS outages, when they occur, affect large areas for several hours at a time.

- o Loran Communication link -- the offset from UTC at each Loran transmitter would be determined accurately and encoded into that transmitter's signal using pulse position modulation.

The inclusion of its own offset data within each Loran signal does not require many bits nor extremely fast response, so the signal-to-noise ratio requirements for decoding the data at the receiving end are not high. Inclusion of this information within the navigation signal is analogous to GPS broadcast of its offsets. There is no waste; data is available to the receiver when needed and only when needed. This offset data is helpful also to users of Loran alone, for range-range and/or cross-chain or single station use. The technique allows retention of the benefits of SAM control for marine users, while mitigating the adverse effect of SAM control in areas away from the monitor station for aviation users.

Other GPS/Loran Interactions

In addition to the combined fix algorithm described above there are other ways that GPS and Loran can interact. They are listed below but will not be considered further in this paper.

GPS Possible Aids to Loran:

Cycle selection
Choice among multiple solutions

Determination of transmitter clock offset at the transmitter
Determination of receiver clock offset
ASF determination for improved data bases

Loran Possible Aids to GPS:

GPS Integrity Channel -- use of Loran as a communication link for GPS data. Analysis of signal-to-noise ratios on NAS shows this could increase availability of integrity if used as a supplement to Receiver Autonomous Integrity Monitoring [2, 6].
Operability before the full GPS constellation is in place

3. ASSUMPTIONS FOR COMPUTER STUDIES

Table 2 lists the GPS assumptions for the studies cited in Sections 4 and 5. Table 3 lists Loran assumptions. Some items are marked with an asterisk to note a particular need for further information or research.

For the hybrid studies we assumed that signal Times of Arrival were all known relative to a common clock.

A number of our studies involved surveying the National Air Space or smaller regions under various scenarios of transmitter failures and atmospheric noise. Availabilities obtained under the various scenarios were weighted by the probability of the scenario and added up. For example, given 21 satellites, the probability of the scenario of exactly 1 satellite being out of service is $21 \times .99^{20} \times .01$, or .17176. This was multiplied by the average availability obtained by failing one satellite at a time on a grid over the entire National Air Space. A similar approach was used to obtain a conservative approximation to the profile of failures under different atmospheric noise conditions. The noise levels chosen to outline the profile were the 0th, 90th, 99th, and 99.9th percentiles. At the 100th percentile, we assumed Loran was unusable.

	Megapulse	Ohio Univ.
* Distribution of pseudorange errors (Selective Availability assumed Gaussian, 0 mean, with satellites independent)	St. dev. 30 meters	Accuracy study: st. dev. not applicable. Integrity study: st. dev. 80 meters.
* Mask angle	7.5 degrees	7.5 degrees
* Probability of hard failure in each satellite	.01	.011; simulation shows can omit short outages
Constellation (fixed ground tracks)	Mostly Optimal 21, some Primary 21 (+3)	Optimal 21, Baseline 21
Sampling rate	6 minutes	10 minutes

Table 2 GPS Assumptions

4. ACCURACY AVAILABILITY STUDIES

GPS Alone

Air Force Colonel Green wrote in a recent paper [7] that starting in the mid 1990s, after the 24-satellite constellation is in place, the Air Force will guarantee certain global availabilities. If we allow for Selective Availability errors, the service being guaranteed corresponds roughly to our nonprecision approach sole means requirement of .3 nautical miles 2 drms.

Prior to completion of the 24-satellite constellation, we will have only 21 satellites, with no guarantee.
According to data in the Green paper, both the 24- and the 21-satellite constellations provide the desired service with an availability > .99995 so long as there are no satellite failures. Launches are to be scheduled every 2 or 3 months for replacement of failed satellites. For our studies, we assumed a probability of .01 for individual satellites to be out of service. This is an optimistic value. Using Green's 4 decimal place data for average availability of the desired service level under different failure levels, and weighting it by the

	Megapulse	Ohio Univ.
Transmitter offset from UTC	Standard deviation of unknown portion = 25 nanoseconds	
Distance cutoff	800 nautical miles	800 nautical miles
Signal attenuation	Ground wave, fair soil	Ground wave, mixed path
Additional Secondary Phase Correction (unmodeled part)	Loran alone: add 200 meters to drms of fix. Hybrid: st. dev. = 100 nsec., no correlation among stations	No correlation among stations
* Atmospheric noise	NTIA Report 85-173, year round at three percentile levels, extrapolated for the very high levels	C.C.I.R. Report No. 322, summer 95 percentile level
Signal-to-noise ratio cutoff	-18 dB atmospheric	-10 dB atmospheric
Noise reduction	Hard limiter receiver, 3-sec phase averaging	Kalman filters
Receiver measurement error	St. dev. = 25 nsec.	
Pseudorange error distribution (generally assumed Gaussian, mean = 0)	St. dev. calculated for each Loran station from quantities above, 45 to 80 m. @ 90% noise level.	Accuracy studies: st. dev. approximately = that of GPS signals. Integrity: 80 meters
* Direction of signal arrival	In horizontal plane	In horizontal plane
Transmitter failures and repair (transmitters considered independent)	Probability p of any one transmitter being out of service = .001	MTTF = 1500 hours, MTTR = 35 min. (p = .00039), ignores planned outages
Availability study sample points	Grids with 60 nm. or less spacing, < 1% of NAS.	10 airports

Table 3 Loran Assumptions

probability of that failure level, we get the following upper and lower limits on overall unavailabilities.

For 24 satellites, at best .003 %
For 21 satellites, at worst .049 %

But we need for sole means $.025 \times 10^{-4}$ %
which = .003/1200 %
and = .049/20,000 %

Thus we need to cut unavailability by a factor of at least 1200, and perhaps as much as 20,000, or even more if our satellite failure probability of .01 was too optimistic.

Loran Alone

Calculations at Megapulse approximated the unavailability of Loran over the National Air Space for a receiver using the best combination of 3 or 4 signals regardless of chain. Possible high noise levels were taken into account, as well as possible transmitter failures with a probability of .001 for each transmitter. For the sole means nonprecision approach requirement, the results were as follows:

For Loran on NAS, at worst .48 %

The data brought out the fact that chain-independent Loran is hurt more by high noise than by station failures. This is because at any one place at normal noise levels there are an average of 7 usable stations, of which it is very unlikely that more than two fail. But high noise will affect all of the received signals at once; at our estimated 99.9 percentile noise level, on average only 3 stations remain above the -18 db atmospheric signal-to-noise ratio cutoff. Thus to make better estimates of availability it is important to obtain better knowledge of high noise behavior in the Loran bandwidth. How high does it really get? Is it a matter of bursts of a few seconds, not affecting receiver tracking? Or obvious thunderstorms that a pilot might avoid in any case? Is noise worse at night when fewer aircraft would be affected?

Hybrid GPS and Loran

Our most optimistic estimate above for GPS required a 1200-fold reduction of unavailability to meet the sole means specification. Since Loran failures are independent of GPS failures, Loran with its unavailability of less than about 1/200 might bring us down to within a factor of 6 of the goal without even combining receivers. The cases remaining are situations where the pilot wishes to make his approach at a time and place where say 2 of the satellites he needs are out of service; in addition there is severe static so there are only 2 Loran stations he can track. Can the hybrid fix algorithm save the day in 5 out of 6 cases?

Unfortunately, the amount of computer time required for a complete survey exceeded the time available. With our current software on the VAX it could easily take 2 years of night and weekend runs. It is necessary at each location on a grid to consider a representative set of orbital configurations, all combinations of 44 transmitter failures up to 3 or 4 at a time, all at several different Loran noise levels. The grid needs to be finer than for GPS alone, first because Loran geometry can change more rapidly, and second, because we are looking now for very rare occurrences.

Instead of checking all of the National Air Space, at Megapulse we covered 8 selected areas at selected times to see what improvement the addition of Loran might bring. The constellation was the interim one, Optimal 21 with fixed ground tracks, no spares. Figures 2 and 3 show results in the Idaho area and in the Chicago area, each covering 1 hour out of the day. Nonprecision approach here means that seasonal Loran ASF corrections are available to the receiver. The horizontal axis is for different 2 drms accuracy requirements; the .3 nautical mile sole means level is 560 meters. The vertical axis gives per cent unavailability, on a logarithmic scale. Notice the 3 decade improvement over GPS when the hybrid fix is used.

The Idaho sample has worse than average GPS unavailability "G". The Loran plot "L" shows good coverage there, but with the lower bound of .05% due to our assumption that Loran is not usable above the 99.95 percentile atmospheric noise level. For the same reason, Loran cannot reduce the GPS unavailability by more than a factor of 2000. If, however, we recalculate using the more optimistic assumption that the noise never gets worse than the 99.9 percentile level, we obtain another decade of improvement, shown in the "N" curve.

In the Chicago sample, we see better, more typical GPS coverage, but worse Loran coverage than in Idaho (due to fewer stations and higher noise). The "B" and "H" curves show the difference between side-by-side receivers and a hybrid receiver and in fact, the improvement is close to the desired factor of 6 mentioned at the beginning of this section. Also notice that even though Loran is less good here, the "H" curve still has the full factor of 2000 improvement over GPS alone. The "N" curve actually meets the sole means requirement.

Our impression is that with the promised 24-satellite constellation, the hybrid system can meet at least the accuracy portion of the sole means requirement. But it must be reiterated that the calculated results are very sensitive to atmospheric noise assumptions.

