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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, and the user community throughout the world, working for the advancement of Loran.

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SESSION I
PLANS AND POLICIES

SESSION CHAIRMAN:
LCDR William J. Thrall, USCG HQS
SESSION I SPEAKERS

David C. Scull

LCMR William Thrall

Andreas Stenseth

Jerry Bradley

David J. Pietraszewski
UPDATE ON THE U. S. FEDERAL RADIONAVIGATION PLAN

David C. Scull

Research and Special Programs Administration
Department of Transportation
Washington, D.C. 20590

ABSTRACT

The purpose of the Federal radionavigation planning process is to continually review the current mix of radionavigation systems and ensure that they are operated in the most efficient and effective manner. This process should not stop at a "status quo" but be a vigorous attempt to introduce new technology into the field of radionavigation that will improve the safety and efficiency of transportation. The Federal Radionavigation Plan was established under direction of the President and Congress to examine the current mix of radionavigation systems in view of the pending implementation of GPS and determine if there is possible overlap and duplication of systems. These two objectives are not in conflict since there is justification for maintaining, improving and expanding certain existing systems before the GPS becomes operational and perhaps even afterwards. One of these situations is the special case of LORAN-C which continues to grow in usage both nationally and internationally. The introduction of low cost receiver technology in the United States, particularly in general aviation, has focused attention on LORAN-C as an interim, supplemental system for enroute navigation and non-precision approach. LORAN-C also has immediate applications to surface transportation in the mid-continent area.

INTRODUCTION

RADIONAVIGATION POLICY

At the time of this writing, a joint Department of Defense (DOD)/Department of Transportation (DOT) policy statement on the future radionavigation system mix is awaiting Secretarial approvals, therefore, it is premature to comment on the latest position. Still, keeping in mind, that the underlying purpose of the Federal Radionavigation Plan (FRP) is to select an optimum mix of systems and several actions have been announced already, we can probably make some valid assumptions. It is now recognized that NAVSTAR GPS can meet a variety of navigational requirements, particularly in view of the recent DOD policy decision, in June 1983, to make 100 meter 2 drms* accuracy available from the Standard Positioning Service (SPS) and the recent Congressional action in removing NAVSTAR GPS user fees. This means the majority of technical requirements for coastal marine navigation and oceanic navigation can now be satisfied by NAVSTAR GPS. The possibility that there will be no direct user fees for NAVSTAR GPS will make it more attractive to the civil aviation community. If the integrity and reliability issues surrounding NAVSTAR GPS can be resolved then it can also meet technical requirements for oceanic, enroute and terminal air navigation as well as for non-precision approaches.

What technical requirements will a 100 meter 2 drms NAVSTAR GPS not meet? Probably those that are tied to the high repeatable accuracy of Loran-C, the geodetic capability of TRANSIT and those that can only be met by precision landing and approach systems. Techniques such as differential NAVSTAR GPS and Very Long Baseline Interferometry (VLBI) give promise of meeting the high repeatability standards set by Loran-C and providing the geodetic accuracies obtainable from the TRANSIT system. The worldwide 100 meters 2 drms accuracy available from the SPS will more than meet the requirements now served by OMEGA.

We can see then that NAVSTAR GPS has the potential to become a replacement system for such systems as TRANSIT, OMEGA and Loran-C. Present plans call for the overseas Loran-C chains operated by the U.S. will be phased out in the 1990's. Once it is determined that the phase-out of Loran-C will not place an economic burden on U.S. users, the domestic chains may also be discontinued over a suitable transition period but this will occur well after the year 2000. TRANSIT will be discontinued in 1994 or

* drms is the square root of the sum of the squares of the one sigma error components along the major and minor axis of a probability ellipse. Values of drms such as 2 drms are derived by using the corresponding values of sigma. There is a range of values of probability associated with a single value of 2 drms. The variation is not large but it ranges from 95.4% to 98.2% as a function of the ellipticity. The ellipticity is defined as the ratio of sigma1 to sigma2.
as soon as the essential military services have been equipped with NAVSTAR GPS. Once NAVSTAR GPS is considered as a cost effective replacement, consultations with the OMEGA partner nations will no doubt be conducted and steps will be taken to phase out OMEGA over a suitable transition period. Thus we will see the end of TRANSIT before the year 2000 but the use of Loran-C and OMEGA continuing well into the 2000's. Since VOR provides redundancy, is used extensively by small general aviation aircraft and is expected to remain as an ICAO international standard, its use like radiobeacons is expected to continue indefinitely.

AUTHORITY AND RESPONSIBILITY

Through the Department of Transportation Act of 1967, the Secretary of Transportation is responsible for providing safe and efficient transportation. Radionavigation systems play an important role in carrying out this responsibility. The two main elements within the Department of Transportation (DOT) that operate radionavigation systems are the Coast Guard and the Federal Aviation Administration (FAA). The Coast Guard has the statutory responsibility to define the need for, and to provide aids to navigation and facilities needed for safe and efficient navigation. Section 81 of Title 14, United States Code provides:

To aid navigation and to prevent disasters, collisions, and wrecks of vessels and aircraft, the Coast Guard may establish, maintain, and operate:

1. "aids to maritime navigation required to serve the needs of the armed forces or of the commerce of the United States;"
2. "aids to air navigation required to serve the needs of the armed forces of the United States peculiar to warfare and primarily of military concern as determined by the Secretary of Defense or the Secretary of any department within the Department of Defense and as requested by any of those officials; and"
3. "electronic aids to navigation systems (a) required to serve the needs of the armed forces of the United States peculiar to warfare and primarily of military concern as determined by the Secretary of Defense or any department within the Department of Defense; or (b) required to serve the needs of the maritime commerce of the United States; or (c) required to serve the needs of the air commerce of the United States as requested by the Administrator of the Federal Aviation Agency."

The Federal Aviation Administration (FAA), under the Federal Aviation Act of 1958 (Public Law 85-726), has responsibility for development and implementation of radionavigation systems to meet the needs for safe and efficient navigation and control of all civil and military aviation, except for those needs of military agencies which are peculiar to air warfare and primarily of military concern. The FAA also has the responsibility to operate aids to air navigation required by international treaties. The Department of Defense (DOD) is responsible for developing, testing, evaluating, operating, and maintaining aids to navigation and user equipment required for National Defense and ensuring that military vehicles operating in consonance with civil vehicles have the navigational capabilities required to operate in a safe and expeditious manner. In addition the Defense Mapping Agency (DMA) is responsible for military mapping, charting, and geodesy aspects of navigation, including geodetic surveys, accuracy determination, and positioning. DMA also serves as a focal point within the DOD for civil and other government agencies; interests in NAVSTAR GPS for geodesy purposes. Unclassified data prepared by the DMA are available to the civil sector.

Reiterating the responsibility of the Secretary of Transportation to provide for safe and efficient transportation we are, to some degree, in a dilemma when it comes to the DOT role in the other half of radiodetermination, that is the half dealing with radiolocation. As we know, systems such as NAVSTAR GPS, TRANSIT and LORAN-C can be used for precise positioning in addition to radionavigation. But DOT's charter is concerned principally with the role of navigation in the transportation industry rather than the role that radiolocation serves in ocean science and geophysical exploration. Still since the DOT is the principal Department of the U.S. Government which collaborates with the DOD on the preparation of Federal Radionavigation Plan, it may also represent the civil interest in this area.

It can be seen that the roles and missions of the DOD and DOT are to a great extent interwined and that the planning for radionavigation systems in common use by the DOD and DOT must be coordinated. Also extensive planning coordination must be accomplished within each department due to the diverse nature of navigational requirements, e.g., marine versus air. An Interagency Agreement between DOD and DOT for Radionavigation Planning became effective April 17, 1979. This agreement
requires coordination between the DOD and DOT internal management structures for navigational planning. The interagency agreement recognized that DOD and DOT have joint responsibility to avoid unnecessary overlap or gaps between military and civilian navigation system services. Further it requires that military and civil needs be met in a cost-effective manner for the government and the civil sector radionavigation readiness for mobilization in national emergencies. A formalized structure has been established for making a national decision on the future radionavigation systems mix. This structure provides lines of communication throughout both Departments, and should ensure that all interests, military and civil, are represented. A less formalized exchange of information and technical dialogue takes place between the individual navigation working groups.

The DOT Navigation Council is the top level of decision-making in DOT. It consists of a Secretarial Officer and one policy level representative each from the Coast Guard, FAA, the Research and Special Programs Administration (RSPA), the Maritime Administration (MARAD), and the St. Lawrence Seaway Development Corporation (SLSDC). The designated members may be augmented by representatives of other operating elements to consider specific issues. The Council meets, as required, under the chairmanship of the Secretarial Officer. The DOT Navigation Council:

- Serves as the focal point to formulate coordinated policy recommendations to the Secretary;
- Coordinates with similar committees in other government agencies in accordance with bilateral or multilateral agreements between DOT and those agencies; and
- Provides guidance to the subordinate Navigation Working Group.

It is the purpose of the navigation working groups within DOD and DOT to support policy formulation by performing the independent studies and economic analysis required to provide the necessary information for decision making. The navigation group in the DOD is called the Positioning/Navigation Working Group while the DOT counterpart is the DOT Navigation Working Group. The DOT Navigation working group consists of one representative each from the Coast Guard, Federal Aviation Administration, Research and Special Programs Administration, and Saint Lawrence Seaway Development Corporation. Each representative may be assisted by advisors. Ad hoc advisors from other DOT operating elements which have an interest in navigation are invited to attend meetings as appropriate. These elements are the Federal Highway Administration (FHWA), the Federal Railroad Administration (FRA), the National Highway Traffic Safety Administration (NHTSA), and the Urban Mass Transportation Administration (UMTA). The Navigation Center at the DOT Transportation Systems Center (TSC) provides technical assistance to the Navigation Working Group, as requested.

The Navigation Working Group facilitates the coordination of:

- Navigational requirements developed by the DOT operating elements;
- Navigational plans;
- Navigational R&D and implementation programs;
- DOT navigational planning with the DOD, the DOC, the NASA, and other Federal Agencies, as required; and
- Multimodal navigational issues with other governmental agencies, industry, and user groups, as directed by the Navigation Council.

In accordance with a DOT order the Navigation Working Group meets on a monthly basis or more frequently when required. It is through this interaction that the FRP is developed and revised in the area of civil radionavigation. Members of the DOT Navigation Working Group also meet periodically with those of the DOD Positioning/Navigation Working Group so that the common civil/military interests in radionavigation can be addressed. It is here that civil navigation requirements are presented to DOD. These discussions ultimately result in the joint DOD/DOT policy recommendations contained in the FRP.

RADIONAVIGATION PLANS

Based on present plans, the status of the radionavigation systems included in the Federal Radionavigation Plan is as follows.

RADIOBEACONS

At present there is no known alternative system which would be as cost effective for the user and the government. No end of
service can be foreseen between now and the year 2000 and radiobeacons are expected to remain well into the next century. DOD will phase out radiobeacons in favor of NAVSTAR GPS by 1997. Growth in aeronautical radiobeacons is now primarily non-Federal and future growth is expected to be at a slightly slower rate that the 40 percent growth experienced in the 1975-80 time period. Only a small expansion is planned for marine radiobeacons even though it is expected that there will be growth in the number of direction-finder-equipped boats.

LORAN-C

LORAN-C serves military, civilian, air and surface users. DOD will phase-out its use of Loran-C by 1992. The U.S. will cease Loran-C operations outside the geographical limits of the United States once its military users are NAVSTAR GPS equipped. The U.S. Coast Guard has notified the cognizant agencies of the Loran-C host nations of these plans but it is not known to what extent these nations may wish to operate Loran-C on their own in the future. Also the U.S. will investigate the continuation of the Angissaq Loran-C station as part of future agreements with Denmark and Canada. The Loran-C system serving the United States and coastal areas will remain at least until the year 2000.

VOR/DME

VOR/DME provides air users with relatively low cost radionavigation and serves as the basis for the present, U.S. airway structure. VOR/DME, as the international standard for civil air navigation, will operate at least until 1995 due its protection by ICAO agreements. Present plans for expansion of the VOR/DME system are limited to site modernization or facility relocation. Planned phase-out of VOR/DME will be completed by the DOD in 1997 (assuming NAVSTAR GPS or other suitable alternatives are identified). Because of its low cost and user acceptance VOR/DME, like radiobeacons, is expected to remain as part of the radionavigation system mix indefinitely.

OMEGA

OMEGA serves both maritime and aeronautical users on a world-wide basis. DOD plans to phase out military use of the system by 1992. Since the OMEGA System is operated under bilateral agreements with six nations, international discussions would be conducted to determine an appropriate phase-out date for civilian use. It is expected OMEGA will remain a part of the radionavigation system mix into the next century.

TACAN

TACAN is a short range navigation system used primarily by military aircraft. The DOD plans to phase out use of land based TACAN by 1997.

ILS/MLS/PDME

These are precision approach and landing systems for both military and civil aircraft. MLS will replace ILS.

TRANSIT

TRANSIT serves both military and civilian maritime needs. It will be replaced by NAVSTAR GPS in 1994 when its operation will cease. There are no plans for a civilian agency of the U.S. Government to operate it in the future.

NAVSTAR GPS

NAVSTAR GPS will serve both military and civil air, marine and land navigation needs. It will be operational in late 1988. Civilian users will be provided with 100 meters 2 drms accuracy from the NAVSTAR GPS Standard Positioning Service. The use of NAVSTAR GPS will be limited in use in civil aviation until issues regarding its coverage, reliability and integrity are resolved.
CIVIL AIR, MARINE AND LAND NAVIGATION REQUIREMENTS

The following navigation requirements are abstracted from the Federal Radionavigation Plan. Some of these are firm, well established requirements, such as those for precision approach and landing; others such as those for harbor navigation may be the best estimates at this time. As more data is collected in the future it is expected that these requirements will be further defined.

AIR NAVIGATION REQUIREMENTS (2 drms)

<table>
<thead>
<tr>
<th>Category</th>
<th>Accuracy</th>
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<tbody>
<tr>
<td>Oceanic</td>
<td>12.6nm or better</td>
</tr>
<tr>
<td>Enroute and Terminal</td>
<td>500-4000m</td>
</tr>
<tr>
<td>Helicopter Operations</td>
<td>500-1000m</td>
</tr>
<tr>
<td>Non-Precision Approach</td>
<td>100m</td>
</tr>
<tr>
<td>Precision Approach - CAT I</td>
<td>9.1m H, 3.0m V</td>
</tr>
<tr>
<td>- CAT II</td>
<td>4.6m H, 1.4m V</td>
</tr>
<tr>
<td>- CAT III</td>
<td>4.1m H, 0.5m V</td>
</tr>
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MARINE NAVIGATION REQUIREMENTS (2 drms)

<table>
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<tr>
<th>Category</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ocean and Coastal Navigation</td>
<td>460-3700m</td>
</tr>
<tr>
<td>Search Operations, Law Enforcement</td>
<td>90-460m</td>
</tr>
<tr>
<td>Recreational</td>
<td>30-180m</td>
</tr>
<tr>
<td>Harbor Navigation</td>
<td>8-20m</td>
</tr>
<tr>
<td>Petroleum Exploration, Mining, Science</td>
<td>1-100m</td>
</tr>
<tr>
<td>Ocean Survey</td>
<td>1-30m</td>
</tr>
</tbody>
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LAND NAVIGATION REQUIREMENTS (2 drms)

<table>
<thead>
<tr>
<th>Category</th>
<th>Accuracy</th>
</tr>
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<tbody>
<tr>
<td>Public Safety</td>
<td>80-300m</td>
</tr>
<tr>
<td>Transportation</td>
<td>150-3000m</td>
</tr>
<tr>
<td>Highway Inventory</td>
<td>30m</td>
</tr>
<tr>
<td>Census</td>
<td>10-50m</td>
</tr>
<tr>
<td>Land Survey</td>
<td>0.1-5m</td>
</tr>
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</table>

As can be seen from the above, accuracy requirements vary greatly depending on the user's application. Some have been categorized as navigation requirements when they may be more properly classified as precise positioning or geodetic requirements. The systems we consider for navigation sometimes serve both needs, however, and satellite systems such as NAVSTAR GPS fall in this category. With accuracy of NAVSTAR GPS, available to the civil community, limited to 100 meters we must look at other techniques for gaining the high accuracy needed for certain operations. Differential NAVSTAR GPS offers great promise in this area as studies indicate that 10 meters 2drms accuracy is possible. VLBI and translocation techniques promise accuracies in the centimeter range. There are other observation techniques that might be applied to other satellites as well that provide again very high accuracy at significant range off-shore. Even if the full accuracy obtainable from the SPS of NAVSTAR GPS, 38m 2 drms, is eventually available to the civil community we will still need these techniques to meet all the accuracy requirements possible. In addition to the accuracy requirements there are other requirements for radionavigation systems. These are listed in the FRP an deal with such parameters as system availability, reliability, fix rate and fix interval. Included with these is the integrity of a system or the ability of a system ensure that it's navigational data is accurate and will not deceive a user into thinking everything is normal when it is not. This is a very important issue to the aviation community as a safety consideration for satellite navigation systems, in particular DOT and the FAA are working with DOD on these technical issues in regard to NAVSTAR GPS. Additional satellites, improved monitoring of the system and receivers design are being examined to resolve these problems.
U.S. RADIOnavigation USERS POPULATION - PRESENT AND FUTURE

The Federal Radionavigation plan (March 1982) has a fairly complete breakdown of present and anticipated future users, both military and civilian. Many of the figures may be inaccurate, however, and are now in the process of being updated. It is not a trivial matter to obtain such data from the civilian sector since radionavigation receivers are not registered with the federal government and sales figures may not be indicative of what is in use. Still some comments can be made regarding present trends.

RADIO DIRECTION FINDERS

This equipment is relatively inexpensive, getting more reliable due to solid-state electronics and hence attractive to the boating public and general aviation. In the maritime and fishing industry the radio direction finder serves as a back-up to Loran-C or TRANSIT. Local governments and private airport operators find that aeronautical beacons are economically feasible hence there still is growth in the number of these. Without another means for homing or a non-precision approach at many airports small general aviation aircraft continue to equip with Automatic Direction Finders (ADF). Radionbeacons are also an integral part of most landing systems and ADF equipment continues to be carried aboard commercial aircraft.

LORAN-C

This is probably the highest growth area for radionavigation receivers today due to ever decreasing cost, computer capability and high reliability. This is true for both the marine and general aviation community. New applications for Loran-C receivers such as harbor navigation, coastal way-point navigation and even land navigation are creating new interest. The introduction of Loran-C receivers to the general aviation community, which includes everything from home built to corporate jet aircraft, has sparked new interest there as well. Besides being useful in VFR operations for flying direct and locating airports in marginal VFR conditions, Loran-C has been certified as a supplemental system for enroute navigation under IFR. Due to these relatively new found applications, Loran-C equippage is growing more than significantly in this country.

OMEGA

OMEGA receivers are now being sold primarily to the aviation community although integrated OMEGA/TRANSIT receivers have found a place in the marine market. Airline operators in the United States have reported fuel savings by flying direct using OMEGA. It is also used by U.S. air carriers as a sole means of navigation in the Carribean and some oceanic areas. It is able to compete economically with inertial navigation and is integrated with some inertial navigation systems.

TRANSIT

TRANSIT is popular with the maritime community engaged in off-shore operations. Low cost receivers have made this system popular with the yachting and fishing industry as well. U.S. sales continue to increase but not at a spiralling rate they did a few years ago when prices first reached the $3k level.

VOR-DME

This equipment is in the cockpit of practically all commercial aircraft and most general aviation aircraft. The equipment has become more reliable and cost effective as solid-state receivers replace older equipment. One of the new techniques in improving the accuracy of the more sophisticated areas navigation systems is the use of multisensors. Loran-C serving as a stable signal source can be used to calibrate the DME system aboard the aircraft.
THE ROLE OF LORAN-C

The Federal Radionavigation Plan was developed in response to Congressional interest, during the 1970's, in NAVSTAR GPS as a common-use military/civil radionavigation system. The intent of Congress in this regard is still evident in the recent action by both the Senate and the House of Representatives to remove the requirement for user fees. Thus the pressure is there to make plans for transitioning to NAVSTAR GPS as rapidly as possible and the elements within the Department of Transportation, namely the FAA and the Coast Guard are working toward that end. The question is asked, however, how can we justify the improvement and possible expansion of a system such as LORAN-C at this time?

First of all, LORAN-C is being proposed as an interim, supplemental system for aviation use. This can be justified on three points: 1) LORAN-C user population, 2) development of procedures for direct routing and non-precision approaches and 3) a sufficient transition period before NAVSTAR GPS is considered operationally acceptable and economically attractive. The first point can be substantiated by the large number of LORAN-C equipped aircraft (estimated to be 20,000 in 1985). The second point is that for either NAVSTAR GPS or LORAN-C, we will have to modify the existing Air Traffic Control (ATC) system to accommodate the full capability of direct routing and non-precision approaches that these systems offer. Much can be learned from LORAN-C which will be directly transferrable later on to NAVSTAR GPS. Thirdly, the mid-continent LORAN-C chain can be in place well before the end of this decade if the commitment is made now. Since all LORAN-C users will not immediately transition to NAVSTAR GPS, due the need for this system reach operational maturity and become economically competitive, there needs to be a suitable transition period. Experience has shown this period to be about 15 years. This period justifies the amortization of costs incurred both by the government and the user.

In spite of points made above, the approval for LORAN-C expansion will not come easily. In a tight budget situation that still continues, the decision will probably made at the highest levels within the Department.

REFERENCES**


** References 1. and 2. are available from NTIS, 5285 Port Royal Road, Springfield, VA 22161. Reference 3. is not in the NTIS listing at this time but copies can be obtained from the Transportation Systems Center. Attn: Code DTS-54, Cambridge, MA 02141.
USCG PLANS FOR LORAN-C...THE 80's AND BEYOND

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ABSTRACT

The USCG has been successfully operating Loran-C since the 60's. Through planning, coordination and commitment the Loran 70's program established Loran-C as the Nation's premier Radionavigation System, creating complete coastal and Great Lakes coverage. Today the USCG is poised to implement a Loran 80's Program. A program for completing and improving the national system and shifting responsibility of international chains to the respective Host Nations. This paper addresses the specific programs that either improve and/or reduce the cost of USCG Loran-C operations and ensure continued operation beyond the year 2000.

PREFACE

As a government agency tasked with providing Radionavigation services, we are guided by the Federal Radionavigation Plan (FRP). This coordinated plan establishes: 1) the requirements for particular services, 2) the overlap and eventual cessation of services.

As an ongoing part of our program management, we are constantly striving to provide a more cost effective way of providing the services (in this case Loran-C service) to the general public. The emphasis these last few years has indeed been--get more bang for the buck.

To that end we within the Loran Branch have been tasked with performing cost-benefit analyses of replacement transmitters, station moves, and more automated operating systems. The following paragraphs explain the various cost-saving programs currently underway or planned as proposed future projects.

DATES...Can't have a Program without Dates.

1986--First, let me underscore that within the Coast Guard Radionavigation program there are some dates that we consider very important for planning purposes. Early this fiscal year we expect the update to the FRP (last updated in 1982) to be signed. This update sets the stage for the final 1986 version which will recommend the mix of RA systems and state the plans necessary to ensure proper coordination between RA systems, ideally eliminating unnecessary duplication of service.

1992--1992 is a key date on the Loran planning horizon. The Department of Defense has stated that it no longer requires Loran-C services after 1992. Therefore, we have been meeting with the Host Nations of the Icelandic, North Atlantic, and Labrador Sea Chains to coordinate plans for either their post-1992 Loran operations or termination. In the near future we hope to participate in similar planning sessions with the nations hosting the Mediterranean Sea Chain and the Northwest Pacific Chain.

2000--As of this writing we are tasked with providing CCZ Loran-C coverage beyond 2000. People ask, How far beyond 2000? The new FRP indicates at least a 15 year overlap with GPS. Assuming GPS comes on-line in 1987, then Loran would operate to 2002. But the truth is...I don't really know. However, between now and the year 2000 there are several projects and events, which I believe will extend the useful life of Loran well beyond 2000.

PROJECTS--Always something to do.

Solid-state Transmitters(SSX)

The first is the current Transmitter Replacement Project--A project designed to replace the aging AN/FPN-42 tube-type transmitters at Baudette, Nantucket, Caribou, Carolina Beach, and Jupiter with new Solid State Transmitters (AN/FPN-64). The SSX Program is already in progress with transmitters in production and delivery of the first SSX anticipated by March 1985. An SSX will be delivered every four months thereafter. Building construction and site preparation are in the initial stages of planning and contracting. Presently, we expect the SSX replacement program to be completed by 1987. The first transmitter is due to be installed at Baudette this spring. This will be followed by Nantucket in January of '86. Then Jupiter in April, Caribou in June, and Carolina Beach in July/August.

Installing the SSX will ensure continued operation through 2000. Additionally, it provides for significant savings in operating and maintenance costs. The O & M at these five sites has been over a $1M annually--excluding personal costs. We project that our new O & M expenses for these same five locations after SSX will be less than $600K. These savings will accrue from the implementation of the Remote Operating System (ROS).

Remote Operating System (ROS)

Remote Operating System Implementation--
When Congress agreed to the purchase of the
SSX, they did so with the proviso that we would reduce the manning level to no more than four. ROS allows all of the watch and support functions to be removed to a central monitor facility. Hence, allowing the reduction of personnel that would stand the watch during each 24 hour day. Therefore, we are implementing a four person work force at the station during day time only, but on-call duty technicians during the remaining 16 hours. This allows all support functions such as cook, storekeeper and non-rated personnel functions to be either eliminated or contracted out as service contracts. We are projecting additional savings of over $300K annually, once the ROS is implemented at just these stations.

This arrangement has worked successfully at Port Hardy, British Columbia and Raymond Inv. involved one of which are SSX stations. Additionally, our technical staffs within Headquarters and at EECEN have now adapted ROS for non-SSX transmitters. Therefore, we have been implementing other ROS installations at Lorias Searchlight, Fallon and George and remoting them to Middletown. This adaptation promises significant cost savings per station per year without significantly reducing available signal time. Again, support personnel are no longer required and manning can be reduced to six. We project $150-200K annual savings from this program just within the West Coast Chain. However, we are also planning on installing ROS in Tok, Alaska and Dana, Indiana. This should result in further annual savings of over $100K.

Between both ROS and SSX programs I project a total annual savings of $1M plus, while continuing to provide the same (if not better) signal availability.

Transmitter Replacement--Gotta operate beyond 021

But saving money is only part of the story. We must ensure continued CCZ coverage beyond 2000. Unfortunately, other parts of the CCZ are covered by stations which reside in remote locations in Alaska. Locations such as Attu, Port Clarence, and St Paul. These stations are currently operating with AN/FPN-42 transmitters, which the USCG can no longer support after 1992. Therefore, another replacement program is in the initial planning stages. This second replacement program replaces the AN/FPN-42 transmitters in NORPAC (9990) with either AN/FPN-44A’s or AN/FPN-64’s (SSX). This replacement program doesn’t propose to save money directly. In fact, it will cost approximately $8M to install. It will ensure continued operation beyond 2000 and will reduce the cost of logistic support by eliminating the need for stocking parts, maintaining specific Loran courses, and maintaining engineering expertise on these old transmitters.Projected annual savings of nearly $700K are anticipated; thus, should the system operate beyond 2003, then the $8M would have been recouped.

DESLOT--He told us so.

De-Energized Standby Loran Transmitter--Last year LTJG Robin Orr presented DESLOT and proposed that it would prove to be a successful, money-saving program. Robin has since transferred to Estartit, Spain, but his prediction has proven to be accurate. DESLOT was successfully implemented throughout the 14th Coast Guard District--Hawaii and Japan. It was also tested at Loran Station Baudette, Minnesota and Loran Station Tok, Alaska. With these latter test sites, Coast Guard EECEN performed an analysis comparing savings against costs and problems encountered plus those anticipated. The result...DESLOT Installation recommended Coast Guard-wide.

I anticipate about a 20% savings in energy costs or approximately $1,000,000 annually. Off-air time may increase as much as 15 minutes per month per DESLOT station, or .038% per month. This could equate to an additional .104% per triad per month. I consider the potential savings to far outweigh the potential increase in bad time...Another example of more bang for the buck.

MONEY--A penny saved is a penny earned!

As you can see we’re striving to provide a continuing (into the 21st Century) signal at a substantial reduction in cost. In fact, if my estimates are close, the U.S. Government will save $2.7 million annually by implementing the CONRUS improvements/enhancements and will save an additional $22 million annually by shifting the responsibility of overseas Loran-C to the Hosting countries by 1992. Loran, which today is costing $33 million annually, will be available for about $8 million annually after 1992.

THE FUTURE--it’s only a budget year away...

The future belongs to those who see and reach for it...for Loran the future certainly looks bright, exciting and improving. For instance, the FAA has recently asked the Coast Guard to explore what is required to close the mid-continent gap. This after Adm Engen prepared a policy statement advocating Loran-C for general aviation.

MID-CENTINENT--completing the national system.

The creation of a mid-continent chain has been a topic of discussion for some time. Many people have yearned to participate in such an expansion. We estimate that the gap can be closed with between four and six stations, at a cost of approximately $50 million. Will the gap be closed? Will OMB approve the FAA budget request? Will Congress support the completion of the national system? Is it cost effective? These questions and others are beyond the power of my crystal ball.
DIFFERENTIAL LORAN-C—getting good to be better.

The FRP requires Harbor and Harbor Approach (HHA) accuracy between 8 and 20 meters. As you know, Loran is good but it’s not that good in the normal mode. However, some of us (both inside and outside of the Coast Guard) have been experimenting with a technique called differential Loran-C. A concept that removes the seasonal variation from the TD and provides a more accurate fix (where the signal is stable enough). The USCG Research and Development Center at Groton, Connecticut has developed a prototype system which receives Loran signals and transmits a differential correction in both voice and digital data messages over VHF radio.

This system has a lot of promise for the future. It will meet the 8 to 20 meter requirements in many harbors. It can be used by fishermen, pilots, and government users for various activities, and, it appears, that it can be used up to 150 miles off shore and 111 miles can be verified! And the cost to the receiver purchaser seems to be somewhere between $200 and $500.

A differential Loran-C demonstration network is established in the New London harbor. Another site for future demonstrations is planned at Hampton Roads. A controlled test of the system measured against an electronic reference positioning system will demonstrate the differential Loran-C accuracy to Coast Guard, Navy, and other government users. The Hampton Roads system will be advertised as a test system and all users will be invited to make use of the differential correction broadcasts and to provide feedback to the Coast Guard.

Only through improved, cost effective operations can differential Loran-C justify itself. It will be up to the potential users and beneficiaries of this system to convince their legislators of the economic benefit to the nation.

HOST NATION OPERATIONS—an international community.

I've mentioned 1992 and the shifting of responsibility of the cost of Loran operations to Host nations. This is a very cost effective effort, but one which is necessarily sensitive. Basically, a Loran Working Group was formed in 1982 at the behest of the Northern Europeans—Norway, Iceland, and Denmark. To date France, Germany, Great Britain, and Canada, as well as the United States have joined Norway, Iceland, and Denmark in discussing and planning for the eventual transfer of operations and funding of the Icelandic, Norwegian, and Labrador Sea chains by 1992.

The discussions are on-going and intense. A final position paper is expected to be presented to the USCG by the LWG by July 1985. Until then four more meetings are planned; one in Copenhagen in early February, another in Oslo (or France) in March/April, another in Washington, D.C. around May, and then the final meeting in June in Oslo.

Additionally, we, within the Office of Navigation, are working with the Department of State to establish similar working groups or discussions with the nations concerned with the MEDSEA and NWPAC chains. Hopefully, dialog will be established soon so that planning can be successfully completed and international cooperation beyond 1992 can be assured.

CONCLUSION—ain't no such thing!

The efforts and projects discussed above illustrate the continued commitment the USCG is and will provide to the Loran-C program. Driven by a policy from the top—work smarter not harder—the Coast Guard will provide more efficient Loran coverage beyond 2000 by implementing improvements and policies that provide lower cost operations. As taxpayers the result is most encouraging—the same or improved coverage for approximately 1/4th the cost!!! This has to be a prime example of a lot more bang for a lot less buck.
ABSTRACT

The Norwegian Sea and North Atlantic LORAN-C chains were established in the early 1960's with U.S. government funds mainly to serve military interests. Today, the chains serve a large number of civilian users from a number of nations, while the United States still has full operational control and pays the operation and maintenance expenses.

The U.S. Coast Guard expressed, in 1981, its intention to cease funding and manning support of these chains beyond the mid-1990's. Based on this information, and after internal discussions held in Norway, an initiative was taken to establish a working group to undertake a comprehensive study on the technical, economical, and organizational aspects of possible continued operation of the LORAN-C chains in question beyond 1992.

The LORAN Working Group (LWG) was established in Oslo on the 3rd and 4th of April 1984 with representatives from Canada, Denmark, Germany, Iceland, Norway, and the United States.

Norway has for some years, independent of these developments, had plans to increase the LORAN-C coverage of Norway's area of interest by building new LORAN-C stations on Norwegian soil. These plans presuppose that the existing chains continue their operation.

This presentation deals with the background for the LWG's work, its terms of reference, composition, working arrangements, and goals as well as studies undertaken and achievements thus far.

BACKGROUND

The North Atlantic and Norwegian Sea LORAN-C chains were established in the 1960's with United States government funds to support military requirements. Today, these chains have a coverage as shown in Figure 1, and are used by a large number of civilian users from many countries in addition to whatever use the military is making of it. The United States still has the full operational control and pays the operation and maintenance costs.
In 1981, the U.S. Coast Guard (USCG) expressed its intention to cease funding and manning support of these chains beyond the mid-1990's. Based on this information, an initiative was taken to establish a working group to investigate the possibility of continuing LORAN-C operation in Northern Europe beyond 1992 under some type of multi-national arrangement.
For some years Norway, independent of these developments, has discussed plans for expansion and enhancement of the present LORAN-C coverage in Norwegian waters by establishing new mini-LORAN-C systems or by adding new stations on Norwegian soil to the chains operated by the U.S. Coast Guard. Some information on these plans will be given later in this briefing but first let us take a look at the LORAN-C LWG which was established at a meeting in Oslo on the 3rd and 4th of April 1984. The meeting was called by the Norwegian Defence Communications Administration (NODECA), as a result of discussions at the LORAN-C Host National Conference in London during October 1983. For those of you who don't already know, NODECA is an organization under the Royal Norwegian Ministry of Defence, responsible for the construction and operation of military communications and electronics systems. NODECA also acts as the advisory board for the Royal Ministry of Fisheries in its capacity as the overall coordinator of plans for and operation of civilian radio-positioning systems. It is in this last capacity that NODECA is involved in the work of the LORAN-C Working Group.

LORAN WORKING GROUP ACTIVITIES

Representatives from the following LORAN-C host nations attended the Oslo meeting: Denmark, the Federal Republic of Germany, Iceland, Norway, Canada and the United States of America. Canada, because the station at Angissqq, Greenland, is serving both the Canadian and the Icelandic LORAN-C systems. In addition to these, the Netherlands, as a user of radio positioning services, indicated an interest in the results of the work of the LWG. The Netherlands are kept informed and have supplied information on national views as to further development of LORAN-C in their area of interest. Later, France and the United Kingdom were made aware of the existence of the LWG with the result that France has taken part in the meetings of the Group since June this year whereas a representative from the United Kingdom is receiving information on the activities of the Group. The French interest is, of course, closely linked with their plan to build new LORAN-C stations which could be part of an extended area of LORAN-C coverage encompassing the Biscay and Channel area in addition to the present coverage further north.

Mr. A. Stenseth, NODECA, was elected chairman of the LORAN-C Working Group. The position of secretariat for the Group was undertaken by NODECA.

Terms of reference were adopted as follows:

1. The U.S. Coast Guard has expressed to Norway, Iceland, and Denmark:
   a. The intention to cease funding and manning support of the North Atlantic and Norwegian Sea LORAN-C stations in 1992.
   b. The need for these nations to make their position with regard to continued LORAN-C operations clear by mid-1985.

To provide the basis for further negotiations between all nations involved, a comprehensive study should be undertaken on the technical, financial, and organizational aspects of possible continued operation of the LORAN-C chains in the North Atlantic and Norwegian Sea areas beyond 1992.
2. A Working Group consisting of representatives from the following agencies has been established:

- CANADA
  Canadian Coast Guard

- DENMARK
  Royal Danish Administration of Navigation and Hydrography

- FEDERAL REPUBLIC OF GERMANY
  Federal Ministry of Transport

- ICELAND
  Icelandic Post and Telecommunications Agency

- THE NETHERLANDS
  Directorate General for Shipping & Maritime Affairs

- NORWAY
  Norwegian Defense Communications Administration

- United States
  United States Coast Guard

Other agencies may be invited to participate. The chairman of the Working Group is appointed by the Working Group.

3. The working group shall undertake a comprehensive study of technical, financial, and organizational aspects of continued operation of the chains. The results of the study shall be published as a joint report, containing relevant suggestions and proposals and shall be submitted to the respective national authorities for consideration. The following aspects shall be considered in detail:

- Future requirements for LORAN-C chains in the North Atlantic and Norwegian Sea areas.

- System configuration.

- Organization of future system operation and administration, including chain control and allocation of responsibilities.