The above plots were done at Megapulse. At Ohio University ten cities were investigated in detail using somewhat different assumptions (see Tables 2 and 3),

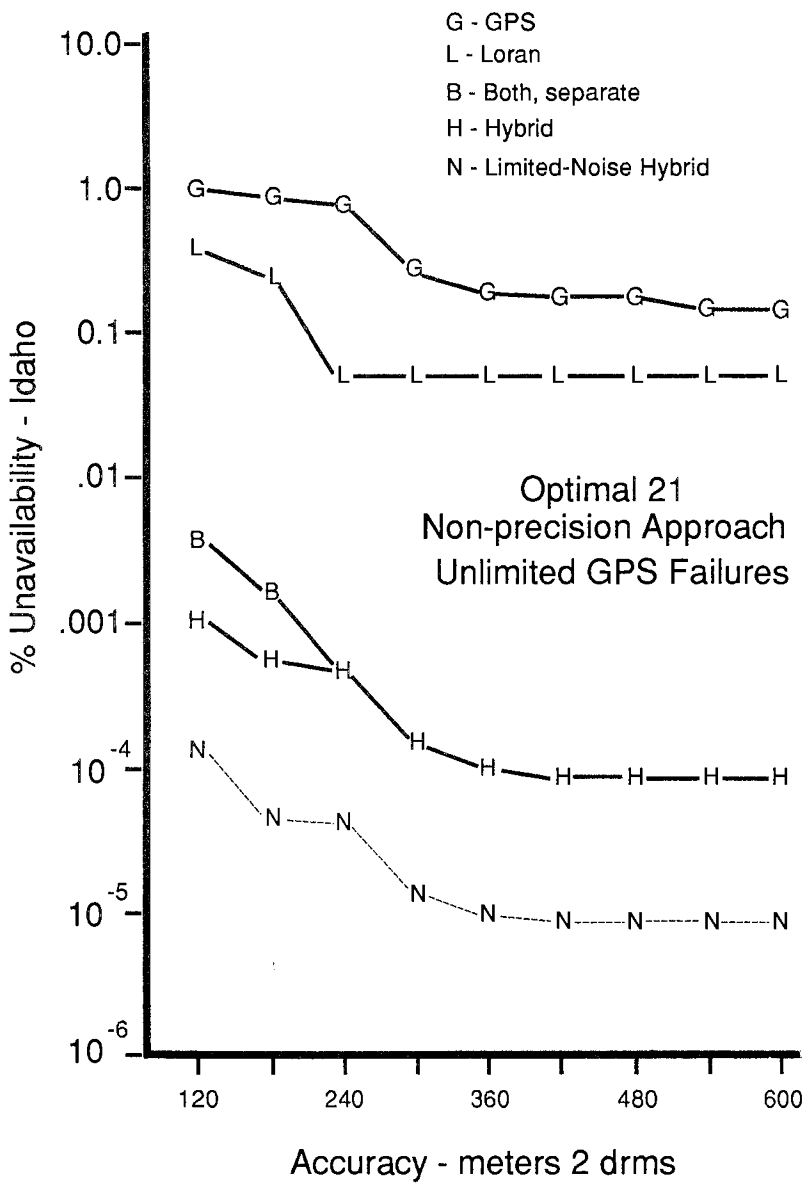

Figure 2. POSITIONING, Idaho

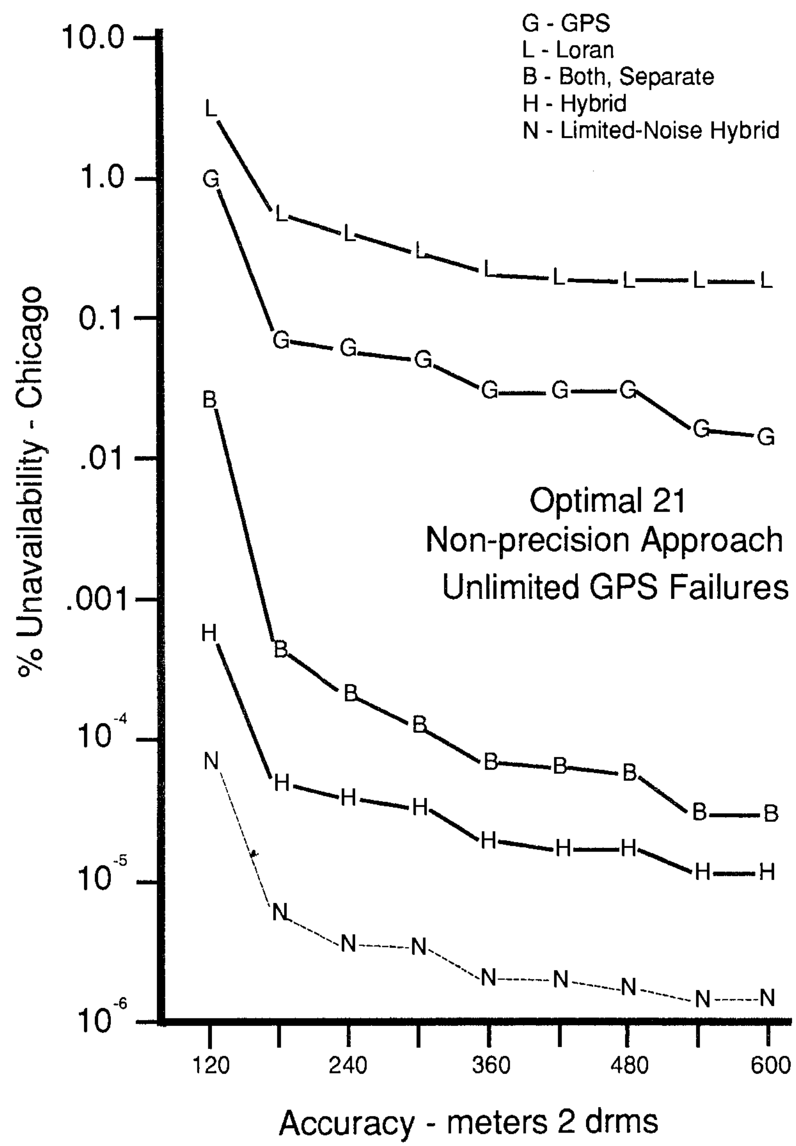

Figure 3. POSITIONING, Chicago

and were found to have an average unavailability of .000035% for a higher 2 drms level of approximately 1000 meters. This result appears to be quite consistent with the Megapulse values.

5. INTEGRITY STUDIES

The Integrity Problem

Figure 4 is a pie chart of position fixing capability at some time and place. Based on the statistical distributions of errors, etc., there are certain probabilities of obtaining a good fix, a poor fix, or no fix. An alarm can certainly be sounded when no fix is available. It is desirable to alarm poor fixes as well. But whatever test is applied, there are apt to be some poor fixes that slip through. These are called "misses" and are dangerous. Also, some good fixes will be eliminated by mistake. These are "false alarms". They are not so dangerous as misses, but they make the system unusable. If the integrity test is made more stringent so as to reduce the miss rate, then the alarm rate rises. In fact any desired low MISS rate can be achieved, by sounding the alarm all the time, and contrariwise any desired low ALARM rate can be achieved by simply never sounding the alarm.

Thus an integrity requirement is trivial unless it specifies maximums for BOTH rates -- miss rate and alarm rate.

"Poor fix" must also be defined. In the GPS system, it has been defined as a position estimate whose error has been outside the "protection limit" for more than a certain elapsed time. The RTCA SC-159 Integrity Working Group has proposed protection limits meeting current requirements in various federal documents for different phases of flight. It has also proposed stringent goals for the future, in particular a 100 meter protection limit for nonprecision approach [3].

However, maximum alarm rates and miss rates have not been specified. Therefore it is not clear exactly what is required. For example, if the protection limit were 600 meters, and the 2 drms accuracy requirement were also 600 meters, one might expect a 2 to 5% alarm rate at least at some points, without even counting false alarms or abnormal situations.

A very high availability of integrity, like accuracy, means that almost every point and time on the coverage grid meets standards. In the cases of both GPS and Loran, system capabilities vary considerably over time and space. Therefore, if practically every point must meet a certain standard, one can be sure that the over all system average performance will be much better. Perhaps even a 10% alarm limit for individual points could result in a tolerable system over all.

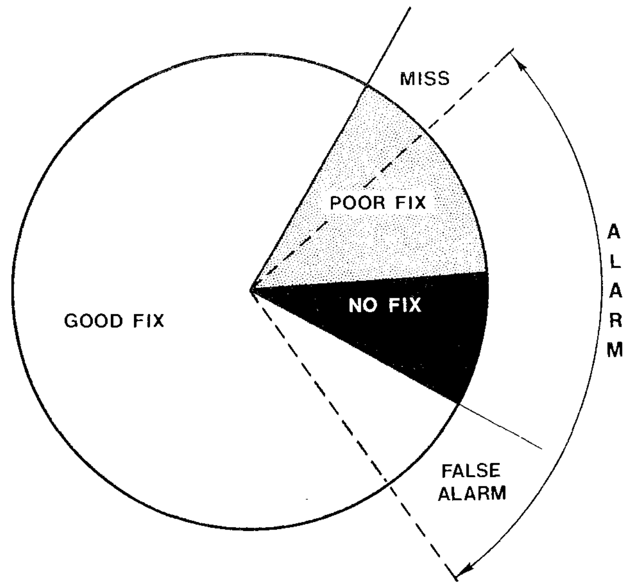

Figure 4. Integrity Pie Chart

Notice that integrity and accuracy requirements overlap in a somewhat confusing way. It would be helpful to combine these and other requirements into one comprehensive and consistent specification.

Some of the ways the GPS and Loran systems perform self-checking were listed in Table 1. The most difficult type of error is a gradual drift in pseudorange error. Health messages broadcast by the satellites normally require an hour or more to be brought up to date. In the meantime, all aircraft in the area are potentially affected. It is best if each receiver can quickly detect errors without outside help.

The two receiver-based error detection techniques most discussed and tested in GPS literature are maximum separation and residuals. Part of the problem in calculating the miss rates and alarm rates that would be produced by these techniques is that the distribution of the DoD intentional Selective Availability errors is not known. There is a strong temptation to use Gaussian statistics and simulations and to assume things like 0 means and independence among the satellites. Another unknown is the probability of soft failures which may result in abnormal error distributions.

Both the maximum separation and the residuals approach provide for fault isolation as well as fault detection, if sufficient redundancy is present. In this situation, omitting one of the signals produces a sub fix which passes the integrity test. Thus the alarm rate can be reduced.

Going back to the pie chart, adding all the Loran signals should help in two ways. The probability of a good fix is increased, and, with more redundancy, the ability to distinguish good fixes from the remaining poor fixes is enhanced. There will be fewer alarms and fewer misses.

The following two sections report on our look at maximum separation and residuals in the hybrid system.

Hybrid Maximum Separation Test

The maximum separation technique is based on the idea that if all the measurements going into a least square fix are consistent, then removal of any one of them will not cause a major change in the position estimate. But if the measurements are inconsistent, the solution will be under stress so to speak, and removal of a measurement, perhaps one in particular, will cause a shift in the position estimate. Therefore measurements are removed one at a time and the maximum distance between sub fixes becomes the test criterion.

It has been estimated for the GPS system alone that an alarm rate under .3% can be obtained if the maximum 2 drms error among the sub fixes is less than .6 times the protection limit. (I.e. the maximum horizontal dilution of position is less than the protection limit in meters divided by 100 [8].) It is not known whether this rule of thumb is appropriate for the hybrid system with its larger number of measurements and different geometry. Nevertheless the Megapulse software calculated at each point on its grids whether or not this standard was met for different protection levels. Figure 5 is a plot of the results, comparing GPS alone with Loran in selected areas. An impressive 1000-fold improvement is shown.

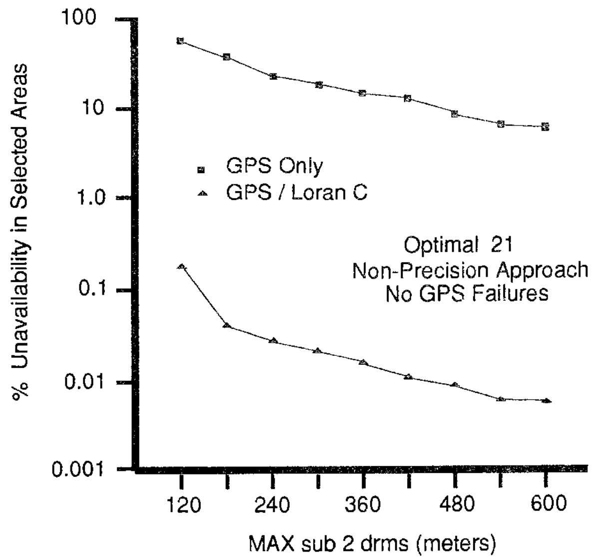

Figure 5. FAULT DETECTION, Selected Areas

Hybrid Residuals Test

The use of residuals as an integrity check was mentioned in Section 2. The square root of the sum of the squares of the residuals, weighted if desired, can serve as the integrity parameter. This is a classic approach; under Gaussian conditions the sum of squares, properly scaled, has a chi-square distribution and various confidence levels can be assigned to the fix results.

At Ohio University, Gaussian computer simulations were made first to determine the behavior of the integrity parameter under ordinary conditions. Eight or more signals were involved in each fix, and random noise with a standard deviation of 80 meters was applied to all the pseudoranges. Under these conditions, the 2 drms fix error was only 101.4 meters. Figure 6 shows the corresponding distribution of the integrity parameter. There were no occurrences above 523 meters.

Next, to simulate pathological conditions, a large error, 1000 meters, was added to one pseudorange measurement at a time, and the fix errors and integrity parameter were observed again. See Figure 7. This time the position error was of course larger, but never exceeded 253 meters. The integrity parameter minimum value was 649, well separated from its previous maximum of 523.

Thus even with the large underlying standard deviations of 80 meters, the integrity parameter can detect the presence of a slowly deviating sick signal before it affects the fix very much.

An advantage of the residuals method is that it does not require the evaluation of sub-fixes unless a fault is detected, and furthermore fault isolation can be accomplished without the sub-sub-fixes required by the maximum separation method.

6. CONCLUSION

It is clear that GPS and Loran make a good pair. Although it was necessary to make many assumptions and estimates in our hybrid simulations and calculations, the results show such dramatic improvements over GPS alone, there can be little doubt that the combined system should be implemented. The excellent results are not surprising in view of the "dissimilar redundancy" in the two systems. With GPS in its 24-satellite "Primary 21"

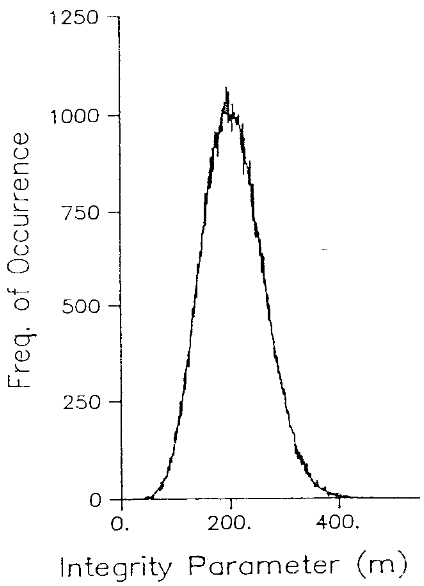

Figure 6. Distribution of Hybrid Residual Integrity Parameter Given an 80 m Pseudorange Sigma.

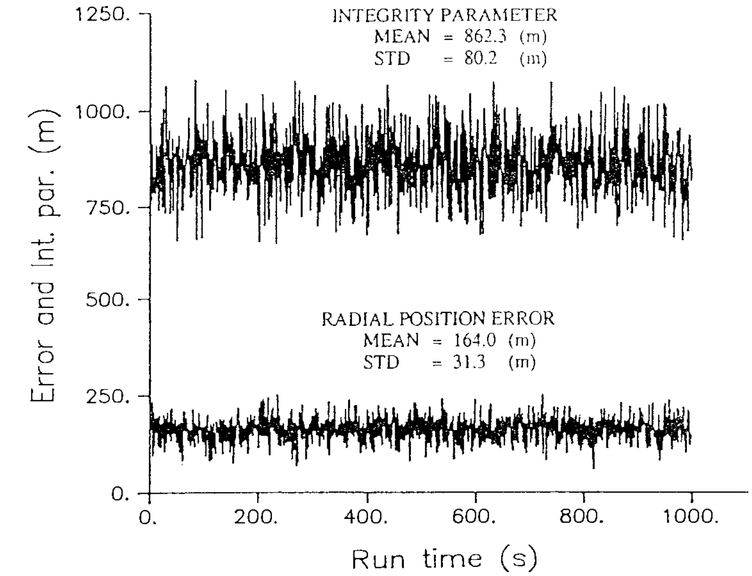

Figure 7. Hybrid Residual Integrity Parameter and Position Error, with an 80 m Pseudorange Sigma and One GPS Pseudorange Biased by 1000 m.

constellation, the Loran/GPS hybrid can probably meet aviation sole means accuracy requirements and possibly integrity requirements as well.

As more GPS experience is gained over the next months and years, information about Selective Availability errors and about GPS hard and soft failure rates will become known and will make possible more accurate determinations of the overall availability of the hybrid system. Also needed is more data on atmospheric noise, which appears to be the limiting influence on Loran availability.

A more complete specification of aviation sole means integrity requirements is needed, along with a practical way of verifying whether the requirements are met.

There are many potential benefits in a hybrid system, and they are obtainable at relatively low cost and with minimal disruption to the either system and its users.

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FLIGHT-TEST RESULTS FOR A PROTOTYPE HYBRID GPS/LORAN RECEIVER

Frank van Graas, James D. Waid, and Paul A. Kline

Avionics Engineering Center
Department of Electrical and Computer Engineering
Ohio University
Athens, Ohio

ABSTRACT

Earth-referenced navigation based on the NAVSTAR Global Positioning System (GPS) and the Long Range Navigation System, LORAN-C, has the potential to satisfy the requirements for a sole means of radionavigation for the conterminous United States. This paper presents the design considerations and architecture of a prototype hybrid GPS/LORAN receiver. The receiver is installed in a research aircraft to evaluate the in-flight performance of hybrid GPS/LORAN. The flight-test data is referenced to a Differential GPS truth trajectory. Initial test results demonstrate hybrid GPS/LORAN accuracies consistent with current requirements for en route and terminal navigation, and non-precision approaches.

BACKGROUND

Air navigation in controlled airspace within the National Airspace System (NAS) requires a sole means of navigation [Federal Regulations, 1987]. Current civil sole means of navigation for the conterminous United States (CONUS) are based on the Very High Frequency Omnidirectional Range (VOR) system and Distance Measuring Equipment (DME). Navigation systems that do not qualify for sole means but may be used in combination with a sole means of navigation are supplemental systems. Examples of supplemental systems are Omega, Non-Directional Beacons (NDB), and the Long Range Navigation system, LORAN-C.