- Financial conditions, including cost sharing (assets, initial, and recurring costs).

- Cooperation with other chains.

- Specification of availability and reliability figures.

- Manning.

- Training.

- Logistic support.
4. The working group shall propose arrangements for possible future transfer of equipment as well as system operation and control.

5. The frequency and location of meetings shall be decided by the Working Group. A draft final report shall be available by 30 June 1985.

As one of the first action items, the members of the Group agreed to investigate national requirements for LORAN-C coverage and inform the Group by the end of 1984. We are not there yet, so consequently I am not able to come up with a definite answer to the question of whether or not LORAN-C will continue to cover northern European waters after 1992. What we do know, however, is that one of the participating nations - Iceland - already has expressed very strong requirements for LORAN-C, and that no other nation has said it has not. Inquiries are initiated in each country - the stage of completion and evaluation is varying from country to country, but I believe they will all be completed for presentation to the LWG as planned in January 1985.

The work of the Group therefore is based on the assumption that such requirements exist, and on this basis we are trying to reach agreement on a proposal of how best to organize multinational cooperation of LORAN-C operations in northern Europe when the U.S. Coast Guard withdraws its support and if the involved countries are to take over.

To this end, we are looking at three possible alternatives:

1. To delegate the operation of nationally owned LORAN-C stations to a multinational body in accordance with a Memorandum of Understanding and controlled by a Steering Committee as indicated in Figure 2.

Such a body would be given the following responsibilities:

- Effective operation of LORAN-C stations in accordance with policies and procedures established by the Steering Committee.

- Cooperation with organizations responsible for the operation of external LORAN-C chains.

- Act as secretariat for the Steering Committee.

- Prepare annual budget estimates and propose Maintenance Standards.

- Management of funds made available to the organization.

- Provide electronic support to LORAN-C stations.

- Inspect the stations and keep records of major installations.

- Coordinate the procurement of spare parts.

- Coordinate training programs.

- Liaison directly with nations on questions concerning the effective operation of LORAN-C systems.
2. One nation will undertake the task of coordinating the operations of all LORAN-C stations in a designated area, on behalf of the owner nations and in accordance with an agreed cost sharing formula.

3. An already existing international organization is asked to operate LORAN-C as an "add on" to present engagements.
There is at present no favorite solution, although it now seems that the third alternative is about to be ruled out. The sort of support we can expect from the U.S. Coast Guard after 1992 in areas like global coordination, timing, technical services, logistics, and training, and the best way to organize such possible support, could favor one of the remaining two options. To investigate the incorporation of possible U.S. Coast Guard services to a LORAN-C system owned and run on a cooperative basis by European nations, is and will continue to be a major task for the LWG.

LORAN-C EXPANSION IN EUROPE

In my introduction I indicated that Norway is considering an expansion and enhancement of LORAN-C coverage in Norwegian waters. Actually the idea was born in a report prepared by a governmental commission in 1977, based on a general requirement for a radio positioning system that could serve the gross of users outside the coverage of systems like Decca, and with accuracies better than that of Consul and OMEGA. Over the years the plan was transformed to a mini-LORAN-C solution independent of present U.S. Coast Guard coverage, and more or less tailormade to off-shore requirements in the form shown in Figure 3. This plan was approved by the Norwegian Parliament in May 1983. The cost was to be split between the off-shore industry and the government.

However, the solution turned out to be more expensive than originally envisaged and the support from industry was withdrawn. As a consequence of this, the government asked for a re-evaluation of the whole project. This re-evaluation led to a new proposal presented to the government in January of this year. In this proposal, the requirements of the gross of users were again pushed up front and the new stations were seen as an "add on" to present U.S. Coast Guard chains in the area.

The new proposal was presented in two alternatives. The first alternative included a new station in the East Finnmark area cooperating with Jan Mayen and Bo i Vesteralen in a dual rated mode - possibly with an assisting mini-station at Bear Island, and a new station on the west coast, south of Bergen as a fifth secondary in the present Norwegian Sea chain. This alternative is illustrated in Figure 4, and makes it necessary to organize a new chain having Bo as master and Jan Mayen, the East Finnmark station, and Bear Island as secondaries.
FIGURE 3. - PROPOSED MINI-LORAN-C FOR NORWAY
FIGURE 4 - NEW PROPOSAL FOR LORAN-C IN NORWAY, ALTERNATIVE 1.
The second alternative is shown in Figure 5 and includes two new mini LORAN-C stations on the Norwegian mainland (Ingoy and Vardo), and one each on Bear Island and Svalbard (Ny Alesund). These stations will cooperate with present stations at Bo i Vesterålen and Jan Mayen in a dual rate mode, and will be organized in two new chains (Ingoy, Vardo, Bo, and Bear Island with Ingoy as master, and Bear Island, Jan Mayen, and Ny Alesund with Ny Alesund as master). This alternative also includes a full size LORAN-C station on the west coast as in alternative 1.
Alternative 1 is the preferred solution, basically because it is the cheapest, easiest to operate, and reduces the use of difficult access sites in the Svalbard Islands. However, alternative 1 includes an element of uncertainty as to the effect of land passages between the station at Bo and a possible new station in the East Finnmark area, on accuracy and availability particularly in the Barents Sea area.

The area of uncertainty is illustrated in Figure 6. A number of theoretical studies have been carried out to find out what the magnitude of the problem is - among them, one conducted by J.R. Johler on request from the U.S. Coast Guard some time ago. None of these studies gave us the final answer to our question but they indicate that the problem could be handled, and recommend field testing to confirm the theoretical findings. Such field testing was initiated in March of this year, and has been going on since then. The results so far are encouraging - we have not, however, seen the full effect of a frozen and snow-covered Finnmark plain, and would not like to draw any conclusions before such results are available. The trials are carried out in cooperation with MEGAPULSE, and based on readouts from an ACCUFIX 500 installation made available by MEGAPULSE, and an AUSTRON 2000 timing receiver on loan from the U.S. Coast Guard. These readouts are processed at our Headquarters in Oslo, and a final report is expected by mid-1985.

**FIGURE 6 - LAND PASSAGES IN NORTH NORWAY**
In connection with the Finnmark trials, and to explore the potential of a general purpose LORAN-C system offering high accuracy to dedicated users in limited areas of operation, we are in the process of investigating differential use of the system. To this end, a study has just been started in cooperation with the Norwegian Institute of Technology in Trondheim.

The tasks set for this study include the investigation of the extent to which differential use of the LORAN-C will improve the accuracy of the system, alternate methods of calibration and the transfer of information from a monitor station to a user and to look at questions like how many monitor stations would be required for a given accuracy in a given area. In addition to this, we take advantage of the work done by the U.S. Coast Guard Research and Development Center in Groton to the extent results of their work on this problem are made available to us. We believe that a differential solution will meet many of the most demanding requirements presented by the off-shore industry - requirements in selected areas down to 20 meters DRMS or better. However, real results will not be available until early next year.

Further south, France is planning two new LORAN-C stations, one at Lessay on the French channel coast and one at Soustons near the Spanish border as shown in Figure 7. These stations will, for one thing, serve French fishing interests in the Bay of Biscay and adjacent areas.

FIGURE 7 - NEW FRENCH LORAN-C STATIONS
Transmitters are believed to be in the 500 kW class. France is looking for possibilities to extend the coverage of this chain by introducing a new station, for instance, at Mizen Head in Ireland and by using the already existing station in the U.S. Coast Guard chain at Sylt in the Federal Republic of Germany. Such arrangements would give a chain as shown in Figure 8. Since Sylt is already part of the Norwegian Sea chain, such cooperation would imply that Sylt would have to operate in a dual rated mode. Further discussions with France on this issue will continue in the LWG as far as cooperation with existing U.S. Coast Guard chains in Northern Europe is concerned.

FIGURE 8 - POSSIBLE ENHANCEMENT OF FRENCH CHAIN
CONCLUSIONS

It is a matter of some concern to people using Northern European seaways and fishing grounds that LORAN-C might disappear as an aid for radio positioning in the beginning of the 1990's. Of course, we know that NAVSTAR GPS is coming and will offer unique services for navigators at sea as well as in the air and on the ground on a global basis. What we know, however, is that NAVSTAR GPS is a military system which at all times should be responsive to military needs and it is obvious to us that to combine this role with fulfilling civilian requirements, will not always be possible. A land-based civilian system, therefore, seems to be necessary - possibly as a secondary system for military use in certain areas. In addition to this is the question of user equipment - when can we expect NAVSTAR receivers to be available for the gross of users, and at what price? LORAN-C is with us; we know what that system can do and what we will have to pay for the different classes of user equipment. These questions and a few others led to the formation of the LORAN-C Working Group, and the fact that the Group was established indicates that there is political will to investigate the problem with an open mind. However, only time can tell whether this will is sufficiently strong to release the funds necessary for a European takeover of LORAN-C in Northern Europe. One factor here, of course, is what type of support we can expect from the U.S. Coast Guard in areas like training, global coordination maintenance programs, etc., in the Northern European theater. I am optimistic because I see no better alternative than a European solution in cooperation with the U.S. Coast Guard, and because I believe we will need a system like LORAN-C for many years to come, despite the introduction of satellite navigation.
FAA RADIONAVIGATION PLANS

NAVAID PLANNING

• VOR/DME
  • Second generation VORTAC (complete by end of 1985)
    - 725 VORTAC
    - 145 VOR/DME
    - 80 VOR
    - 950
  • Networking program

• NDB
  • Convert to all solid-state equipment
  • A few new sites are planned
  • Total of 669 Federal NDBs
  • Many non-Federal

• MLS/ILS – Transition from ILS to MLS

• OMEGA/VLF
  • RTCA SC 137 preparing Minimum Operational Performance Standards (MOPS)
  • Draft National Aviation Standard for OMEGA

• GPS
  • Draft National Aviation Standard for GPS
  • Draft Memorandum of Agreement between DoD and FAA for civil aviation use of GPS
  • Request RTCA to prepare MOPS for GPS avionics
  • Resolve coverage reliability issue for civil aviation
  • Resolve integrity issue for civil aviation
  • Prepare for civil aviation use of GPS when operational as a supplemental system
  • Work toward making GPS a sole means Civil Aviation Navigation System
FAA RADIONAVIGATION PLANS

NAVAID PLANNING (continued)

• • Issued Advisory Circular 20-120, Airworthiness Approval of Airborne LORAN-C Systems for use in the U.S. National Airspace System (August 23, 1984)
• • Working with RTCA SC 137 to prepare MOPS for LORAN-C
• • Draft Memorandum of Agreement between USCG and FAA for aviation use of LORAN-C
• • Draft National Aviation Standard for LORAN-C making it a part of the National Airspace System
• • Determine what is required for LORAN-C to be approved for non-precision approaches
• • Fill the mid-continent gap
• • Plan to make LORAN-C a full-service aviation supplemental IFR navigation system

• • LORAN-C
  • • Airborne LORAN-C sets
    – Over 20 different models
    – At least 9 different manufacturers
    – Price range from under $1,000 to over $30,000
    – Many are VFR use only
    – None are approved for non-precision approaches yet
  • • At least six papers at this symposium on aviation use of LORAN-C
  • • Session II is on the aviation environment
  • • Session V, the final session on Friday afternoon, is on LORAN-C and aviation
FAA RADIONAVIGATION PLANS

FAA NAVIGATION POLICY

Draft Policy

The FAA, under Public Law 85-726, has the responsibility for the development and operation of a common system of air traffic control and navigation for both military and civil aircraft. Accordingly, the FAA has established and continues to operate and maintain a short-range navigation system in support of the National Airspace System (NAS); establishes minimum navigation performance standards for oceanic, offshore, and United States systems; and approves airborne navigation system installations meeting these minimum navigation standards. Within the context of FAA's mission, the following specific policy statements apply:

• FAA will support VOR-DME, at least its present level of performance and coverage area, as the primary short-range radionavigation system for use in the United States National Airspace System at least until 1995.

• FAA reaffirms its support to the International Civil Aviation Organization (ICAO) commitment to continue to operate the VOR-DME as the primary civil air navigation system at least until 1995.

• In consideration of both government and user investment and time required to transition to any new primary radionavigation system, FAA will provide VOR-DME service for an appropriate period after any new primary system is introduced.

• Implementation of any new primary aviation radionavigation system in the post 1995 time frame will be based upon proved technological capability and cost-effectiveness considerations for both users and the Federal Government as specified in the Federal Radionavigation Plan.

• FAA will support TACAN as long as the DOD requires the service.

• FAA endorses the concept of area navigation to permit operators to use direct routings in the National Airspace System, wherever practical.

• FAA will continue to relocate VOR-DME/VORTAC facilities as required to provide operationally acceptable airway/route alignment, required coverage, and support of direct-route operations where practical.

• FAA will prepare aviation national standards, TSO, and approval criteria for additional radionavigation systems when it is determined that use of such systems is needed to provide supplemental coverage and the systems are suitable for use in the National Airspace System (e.g., LORAN-C, OMEGA, and NAVSTAR/GPS).

• FAA will continue to approve privately-owned and non-Federal publicly owned navigational aids which do not yet meet FAA establishment criteria but do meet applicable minimum performance standards. These facilities would meet specific user requirements in areas where supplementary coverage is needed and not provided by a DOT supported system. Where such aids are used for IFR service, signal continuity, format, reliability and integrity must be established. The FAA will not assume maintenance or logistic support for these aids.

This policy statement is issued under the authority of Sections 307(a) and 312(a) of the Federal Aviation Act of 1958 (49 U.S.C. 1348(a) and 1353(a)) and Section 6(c) of the Department of Transportation Act (49 U.S.C. 1655(c)).

(Attachment C to 13 Dec 1983 ltr to Chairman, DOT Navigation Council)

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FAA RADIONAVIGATION PLANS

THIRD EDITION FEDERAL RADIONAVIGATION PLAN (SOMETIME IN 1984)

Proposed Policy

1. NDB: Part of the system well into the next century
2. LORAN-C: Part of the system into the next century
3. OMEGA: Part of the system until at least the year 2000
4. VOR/DME: Short-range standard well into the next century
5. TACAN: Phase out land-based by 1997
6. ILS/MLS: MLS will replace ILS; ILS will continue into the next century
7. GPS: Standard position service will be made available to all users and will provide 100 meter 2 drms navigation accuracy

FAA RADIONAVIGATION PLANS

NAVIGATION REQUIREMENTS FOR THE POST-1990 TIME PERIOD (13 DECEMBER 83)

• "Since there are no user-perceived requirements that could not be met with an appropriate mix of current systems, the FAA recommends that the current system mix be retained until at least the year 2000."

• VOR/DME: National and International Aviation Standard Short-Range Navigation System – Protected in ICAO through 1984
• OMEGA/VLF: Aviation Oceanic Navigation System and supplement to VOR/DME for domestic en route
• LORAN-C: Domestic interim supplement to VOR/DME
• NDB: Standard for low-use non-precision approaches and ILS outer marker locator
• TACAN: DoD standard colocated at VORs
• Inertial and Doppler: Self-contained systems
• MLS/ILS: MLS to replace ILS

• GPS “...has been shown to have the potential of being part of the future Radionavigation System mix because of its high accuracy and world-wide coverage.”

• Significant Concerns:
  1. Denial of Accuracy (now resolved at 100m 2 drms)
  2. Coverage
  3. Reliability
  4. Integrity
  5. Cost Recovery (now resolved with no special user fee)

• "FAA will continue to examine the potential of GPS as an element of the Civil Navigation System mix."

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A SHORT AND LONG TERM COMPARISON OF LORAN-C AND CIVIL NAVSTAR GPS SIGNAL STABILITIES

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ABSTRACT

Under development by the Department of Defense (DOD) is a navigation system based on radio transmissions from orbiting satellites. This system, called the NAVSTAR Global Positioning System, is scheduled to become the principal navigation system used by the DOD by 1997. The precise positioning military signals will be transmitted with a special code and will not be available for unclassified use. The unclassified civil portion of the system is presently operating without error being purposely added by the DOD control segment. This provides the opportunity to characterize the stability of this portion of the system before intentional error is introduced.

At present, a prototype network of satellites is available for several hours each day. Two receiving systems have been set up at the U. S. Coast Guard R&D Center at Avery Point in Groton, Connecticut to monitor the short and long term stability of Loran-C (NEUS) and the civil signals transmitted by the prototype satellites. This paper presents analysis of the observations made during the period from October 1983 to November 1984. The analysis shows that the short term stability of both systems is similar and that the long term stability of NAVSTAR GPS is better than Loran-C.

INTRODUCTION

The U. S. Coast Guard anticipates that the clear acquisition (C/A) signals transmitted by the NAVSTAR Global Positioning System (NAVSTAR GPS) will eventually be widely used by the maritime community. A research effort has been initiated to evaluate the C/A signal's navigation capability. The DOD does not intend to use the C/A signal for its navigation needs. The primary objective of present research is to determine the capability of the C/A signal and how well it satisfies civil marine navigation requirements in the Coastal Confluence Zone and harbor and harbor entrance areas. This research will become part of the technical base used to support future government policy decisions.

As part of this research, equipment and software have been set up at the U. S. Coast Guard Research and Development Center (R&D). It is used to monitor, record, and analyze the repeatable accuracy of the NAVSTAR C/A signal and (as a reference) the local Loran-C signals. Repeatable accuracy is the ability of a system to provide location information that will allow the user to return to a previously established location. For both systems this can be measured by analyzing the perceived movement of a receiving system at a fixed location. In navigation, accuracy can be defined as absolute, relative, or repeatable. The present work studies the repeatable accuracy of Loran-C and NAVSTAR GPS. Future work at R&D will be concerned with testing the concept of differential NAVSTAR GPS. Relative accuracy will be studied at that time. At the present time, verification of the absolute accuracy of NAVSTAR GPS is not scheduled.

The monitoring, recording, and analysis of signals from both systems will continue into 1985. This paper represents a summary of the observations made during the past year. The information presented is based on the static data recorded. If the reader desires a technical description of the NAVSTAR GPS, the author recommends reference 1. If the reader desires more information concerning the political and policy aspects of the system, the author recommends references 2 and 3.

DESCRIPTION OF SIGNALS

NEUS Loran-C Chain

For several years the Loran-C signals provided by the Northeast U. S. Loran-C chain (GRI=9960) have been monitored and analyzed at R&D. Five transmitters make up the chain. The master (M) station is the Seneca, NY transmitter. The most stable signals are provided by the secondary transmitters at Nantucket, MA (X) and Carolina Beach, NC (Y). All Loran-C position stability in this report is based on this M-X/M-Y combination. The detailed daily analysis also includes the position statistics based on the M-W/M-X and M-W/M-Y combinations (W is the transmitter at Caribou, ME). The stability of the NEUS chain was typical throughout the periods during which experiments were conducted.

Prototype NAVSTAR GPS C/A-code

The prototype NAVSTAR satellite transmits three coded signals on two frequencies. This work analyzes the stability of the C/A code transmitted on 1575.42 MHz. The use of the other two signals would give better results, but they are scheduled to become classified and will be unavailable for civil use when the system becomes operational. Except for equipment malfunctions and scheduled testing, the most accurate C/A signal possible was provided during the past year. There were periods during testing when problems caused the signals to be less accurate than normal. An effort has been made to remove these measurements from the results presented here.

An important policy position maintained by DOD should be kept in mind. As the NAVSTAR GPS becomes operational, the accuracy of the C/A signal will be intentionally degraded. At the time of this writing, DOD plans to degrade the signal so that the family of position determinations in the horizontal
plane has a 2DRMS error of 100 meters. This intentional degradation is referred to as Selective Availability (SA).

In the Loran-C system the transmitters remain at fixed locations and maintain a constant geometric relationship. The hyperbolic lines of position created by the points of constant time difference maintain a somewhat fixed relationship to the earth and can be drawn on a chart much as are the lines of latitude and longitude.

The NAVSTAR satellites are not in geostationary orbits. They are in constant motion relative to the earth. A particular geometric relationship exists for only an instant in time. The receiver uses the satellite signal to calculate the distance to the satellite. The orbital information transmitted by the satellite is used to calculate the position of the satellite. Knowing the position of the satellite and the distance from the satellite creates a "sphere-of-position" in space and the receiver antenna is located somewhere on the surface of that sphere. A three dimensional position is established by the intersection of three such spheres. If the receiver clock provides the exact time, only three satellites are needed to establish a position fix. By using the signal from a fourth satellite, the receiver is able to synchronize its imperfect clock to the satellite time system. The use of computer processor based hardware in the receiver is essential to perform the necessary computations.

The idea of three "spheres-of-position" can be combined with other spheres or lines of position provided by other systems or derived internally by the receiver. This reduces the number of satellites that must be tracked to establish a position fix. The marine user has available a sphere in space called sea level (constant distance from the center of the earth). Maintaining a constant altitude allows the user to establish a two dimensional position fix using three satellites or using two satellites and a very accurate clock.

Fixed Altitude Operation

The objective of this research is to study the use of GPS for marine navigation. As a practical matter, the typical marine user does not change the altitude of his vessel to any great degree. For this reason, the bulk of this work is done with the altitude fixed at a specific value.

With a fixed altitude, two benefits are obtained. First, the GPS can be used when only three satellites are available. Presently, this provides an additional three and one half hours of coverage. Second, the one and a half hour period when only space vehicles 6, 8, 9, and 11 are available is troubled by poor geometry near the middle of the period. Using fixed altitude eliminates the effects of this poor geometry on the position solution. The effect of using fixed altitude is to extend the usable period for GPS coverage to 32% of the day. If use of the system is limited to the times when four satellites are available with good geometry, GPS can be used for about 12% of the day. This difference is significant. This improvement will continue to be available at various percentages until the scheduled full 3D operation in 1989.

A limited number of "altitude sensitivity" experiments were done during the test program. Introducing error into the altitude estimate caused a lesser amount of error to be driven into the horizontal solution. The degree was dependent on the geometry of the satellite and user. The introduction of an error as large as 50 feet into the fixed altitude produced very little error in the horizontal solution. This error was on the order of the noise level of the measurements themselves. GPS user equipment should be designed for fixed altitude operation regardless of the number of satellites being tracked (3, 4, or all-in-view).

**AVAILABILITY OF SIGNALS DURING FY84**

Several changes to the identity and number of satellites available in the prototype constellation were made during the year. These changes were used to designate the end of one R&D experimental period and the beginning of another. Representative data from each of these experiments will be presented later in this paper. A total of three experiment periods have been completed and a fourth one started.

**Experiment 1** began on October 11, 1983 using space vehicles (SVs) 5, 6, 8, 9, and 11. After November 25, 1983, SV 5 was set unhealthy by the control segment (An unhealthy satellite automatically signals the receiver not to use the satellite). Problems with the stabilization system caused the satellite to lose earth lock. Attempts were made in early 1984 to correct this problem without success. SV 5 is no longer available for use.

**Experiment 2** began on November 30, 1983 using SVs 4, 6, 8, 9, and 11. SV 4 was set healthy although operating with only a crystal oscillator. The control segment made frequent uploads to the satellite while it was in view. This was done to minimize the error being introduced into the system because of its unpredictable clock drift. Performance of the C/A signal degraded slightly as a result.

**Experiment 3** began on July 10, 1984 using SVs 6, 8, 9, 11, and 12. SV 13 was a new satellite launched several weeks earlier. It filled the coverage hole created with the loss of SV 5. Since SV 4 was no longer needed, it was set unhealthy.

**Experiment 4** began with the addition of the latest satellite (SV 12) on October 3, 1984. Selection of the orbital position of SV 12 was done based on coverage needs at Yuma, Arizona. The improvement in primary coverage at Groton, Connecticut was not significant. Significant was the creation of a usable secondary (short) coverage period. The conjunction of SVs 6, 9, and 12 can be seen in figure 4. At the present time all the healthy satellites are using atomic clocks (rubidium or cesium). SV 9 has a clock control circuit problem that is causing
random clock jumps to occur.

In addition to the health of the individual satellites, signal availability depends on the user's location, local time of day, time of year, the visible horizon, and the mode of receiver operation. At a fixed location, satellite visibility occurs about 4 minutes and 5 seconds earlier each day. The satellites are in 12 sidereal hour orbits. This is about 2 minutes less than 12 solar hours. The remaining precession is nodal regression due to the earth's equatorial bulge. Figures 1 through 4 are selected plots of the elevation angle of the available satellites on April 22 and October 17, 1984 at Groton, Connecticut and Yuma, Arizona. Note that these two days are about 180 degrees (12 hours) apart in the yearly precession cycle of the primary constellation. The prototype constellation signal availability varies widely throughout the world. This situation must be taken into consideration if use of the prototype system is being considered.

MEASUREMENT SYSTEMS

Overview

Two separate receiving systems with data recording equipment have been set up. The Loran-C receiver is an Internav LC-404 receiver which is used extensively in the Loran-C stability work being done at R&DC. The NAVSTAR GPS receiver was obtained through the facilities of the Joint Program Office. It is a receiver developed by Magnavox called the "SET Z" under a "Phase I" contract. (The author refers to this receiver as the Z-set throughout this paper.)

The measurements made by the receivers are first recorded on magnetic tape. Measurements are recorded for a variety of time periods ranging from three to seven hours. The times are selected to catch the NAVSTAR satellites in their most useful relationship for navigation. The Loran-C signals are available twenty-four hours each day, but data is only recorded for five hours during the heart of the primary NAVSTAR GPS constellation. After data collection is complete, the recorded data is transferred to a Hewlett-Packard 9836 microcomputer system for analysis. Each of the data reports contained in this document was generated using the HP 9836. Where possible, the analysis programs have been written using the Pascal language.

Loran-C Signal Monitor

The Loran-C data is being collected using the basic data collection system developed at R&DC during 1979/80 for the Loran-C Harbor Monitor System project (see reference 5). The heart of the system is an Internav LC-404 controlled by a PCM-12 microcomputer. The data collection software has been designed to provide time difference measurements at an operator selectable interval. Two methods are used to record measurements. The microcomputer continuously requests measurements during the sampling interval. It records both the average value calculated over the interval and the single last reading of the interval. Analysis of both types of data is done on a daily basis. The measurements are recorded on a cassette tape transport (175,000 byte capacity). An external notch and spectrum analyzer have been added to the receiver. They are used to assure reception of clean Loran-C signals.

NAVSTAR GPS Signal Monitor

The Z-set is a C/A code receiver designed and built by Magnavox during Phase I GPS user equipment development. In its original form, it had no data recording ability. To add this ability, an HP-21MX minicomputer with an HP-2644A terminal was interfaced to the main processor of the Z-set under contracts to Magnavox and Texas A&M. The data collection software for the HP-21MX was written at Texas A&M. During late 1983 and early 1984 measurements were recorded on the tape drive portion of the HP-2644A terminal, and the Z-set was initialized by an operator at the start of each satellite pass. During 1984 a PCM-12 was interfaced to the Z-set. It is designed to control the operation of the Z-set and eliminate the need for an operator to be present during data collection. A larger magnetic tape system (16.7 Mbyte capacity) has also been added to the interface between the HP-21MX and HP-2644A. This addition provided the storage needed for extended periods of unattended operation.

Analysis System

All the data analysis and data storage for this work is done on an HP-9836 series computer. The HP-9836 contains 896,000 bytes of RAM, a two-channel DMA controller, an additional HP-IB interface, and a datacomm interface. The mass storage device is the HP-7908P, 16.5 Mbyte Winchester disk with a cartridge tape backup unit. The analysis is printed using the HP-2631G graphics printer or the HP-7470A plotter. All experimental data is loaded into the system through the serial datacomm interface and stored on the Winchester disk. Eventually the data is archived on the cartridge tape backup unit. The analysis programs have been run on both the HP-9836 and HP-9836C computers.

The Pascal language is used to write all the necessary programs for the HP-9836. The programs have been designed to interact with the operator through a series of menus. Three programs have been written to load data into the HP-9836. The program selected depends on which magnetic tape device contains the desired data. (HP-264A mini-cartridge, MPE-5000, or UT2210). Two separate programs are used to analyze the NAVSTAR GPS or Loran-C data. The analysis always works from the original data set. The original data set is never changed. An edit feature built into the analysis programs does allow the removal of selected data points for the purpose of analysis, but this does not affect the original data as recorded.

DATA RECORDED BY MONITOR SYSTEMS

Loran-C Monitor Data

The PCM-12 microcomputer that controls the LC-404 receiver records the NEUS Loran-C time differences in two forms. When the system is initialized, the operator is given the option

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of selecting the time interval between recorded data samples. This value is typically 20 seconds. During each interval, the PCM-12 acquires time difference readings from the receiver at a rate of about one complete set every second. At the end of the interval, the time difference average is calculated for each secondary and recorded on the magnetic tape. In addition, the very last "instantaneous" time difference acquired for each secondary is also recorded on the tape. All four NEUS secondaries are being tracked and recorded, but only the W, X, and Y time differences are analyzed each day. Also recorded on the tape is the Julian day (GMT), GMT time, and the number of samples making up the average values calculated.

**NAVSTAR GPS Monitor Data**

The HP-21MX minicomputer obtains two types of data from the Z-set. They are satellite orbital parameters and antenna position. The current satellite orbital parameters for each healthy satellite listed in the receiver almanac are recorded on magnetic tape each day. The quantity of raw data that is generated during each day's testing is substantial. In terms of the digital storage required, a typical one day set of measurements from the NAVSTAR GPS monitor is 160,000 bytes, and the data from the Loran-C monitor is 130,000 bytes. The analysis of the data is done within a variety of time frames. The shortest being the use of a single satellite constellation. The longest period spans the entire test program. The figures in this report are a sampling of those created to summarize the recorded measurements.

Appendix A gives a detailed view of the analysis done on the measurements recorded during the October 17 test. This type of analysis is performed on each set of measurements. Thus far, over 200 similar data sets have been recorded and analyzed.

Representative data from each of the four experiment periods has been provided. Figures 9, 10, 11, and 12 show the resulting latitude and longitude plots for both GPS and Loran-C recorded on November 21, 1983. This is the same data set used in reference 4. It is representative of good experiment 1 data. In a similar fashion, samples of experiment 2 and 3 measurements are shown in figures 13 through 20. A similar set of results from experiment 4 can be found in figures A-8, A-10, A-28, and A-29.

The Loran-C data in all of these figures is from the "AVL" family of data. All the data in this family is averaged over the "sample interval". This averaging tends to reduce rapid measurement to measurement changes. Compare figure A-24, which is made up using instantaneous measurements, with figure A-28, which is made using averaged measurements. Although this measurement to measurement noise can be reduced by changing the reception and recording methods, the hour to hour variations are not affected. As an example look at figures A-24 and A-28. The "bump" at about 18h 30m GMT is visible in both curves. The "measurement to measurement" and "hour to hour" changes are the two types of short term noise being referred to in this paper.

**RESULTS OVER DAILY PERIODS**

As pointed out in Appendix A, the Z-set selects the satellites that are used to determine position. Although the operator cannot select the satellites, some options on how the Z-set uses the satellites are available. They are "fixed altitude", "fixed altitude with 3 satellites", and "fixed altitude". The mode "fixed altitude off" only allows navigation when four or more satellites are available. It provides...
altitude, latitude, longitude, and time solutions. The "fixed altitude with 3 satellites" allows navigation with only three satellites when the user provides altitude information. When four or more satellites are available, the user provided altitude is not used, and the solution is the same as that obtained with "fixed altitude off". These two modes have not been used very often throughout the test program. The bulk of data collection has been done with the 3-set in the "fixed altitude" mode.

In the "fixed altitude" mode, an operator enters the known altitude of the antenna, and thereby establishes a constant "sphere-of-position". In this mode the 3-set can navigate with only three satellites. If a fourth satellite is available, it is also used along with the known altitude and an "over determined" navigation solution results. Essentially the four range measurements are used to find latitude, longitude, and time (four equations with but three unknowns). The greatest benefit to using this seems to be "more information than is needed", during the daily operation of the prototype system, is to significantly reduce the effects of the bad geometry that sometimes exists.

For example, during a typical "Experiment 4" primary pass, the length of time, that only four satellites are available, is about two hours and ten minutes. For a major portion of the SV 6-8-9-11 constellation (Figure A-4) the geometry of the satellites becomes poor and the navigation solution degrades. Use of fixed altitude eliminates the effects of this geometry problem. Even when the geometry is good, as it is for the last four satellite constellation SV 9-11-12-13, small position fluctuations are reduced by using a fixed altitude.

The minimum GPS solution for the marine user is fixed altitude and three satellites. The minimum Loran-C solution is one pair of time difference measurements. The reader may compare the performance of the two systems in a variety of ways. In this paper the author has chosen to compare the best pair of Loran-C time differences (M-X/M-Y) with the fixed altitude solution. The statistics of the present fixed altitude four satellite solution are probably very close to the optimally fixed altitude three satellite solution of a fully operational GPS. That is, if the C/A signal is not degraded by the introduction of selective availability.

Figures 9 through 20 are presented in such a way that the reader can compare the short term Loran-C and GPS latitude and longitude stability. The data sets presented are typical samples of those acquired during each of the three experiment periods. A similar set of plots can be found in Appendix A. Figure A-8 can be compared to A-28, and A-10 can be compared to A-29.

The Loran-C longitude variation (Figures 12-16, 20, and A-29) consistently contains the least amount of short term noise. The Loran-C latitude variation contains about the same amount of short term noise as the GPS latitude and longitude, but the average position moves about significantly. This gross movement in position will be discussed in the next section.

Both the Loran-C and GPS position variations move smoothly about an average value. The average GPS position seems to depend on the satellites being used. The same situation exists for the Loran-C if the user changes the secondaries being used. In the case where repeatable accuracy is of interest, the Loran-C user can always select the same pair of secondaries. The GPS user must use the satellites available at any arbitrary time. A specific set of satellites is available for only a limited portion of the day. And even then, the geometry of the satellites is constantly changing.

Fortunately, the jumps in the average position from one satellite constellation to another are often not very large. These jumps are caused by parametric changes to the equations providing the position solutions. The parameters that change are provided by the satellites. A more detailed discussion of how this can happen is provided in Appendix A under the "Figure A-8" description. Jumps in the Loran-C position are smaller in magnitude and are often covered up in the noise of the solution. These jumps are caused by adjustments made to the transmitters.

The measurement to measurement variations in both the Loran-C and GPS data seems related to internal receiver operations and noise and not due to variations in the navigation signals. The large variation in the Loran-C data are most likely due to radio interference and noise. The GPS variation spikes occur as the 2-set temporarily uses an almanac orbital data to calculate the newly acquired satellite position before the new ephemeris has been received from that satellite.

The gentle drifting of the Loran-C position solutions are due to slow changes in the frequency of the cesium oscillators at the transmitters and changes in the speed of light with time over the propagation path. The change in the speed of light is primarily caused by changes in atmospheric conditions. The gentle drifting of the GPS solutions are due to unmodeled changes in the satellite orbits or clocks. Some of the GPS drift is due to the constantly changing propagation path between the satellite and the user.

The sample data sets that have been provided span a period of about fourteen months. The analysis has shown that the stability of both the NAVSTAR GPS and Loran-C system signals is about equal. This result has been reinforced by a second additional set of data collected. The analysis also shows that both systems are performing significantly better than their advertised stability. Each system has its own unique sources for major errors. Throughout the data collection and analysis, we have not been able to detect any major source of error that affects both systems in a similar way.

Within the boundaries of good Loran-C coverage, a modern Loran-C receiver, that is properly installed and operated, should provide short term repeatable accuracy equal
to similar NAVSTAR GPS C/A code equipment. In these same areas at the present time, Loran-C provides the superior coverage and reliability. During our tests, the Loran-C signals were always available and of consistent quality. Because the prototype NAVSTAR satellites are still being used for testing, position data was extremely poor or non-existent on occasion. The GPS must be used with extra caution during this phase of prototype operation.

**RESULTS OVER FY84 PERIOD**

The short term repeatable accuracy of both Loran-C and NAVSTAR GPS has been found to be about equal. Taking the average positions calculated during each test period, figures 5, 6, 7, and 8 were created. To give the plot of average position more substance, a line rather than a dot was drawn centered on the average variation for each of the test periods. The length of the line was adjusted to be two standard deviations long. The standard deviation is calculated for each data set along with its average (see figure 4). Some of the results give a good feeling for the long term stability of the latitude and longitude as well as an idea of how uncertain the average value is.

During January, February, and March, the Z-set was being modified for unattended operation. Final testing was completed in March. Neither GPS nor Loran-C data was recorded during this period. Data sets collected during GPS control segment testing, satellite malfunctions, and R&D Center Z-set testing were not used in constructing these figures.

The Loran-C seasonal variation is most obvious in figure 6. A partial picture for the 83/84 winter can be seen as well as the beginning of the 84/85 winter shift. This figure depicts the position stability of Loran-C over the long term. The magnitude and timing of the "position migration" depends on geography and geometry. Figure 8 shows the longitude stability. In this dimension Loran-C seems to demonstrate very good long term stability with little sensitivity to conductivity and atmospheric changes. Remember that these results are not general. They are true only for a Loran-C user in the area of Groton, Ct. using the NEUS chain M-X/H-Y time differences. The stability in longitude is due to the fact that the Loran-C system area monitor at Sandy Hook, N. J. is seeing similar seasonal variations on the M-X time difference and causing them to be adjusted out.