The NAVSTAR Global Positioning System (GPS) is a radionavigation system currently under development by the Department of Defense (DoD). When GPS becomes operational in the early 1990's, it will only be certified as a supplemental navigation system [FRP, 1986]. GPS lacks a sufficient level of integrity, and the planned 21-satellite constellation will only provide an availability of 98% for an operational constellation of eighteen satellites. Several techniques have been proposed that improve the GPS performance in the areas of availability and integrity with the intent to meet sole-means requirements [A. Brown, 1988]. For the CONUS, the combination of GPS and LORAN-C has been identified as a promising approach to fulfill the integrity and availability requirements. In addition, hybrid GPS/LORAN is anticipated to meet all requirements for a sole means of navigation for the CONUS and could lead to a new generation of air radionavigation systems [Vicksell, 1989]. This paper is addresses the GPS/LORAN navigation solution and the in-flight performance of the hybrid system.

Early in-flight comparison of GPS and LORAN-C positioning data indicated 2-dimensional differences of up to 300 meters for data collected during June of 1986, across southern and central Ohio [Van Graas, 1988a]. Most of the navigation error was found to be inherent to the LORAN-C part of the system. Since then, a prototype hybrid GPS/LORAN receiver test bed has been under development at Ohio University. The next four sections describe the architecture of the hybrid GPS/LORAN receiver and the navigation solution. Next, the differential GPS truth reference system is presented, followed by flight test results for the hybrid receiver.

PROTOTYPE HYBRID GPS/LORAN RECEIVER ARCHITECTURE

A hybrid GPS/LORAN receiver architecture has a substantially better performance than the sum of the two separate systems. In addition, less hardware is required, as the frequency reference source, the receiver processor, the navigation calculations, and the user interface are shared by the GPS and the LORAN-C sensors. Some of the practical advantages of a hybrid receiver architecture include increased system availability, extended coverage, and greatly enhanced signal failure detection and isolation capabilities [Vicksell, 1989]. It is also desirable for the hybrid receiver hardware to be structured in a generic way to allow for addition of other sensor inputs, for example those obtained from an altimeter, DME, Omega, or other satellite navigation systems. Figure 1 shows the functional block diagram of a generic, hybrid navigation receiver [Van Graas, 1988b].

HYBRID GPS/LORAN NAVIGATION SOLUTION

Several schemes can be implemented to combine the navigation data from LORAN-C and GPS. This paper presents a navigation solution which is based on generic pseudorange processing that emphasizes effective, modular, and transparent rather than

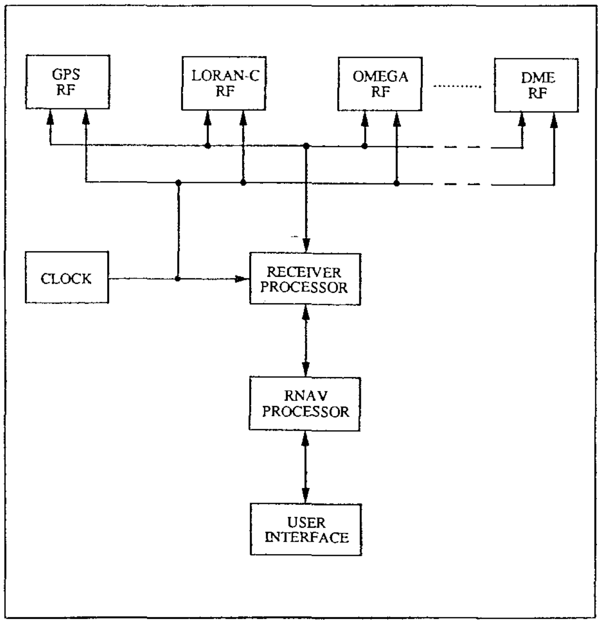

Figure 1. Functional block diagram of a generic, hybrid navigation receiver.

optimal processing. Based on the equations and results provided in this paper, a less complete solution could be developed which emphasizes computational speed instead of accuracy.

Pseudorange measurements are in common to both GPS and LORAN-C. Although LORAN-C is normally operated in the hyperbolic mode, the range mode of operation will make LORAN-C a better system. This will especially be true when all LORAN-C master transmitters are synchronized. Other advantages of LORAN-C ranging are the additional clock phase offset and drift information and the option to use single transmitters instead of pairs. Knowledge about the receiver clock phase offset and drift can be used to aid the tracking of the navigation signals and also allow the receiver to coast for several minutes on the receiver clock as a replacement for one of the measurements.

Noise on the pseudorange measurements can be effectively reduced by range domain filtering techniques [Paielli, 1987]. Although process noise cross-correlation terms are discarded in the range filters, it was shown for stand-alone GPS that the overall system performance is essentially that of navigation domain filters. Similar results may be expected for a solution based on both GPS and LORAN-C pseudorange measurements. It should be noted that under conditions of poor GPS/LORAN geometry, other processing techniques such as Ridge Regression should be considered as described by [Kelly, 1989].

Integrity is an essential part of the navigation solution. Integrity can be obtained from an external source, or through utilization of redundant measurements from GPS and LORAN-C. Receiver autonomous integrity monitoring (RAIM) techniques are currently being considered for GPS receivers [R.G. Brown, 1989]. The GPS RAIM techniques can be directly applied to the hybrid GPS/LORAN receiver.

HYBRID GPS/LORAN MEASUREMENT EQUATIONS AND ERROR MODELS

Pseudorange measurements to GPS satellites are made by taking the difference between the measured time of signal arrival and the corresponding known time of signal transmission, corrected for known and estimated error sources. The equation for the measured pseudorange is given by [Van Graas, 1988b]:

$$P_i(t) = | S_i(t-\beta_i(t)) - U(t) | + c\,(T_{GPS}(t) - T_{Si}(t) + d_{GPSi}(t,r)) \quad (1)$$

where:
- S_i is the position vector for satellite i (m).
- β_i is the line-of-sight travel time for signals from satellite i (s).
- U is the user position vector (m).
- c is the GPS speed of light (299792458 m/s).
- T_{GPS} is the user clock offset from GPS time (s).
- T_{Si} is the clock offset for satellite i from GPS time (s).
- d_{GPSi} is the delay for measurement i caused by GPS error sources (s).

Satellite positions and satellite clock offsets from GPS time are calculated from the navigation data transmitted by the satellites [ICD, 1984]. Positions are expressed in the ECEF coordinate system at the time of signal reception. Therefore, the satellite positions are corrected for the rotation of the earth during the signal travel time (β).

Tropospheric propagation delays are modeled using the following equation [Greenspan, et al., 1986]:

$$d_{tropo} = \frac{2.4224}{0.026 + \sin(E)}\, e^{-0.13345\,h} \quad (m) \quad (2)$$

where:
- E is the satellite elevation angle (rad).
- h is the altitude of the receiver (km).

The model for the ionospheric propagation delays is based on parameters transmitted by the satellites and is given in reference [ICD, 1984].

Within the coverage area, LORAN-C ground waves travel great-circle distances. A receiver at sea-level will interpret the signals as if they came from transmitters located in the locally level plane at distances equal to great-circle distances to the transmitters. Adding measurement errors and a possible LORAN-C transmitter clock offset with respect to LORAN-C system time, the LORAN-C pseudorange measurement equation is given by:

$$P_i(t) = | L_i'(t) - U(t) | + \\ + c\,(T_{LC}(t) - T_{Li}(t) + d_{LCi}(t,r)) \quad (3)$$

where: L_i' is the position vector of LORAN-C transmitter i corrected for earth curvature (m).
U is the user position vector (m).
c is the speed of light in vacuum (m/s).
T_{LC} is the user clock offset from LORAN-C time (s).
T_{Li} is the clock offset for transmitter i from LORAN-C time (s).
d_{LCi} is the delay for measurement i caused by LORAN-C error sources (s). The delay is both a function of time and receiver location.

LORAN-C transmitter locations are known. Transmitter synchronization is currently established for each chain only. Synchronization of all master stations to within 100 nanoseconds with respect to Universal Time, Coordinated (UTC) will remove a large part of the LORAN-C timing uncertainty. Propagation models for LORAN-C are more complicated than those for GPS. For this study, the LORAN-C errors are assumed to be calibrated using a known location. The navigation results are then evaluated using the expected modeling accuracies. The following recommendations are made with respect to the LORAN-C propagation models for the hybrid GPS/LORAN receiver.

- Geophysical variations should be calibrated as a function of location. Remote areas would only require a few calibration points. In the vicinity of airports, a denser calibration grid is recommended to reduce interpolation errors.

- Meteorological variations should be modeled as a function of surface impedance, distance to the transmitter, user altitude, and the vertical lapse factor for the index of refraction of air at the surface [Campbell, et al., 1979]. Some of these parameters could be determined by long-term monitoring of the LORAN-C signals [Comparato, et al., 1988].

HYBRID GPS/LORAN NAVIGATION EQUATIONS

The pseudorange equations for GPS and LORAN-C given by equations (1) and (3) can be rewritten as follows:

$$P_i' = ((X_i-X)^2 + (Y_i-Y)^2 + (Z_i-Z)^2)^{1/2} + b \quad (4)$$

where: P_i' is pseudorange measurement i, corrected for known and estimated error sources (m).
X_i,Y_i,Z_i are the coordinates of the ith GPS satellite or LORAN-C transmitter, corrected for earth curvature (m).
X,Y,Z are the user coordinates (m).
b is the receiver clock offset with respect to UTC (m).