Seasonal variations, or any other long term variation, in the GPS position are not apparent in figure 5 or figure 7. If there is a long term variation, its magnitude is much less than the shift that Loran-C experiences. The stability of the GPS position also points out the ability to add and remove satellites without significantly affecting the overall performance. The GPS position data collected during October 1983 was done using SVs 5, 6, 8, 9, and 11. By November 1984, 1985 prototypes, satellites being used were SVs 6, 8, 9, 11, 12, and 13 which represents an overall change of three satellites. This lack of long term drift makes the long term repeatable accuracy of NAVSTAR GPS better than Loran-C.

**EARLY RESULTS USING SECONDARY GPS PASS**

The latest addition to the prototype GPS satellite constellation is NAVSTAR 10 (SV 12) which was added on October 3, 1984. Because our interest in marine navigation allows the use of only three satellites, this addition created a second time period for additional independent observations (see figure 4). NAVSTAR satellites 3, 6, and 10 (SVs' 6, 9, and 12 respectively) provide a three satellite constellation about five hours after the primary grouping of satellites. The geometry of this constellation does not degrade during the last half hour that it is available, but it is good for about the first hour.

This secondary pass provides an additional opportunity to measure the repeatable accuracy of GPS. From October 7 to October 31, 1984 measurements were made during eleven secondary passes. The results for October 18, 1984 are shown in figures A-1, A-2, A-3, A-4, A-5, A-6, A-7, A-8, A-9, A-10, A-11, A-12, A-13, A-14, and A-15. Of the eleven days, these results are the best in terms of minimum standard deviation and average variation from the reference position.

The overall variation in position was averaged for the eleven data sets. This average varied 1.7 meters to the north and 16.6 meters to the west. By comparison, the variation in position was averaged for the corresponding four satellite position measurements taken during the primary pass. For the same eleven days this average varied 2.6 meters to the north and 3.0 meters to the west.

This test serves to demonstrate the absolute and relative variations in position that are not apparent in the primary pass. The major changes include the parameters being transmitted by each satellite that describe the satellite orbit and clock drift, the geometric relationship between the user and the satellites, and the variation in the ionosphere from day to day. The closeness of these independent measurements serves to improve user confidence in the internal consistency and accuracy of the GPS system.

**SUMMARY/CONCLUSIONS**

This report provides a comparison of the repeatable accuracies of the electronic navigation signals provided by Loran-C and prototype NAVSTAR Global Positioning System. This comparison is done using measurements made at the U. S. Coast Guard R&D Center from October 1983 to November 1984. Both the short and long term stabilities are presented. A detailed analysis of the measurements made on October 17, 1984 is also presented. The short term stability is measured over a five hour period each day during which both Loran-C and GPS are concurrently available.

The short term stability of the present prototype NAVSTAR GPS is found to be similar to the present Loran-C signals. In areas of good Loran-C signal strength and geometry, the short term Loran-C stability is
better than GPS. Over the long term, the stability of GPS is better than Loran-C and very much similar to its own short term stability. NAVSTAR GPS does not appear to have any significant seasonal variations. The seasonal variations in Loran-C make it less stable than GPS over the yearly cycle.

The long term stability of the GPS signals also demonstrates the ability of the systems control segment to maintain system accuracy despite changes to the system. During a year of observations, several satellite additions and deletions were made to the system. The calculated position continued to remain constant despite these changes.

The use of fixed altitude operation has demonstrated an improvement in performance that is attractive for marine navigation. Forcing the solution to a known altitude improves the stability of four satellite navigation and makes it possible to navigate using three satellites with slightly reduced stability. Fixed altitude operation should always be used in marine GPS receivers for 3, 4, or “all-in-view” satellite tracking strategies.

The stability analysis provided in this report is for single frequency (L1) uncontaminated C/A code GPS. Recent policy statements by DOD indicate that this performance is better than what will be provided by the completed system. Plans are to degrade C/A code stability to 100 meters 2DRMS horizontal error. This single source of error is significantly larger than the errors observed in the prototype system. If GPS is purposely degraded, its short term stability will be significantly worse than Loran-C. In that event, it may be necessary for marine navigation systems to use Loran-C to provide short term stability and NAVSTAR GPS to provide long term accuracy. Such a combination system should be capable of overall performance better than either system used alone.

ACKNOWLEDGEMENTS

The author wishes to thank Mr. Lee Luft, Mr. Kenneth Vaccaro, Mr. Michael McKaughan, and CW2 Gary Soula for their efforts as members of the GPS project team. Their diligent work and attention to detail resulted in the combination of hardware, software and analysis needed to produce the information contained in this report. Without their contributions, this report would not be possible.

REFERENCES

2. "Civil Use of the NAVSTAR Global Positioning System" (two volumes), National Security Industrial Association, Washington, D.C.
Figure 1. Elevation angle of NAVSTAR satellites visible at Groton, Connecticut during primary pass October 17, 1984. (time axis, 1 GMT hour/int.)

Figure 2. Elevation angle of NAVSTAR satellites visible at Yuma, Arizona during primary pass October 17, 1984. (time axis, 1 GMT hour/int.)

Figure 3. Elevation angle of NAVSTAR satellites visible at Groton, Connecticut during primary pass April 22, 1984. (time axis, 1 GMT hour/int.)

Figure 4. Elevation angle of NAVSTAR satellites visible at Groton, Connecticut during secondary pass October 17, 1984. (time axis, 1 GMT hour/int.)
Figure 5. Variation in average latitude position calculated using 4 NAVSTAR satellites. Each sample period average is plotted using a line length $+/-$ one standard deviation of the sample set.

Figure 6. Variation in average latitude position calculated using Loran-C NEUS M-X/M-Y time differences. Each sample period average is plotted using a line length $+/-$ one standard deviation of the sample set.
Figure 7. Variation in average longitude position calculated using 4 NAVSTAR satellites. Each sample period average is plotted using a line length +/- one standard deviation of the sample set.

Figure 8. Variation in average longitude position calculated using Loran-C NEUS M-X/M-Y time differences. Each sample period average is plotted using a line length +/- one standard deviation of the sample set.
Figure 9. Latitude variation from reference and latitude dilution of precision using GPS C/A signals. (November 21, 1983)

Figure 10. Longitude variation from reference and longitude dilution of precision using GPS C/A signals. (November 21, 1983)

Figure 11. Latitude variation from reference using averaged Loran-C NEUS M-X/M-Y time differences. (November 21, 1983)

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Figure 13. Latitude variation from reference and latitude dilution of precision using GPS C/A signals. (December 20, 1983)

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Figure 15. Latitude variation from reference using averaged Loran-C NEUS M-X/M-Y time differences. (December 20, 1983)

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Figure 17. Latitude variation from reference and latitude dilution of precision using GPS C/A signals. (July 19, 1984)

Figure 18. Longitude variation from reference and longitude dilution of precision using GPS C/A signals. (July 19, 1984)

Figure 19. Latitude variation from reference using averaged Loran-C NEUS M-X/M-Y time differences. (July 19, 1984)

Figure 20. Longitude variation from reference using averaged Loran-C NEUS M-X/M-Y time differences. (July 19, 1984)
APPENDIX A
DAILY ANALYSIS OF NAVSTAR GPS AND LORAN-C MEASUREMENTS

This appendix contains portions of the results obtained from the analysis of NAVSTAR GPS and Loran-C data collected on October 17, 1984. Figures A-1 through A-29 are graphs and numeric summaries for that day. These figures capture the spirit of the stability characterization analysis of a "typical day's data. An effort has been made to present the data so that both systems can be compared using a common reference system.

Figures A-1 through A-3 deal with the detailed numeric results of the analysis. Figures A-4 through A-29 are point by point presentations of measured and calculated parameters. Each of these figures is described below. The actual daily analysis contains more of the graphic presentations as well as information supplied by the NAVSTAR GPS control center at Vandenburg AFB. The information supplied by the control center plays an important part when the data collection is not "typical" and an attempt is made to determine what happened during the test.

The graphs contained in figures A-4 through A-29 use the same general format. Each graph is titled with the name of the data set used in calculating the value of the parameter being plotted. Take as an example figure A-4. The "AV" in "AVG291.84" represents the location where the receiver was set up. In this case it is Avery Point, Groton, CT. The third letter ("G") indicates that this is the data from the 2-set/21MX NAVSTAR GPS receiver. An "L" would represent averaged Loran-C data, and an "I" represents instantaneous Loran-C data. The number before the decimal point is the Julian day that the data was collected. As an arbitrary convention, the Julian GMT (UTC) day that is selected is the one in which the sidereal time 18:00 occurs. The number following the decimal point is the last two digits of the Gregorian year of the selected Julian day.

In all cases, except for "scatter plots", the horizontal axis is time. The lowest horizontal grid is marked off in sidereal time. The uppermost horizontal grid is marked off in GMT (UTC) time. This drifts to the right a little over 4 minutes each day. The time of each satellite constellation change is indicated by a vertical dashed line. The identification of the satellites making up the constellation is shown to the right of the dashed line.

The left vertical axis is labeled with the principal data plotted on the graph. In the latitude variation plots, the distance from the reference position increases in the north direction (increasing latitude). In the longitude variation plots, the distance from the reference position increases in the east direction (decreasing longitude). This is done to maintain the local right hand grid system of "east-north-up". The right vertical axis is labeled with the secondary data contained on the plot. This feature is not always used.

Figure A-1
The GPS position supplied by the combined 2-set/HP-21MX system is based on an Earth Centered Earth Fixed (ECEF) coordinate system. Each position is convected to latitude, longitude, and altitude by the analysis system. Using an arbitrary reference position established in the Fall of 1983, the average position shift and its standard deviation are calculated for each of the satellite constellations used during the data recording period. Numeric results for two satellite operation are not calculated. The groupings for combined data sets (3, 4, and 3+4 SVs) are separate calculations using the original data sets and not combinations of the previous separate constellation statistics.

A few comments about "Maximum Variation from Mean" are necessary. These two numbers represent the peak excursions of the data set from the mean (average) value of that particular data set or subset. It is not the excursion from the reference position. As an example that will also serve to clarify another point, look at the radial error for SVs 6, 8, and 11. The horizontal radial error is the distance from the reference position to the measured position. This value is always positive. The "Low Maximum Variation from Mean" is always a negative number. In this case it represents the single measurement that came closest to the reference position. Here the mean radial error is 15.1 meters, and the low maximum variation from the mean is -13.6 meters. It can be correctly interpreted that at least one of the 257 measurements in this data set came within 1.5 meters of the reference position.

The 2-set selects the satellites that will be used at any given time. The receiver takes into account the geometry of the available satellites and the past performance of the satellites. The operator cannot control the satellites that should be used or not used.

Figure A-2
Each day the particulars of the equipment settings are noted in a test almanac. In interim reports about this test, this section will include opinions and comments about this test and its relationship to the general trend of recent or subsequent tests. It may also bring attention to special conditions concerning either NAVSTAR GPS or Loran-C system operation.

Figure A-3
The Loran-C time difference measurements are recorded two ways. The recording processor adds the time difference measurements obtained from the receiver as quickly as they become available for the sample interval (here it is 20 seconds). At the end of the sample interval, both the average and the last receiver measurements for each time difference are recorded. The analysis is then done separately on both the averaged and sampled data sets.
The time difference statistics are calculated directly from the raw data. The average time difference for the five hour period tends to be the same for both the averaged and sampled data sets. The standard deviations and peak to peak variations tend to be larger for the single measurement data.

Each combination of two time differences taken at the same time creates a position measurement relative to the established time difference reference point. Using time difference to distance and direction parameters provided by the USCG EEE-10 computer program, each pairing of time difference measurements (W-X, W-Y, and X-Y) is converted to a position relative to the reference time differences in an east-north grid. An actual Loran-C derived "latitude" and "longitude" position is never calculated. The various statistics of these three relative position grids are calculated and listed. This set of calculated positions becomes the data base for the various position plots shown in the later figures.

Both the averaged and sampled data are analyzed and presented in this figure. The analysis is presented in the same format as the GPS analysis in figure A-1. Also, an analysis of the data in the time difference domain is included. The time difference and position calculations are done separately using the original measurement data each time. Neither of these results are calculated from the other.

Figures A-4 through A-7

Early in each test the almanac of orbital parameters being broadcast by the NAVSTAR satellites is acquired and recorded. These orbital parameters help the z-set determine which of the satellites should be used at any particular time for navigation. These same parameters are used by the analysis program to calculate the local azimuth (0 degrees = north) and elevation (0 degrees = horizon) of each satellite during the test period. Each curve is identified with the SV number of the satellite (NAVSTAR 3 = SV6, NAVSTAR 4 = SV8, NAVSTAR 5 = SV9, NAVSTAR 6 = SV11, NAVSTAR 9 = SV13, and NAVSTAR 10 = SV12).

Until the launch and activation of NAVSTAR 10, the prototype constellation was only usable during the "primary" constellation. With the addition of NAVSTAR 10 and the use of "fixed altitude" receiver operation, a "secondary" constellation period has been created. As will be seen in later figures, this constellation can be used for navigation.

During those periods when a particular satellite is "in view" but is not being used in the solution, the elevation and azimuth plot lines are a dotted line. When the satellite is being used, the line is solid.

The GDOP calculated for the four satellites in use plus fixed altitude is plotted for the respective time intervals in both figures A-4 and A-5. This calculation is done by the analysis program based on geometry and it does depend on the receiver altitude mode. If the z-set has fixed altitude ON, the GDOP will be calculated for the periods with three satellites as well as four satellites. The four satellite GDOP will be lower than that calculated for the same satellites with the altitude not fixed. In the fixed altitude OFF mode, the GDOP is not calculated for the three satellite periods.

Figure A-8

Latitude variation is equal to the measured latitude minus the reference latitude. This plot shows how a static receiver appears to move in the north-south direction over time due to various error sources. It is worth remembering that the receiver is "static" only in the reference system (ECEF) used by NAVSTAR GPS. In fact, the receiver and satellites are moving in both time and space varying electromagnetic and gravity fields as the earth rotates and orbits the sun.

The close cooperation needed between the GPS control segment and the user equipment designer and how they can influence the overall system performance, as seen by the user, can be shown in this figure. It has to do with the drift prediction of the satellite clocks and satellite orbital predictions and how changes to these parameters can impact the position solution.

Early in each primary pass the latest estimates of the satellite orbit and clock drift are uploaded from the control segment to each satellite. It is this information that is broadcast by the satellite to the user equipment. Each receiver uses these parameters to calculate position.

At the beginning of this test on 17 October, the z-set began by tracking SVs 6, 8, and 11. These being the only visible healthy satellites (see figure A-4). From the daily control segment report we learned that the most recent update of orbital and clock parameters had occurred on 16 October at 17:15, 17:25, and 18:25 sidereal for SVs 6, 8, and 9 respectively. Therefore, the z-set began navigating at 17:05 sidereal on 17 October using the orbital data uploaded to the satellites 24 hours earlier on 16 October.

The 17 October uploads to SVs 6 and 8 occurred at 17:15 sidereal, and to SVs 9 and 11 at 17:46 sidereal. The z-set is a single channel time multiplexed receiver. The process of tracking satellites and calculating position does not include the continuous monitoring of each satellites data message. That function is only done when the z-set determines that it "needs" an update. So, even though the satellites began broadcasting new orbital parameters, the z-set wasn't listening! Therefore, the position solution during the three satellite constellation of 6-8-11 was based on the 16 October parameters uploaded about 24 hours earlier.

At 18:09 sidereal the z-set acquired and began tracking SV 9. This was after its 17:46 sidereal upload. It would seem then that the first four SV solution (6-8-9-11) is based on three sets of parameters over 24
calculated position to the west to be negative. This position is plotted east to be positive and variations to the different and the position measurement. This is due to the geometry of the transmitters remaining constant in the Loran-C system, but the direction of the ellipse axis does not depend on how the latitude variation is calculated.

These position scatter diagrams are similar to figure A-9. They provide a picture of how large an area is covered by the positions calculated using measurements from each secondary pair. Note that the pattern is quite elliptical in some cases. This is due to the geometry of the solution and correlation of the noise contained in the measurements. This error ellipse occurs in the GPS scatter plots, also, but it tends to "smudge" out because the geometry of the transmitters is constantly changing. The geometry of the transmitters remains constant in the Loran-C system, but the direction of the ellipse axis does depend on the combination of transmitters being used in the solution.

Figure A-18, A-22, and A-26

The longitude component of the static Loran-C receiver position measured using each combination of secondary pairs is plotted with east being positive. The longitude variation is calculated in a manner similar to how the latitude variation is calculated.
The value noted along the right vertical axis is the average variation of the position from the reference position.

**Figure A-19, A-23, and A-27**

The actual time difference measurements for each secondary versus time are also provided. Many Loran-C receivers present their information in the form of time difference. Many people find these plots of interest. A line the length of the plot marks the reference value of the time difference. The value of this reference line is printed along the right vertical axis in microseconds. The left vertical axis is labeled only with the hundreds of nanoseconds. The total time difference value can be figured out by using the reference line. For example, the lowest horizontal axis in figure A-19 represents a time difference of 14699900 nanoseconds. The top horizontal axis represents 14700400 nanoseconds.

**Figure A-28 and A-29**

All of the Loran-C data presented in the other plots consisted of single measurements taken from the receiver during each sample interval. In addition, a complete set of measurements was recorded using the average value provided by the receiver during each sample interval. The resulting plots of this data are quite similar to the plots using the sampled values. As an example, the calculated latitude and longitude variations using the averaged measurements for the X and Y secondaries are provided here. Figure A-28 can be directly compared with figure A-24 and figure A-29 can be directly compared with figure A-26. The general character of the position drift with time is the same in both pairs of figures. The sampled measurements only seem to be noisier.

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**STATISTICAL REPORT FOR NAVSTAR GPS DATA RECORDED DAY 291 YEAR 1984**

Summary of latitude and longitude position calculations using the WGS-72 sea level average latitude of 41.316811 degrees North and the average longitude of 72.063733 degrees West. (with data outliers removed)

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</tr>
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<td>Longitude</td>
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<tr>
<td>Altitude</td>
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<tr>
<td>Radial Error (horiz.)</td>
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**Figure A-1. Statistical report for NAVSTAR GPS C/A signal position data for October 17, 1984. Summary grouped according to satellites used in position solution. (fixed altitude ON)**
Figure A-2. Summary of monitor equipment conditions and position reference points for test conducted October 17, 1984.

Figure A-3. Statistical report for Loran-C position data for October 17, 1984. Summary grouped by sampling method.
Figure A-4. Elevation angle of NAVSTAR satellites and geometric dilution of precision for selected satellites. (primary pass, 17-OCT-84)

Figure A-5. Elevation angle of NAVSTAR satellites and geometric dilution of precision for selected satellites. (secondary pass, 18-OCT-84)

Figure A-6. Azimuth angle of NAVSTAR satellites versus time. (primary pass, 17-OCT-84)

Figure A-7. Azimuth angle of NAVSTAR satellites versus time. (secondary pass, 18-OCT-84)
**Figure A-8.** Latitude variation from reference and latitude dilution of precision using GPS C/A signals. (primary pass, 17-OCT-84)

**Figure A-9.** GPS fixed position "scatter plot" using 4 satellites. (primary pass, 17-OCT-84)

**Figure A-10.** Longitude variation from reference and longitude dilution of precision using GPS C/A signals. (primary pass, 17-OCT-84)

**Figure A-11.** Radial horizontal position error from reference and horizontal dilution of precision using GPS C/A signals. (primary pass, 17-OCT-84)
Figure A-12. Latitude variation from reference and latitude dilution of precision using GPS C/A signals. (secondary pass, 18-0CT-84)

Figure A-13. GPS fixed position "scatter plot" using 3 satellites. (secondary pass, 18-0CT-84)

Figure A-14. Longitude variation from reference and longitude dilution of precision using GPS C/A signals. (secondary pass, 18-0CT-84)

Figure A-15. Radial horizontal position error from reference and horizontal dilution of precision using GPS C/A signals. (secondary pass, 18-0CT-84)
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Figure A-17. Loran-C fixed position "scatter plot" using single NEUS M-W/M-X time differences. (17-OCT-84)

Figure A-18. Longitude variation from reference using single Loran-C NEUS M-W/M-X time differences. (17-OCT-84)

Figure A-19. M-W time difference variation from reference using single measurements. (17-OCT-84)
Figure A-20. Latitude variation from reference using single Loran-C NEUS M-W/M-Y time differences. (17-OCT-84)

Figure A-22. Longitude variation from reference using single Loran-C NEUS M-W/M-Y time differences. (17-OCT-84)

Figure A-21. Loran-C fixed position "scatter plot" using single NEUS M-W/M-Y time differences. (17-OCT-84)

Figure A-23. M-Y time difference variation from reference using single measurements. (17-OCT-84)
Figure A-24. Latitude variation from reference using single Loran-C NEUS M-X/M-Y time differences. (17-OCT-84)

Figure A-25. Loran-C fixed position "scatter plot" using single NEUS M-X/M-Y time differences. (17-OCT-84)

Figure A-26. Longitude variation from reference using single Loran-C NEUS M-X/M-Y time differences. (17-OCT-84)

Figure A-27. M-X time difference variation from reference using single measurements. (17-OCT-84)
Figure A-28. Latitude variation from reference using averaged Loran-C NEUS M-X/M-Y time differences. (17-Oct-84)

Figure A-29. Longitude variation from reference using averaged Loran-C NEUS M-X/M-Y time differences. (17-Oct-84)
SESSION II
THE AVIATION ENVIRONMENT

SESSION CHAIRMAN
Mr. William Polhemus
SESSION II SPEAKERS

Robert Erikson

Robert W. Lilley

Kristen J. Venezia

Daniel C. Slagle

Janis Vlcans

62
EVALUATION OF LORAN C NAVIGATION FOR NON-PRECISION APPROACHES

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ABSTRACT

Many airports in the United States are unable to support approaches during poor visibility because they lack landing aids. The lack of landing aids is generally due to insufficient aircraft activity at an airport to justify the expense of installing an instrumented landing system (ILS) or the airport's location with respect to existing navigation aids is not correct to establish an approved approach. Loran C provides a method to conduct nonprecision approaches to airports without the need to install a landing aid at the airport. Due to the potential benefit, the Federal Aviation Administration (FAA) is investigating the approval of Loran C receivers for nonprecision approaches. The evaluation used Loran C receivers from Advanced Navigation Inc., Micrologic Inc., Teledyne Systems Co., and Texas Instruments Inc. Flights were conducted at six airports across the continental U.S. to evaluate the effects of geometric dilution of precision (GDOP), signal-to-noise ratio (SNR), and envelope-to-cycle deviation (ECD). From the test results, establish limits for GDOP, SNR, and ECD that will determine areas where Loran C should be approved for nonprecision approaches. Methods to improve Loran C accuracy were to be investigated.

Results of the tests indicate: (1) area calibration is necessary to meet the accuracy requirements, and (2) use of area calibration only affects the mean of the position errors. Variation of the position errors is a function of geometry and time difference variation. When operated within the proper GDOP using area calibration Loran C can meet the accuracy requirements for nonprecision approaches.

INTRODUCTION

The objective of this project was to provide an input for developing an Advisory Circular (AC) and a National Standard for Loran C nonprecision approaches. The following key issues were to be evaluated:

1. Minimum signal in space requirements such as geometric dilution of precision (GDOP), signal-to-noise ratio (SNR) and envelope-to-cycle deviation (ECD).
3. Procedures required to ensure proper and safe Loran C operations.

Several documents have been written which must be used as guidelines. These documents describe the accuracies required for an area navigation system to be approved for nonprecision approaches, procedures for instrument approaches based on these accuracies, and, recently, the use of Loran C in the U.S. National Airspace System. The documents are:

3. AC 20-121, Airworthiness Approval of Airborne Loran C Systems for Use in the U.S. National Airspace System.
4. FRP, DOD-4650.4 parts 1 to 4, DOT-TSC-RSPA-18-12, 1 to 4.

When evaluating any new navigation system for approval many factors must be examined. Certainly of prime importance is the accuracy achievable for the navigation equipment, the pilots ability to follow course guidance, and the aircraft position with respect to the desired track. Not visible to many people is the impact of such an approval on the entire National Airspace System, which must be considered. For example, one of Loran C's most attractive features is the ability to make nonprecision approaches to airports that to date were unable to qualify for any other approach aid. In order for a nonprecision approach to be certified, an approach plate must be generated. A unique approach plate is generated for each runway. The approach plate identifies the waypoints to be used, the altitude for each segment of the approach, the procedures to follow if the runway is not visible when at the decision point or if the landing aid guidance is lost, and, finally, the minimum visibility and ceiling required for an approach. Obstructions such as
mountains, bridges, tall buildings, and towers affect the altitudes and approach paths for a given runway. It is the job of a procedures specialist to follow established regulations to design an approach which has the necessary distance above or around obstructions. The procedure specialist generally uses obstruction charts which define the height and position of all known obstructions. Obstruction charts are produced after the need for an approach is established. Other methods have been used but require the gathering of obstruction data from existing geologic maps and field work. Requirements for reviewing existing published approaches keep these people busy. The addition of many new Loran C nonprecision approaches could cause an overload if all had to be generated at once. If the approaches are to be phased in, what guidelines need to be established?

Another concern is the need for weather reporting facilities at a Loran C approved nonprecision approach airport. Air taxi operators and commercial operators operating under Part 135 of the Federal Air Regulations require authorized weather reports from the destination airport and an alternate before starting an IFR flight. No pilot may begin the final approach segment without the latest weather report. Regulation for private civil aircraft are less stringent. Included in the weather report are visibility, ceiling, the barometric altimeter setting, and winds. If approaches are to airports without established approach plates, it is very likely no authorized weather reports will be available. Can the requirements be relaxed or who will be responsible for the purchase, installation, and operation of the equipment?

Also of great concern is integrity! Questions which continue to surface are: what happens to the position accuracy and pilot workload if a Loran C station in the position solution is lost? What is the affect if the station loss is only a momentary? How susceptible are the receivers to acquisition on the wrong cycle or cycle slip? How stable is the Loran C grid at an airport as a function of the various seasons? What type of blunder errors are possible using a Loran C receiver? What parameters need to be annunciated? How much time can be allowed between the loss of a station or similar fault and the lighting of a warm or advise annunciator? Should a Loran C monitor be required at each airport?

In the proceeding text many issues were presented which must be addressed by policy, flight standard, and procedure specialists which are beyond the scope of this project. When evaluating Loran C for nonprecision approaches, AC 90-45A must be used as a reference. The AC budgets navigation along-track and crosstrack errors at 0.3 nmi with 95 percent probability. Flight technical error is budgeted at 0.3 nmi with 95 percent probability. Total system crosstrack (TSCT) error is budgeted for 0.6 nmi with 95 percent probability and total system along-track error for 0.3 nmi with 95 percent probability. Flight technical error is only included in the crosstrack component and not the along-track component. Figure 1 shows a graphic representation of these errors. Navigation equipment errors are the difference between the Loran C indicated position and the actual position of the aircraft. Navigation equipment errors are divided into crosstrack and along-track components. Before along-track and crosstrack components can be calculated, a desired track must be established using two waypoints. The difference between the actual aircraft position and Loran C indicated position which is parallel to the desired track is known as along-track error, while that perpendicular is known as crosstrack error. Total system crosstrack is the perpendicular distance between the desired track and the actual position of the aircraft. Flight technical error is a measure of the pilots ability to follow course guidance displayed on a course deviation indicator. Flight technical error is measured by recording the information displayed on the course deviation indicator.

Loran C has several types of errors which must be accounted for. It is well known that the location of the Loran C receiver with respect to the master and two secondaries will determine the gradient of each time difference (TD) and the crossing angle. The gradients and crossing angles in conjunction with TD variation will cause the position fixed to vary and, therefore, affect accuracy. TD variation is due to variations in the propagation velocity of the transmitted signal, noise, and changes in the emission delays of the secondaries. Emission delays of the secondaries are changed by the U.S. Coast Guard to maintain a control time difference at the system area monitor. The Loran C receiver may also add variation to the time differences with time delays, precision, and filtering included in its TD measurement and processing. TD variations may be evaluated over many different time periods. The long term seasonal effect takes a year to complete one cycle. To a Loran C receiver, during an approach of only about 10 minutes, the seasonal effect looks like a constant bias. The bias must be corrected using an area calibration value to make the reference time difference measured at one season agree with the currently measured TD. It is the short-term TD variations that will cause the Loran C indicated position to vary. Current airborne Loran C receivers include coordinate converters. The coordinate converter changes TD's to geodetic position and geodetic position to TD's. Each coordinate converter must use a propagation velocity and emission delay. The value used for the propagation velocity varies from a single fixed value to one that is dependent on the path between the transmitter and receiver. Because the propagation velocities and emission delays are only estimates of the actual values, difference between calculated and measured TD will exist. The area calibration value can be used to reduce these errors. Position error variations may also be affected by the coordinate converters conversion rate, resolution, and filtering.
To evaluate the performance of current airborne receivers, equipment from four different manufacturers were flown at six airports. The receivers were chosen to represent a cross-section of receivers available at the beginning of the project. The receivers used were an Advanced Navigation Inc. ONI-7000 (612 each), Micrologic ML-4000, Teledyne TDL-711 and TDL-711A, and Texas Instruments TI-9100. The six airports were chosen to represent various geometries, SNR's, ECD's, Loran C chains, and terrains. Figure 2 shows the airports selected and their relationship to the U.S. Coast Guard published areas of coverage. The coverage limit for the 9780 chain is defined by triangles. Dots are used to define the coverage limit for the 8970 chain. A solid line defines the coverage area for the 9940 chain on the east coast and the 9860 chain on the east coast. London, Kentucky; Saginaw, Michigan; and Atlantic City, New Jersey, were chosen for good GDOP and SNR. Billings, Montana; and Grand Junction, Colorado, were chosen for the mountains. A receiver was chosen for the mountainous receiver-run with area calibration, alternate triad with area calibration, and primary triad uncalibrated. At each airport, data were collected under five different conditions: automatic station selection, primary triad uncalibrated, primary triad with area calibration, alternate triad uncalibrated, and primary triad uncalibrated. Triads were selected to be master dependent, in conformance with minimum performance receiver specifications; but on the west coast this was not possible for some alternate triads. Five approaches were conducted under each condition with data being collected from all receivers. One receiver was selected to be used for guidance for each condition. It was not always possible to process five runs. AC 90-45A specifically excludes blunders from the accuracy requirements. Five approaches were conducted during good visibility. Approaches were straight in, starting 10 nmi from the runway. The approaches overlaid existing published approaches for VOR, ILS, and RNAV. The actual aircraft position was obtained from a specially designed and constructed portable multi-DME positioning system.

RESULTS

Table 1 shows the results of testing at the six airports. In the table a receiver-run is defined as one receiver on one approach. The mean and standard deviations were calculated for the along-track and cross-track errors. Data were only processed from the final approach fix to the missed approach point, a distance of 5 nmi. If five approaches were made and all receivers operated properly, 30 receiver-runs would be flown. A run meets AC 90-45A if the mean plus two times the standard deviation for along-track and cross-track error meet AC 90-45A criteria. From the table it can be seen that no airport had 100% of the receiver-runs meeting the AC without area calibration. If area calibration is used, two airports have 100% of the runs meeting the AC. The percentage of runs meeting AC 90-45A with area calibration increased over those without area calibration. As can be seen at Atlantic City, good GDOP does not guarantee meeting AC 90-45A without area calibration. In Gallup where GDOP went to 56, area calibration did not help any receiver meet the AC criteria. The table shows that modeling error and geometry have an effect on position error. Work done by Dr. Pierce (ref. 1), and Slagle and Wenzel (ref. 2) show variation in position errors are a function of TD variation, TD correlation, gradient and cross-angle. If the TD variation and TD correlation are calculated from many TD measurements an error ellipse can be drawn that will contain some defined probability of the individual measurements.

Figure 3 shows three error ellipses drawn for the geometry at Saginaw, Michigan using the 9960 chain and MY2 triad. TD standard deviations were chosen at 0.3 microseconds with correlation coefficients of -0.8, 0, and 0.8. The dashed line shows the direction of the approach. Error ellipses are rotated and the ratio of the semi-major to semi-minor axis change as a function of correlation coefficient at a fixed point with fixed TD variations. As the direction of flight is changed the resulting along-track and cross-track errors will also change. The selection of TD standard deviation and correlation coefficient is a function of what errors are to be considered. Work done by Slagle and Wenzel use values derived from one year of seasonal data. In effect, this is the position variation that would be expected over an entire year. An aircraft approach is only about 5 to 10 minutes in duration, therefore, the seasonal effect would appear as a bias that would be removed with area calibration. For airborne receivers, TD standard deviation and correlation coefficient should describe short-term variations which are a function of noise. Due to the dynamic requirements, large amounts of filtering cannot be used to reduce this effect. The TD to lat/long conversion may also add some position variations. If variations in position errors are, in fact, caused by geometry, the standard deviations of along-track and cross-track should not vary with and without area calibration. Figure 4 shows this assumption to be valid. Standard deviations computed for each condition and receiver were plotted as the uncalibrated value with respect to the area calibrated value. The axis is divided by tic marks spaced 100 feet apart. The dashed line represents the point where the two values would be equal. For the most part, data are grouped about the dashed line indicating area calibration does not affect position variation.

Area calibration is designed to reduce modeling errors. Theory indicates all errors due to modeling should be zeroed out with area calibration. Figure 5 shows this is not true. Area calibration values were calculated using the manufacturers defined methods. The aircraft was parked over a known geodetic position, and the
values calculated just prior to flying the approaches for that series of tests. The known geodetic position was tied into the same geodetic grid used for the aircraft positioning system. The mean along-track and crosstown errors for each receiver were combined in a root-sum-square manner to obtain a radial mean. The radial mean was then plotted against the GDOP for that airport. The vertical variation of the data points at a particular GDOP shows the variation between receivers. Radial mean errors for a GDOP of 5.4 are not in-line with radial mean errors at other GDOP's. Rechecking of the data showed no reason for this. The errors seem to increase with GDOP. As GDOP increases the gradient increases and the crossing-angle decreases. The effect is larger position shifts for smaller variations in time differences. Figure 6 shows a scatter plot of the mean along-track and crosstown errors with area calibration. The errors are well distributed. To sum up the effects of geometry and modeling, position errors for the TDL-711A at Atlantic City and Saginaw, with and without area calibration, are presented. Figure 7 shows data for Atlantic City and figure 8 for Saginaw. The cluster of data near the center of the pilot is with area calibration and the other without area calibration. What should be noticed is that the shape of errors remains the same with and without area calibration and that the center of the cluster is closer to a zero position error with area calibration but not zero. The results were typical for all receivers and airports.

Figures 9 and 10 show the actual track of the aircraft when the pilot was using the Loran C receiver for navigation; the airport is Saginaw, Michigan. In each plot the dashed line shows the 0.6 nmi TSCT limit defined in AG 90-45A. Three waypoints were used to establish the desired track, the initial approach fix (I), final approach fix (F), and missed approach point (M). Figure 9 shows TDL-711A performance using the 8970 MY triad without area calibration; figure 10 shows the ONI-7000 using the 9960 MY triad. Common to both figures is the larger position variations as the pilot turns onto the approach and up to the final approach fix. After the final approach fix, each run is very repeatable and variations are small. Each run was less than the 0.6 nmi limit. These figures represent typical performance for the receivers, operating in good GDOP. The pilots were very impressed with the repeatability and flyability of the course deviation indicator.

No evaluation of receiver performance would be complete without some discussion of operational problems. Two areas need to be addressed, human factors and cycle acquisition and track. Each receiver operated differently. Some receivers had rotary switches to select the various functions while others used multifunction push buttons. The multifunction push button method did not always annunciate the function selected, requiring the interpretation of the display to determine function. Push buttons for data entry also varied in size and spacing. As the size and spacing between the push buttons became smaller, it became more difficult to ensure the correct buttons were selected. Adding to this difficulty for one receiver, was the long time delay between button depression and the character appearing on the display. The delay often caused multiple character entry, which required correction. The method used by each manufacturer to calculate and insert area calibration also varied. Some receivers when given the correct geodetic position automatically calculated the area calibration value that could be inserted or recorded for latter use, others required the operator to do the necessary math. Area calibration values required to be inserted into the receivers included measured time differences and the correct geodetic position, time difference bias (the difference between model value and measured value), and delta lat/long. Most receivers required the values to be entered only once, but one receiver required the values to be entered for each waypoint. Associating the corrections to waypoints is good for en route, but adds to the workload for approaches.

A feature on some receivers was the ability to insert the area calibration values at any time, and then select their use when needed. This method allows the values to be entered before the pilot gets into the approach, where the workload is increased. Some receivers did not annunciate area calibration in use with a separate indicator/lamp. On several occasions no area calibration values or the wrong values were used.

The storage of area calibration values when power is turned off may be a good feature but can lead to problems. The problem would arise if the area calibration values are automatically added into the position solution when power is restored without pilot intervention. The pilot would not be aware of the area calibration annunciator on and not check to see if the area calibration values are correct for the airport. Errors were made in the operators calculation of area calibration values several times. They were not detected until after the approach data was processed.

The Radio Technical Committee for Aeronautics (RCA) document Loran C Minimum Operational Performance Standard (MOPS) has addressed the problem of area calibration entry. The document requires receivers to enter the area calibration as two 4-digit numbers. Area calibration values would be the difference between the measured time difference and a computed value using a published model for the reference TD. This method will reduce the number of digits required for area calibration. Data entry using a large number of digits is always a possible source of error.