This equation is non-linear, therefore a variation of Newton's method for nonlinear systems has been developed to solve for the three-dimensional user coordinates and clock offset. Newton's method is generally expected to give quadratic convergence, especially if the estimate is close to the solution.

Define a user state vector $\mathbf{x}$ containing the user position coordinates and clock offset, and a measurement vector $\mathbf{z}$, containing the corrected pseudorange measurements:

$$\mathbf{x} = \begin{bmatrix} X \\ Y \\ Z \\ b \end{bmatrix} \qquad \mathbf{z} = \begin{bmatrix} P_1' \\ P_2' \\ \vdots \\ P_n' \end{bmatrix} \quad (5)$$

Next, the pseudorange equations are linearized using the partial derivative, or Jacobian, matrix $\mathbf{H}$ which relates a change in the user state vector $\mathbf{x}$ to a change in the measurement vector $\mathbf{z}$.

$$\partial \mathbf{z} = \mathbf{H}\,\partial \mathbf{x} \quad (6)$$

where each row of the H-matrix is given by:

$$\begin{bmatrix} \frac{\partial P_i'}{\partial X} & \frac{\partial P_i'}{\partial Y} & \frac{\partial P_i'}{\partial Z} & \frac{\partial P_i'}{\partial b} \end{bmatrix} \quad (7)$$

where: $$\frac{\partial P_i'}{\partial X} = \frac{X-X_i}{P_i'-b} \qquad \frac{\partial P_i'}{\partial Y} = \frac{Y-Y_i}{P_i'-b}$$
$$\frac{\partial P_i'}{\partial Z} = \frac{Z-Z_i}{P_i'-b} \qquad \frac{\partial P_i'}{\partial b} = 1 \quad (8)$$

Equation (6) can be rewritten to obtain the Least Mean Squares solution:

$$\partial \mathbf{x} = (\mathbf{H}^T\mathbf{H})^{-1}\,\mathbf{H}^T\,\partial \mathbf{z} \quad (9)$$

If a positive definite weighting matrix $\mathbf{W}$ is added to the pseudorange processing, equation (9) can be written as:

$$\partial \mathbf{x} = (\mathbf{H}^T\,\mathbf{W}\,\mathbf{H})^{-1}\,\mathbf{H}^T\,\mathbf{W}\,\partial \mathbf{z} \quad (10)$$

The navigation solution algorithm contains two iteration loops. One iteration loop is used to update the LORAN-C transmitter and GPS satellite coordinates in the locally level plane with respect to the user estimate. The second iteration loop is used to update the user state vector in the locally level plane based on the difference between predicted and actual pseudorange measurements. The algorithm proceeds as follows:

1. Obtain the user state estimate $\tilde{\mathbf{x}}$ and the pseudorange measurement vector $\mathbf{z}$.

2. Convert the LORAN-C transmitter coordinates to the locally level plane (East-North-Up coordinates) with $\tilde{\mathbf{x}}$ as the origin.

3. Convert the GPS satellite ECEF-coordinates to the ENU-coordinates with $\tilde{x}$ as the origin.

4. Calculate the estimated pseudorange vector $\tilde{z}$ using $\tilde{x}$, GPS satellite positions, and LORAN-C transmitter positions.

5. Calculate the partial derivative matrix **H**, the rows of **H** are obtained from equations (7) and (8).

6. Calculate the user state update as follows:

$$\partial x = (H^T H)^{-1} H^T (z - \tilde{z}) \tag{11}$$

7. Update the user state with δx:

$$\tilde{x} = \tilde{x} + \partial x \tag{12}$$

8. If the update is too large ($|\partial x| > \epsilon$), go to step 4.

9. Use the new user state estimate $\tilde{x}$ in the locally level plane (ENU) to update the user position in latitude, longitude, and height.

10. If the update is too large ($|\tilde{x}_{ENU}| > \mu$), go to step 2.

11. Repeat steps one through ten for the next set of measurements.

The second step of the algorithm is relatively straightforward for a receiver at sea-level. The azimuth (Φ) between user and transmitter along with the great-circle distance (s) are calculated based on the modified Rainsford's Method with Helmert's Elliptical Terms as given by [RTCA, 1982]. The transmitter coordinates in the locally level plane are then given by:

$$\begin{aligned} X\ (\text{east}) &= s * \sin(\Phi) \\ Y\ (\text{north}) &= s * \cos(\Phi) \\ Z\ (\text{up}) &= 0 \end{aligned} \tag{13}$$

The signal propagation for a receiver at altitude is not any longer described by a pure groundwave. For instance, an aircraft flying directly above a LORAN-C transmitter would receive a direct wave. It is shown by [Field, et al., 1981] that for receiver altitudes of less than ten times the distance to the transmitter, the phase error for a receiver at 1.3 km is about 30 meters. Models can be applied to limit the phase error to 30 meters for all altitudes.

The third step of the algorithm consists of a coordinate transformation given by:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{ENU} = \begin{bmatrix} -\sin\phi & \cos\phi & 0 \\ -\sin\theta\cos\phi & -\sin\theta\sin\phi & \cos\theta \\ \cos\theta\cos\phi & \cos\theta\sin\phi & \sin\theta \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{ECEF} \tag{14}$$

where: ENU is the locally level coordinate system (East, North, Up) (m).
ECEF is the earth-centered-earth-fixed coordinate system (m).
ϕ is the latitude of the receiver location (rad).
θ is the longitude of the receiver location (rad).

The elements of the estimated pseudorange vector $\tilde{z}$, in step 4, are calculated as the sum of the estimated clock offset and the distance between the estimated user position and satellites or transmitters. Finally, the user state update in latitude and longitude (step 9) is approximated by:

$$\begin{aligned} lat_{new} &= lat_{old} + Y_{ENU}(\text{north})*C \\ lon_{new} &= lon_{old} + X_{ENU}(\text{east})*C*\cos(lat_{new}) \end{aligned} \tag{15}$$

where: C is the conversion factor from meters to degrees in latitude (1/(1852*60)).

Altitude can be updated directly:

$$alt_{new} = alt_{old} + Z_{ENU}(\text{up}) \tag{16}$$

The clock estimate is replaced (not updated), since a coordinate transformation does not change the time-axis:

$$bias_{new} = bias_{ENU} \tag{17}$$

If the clock offset between GPS and LORAN-C is not known, the user state vector, equation (5), is replaced by:

$$x = \begin{bmatrix} X \\ Y \\ Z \\ b_{GPS} \\ b_{LC} \end{bmatrix} \qquad z = \begin{bmatrix} P_1' \\ P_2' \\ \vdots \\ P_n' \end{bmatrix} \tag{18}$$

equations (6) and (7) are replaced by:

$$\partial z = H\, \partial x \tag{19}$$

where each row of the H-matrix is given by:

$$\begin{bmatrix} \frac{\partial P_i'}{\partial X} & \frac{\partial P_i'}{\partial Y} & \frac{\partial P_i'}{\partial Z} & \frac{\partial P_i'}{\partial b_{GPS}} & \frac{\partial P_i'}{\partial b_{LC}} \end{bmatrix} \tag{20}$$

where: $\frac{\partial P_i'}{\partial b_{GPS}} = $ 0, for LORAN-C pseudoranges; 1, for GPS pseudoranges

$\frac{\partial P_i'}{\partial b_{LC}} = $ 1, for LORAN-C pseudoranges; 0, for GPS pseudoranges

The hybrid navigation solution has been exposed to extensive computer simulations to confirm the accuracy and the convergence properties of the navigation solution. The user position was found to be within the bounds of the desired accuracy as specified in step (10) of the positioning algorithm. Convergence was found for distances of up to 2000 kilometers between the user estimate and the true user position [Van Graas, 1988b].

DIFFERENTIAL GPS TRUTH REFERENCE SYSTEM

To establish a reference trajectory for a dynamic hybrid GPS/LORAN receiver test, a Differential GPS (DGPS) system has been developed. The DGPS approach is based on a GPS receiver at a known location. This receiver compares the measured GPS ranges to the actual ranges calculated from the known receiver and satellite positions. The differences, or differential corrections, are then transmitted to suitably equipped users to allow them to improve their own solutions to an accuracy of better than 10 meters (2 drms) [Edwards, et al., 1988]. This level of accuracy qualifies DGPS very well for a truth reference system for the evaluation of navigation results where the highest accuracy requirement is 100 m (2 drms).

Ideally, the differential correction contains only those error sources that are both unobservable to the user and common to the user and the reference station. Fortunately, the majority of GPS errors meet this requirement. Furthermore, biases that are common to all measurements do not affect the navigation solution as they appear as a clock bias in the solution for the clock offset.

The differential correction is obtained by taking the difference between the measured pseudorange and the calculated pseudorange corrected for known error sources such as space vehicle clock offset. The resulting correction can be written as follows:

$$\Delta P_r = d_{tropo} + d_{iono} + URE + \delta_{bias} + \delta_{noise} \quad (21)$$

where: d_{tropo} is the tropospheric propagation delay (m).
d_{iono} is the ionospheric propagation delay (m).
URE is the user-equivalent ranging error due to satellite ephemeris and clock errors (m).
δ_{bias} are biases caused by receiver measurement circuitry, antenna location uncertainty, and biases that are common to all measurements (clock and hardware) (m).
δ_{noise} is receiver measurement noise, clock noise, and multipath noise (m).