Waypoint sequencing was another area which caused problems. Most receivers automatically sequenced through the waypoints while in the approach mode, one receiver did not. The approaches in this evaluation used three waypoints, mode, the need to change selected waypoints existed. The automatic waypoint sequencing receivers presented no problems. The
operator work load was too labor intensive for the receiver without automatic sequencing. It took the whole approach to change the selected waypoints, certainly not acceptable for a pilot flying in poor visibility. If only two waypoints had been used for the approach, this would have presented no problems. If receiver manufacturers choose not to implement automatic waypoint sequencing during an approach the pilot workload required to change waypoints must be minimal.

SUMMARY

Results of the tests indicate: area calibration is necessary to meet the accuracy requirements, use of area calibration only affects the mean of the errors, and variation of the position error is a function of geometry and time difference variation. When operated within the proper GDOP using area calibration, Loran C can meet the accuracy requirements for nonprecision approaches.

TABLE 1. REVIEW OF RECEIVER PERFORMANCE

<table>
<thead>
<tr>
<th>Airport</th>
<th>Chain</th>
<th>Triad</th>
<th>UNCALIBRATED</th>
<th>AREA CALIBRATED</th>
<th>GDOP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total Rcvr Runs</td>
<td># meeting AC-90-45A</td>
<td>% Meeting AC-90-45A</td>
</tr>
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<td>Saginaw</td>
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<td>MXY</td>
<td>30</td>
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<td>67</td>
</tr>
<tr>
<td></td>
<td>9960</td>
<td>MYZ</td>
<td>30</td>
<td>3</td>
<td>10</td>
</tr>
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<td>MXY</td>
<td>25</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>Billings</td>
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<td>MXY</td>
<td>25</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
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<td>9940</td>
<td>WXY</td>
<td>10</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Grand Junction</td>
<td>9940</td>
<td>WXY</td>
<td>25</td>
<td>9</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td>9940</td>
<td>WXY</td>
<td>10</td>
<td>3</td>
<td>30</td>
</tr>
<tr>
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<td>9940</td>
<td>MXY</td>
<td>15</td>
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<td>0</td>
</tr>
<tr>
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<tr>
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<td>9960</td>
<td>MYZ</td>
<td>25</td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>

REFERENCES


UNITED STATES COAST GUARD PREDICTED LORAN-C COVERAGE. (REF. 3.)

FIGURE 1
TSCT = TOTAL SYSTEM CROSS TRACK ERROR
ATE = AIRBORNE EQUIPMENT ALONG TRACK ERROR
CTE = AIRBORNE EQUIPMENT CROSS TRACK ERROR
FTE = FLIGHT TECHNICAL ERROR

FIGURE 2  NAVIGATION SYSTEM ERROR TERMS
ERROR ELLIPSES FOR SAGINAW, MICHIGAN

APPROACH HEADING: 225.0000
ELLIPSE PROBABILITY: .9500
STD. DEV. US T01: .300
STD. DEV. US T02: .300
LAT OF SITE (dd.mmss): 42.3200
LON OF SITE (dd.mmss): 84.0500
CHAIN & TRIAD: 9600 MZ
GRADIENT T01 FEET/MICROSEC: 1068
GRADIENT T02 FEET/MICROSEC: 569
CROSSING ANGLE DEGS: 32
NUM OF T0 STD DEVS PLOTTED += 2
RHO MAX ATE(FT) MAX CTE(FT)
-.00 +220 +1360
+.00 +491 +1382
+.80 +654 +877

TIC SPACING 100 FEET

FIGURE 3

NAVIGATION EQUIPMENT ERRORS (STANDARD DEVIATION)
AREA CALIBRATION VERSUS UNCALIBRATED

ALONG-TRACK ERRORS IN FEET  CROSS-TRACK ERRORS IN FEET

FIGURE 4
NAVIGATION EQUIPMENT ERROR
RADIAL MEAN VS GDOP
WITH AREA CALIBRATION

RADIAL ERROR = SQRT(((MEAN ATE))² + ((MEAN CTE))²)
AREA CALIBRATION RESOLUTION .1 AND .01 MIN.

MEAN NAVIGATION EQUIPMENT ERROR
WITH AREA CALIBRATION

TIC SPACING 100 FEET
NAVIGATION EQUIPMENT ERRORS (FT.)
FOR ATLANTIC CITY USING TDL-711A
9968 MXY

WITH AREA CALIBRATION

WITHOUT AREA CALIBRATION

NAVIGATION EQUIPMENT ERRORS (FT.)
FOR SAGINAW USING TDL-711A
8970 MXY

WITH AREA CALIBRATION

WITHOUT AREA CALIBRATION

FIGURE 7

FIGURE 8
EVALUATION OF LORAN-C FOR INSTRUMENT APPROACHES IN OHIO

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ABSTRACT

A feasibility study evaluating Loran-C approach potential at airports in north-central Ohio is documented. Satellite surveys of runway locations, followed by flight data collection, with ground truth information provided by a tracker/ranger provided encouraging results. Loran-C approach guidance was found to be both accurate and flyable. Issues such as missed approach procedures, determination of minima and a method for independent confirmation that the Loran-C receiver is operating properly have yet to be specified. The available signals in space, however, appeared to offer high-quality guidance in the region during the time when measurements were taken. Long-term monitoring is anticipated to begin in late 1984, with a site at Galion, Ohio.

INTRODUCTION

The Loran-C navigation system offers the potential for low-cost instrument approaches for airfields where traditional activity measures do not justify the expense of approaches requiring ground installations. The measurements reported here result from a feasibility study conducted in north-central Ohio, to gain experience with available Loran-C signals and with measurement methodology which may be applied to approach evaluations involving Loran-C.

Data collection procedures are described for determining runway location and the quality of local Loran-C guidance. Results include flight data from multiple approaches, both on the visual runway centerline and on the Loran-C zero-CDI approach path. Ideally, these two flight paths would coincide; the purpose for flight measurement is to detect and quantify differences.

APPROACH DESIGN

For this feasibility study, runways were chosen which had existing non-precision approaches, so that TERPS terrain clearance would not become an issue, and so that it would not be necessary to design approaches from scratch. For Galion, Ohio Municipal Airport and Mansfield, Ohio Lahm Airport, five-mile straight-in approaches were designed for runways 5 and 23. For Ohio State University Airport at Columbus, similar approaches were considered for runways 9R and 27L. Using surveyed coordinates for runway thresholds and the measured magnetic bearing of the runway, final-approach fixes were computed for each runway.

Intercept altitude at the final approach fix (FAF) was computed for each runway using a 3-degree elevation angle and assuming a 55-foot threshold crossing height. This altitude, together with visual cues during evaluation flights, was used for maintaining realistic altitudes during approaches.

The principal parameters of interest were position of the Loran-C approach path as compared with the geographic line between the final approach fix and the associated runway threshold, and the structure of the Loran-C path during flight. No attempt was made to design specific minimum descent altitudes or missed-approach procedures during this study.

MEASUREMENT METHODS

Surveys of runway threshold positions using the Navy Transit satellites, followed by flight data collection over the approach path defined by these surveys, provided the data reported here. The runway survey was accomplished using commercially-available satellite measurement equipment; flight measurements required custom instrumentation. Both airborne and ground measurement systems were required, to observe Loran-C signals and to reference these observations to the true aircraft position relative to the runway threshold. A digital data link was provided to merge the airborne and ground data streams as data were collected.

Ground Survey

A Transit satellite receiver was located at each of the three airports to be studied, and data were collected for a minimum of sixteen satellite passes. At the Galion site, for example, figure 1 gives the ground geometry. A laser ranger combined with a theodolite permitted measurement of satellite antenna position relative to the runway and thresholds. Runway bearing was measured at multiple points using a magnetic compass.

Figures 2 and 3 illustrate convergence on final values for latitude, longitude and height at the Galion site. Additional time on site may have improved final values somewhat, but limited availability of the survey receiver prevented this.

Survey accuracy goals were set after review of available RNAV approach coordinates (to 0.1 minute latitude and longitude) and the pilot's data entry resolution (the same). The 0.1 minute figure translates to some 60 meters in latitude and 40 degrees North, and 180 meters in longitude. It was desired to obtain survey data to an order of magnitude better than these published values, and this goal was substantially achieved.

Flight Data Collection

Ground reference position measurement was accomplished using a modified two-axis theodolite, which provided azimuth and elevation data resolved to 0.01 degree. These
Figure 1. Survey Geometry, Galion, OH

Figure 2. Lat/Lon Convergence; Galion Municipal Runway 23.
Theodolite azimuth (AZ) and elevation (EL), plus Hiran range (GR) are available from the ground position data. The ground range (GR) is computed as

\[
GR = SR \cos(EL) \tag{1}
\]

and cross-track distance by

\[
XTD = GR \sin(AZ) \tag{2}
\]

The along-track range, which is the distance to the aircraft measured along runway centerline, is found by

\[
ATR = GR \sin(AZ) - R - D \tag{3}
\]

which permits calculation of distance to go:

\[
DTG = \sqrt{ATR^2 + XTD^2} \tag{4}
\]

Data produced by the Loran-C receiver includes observed distance to waypoint (DTW) and course deviation (CDI). Cross-track and along-track errors (XTE and ATE) are found by:

\[
XTE = CDI - XTD \tag{5}
\]

\[
ATE = DTW - DTG \tag{6}
\]

These measures are differential in nature; for a perfect Loran-C path coincident with runway centerline, both should be zero throughout the approach assuming the theodolite accurately tracks the aircraft. Even if the aircraft is not flown precisely on the expected approach path, the effect of the ground reference system is to remove this deviation.

**Results**

**Ground Survey**

The Motorola satellite survey system was operated at the three airport sites for time periods consistent with ±6-7 meter accuracy as suggested by the manufacturer. The equipment operated nominally at all sites. Point-position coordinates for runway thresholds and calculated FAF coordinates appear in table I. Receiver waypoint data were entered from this table, with seconds of arc converted to tenths of minutes as required by the receiver.

**Flight Data**

The Galion site was selected for primary data-collection. The scope of the project permitted airborne data collection at Galion with the ground tracker on runway 23, flying runway 5 for verification and video recording, and flying Mansfield runways 5 and 23 for subjective verification of Loran path position and flyability.

Ground measurement equipment was located as shown in figure 4 and calibrated. A ground monitor receiver was included, to detect any Loran-C signal anomalies during the measurement flights (none were detected). The TL-9100 receiver aboard the test aircraft was initialized with the surveyed points for runway threshold and FAF as waypoints. The 9960 chain Y, Z triad (Seneca - Dana - Carolina Beach) was used, with no local calibration inserted.

Ten approaches were recorded at Galion for runway 23. Table II gives the resulting data. Most flights were made using the visible runway centerline as a reference. Two flights used the Loran-C CDI as a guide; one followed the indicated Loran-C path and the other was deliberately flown slightly off-angle to illustrate theodolite error-removal. Note that no apparent differences were detected between the two approach types.

Figures 6, 7 and 8 show the data collected and processed in the field for each approach. Raw Loran-C position is plotted for each received data point which is matched by a ground-tracker position fix. The raw data give an immediate indication of path offset of approximately 0.2 nm to the left (negative values) of centerline, as indicated by the receiver. When cross-track error, including ground tracker correction, is plotted as in figure 7, this indication is confirmed. Along-track error values are predominantly positive, indicating what may be a slight receiver lag in providing this value. The peak in ATE values at threshold may also be caused by this lag, since tracker distances would become negative, while the receiver continued to output positive values for a short period after passing the threshold waypoint.
Figure 3. Height Convergence; Galion Municipal Runway 23.

Angle data were combined with slant range, measured by a Motorola Miniranger, with interrogation from the ground and reply from a transponder aboard the aircraft. Ground data were then formatted and sent to the aircraft over the Miniranger digital data link. The Miniranger unit is specified to ±2 meters probable error.

The Piper Saratoga aircraft N8238C used by the Avionics Engineering Center in a variety of measurement programs, was fitted with the Texas Instruments TI-9100 Loran-C receiver. CDI outputs were switched into an existing panel instrument, and the TI-9100 serial output port was wired to the rear of the cabin. A Heath H-89 computer received the data streams from the Loran-C receiver and from the data link and recorded both data streams on tape.

Tape data for each approach included a file header, run identification records and a series of ground and airborne data records. The following data elements were captured, and are shown with their resolution values:

**Ground:**
- Time of Day (1 millisecond)
- Theodolite Elevation (0.01 degree)
- Theodolite Azimuth (0.01 degree)
- Range to Aircraft (1 meter)
- Event Number
- Go/No-Go Flag

**Airborne:**
- Latitude (0.1 minute)
- Longitude (0.1 minute)
- Cross-Track Distance (0.01 nm)
- Distance to Waypoint (0.1 nm)

Additional data were recorded, but not used directly for this study:
- Est. Time to Waypoint (1 second)
- Radial Angle to Waypoint (1 degree)
- Waypoint Verification (0.1 minute)
- Ground Speed (0.1 kt)
- Ground Track Angle (1 degree)
- Magnetic Variation (0.1 degree)

**Flight Data Reduction**

Figure 4 shows data reduction geometry. The goal of the postprocessing program is to produce cross-track and along-track error values at each point where both airborne and ground measures of aircraft position are available.
TABLE I. Satellite Survey and FAF Data

<table>
<thead>
<tr>
<th>SITE</th>
<th>THRESHOLD*</th>
<th>FAF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galion 05</td>
<td>40°45'01.937&quot;N 82°43'41.101&quot;W 1222.0 ft. MSL</td>
<td>40°41'41.7&quot;N 82°40'35.6&quot;W 2870 ft. MSL</td>
</tr>
<tr>
<td>Galion 23</td>
<td>40°45'23.920&quot;N 82°43'09.017&quot;W 1220.60 ft. MSL</td>
<td>40°48'45&quot;N 82°38'15&quot;W 2868 ft. MSL</td>
</tr>
<tr>
<td>Mansfield 05</td>
<td>40°48'41.640&quot;N 82°31'29.734&quot;W 1286.55 ft. MSL</td>
<td>40°45'17&quot;N 82°36'19&quot;W 2935 ft. MSL</td>
</tr>
<tr>
<td>Mansfield 23</td>
<td>40°49'27.302&quot;N 82°30'25.126&quot;W 1289.70 ft. MSL</td>
<td>40°52'32&quot;N 82°25'35&quot;W 2938 ft. MSL</td>
</tr>
</tbody>
</table>

*Satellite data accurate to ±6.87 meters or better, latitude & longitude ±5.59 meters or better, height.

Figure 5. Galion Airport—Measurement Geometry for Runway 23
## TABLE II. Flight Data Summary

### Galion, Ohio Runway 23

<table>
<thead>
<tr>
<th>Approach Type</th>
<th>N</th>
<th>n</th>
<th>Cross-Track Error (nm)</th>
<th>Along-Track Error (nm)</th>
</tr>
</thead>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Mean</td>
<td>Std.</td>
</tr>
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<td>Runway Centerline</td>
<td>8</td>
<td>173</td>
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<tr>
<td>Loran-C CDI</td>
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<td>All Approaches</td>
<td>10</td>
<td>219</td>
<td>-0.20</td>
<td>0.006</td>
</tr>
</tbody>
</table>
Galion runway 5 FAF and threshold waypoints were inserted and the Loran-C and runway centerline paths flown. As expected, the Loran-C path was detected 0.2 nm to the right of runway centerline, and evidenced the same smooth structure as for runway 23, as viewed on the CDI. With a receiver offset of 0.2 nm entered, an approach was made under the hood, with video tape recording from the cockpit. The approach path remained over the paved runway surface with the CDI centered as threshold was approached and a low pass executed.

Mansfield, Ohio FAF and threshold survey coordinates were entered in turn as waypoints for runways 5 and 23. Subjective observations confirmed the Galion result: the Loran-C path was essentially parallel to the runway and 0.2 nm offset to the southeast.

CONCLUSIONS

The Loran-C approach path at Galion and Mansfield, Ohio for runways 5 and 23, using the Y, Z triad at both airports lies parallel to, and 0.2 nm offset from runway centerline. The path structure is smooth and easily flyable.

The theodolite/ranger ground truth system is an effective measurement tool for evaluating potential Loran-C approaches. The satellite survey system gives moderate accuracy with low operating cost; larger-scale survey programs could take advantage of translocation for increased accuracy.

The light aircraft is a low-cost and suitable vehicle for Loran-C approach evaluation measurements.

RECOMMENDATIONS

The Galion site should be equipped with a ground monitor for collecting Loran-C stability data over a one-year period. The site should be flown again during the winter months, to add to the data collected for this study, during June.

This study adds to the growing body of measurements of Loran-C in the approach environment. The apparently good available accuracy should encourage continued progress toward certification of Loran-C for non-precision approach use.

Measurement of cross-track deviations would be facilitated by an expanded-scale CDI, and modification of the receiver to display more digits.

Waypoint survey accuracy should be improved using the translocation technique in the future. Appropriate guidelines for survey accuracy and methodology should be developed.

REFERENCES

1. Lilley, R., "Use of Navy TRANSIT Satellites for Surveys of Airport Runway Locations," Technical Memorandum 0-1, Avionics Engineering Center, Ohio University,
ACKNOWLEDGEMENTS

The authors acknowledge support by the State of Ohio, Department of Development, which provided funding through Aviation Safety Institute, of Worthington, Ohio. Personnel of the Ohio Department of Transportation, Division of Aviation, the Department of Natural Resources, and the management of Galion, Mansfield, and Ohio State University airports were most helpful throughout the work.

Daryl McCall and Rachel Pollard aided in the satellite runway survey, Tim Murphy and David Dudding assisted with field data collection, Tamara Weigand prepared data-reduction routines and Alicya Shade prepared the manuscript. All are with the Avionics Engineering Center.
CONUS LORAN-C FLIGHT TEST
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ABSTRACT

This paper contains the description and results of a Loran-C flight test program conducted in the Continental United States (CONUS). The testing period was from 5 July 1983 to 15 July 1983. The purpose was to collect Loran-C signal coverage and accuracy data representative of low altitude, low speed operations typical of helicopters and general aviation aircraft.

Navigation system errors were quantified for the Loran-C unit tested. The errors were computed from knowledge of position calculated from ground truth data and the indicated position of the navigator. Signal coverage, bias and flight technical error data were also obtained. Multilateration ground truth and data acquisition systems were carried onboard the test aircraft. Over 9,500 nm were flown and more than 78 hours of Loran-C data were collected.

Route segments covering much of CONUS were flown during the project. The route segments were chosen in such a manner that all stations in each of the four U.S. Loran-C chains were used at sometime during the test.

In addition to the enroute segments, five calibration segments were flown to specifically evaluate the effectiveness of using area calibration procedures in a localized area. Calibration segments were flown at London, KY; Burlington, VT; Muskegon, MI; Fresno, CA; and Lafayette, LA.