The biases that are different for all measurements are relatively small, generally less than one meter. Noise can most effectively be reduced by taking multiple measurements, through carrier phase tracking, and by filtering. The combination of tropospheric, ionospheric, and URE is typically around 20-40 meters, and is a function of location. The URE is not much affected by the separation distance between the user and the reference station. Ionospheric and tropospheric delays do decorrelate with increasing separation distances. Horizontal decorrelation is generally less than 0.2 meter over distances up to 100 km [Sharma, 1987]. Vertical decorrelation does not affect the ionospheric delays (up to ionospheric altitudes), but greatly affects the tropospheric delay. Most of the tropospheric vertical decorrelation can be corrected using a relatively simple model as given by equation (2). Reference [Van Graas, 1988b] describes the DGPS used for this study in detail.

GPS/LORAN FLIGHT EXPERIMENT

The GPS/LORAN flight experiment is designed to evaluate the hybrid GPS/LORAN navigation solution with actual measurement data. Figure 2 provides an overview of the airborne and ground equipment for the dynamic experiment. GPS and LORAN-C data are collected during the flight and stored on magnetic devices for off-line analysis in combination with simultaneously collected GPS data on the ground. The airborne GPS receiver serves both as part of the hybrid GPS/LORAN system and as the airborne Differential GPS component. All software implemented on the microcomputers requires a minimum of operator interaction.

The GPS/LORAN equipment is installed in a Piper Saratoga PA-32-301, N8238C, which is owned by Ohio University. The N8238C is a 1980 model aircraft with a fixed landing-gear, and a useful load capacity of 1,537 pounds. The aircraft is equipped as a flying laboratory.

An overview of the data processing for the hybrid GPS/LORAN receiver is presented in Figure 3. The GPS/LORAN navigation solution is compared to the truth trajectory generated by the Differential GPS system. Pseudorange data from the LORAN-C receiver are filtered by a two-variable Kalman filter and corrected for propagation delays. For this study, the LORAN-C propagation delays are modeled by a first order approximation as a function of the distance to the transmitter. Initial values for these delays are determined using validated LORAN-C positions from the beginning of the data collection. GPS pseudoranges are also filtered by a two-variable Kalman filter. Ionospheric and tropospheric propagation corrections are applied before the pseudoranges are entered into the navigation solution. Satellite positions and clock offsets are calculated from the satellite navigation data. The hybrid navigation solution solves for three-dimensional position, clock offset from GPS time, and clock offset from LORAN-C time, see equations (19) and (20).

Filtered GPS pseudoranges are also corrected for the tropospheric delay difference between the ground reference receiver and the airplane. The resulting pseudoranges are then corrected for remaining error sources by the filtered differential corrections from the reference GPS receiver. Ideally, the corrected pseudoranges only contain errors on the order of less than one meter. After conversion into the position domain, a reference trajectory is established for the flight test.

The two-dimensional navigation error of the hybrid GPS/LORAN receiver is then determined by taking the difference between the hybrid position and the DGPS position.

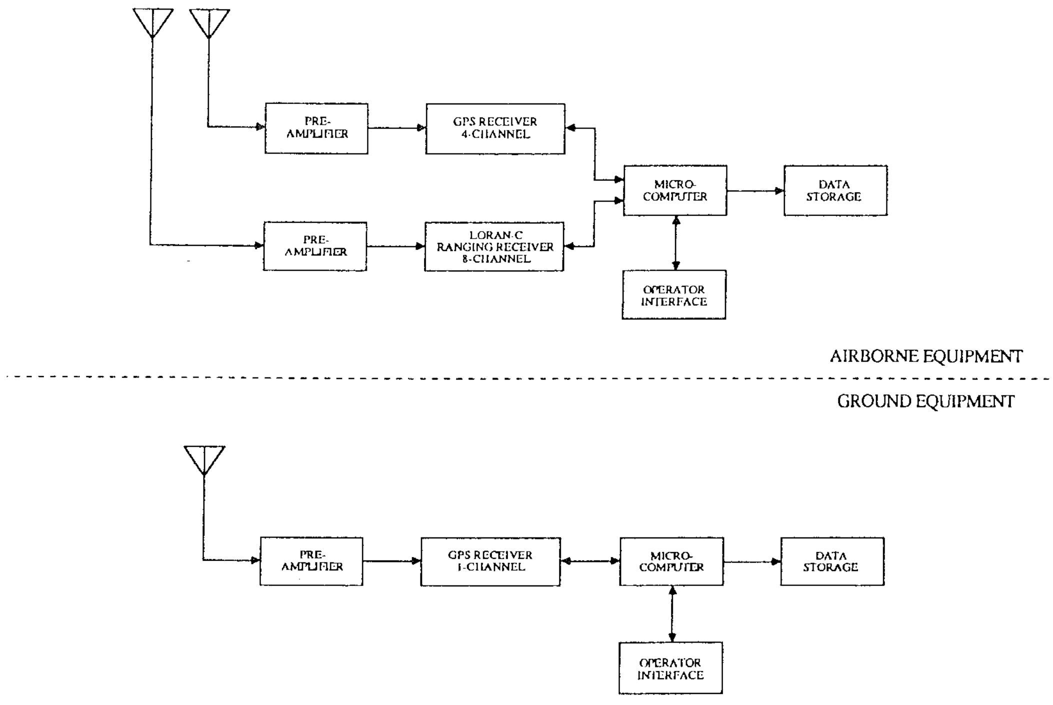

Figure 2. Overview of the hybrid GPS/LORAN flight experiment equipment with a Differential GPS truth reference system

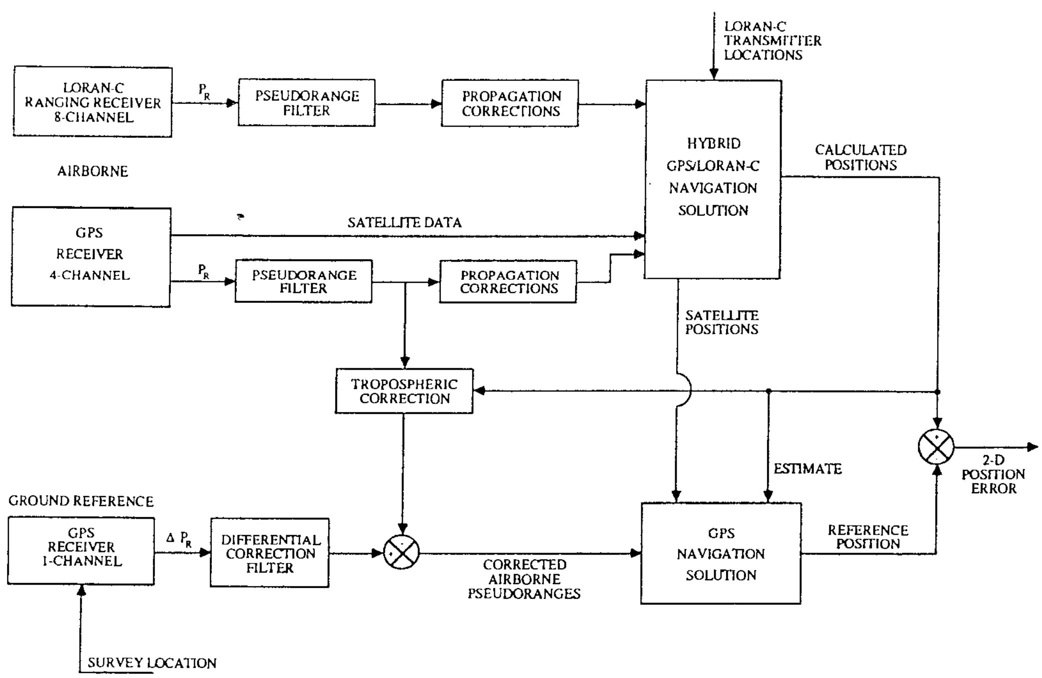

Figure 3. Hybrid GPS/LORAN data processing with a Differential GPS truth reference system.

DYNAMIC TEST RESULTS

The hybrid GPS/LORAN system was flown on September 16, 1988 for a period of 70 minutes in the vicinity of the Ohio University Airport (Albany, Ohio). At the same time, GPS data were also collected by the ground reference system to establish a reference trajectory. Six GPS satellites were used, SV3, SV6, SV9, SV11, SV12, and SV13, in combination with three LORAN-C transmitters from the Northeast U.S. Chain, Dana, Nantucket, and Carolina Beach.

Figure 4 shows the ground track based on the Differential GPS reference trajectory. The Differential GPS station is located at Ohio University. Two relatively large discontinuities in the reference trajectory are caused by the exchange of flexible disks and by a system restart. The system was restarted to evaluate the re-acquisition of the navigation signals during operational conditions. A few smaller discontinuities are the result of satellite switching by the airborne GPS receiver. During satellite switching, the receiver temporarily enters an altitude-hold mode. The accuracy of the resulting Differential reference trajectory is then no longer determined, and consequently, the trajectory cannot be used for the evaluation of the hybrid GPS/LORAN receiver. Note that the hybrid receiver could still continue to provide a solution based on the three remaining satellites and one or more LORAN-C transmitters.

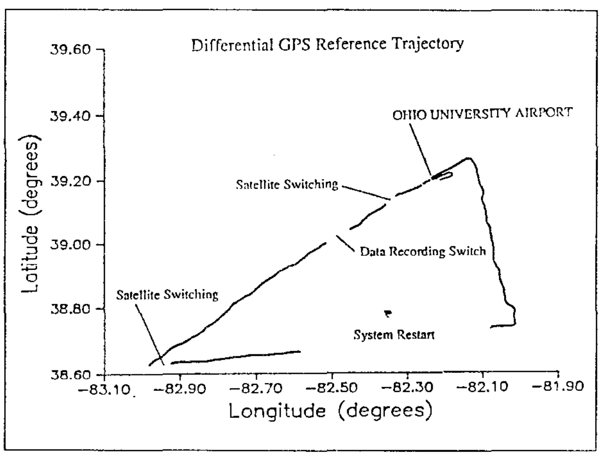

Figure 4. Differential GPS ground track for a 70 minute hybrid GPS/LORAN test flight in the vicinity of Ohio University airport.

The ground track for the hybrid receiver is almost identical to the reference trajectory. Differences between the ground tracks as a function of time are shown in Figure 5. Figure 6 provides a scatter plot of the position errors. The largest position errors occur during the middle of the flight. These deviations are caused by a relatively poor GPS geometry. Also, all sudden changes in the magnitude of the two-dimensional error are caused by transitions to different sets of four GPS satellites. The horizontal position accuracy for

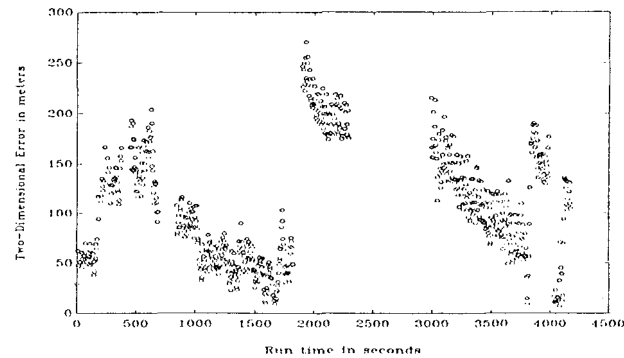

Figure 5. Two-dimensional position errors for the hybrid GPS/LORAN receiver for a 70 minute flight.

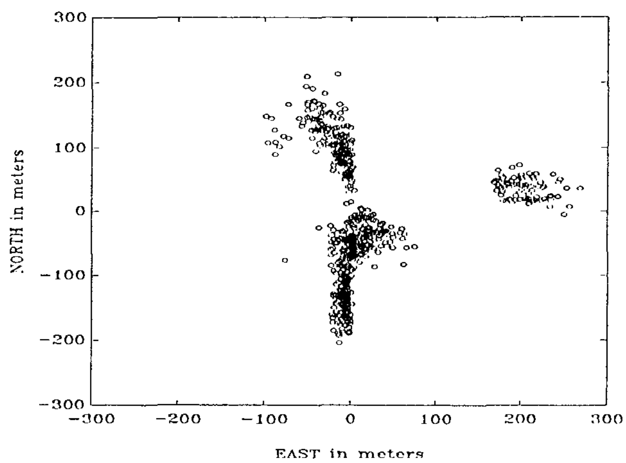

Figure 6. Scatter plot of two-dimensional position errors for the hybrid GPS/LORAN receiver for a 70 minute flight.

the hybrid system, based on all measurements (785 data points), is 210 meters (2 drms), with respect to the Differential GPS trajectory. The mean position errors in the North and East directions were found to be -52 meters and 30 meters, respectively. The 2 drms positioning accuracy is well within the current requirements for enroute domestic navigation (2778 m), terminal navigation (2037 m), and nonprecision approaches (556 m).

CONCLUSIONS

Hybrid GPS/LORAN has the potential to satisfy the requirements for a next generation of sole means air navigation for the conterminous United States. Generic pseudorange measurement processing is an effective and modular approach to combine measurement data from GPS and LORAN-C. The navigation solution presented in this paper is a variation on Newton's method for nonlinear systems and is numerically stable over a large range of initial estimates. The navigation solution implementation can be easily extended to include pseudorange data from other sensors, such as Omega, Distance Measurement Equipment, altimeter, and other satellite navigation systems.

The hybrid GPS/LORAN navigation system as described in this paper provides horizontal position accuracies consistent with current requirements for domestic enroute navigation, terminal navigation, and nonprecision approaches. Flight data show a horizontal position accuracy of 210 meters (2 drms), based on equally weighted GPS and LORAN-C measurements, with respect to a Differential GPS reference trajectory (accuracy better than 10 meters, 2 drms).

Efforts are continuing on the implementation of receiver autonomous integrity monitoring techniques on a real time GPS/LORAN test bed.

ACKNOWLEDGEMENTS

The work presented in this paper was funded in part by the FAA and NASA Langley Research Center under the Joint University Program for Air Transportation Research under Grant NGR-009-017. Additional funding was obtained from the FAA under Contract DTRS-57-87-C-00006, TTD-13.

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GPS/LORAN INTEROPERABILITY - CONGRESSIONAL INTEREST & CONCERNS

Summary of remarks made by Daniel C. Cross

Mr. Cross noted his leaving the staff of Congressman Denny Smith of Oregon, on November 1. He outlined several congressional concerns with the continuing proliferation of radionavigation systems at considerable Government expense. PL 100-223, sponsored by Congressman Smith, was intended to determine the full capability of a coordinated Loran-C and GPS system.

Since the Department of Transportation has determined that such a system has the potential to serve as a sole means of navigation for all phases of flight from departure through nonprecision approaches, the Congress can be expected to press FAA to upgrade its Air Traffic Control procedures to better accommodate area navigation systems of this type.

Mr. Cross noted specifically air traffic controllers are not given any training or experience with area navigation concepts until late in their indoctrination. From the first day of indoctrination training through the first one or two years of field experience the only navigation concept taught is pre-published routes. Discussions between Congressman Smith`s staff and the Manager of Air Traffic Control Training in Oklahoma City, have not been successful in raising the priority of area navigation concepts in the air traffic control curriculum.

Mr. Cross noted that the DOT response to PL 100-223 indicated a cooperative effort between the FAA and USCG. There remains some Congressional concern that neither Agency fully appreciate the need for a common system of radionavigation for the entire nation. Too much interest remains in promoting the individual systems each Agency manages.

Mr. Cross concluded with an opinion that the FAA, USCG, and DOD must work together to satisfy the concerns being expressed by the Congress to improve the transportation system of the nation.

SUMMARY OF THE GPS/LORAN INTEROPERABILITY PANEL DISCUSSION

Moderator: Chic Longman

Panelists: David Olsen, DOT,RSPA - Acting Chairman of the DOT Navigation Working Group

David Scull, Consultant - Past Chairman, DOT Navigation Working Group

Jerry Bradley, FAA

Lt. Cdr. Gary Westling, USCG

Mr. Olsen opened the discussion by noting that public hearings associated with the next issue of the Federal Radionavigation Plan (FRP) are scheduled Nov. 15-16. All interested persons were urged to attend. The moderator also commented on the importance of the FRP and the need for the public to participate in its formulation.

No other special opening remarks were offered.

The panel responded to several questions from the moderator and the audience. Most dealt with the FRP. The status of the new Loran chains, NOCUS and SOCUS; the status of discussions with the USSR regarding Loran and GLONASS, the plans for increased acceptance of area navigation in the NAS, and plans for GPS Integrity Channel were some of the specific subjects brought up through the question and answer session.

Mr. Olsen noted that a permanent replacement for Mr. Scull in DOT is expected in a few weeks. It is expected that this new employee will become the Chairman of the DOT Navigation Working Group.

A video tape version of the DOT response to Congress pursuant to PL 100-223 was shown at the end of the panel discussion.

1989 Convention Attendance

Name	Affiliation
Acard, Christian	MORS Technologies, Inc.
Alexander, James O.	Alexander Marine Transportation
Allan, John David	Megapulse, Inc.
Ambos, Doug	Datamarine International
Ambroseno, Bernard	EPSCO Inc.
Amos, David H.	Synetics Corporation
Andren, Carl S.	Racal Marine, Inc.
Barnett, Lt. JC Roger D.	U.S. Coast Guard (G-NRN-2)
Beckmann, Martin	Delft University of Technology
Berger, Philip	Enduratek Corporation
Beukers, John M.	Beukers Technologies, Inc.
Bochniarz, James F.	II Morrow, Inc.
Boyce, Ransom	II Morrow, Inc.
Bronson, John	II Morrow, Inc.
Brooks, Kent	Consultant, Ohio University
Brown, Herbert L.	Cetrek Navstar Inc.
Brusin, Eugene M.	Megapulse, Inc.
Buddenberg, LCDR Rex	U.S. Coast Guard
Burgin, William F.	Hondex Marine Electronics
Callanan, Daniel E.	Callanan, Inc.
Campbell, CDR Perry W.	U.S. Coast Guard
Canniff, John	DOT/Transportation Systems Center
Carroll, James V.	Computational Engineering
Carter, David A.	Advanced Navigation, Inc.
Cassidy, Frank	Datamarine International
Castonia, John C.	Illgen Simulation Technologies, Inc.
Catlin, Jeffrey D.	Synetics Corporation
Charron, Laura G.	U.S. Naval Observatory
Chin, Kam	DOT/Transportation Systems Center
Cortland, Larry J.	II Morrow, Inc.
Cross, Daniel C.	Consultant
Crowell, Robert	U.S. Coast Guard R&D Center
Culbertson, James F.	Capt. U.S. Coast Guard (Ret.)
Dahl, Harald	Consultant
Dana, Peter H.	Consultant
Davies, Mike	Racal Survey
Dean, Walter N.	ARNAV Systems Inc.
De George, William A.	Advanced Navigation, Inc.
Dickinson, Ronald R.	Federal Aviation Administration
Elsner, Robert W.	Global-Wulfsberg Systems
Enerstad, Kjell	Norwegian Defense Comm. Admin.
Enge, Per	Worcester Polytechnic Institute
Ezhov, Mr.	USSR
Farrar, Helen	Megapulse, Inc.
Foret, Kenneth B.	Eventide, Inc.
Frank, Robert L.	Consultant
Fraughton, Edward J.	Terrastarr
Gagne, Mark	Whistler Corp.
Garmany, William J.	ITT (Ret.)

Name	Affiliation
Gay, David R.	Navigation Systems Specialists
Gibbs, Paul D. (Doug)	Foster Airdata Systems, Inc.
Goddard, Robert B.	Megapulse, Inc.
Goudie, Edward B.	Canadian Coast Guard
Gray, David H.	Canadian Hydrographic Service
Guzhva, Mr.	USSR
Hattori, Keisuke	Koden International, Inc.
Hensel, Bruce	Jet Electronics and Technology, Inc.
Higginbotham, Lloyd D.	Self
Holcomb, Judy	Federal Aviation Administration
Illgen, John D.	Illgen Simulation Technologies, Inc.
Irwin, Barry J.	U.S. Geological Survey
Ivanov, Mr.,	USSR
Jacobs, Andre	Natl Assn Priv Trans Opers SA
Jandreau, LT Peter	U.S. Coast Guard - COCO SE Chain
Johannessen, Paul R.	Megapulse, Inc.
Johnson, Dale E.	II Morrow, Inc.
Johnson, Vernon L.	ITT (Ret.)
Jolly, Jon B.	Jon B. Jolly, Inc.
Justice, Charles	U.S. Coast Guard
Kelly, James D.	TASC
Kern, John	Federal Aviation Administration AVR-2
Kraemer, John H.	DOT/Transportation Systems Center
Kunches, Joseph M.	NOAA Space Environmental Service Center
Lachapelle, Gerard	University of Calgary
Lancaster, Richard	Transtrack Inc.
Last, Dr. David	University of Wales
Law, Bill	Ministry of Transportation, Ontario
Letts, Martin A.	U.S. Coast Guard EECEN
Lilley, Robert W.	Ohio University
Longman, Chester	Air Navigation Consultant
LoVecchio, Joseph A.	DOT/Transportation Systems Center
Martini, CDR Gaetano	U.S. Coast Guard
Marx, Capt. Henry E.	Landfall Navigation
Matthews, Norman	Int. Assoc. Lighthouse Authorities
McCann, Mark J., Jr.	DOT/Transport. Systems Center (Ret)
McCullough, James R.	WHOI/U.S. Geological Survey
McGann, Edward L.	Megapulse, Inc.
Meranda, James I.	Consultant
Miller, Paul G.	U.S. Coast Guard
Miller, Robert H.	II Morrow, Inc.
Mockler, Capt. Rick	DOT/Transportation Systems Center
Morel, Claude	Natl. Center for Atmospheric Research
Morgenthaler, Mark	Trimble Navigation Company
Moroney, Maurice J.	DOT/Transportation Systems Center
Nelson, RADM Robert T.	U.S. Coast Guard/DOT
Noseworthy, Gary L.	Synetics Corporation
Nsibirwa, Charles K.	B&M Technological Service Inc.
O'Halloran, William F.	Synetics Corporation
Olsen, CDR David L.	U.S. Coast Guard
Patel, Hank	Ross Engineering Company
Philbrick, Otis	Digital Marine

Name	Affiliation
Piccioni, LCmdr Rick	U.S. Coast Guard
Pieterse, Martin	Forum Consultants - South Africa
Pipkin, Jesse	Self
Polhemus, William L.	Polhemus Associates, Inc.
Poppe, Martin C.	Cambridge Engineering, Inc.
Post, Kendall E.	Bahr Technologies, Inc.
Quinn, George	Federal Aviation Admin. - ASA-130
Raasok, Kjell	Ministry of Fisheries, Norway
Ray, Malcolm	Department of Transport - Canada
Reed, David	Digital Marine
Rome, H. James	University of Lowell
Roth, Linn	Bahr Technologies, Inc.
Roth, Steve	II Morrow, Inc.
Ruaro, Gerard	Techniphone
Ruttle, Dr. S.G.R.	Commissioners of Irish Lights
Saether, Kolbjorn	Norske Shell
Saratov, Mr.	USSR
Scull, David C.	Adroit Systems, Inc.
Sewell, William G.	NAVCOM Systems, Inc.
Shuey, Martin W.	AOPA
Simmons, Patrick M.	Navigation Technology Int'l.
Skaggs, Gary A.	National Severe Storms Laboratory
Smid, LT Scott	U.S. Coast Guard-Chain Mgr.Atlantic
Smyser, Michael I.	Foster Airdata Systems, Inc.
Stein, Kenneth J.	Avionics Consultant
Stene, Kjell	Geometrix as
Stenseth, Andreas	Norwegian Defense Comm. Admin.
Tepper, Bert	Transport Canada - Coast Guard
Terkin, Mr.	USSR
Toms, Jimmie L.	Advanced Navigation, Inc.
Tretyakov, Mr.	USSR
Turner, John H.	Whistler Corp.
Uttam, Bahar J.	Synetics Corporation
Van Etten, James P.	Consultant
van Graas, Dr. Frank	Ohio University
Van Willigen, Dr. Durk	Delft University of Technology
Vestmo, Einar	Kongsberg Navigation - Norway
Vicksell, Frona B.	Megapulse, Inc.
Walker, Carl D.	Digital Marine
Wall, Glenn	Federal Express Corporation
Ward, Dr. Nicholas	Trinity House Lighthouse Service
Warr, Patrick H. J.	Racal-Decca Canada, Ltd.
Watanabe, LCDR Clyde K.	U.S. Coast Guard
Westling, LCDR Gary R.	U.S. Coast Guard - Office of Navig.
White, Wilfred St. John	Racal Decca Ltd.
Wilmert, Jerry	Jet Electronics and Technology, Inc.
Wojcik, Leonard	Terrastarr
Wojnar, RADM Ted	Water Resources Congress
Wood, RADM Raymond	U.S. Coast Guard (Ret.)
Wooldridge, David	Motorola
Wychorski, Henry J.	Northeastern University
Young, Elizabeth L.	COMSAT

HIGHLIGHTS

(Top row, left to right) Mrs. Marilyn Beukers opened the Symposium with a beautiful rendition of our National Anthem; Captain Rick Mockler, accompanied by a U.S. Coast Guard color guard, escorted Mrs. Beukers.
(Second row) Admiral Robert T. Nelson was the guest speaker at the luncheon on October 30, 1989; Edward L. McGann chaired the session on worldwide events; Technical Co-chairmen Per Enge and Frank Cassidy.
(Bottom row) President Jim Culbertson outlined his agenda for growth of the WGA during his luncheon address on November 1, 1989; seated at the head table were WGA Board members Vern Johnson,Jim Alexander,Bob Lilley, Jim Van Etten, and Mike Moroney. Jerry Bradley of the FAA was a speaker at the LORAN/GPS Interoperability session.

WGA BANQUET

18th ANNUAL TECHNICAL SYMPOSIUM

(Top row,left to right) Congressman Denny Smith, Republican, Oregon, was the featured speaker. National issues facing the Congress, as well as his personal concerns for aviation navigation, highlighted his address. Seated at the head table were: incoming WGA President Jim Culbertson: Convention Co-chairman Ed McGann, Chairlady Spouses Program Pauline Moroney; Convention Co-chairman Mike Moroney.
(Second row) President John Illgen; Congressman Smith; Susanne Illgen; Treasurer John Beukers; Marilyn Beukers; Norman Mathews, IALA; Symposium Technical Co-chairman Per Enge; Convention Treasurer Bob Goddard.
(Bottom row) Symposium Technical Co-chairman Frank Cassidy; Lynda Cassidy; immediate past President, Walt Dean; Marge Dean.
(Bottom right) Distinguished attendees at front table included: Vern Johnson; Paul Johannessen; Astrid Johannessen; Jim Van Etten; Grace Van Etten; Lloyd Higgenbotham; Evelyn Higgenbotham; Dorothy Johnson.

AWARDS CEREMONY

(left to right, top row) Per Enge, Symposium Technical Co-chairman, presented an award to Henry J. Wychorski of Northeastern University for best paper at the 1989 meeting submitted by a student; President John Illgen, assisted by Awards Chairman Bob Frank, presented the WGA Medal of Merit to Maurice J. Moroney and George H. Quinn; (second row) Bob Miller, 1988 WGA Symposium Technical Chairman received the Service Award; John Bronson accepted the Service Award on behalf of his brother Bob who chaired the 1988 convention; Mark Morganthaler accepted awards for best paper which he co-authored with Russ Gordon for the 1988 Symposium; R. Michael Eaton, represented by Gerard LaChapelle, received a certificate for Honorary Membership; (bottom row) Jim McCullough was honored for his outstanding contributions in the area of LORAN electromagnetic propagation; John Illgen was given the Service Award by Jim Culbertson, who previously received the President's Award.

The WGA Awards Committee members are: Bob Frank, Chairman, assisted by Jim Van Etten and Gary Westling.

DELEGATION FROM SOVIET UNION

Jim Culbertson and John Illgen were pleased to welcome the largest contingent of Russians ever to participate in a Wild Goose Association symposium. The broad international representation at this meeting is indicative of the growing worldwide interest in LORAN navigation.

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The Wild Goose Association
P.O. Box 556
Bedford, Massachusetts 01730