Some of the results indicate that during the enroute phase of the flight test total system crosstrack errors were better than current enroute accuracy standards contained in the Federal Aviation Advisory Circular 90-45A for non-VOR/DME systems. Total system alongtrack errors were also better than the current standard. These data were measured in areas of good Loran-C coverage areas as defined by the U.S. Coast Guard. The errors were poorer than the accuracy standard in areas of poor geometry. During the calibration flights in which the Loran-C position was corrected at a known ground reference point, total system alongtrack and crosstrack errors were better than AC 90-45A enroute and terminal accuracy standards. The crosstrack error was within approach accuracy standards and the alongtrack error was very nearly within approach accuracy standards throughout the calibration area.

INTRODUCTION

The purpose of the project was to collect Loran-C data and develop error budgets which emphasize low altitude operations typical of general aviation aircraft and helicopters. Enroute data was collected across the Continental United States 'touching' as many of the forty-eight contiguous states as possible.

Navigation system errors in alongtrack and crosstrack coordinates were quantified for the Loran-C unit tested, the Teledyne TDL-711. Accuracy and flight technical error data were determined from a multilateration ground truth and data acquisition system carried onboard the test aircraft.

OBJECTIVES

The specific objectives of this flight test were defined as follows:

- Collect data that is representative of general aviation (GA) operations.

NOTE: This work was supported by the Federal Aviation Administration under Contract Number DTFA01-80-C-10080. The information presented does not necessarily reflect the official view or policy of the FAA.
Collect data over a broad geographical area of the domestic U.S.

Collect data in both good and poor coverage areas. Coverage was limited by the lack of available signals, poor geometry of the Loran-C lines of position, and local noise.

Collect data to reveal the bias error characteristics of Loran-C time differences.

Collect and process data to produce Loran-C error budgets.

**FLIGHT TEST ROUTES AND PROCEDURES**

For the purposes of this test one 'round robin' route covering most of CONUS was flown. The Loran-C airborne system was tested over a 7000 nautical mile route. Five locations were also chosen for area calibration flights. Each of these flights covered approximately 500 nm within a 75nm radius of the test location. In total, approximately 9,500 nautical miles of Loran-C data were collected. In order to minimize the number of ATC directed course deviations, all enroute segments followed the Victor Airway structure. The overall route of flight is depicted in Figure 1.

As shown in Figure 1, the major test locations were:

- West Palm Beach, FL
- London, KY
- Atlantic City, NJ
- Burlington, VT
- Muskegon, MI
- Kansas City, MO
- Rapid City, SD
- Eugene, OR
- Fresno, CA
- Phoenix, AZ
- San Antonio, TX
- Lafayette, LA

Of the major test locations, the five places which were utilized for area calibration test sites were as follows:

- London, KY
- Burlington, VT
- Muskegon, MI
- Fresno, CA
- Lafayette, LA

Each test utilized a different Loran-C chain/triad configuration. There were two important reasons for the area calibration tests: first, to determine how time difference (TD) corrections can be used for Loran-C approaches in the future; second, to determine how far from the area calibration point TD corrections are valid. For the purposes of this test a 75nm radius was examined in all directions. The pattern, depicted in Figure 2, was designed to investigate all quadrants within a 75nm radius of the area calibration point.

**TEST VEHICLE AND EQUIPMENT**

The aircraft used in the test was a twin engine Beechcraft Queen Air Model 65. During the data collection activity, a dedicated course deviation indicator (CDI) display was utilized to display Loran-C steering commands at all times. The safety observer monitored aircraft position by standard VOR navigation using a standard CDI display on the right side of the front instrument panel.

The Loran-C airborne system used for the flight test program was a Teledyne TDL-711 micro-navigator system consisting of an E-field vertical antenna; a receiver/computer unit mounted on the data acquisition rack; a control display unit (CDU) mounted on the aircraft's center console; and a CDI in the center of the pilot's instrument panel to display Loran-C course deviation.

The output of the Loran-C navigator drives a deviation indicator (CDI), giving linear deviation from the selected 'TO' waypoint course. Full scale deflection left or right of center is 1.28 nautical miles. The 'TO' flag indicates that the aircraft is located short of the 'TO' waypoint. The 'FROM' flag indicates a position beyond the 'TO' waypoint. The red 'NAV' flag indicates that steering commands are invalid.

The Loran-C receiver is designed to operate a remote display unit (RDU). The information it provides to that remote display can be externally programmed.

**REFERENCE SYSTEMS**

A multiple DME positioning system, a Rockwell-Collins DME-700, was used to fix the aircraft's actual position. The DME-700 transmits pulsed signals to a ground station and receives

84
Figure 1 Loran-C Flight Test Route

Figure 2 Area Calibration Pattern (75nm radius of validity)
The data acquisition package utilized during the flight test program consisted of the following major components:

- **MFE 4528 Cassette Recorder**
- **Rockwell Collins DME-700**
- **Microcomputer Chasis, Logic and Interface Boards**
- **Keyboard and Alphanumeric Display**
- **System RDU Loran-C**

The data were recorded from three distinct sources via the microcomputer logic and interface boards. The three sources were as follows: Collins DME-700, analog voltages representing aircraft systems and the Loran-C RDU. The operator system interface components consisted of a keyboard, alphanumeric display and a CRT console, to be used for post-flight quick-look data verification. The navigation RDU data stream provides Loran-C derived latitude and longitude, crosstrack deviation (flight technical error), and distance to waypoint (DTW) data.

### DATA PROCESSING

The data obtained during the flight test consisted of digital data recordings on magnetic tape and observations of the pilots and flight test observer.

Through the use of the aircraft’s position, computed from the DME data, the navigation data and Loran-C data recorded from the Loran-C navigator, many accuracy parameters could be determined. These include:

- Easting and northing position errors
- Loran-C time difference errors
- Total system alongtrack and crosstrack errors
- Navigation sensor alongtrack and crosstrack errors
- Navigation computer alongtrack and crosstrack errors
- Flight technical error (FTE)

A diagram defining these error relationships is shown in Figure 3.

### OPERATIONAL RESULTS

**General**

Operationally the short-term Loran-C signal was stable so that pilot FTE, or steering error, was quite low. Even when flying the CDI needle movement was only affected by aircraft heading or wind, and did not exhibit the significant variations often encountered with either flying VOR radials, or, to a lesser extent, when flying VOR/DME RNAV.

Four operationally significant circumstances were observed during the conduct of these tests. All four problems have been observed and documented in previous tests (References 3 & 4).

On several occasions, such as flying into Kansas City, MO, the Loran-C accuracy markedly degraded, with no overt indication to the pilot that such a situation existed. In some cases the Loran-C accuracy diverged from a value of approximately 1nm to a value approaching 7nm. From the pilot’s point of view the system is performing perfectly (i.e., the system is locked-on with an adequate set of signal strengths, the CDI flag is pulled out of view, and CDI steering signals are available). However, without some supplemental position fixing aid, such as VOR and DME, or visual fixes, the pilot is not aware that his guidance could be in error by 7nm.

The problems stated here may be specific to the Loran-C receiver. The receiver used during this flight test did not indicate to the pilot anomalies such as bad station geometry or low signal-to-noise ratio values. Also, no published documentation was available to indicate the operational areas applicable to this receiver. A current FAA advisory circular...
Some short duration navigation outages were noted on several occasions. These outages produced a loss of navigation for periods of 30 to 60 seconds. Post flight data analysis revealed that these outages were caused by momentary Loran-C transmitter outages and low signal-to-noise ratio values on one or more of the received signals. Often these outages occurred during periods of rain and thunderstorm activity in the vicinity of the aircraft. It is believed that some of these outages were caused by precipitation static and/or ambient noise. The aircraft was equipped with static wicks on the control surfaces to dissipate skin currents, however, these wicks may not have been totally effective in eliminating signal reception problems caused by precipitation static.

During the enroute transition phase of testing, no 'mid-continent gap' was encountered per se. Although at times signals were weak and accuracy was poor, the navigator continued to operate and provide guidance for most of the flight. The most significant occurrence of poor accuracy and weak signals was observed in the southwest U.S. Specifically, the segment flown between Phoenix, AZ and Lubbock, TX resulted in large navigational errors due to the poor signal geometry characteristics in that area. There were times when the system lost the signal for brief periods of time enroute, but these occurrences were of limited duration.

Several problems were experienced on the east coast of the United States while flying the enroute segments. It should be noted that the problems discussed here were the result of improper operation of the Loran-C receiver. A better understanding of these operational characteristics, by the operators, would have alleviated these problems. On the first segment from West Palm Beach, FL to London, KY, the system repeatedly 'lost-lock'. This might be attributed to the local thunderstorm activity encountered while enroute. The severe lightning associated with these storms could have possibly caused a great deal of interference in the 100 kHz spectrum.

On the segment from London, KY to Atlantic City, NJ, the system 'lost-lock' for forty-five (45) minutes outside of London. The system did not acquire adequate signals for the remainder of the flight. Similarly, the same problem was experienced on the flight from Atlantic City, NJ to Burlington, VT: the only difference being the system 'lost-lock' when triads were changed and the system never 'locked-on' again. The SNRs for all of the stations were quite low when the system was trying to acquire the new triad. Note in both cases the system did 'lock-on' on the ground after landing, using the same triad. This problem was studied during the post flight data analysis activities and it is believed that a procedural change in operating the navigation set during triad changes would eliminate or reduce the occurrence of this problem.

It should be noted that for each occasion which the system 'lost-lock' the Loran-C receiver alerted the operator via annunciators.
Area Calibration Tests

With only a few exceptions the Loran-C unit performed impressively during the area calibration tests. During the conduct of these tests all four U.S. Loran-C chains were utilized. In all five area calibration tests the aircraft was area calibrated at a predetermined location and after the completion of each flight the aircraft was returned to the same location. In each case the recorded position and time difference values were the same at the start and completion of each area calibration flight. When area calibrated, the TDL-711 performs with remarkable accuracy and repeatability. On two of the tests the system 'lost-lock' for brief time periods (30-120 seconds). This occurred three times during the London, KY test and twice during the Muskegon, MI test. At London, KY the system 'lost-lock' due to a momentary outage of the Dana station. One of the 'lost-lock' occurrences at Muskegon, MI was due to a momentary station outage and the other was due to low signal to noise ratios on all stations. No other noticeable problems were experienced except for some known accuracy degradation west of Lafayette, LA due to poor geometry.

NAVIGATION COMPUTER ACCURACY

Statistical values for navigation computer error in alongtrack and crosstrack coordinates were evaluated for the seventeen flight segments and five area calibration tests. The errors were statistically small and produced, to some extent, by filtering and smoothing of the Loran-C guidance data and computer algorithms.

The mean value and standard deviations for the seventeen flight segments are as follows:

<table>
<thead>
<tr>
<th>Error</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crosstrack</td>
<td>.00nm</td>
<td>.01nm</td>
</tr>
<tr>
<td>Alongtrack</td>
<td>-.05nm</td>
<td>.06nm</td>
</tr>
</tbody>
</table>

The mean value and standard deviations for the five area calibration tests are as follows:

<table>
<thead>
<tr>
<th>Error</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crosstrack</td>
<td>.00nm</td>
<td>.01nm</td>
</tr>
<tr>
<td>Alongtrack</td>
<td>-.05nm</td>
<td>.05nm</td>
</tr>
</tbody>
</table>

FLIGHT TECHNICAL ERROR

Flight technical error, based on the deviation signal presented to the pilot, was evaluated for the seventeen enroute segments and the five area calibration tests. The errors were small in terms of deflection values (+5 dots was full scale). The deviation signal presented to the pilot has a high sensitivity of 1.28nm full scale (or 3.9 dots per nm). Due to this high sensitivity, even though the deflections appear large, the flight technical error is fairly small in terms of nautical miles.

For the seventeen enroute segments, the statistical values were found to be:

<table>
<thead>
<tr>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loran-C Flight</td>
<td>.02nm</td>
</tr>
<tr>
<td>Technical Error</td>
<td>-.08 dots) (.71 dots)</td>
</tr>
</tbody>
</table>

For the five area calibrations tests, the statistical values were found to be:

<table>
<thead>
<tr>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loran-C Flight</td>
<td>.03nm</td>
</tr>
<tr>
<td>Technical Error</td>
<td>-.12 dots) (.67 dots)</td>
</tr>
</tbody>
</table>

OVERALL SYSTEM PERFORMANCE

Overall Enroute System Performance

A summary of the statistical errors in terms of the mean, standard deviation, and the mean plus/minus two standard deviation are presented in Table 1. Also shown in Table 1 are the area navigation accuracy requirements in FAA Advisory Circular 90-45A for non-VOR/DME area navigation systems. It can be observed that the Loran-C crosstrack accuracy experienced during the flight test nearly meets the AC 90-45A requirements, only exceeding it by 0.10nm. However, the alongtrack error exceeds the requirement by 0.96nm. Note that these errors include both areas of good and bad geometry. When limited to areas of good geometry, the accuracy would fall within the requirements of AC 90-45A.

There are various problem areas that are of some concern. These are:

- System outages due to the failure of the system to switch to a new chain/triad...
LEGEND for Tables 1, 2, and 3:

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DRMS</td>
<td>Root Mean Square Radial Error</td>
</tr>
<tr>
<td>TSCT</td>
<td>Total System Crosstrack</td>
</tr>
<tr>
<td>TSAT</td>
<td>Total System Alongtrack</td>
</tr>
<tr>
<td>NSCT</td>
<td>Navigation System Crosstrack</td>
</tr>
<tr>
<td>NSAT</td>
<td>Navigation System Alongtrack</td>
</tr>
<tr>
<td>NCCT</td>
<td>Navigation Computer Crosstrack</td>
</tr>
<tr>
<td>NCAT</td>
<td>Navigation Computer Alongtrack</td>
</tr>
<tr>
<td>FTE</td>
<td>Flight Technical Error</td>
</tr>
<tr>
<td>TD-A</td>
<td>Time-Difference A</td>
</tr>
<tr>
<td>TD-B</td>
<td>Time-Difference B</td>
</tr>
<tr>
<td>CTD</td>
<td>Crosstrack Deviation</td>
</tr>
</tbody>
</table>

Table 1 Loran-C Enroute Accuracy Aggregation in Areas of Both Good and Poor Coverage

<table>
<thead>
<tr>
<th>ERROR QUANTITY</th>
<th>MEAN (X)</th>
<th>STANDARD DEVIATION (σ)</th>
<th>X-2σ</th>
<th>X+2σ</th>
<th>AC 90-45A REQUIREMENTS ENROUTE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northing Error</td>
<td>-0.35</td>
<td>1.14</td>
<td>-2.63</td>
<td>1.93</td>
<td></td>
</tr>
<tr>
<td>Easting Error</td>
<td>0.06</td>
<td>1.08</td>
<td>-2.10</td>
<td>2.22</td>
<td></td>
</tr>
<tr>
<td>DRMS</td>
<td>1.20</td>
<td>1.08</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TSCT</td>
<td>-0.42</td>
<td>1.09</td>
<td>-2.60</td>
<td>1.76</td>
<td>2.50</td>
</tr>
<tr>
<td>TSAT</td>
<td>-0.38</td>
<td>1.04</td>
<td>-2.46</td>
<td>1.70</td>
<td>1.50</td>
</tr>
<tr>
<td>NSCT</td>
<td>-0.49</td>
<td>1.08</td>
<td>-2.65</td>
<td>1.67</td>
<td></td>
</tr>
<tr>
<td>NSAT</td>
<td>-0.33</td>
<td>1.04</td>
<td>-2.41</td>
<td>1.75</td>
<td></td>
</tr>
<tr>
<td>NCCT</td>
<td>0.00</td>
<td>0.01</td>
<td>-0.02</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>NCAT</td>
<td>-0.05</td>
<td>0.06</td>
<td>-0.17</td>
<td>0.07</td>
<td></td>
</tr>
<tr>
<td>FTE</td>
<td>0.03</td>
<td>0.17</td>
<td>-0.31</td>
<td>0.37</td>
<td></td>
</tr>
<tr>
<td>TD-A</td>
<td>-0.61</td>
<td>10.56</td>
<td>-21.73</td>
<td>20.51</td>
<td>2.50</td>
</tr>
<tr>
<td>TD-B</td>
<td>1.56</td>
<td>8.90</td>
<td>-16.24</td>
<td>19.36</td>
<td></td>
</tr>
<tr>
<td>CTD</td>
<td>0.07</td>
<td>0.18</td>
<td>-0.29</td>
<td>0.43</td>
<td></td>
</tr>
</tbody>
</table>

NOTE: Based on 8233 data points all values are in nautical miles except TD-A and TD-B which are in microseconds.
combination while being selected enroute. This problem is associated with the procedures in operating the Loran-C equipment and not with the CONUS Loran-C transmitters.

- Large errors, during times when the receiver was experiencing poor station geometry, were not recognized by the receiver (no indication to the pilot). The operations manual of the receiver also did not indicate to the pilot areas which may cause large navigation errors due to poor geometry. Advisory Circular (AC) 20-120 addresses these concerns.

- Increasing errors and a lack of reliable navigation in areas where station signal strength is low (mid-continent gap).

Overall Area Calibration System Performance

A summary of the error statistics in terms of the mean, standard deviation, and the mean plus/minus two standard deviations are presented in Table 2 for each of the five area calibration flights, while Table 3 depicts the aggregate error statistics for all calibration flights. Also shown in Tables 2 and 3 and in Figure 4 are the area navigation accuracy requirements for non-precision approach in FAA Advisory Circular 90-45A for non-VOR/DME area navigation systems. It can be observed that, with one exception, the Loran-C alongtrack and crosstrack accuracy experienced during the area calibration test meet, or very closely meet, the AC 90-45A criteria for non-precision approach. The exception is the total system crosstrack error at Burlington, VT. This error exceeds the requirement by 0.24nm.

CONCLUSIONS

The following conclusions were developed from the flight test of the Teledyne TDL-711 Loran-C navigation system in CONUS:

- During the enroute phase of the flight test total system crosstrack errors were slightly larger (0.10nm) than current enroute accuracy standards contained in the Federal Aviation Advisory Circular 90-45A for non-VOR/DME systems. Total system alongtrack errors were also larger (0.96nm) than the current standard. These data were measured in areas of both good and poor Loran-C coverage areas as defined by the U.S. Coast Guard.

- In areas of good geometry, as defined by the U.S. Coast Guard, the errors were within AC 90-45A enroute accuracy standards.

- Neither the receiver nor the operators handbook provided the pilots with a warning of poor geometry or poor coverage areas of the Loran-C signal.

- During the calibration flights in which the Loran-C position was corrected at a known ground reference point, total system alongtrack and crosstrack errors were better than AC 90-45A enroute and terminal accuracy standards and very close to non-precision approach accuracy standards.

- The major source of Loran-C system error is propagation model error which is a result of an inadequate knowledge of the propagation velocity of the signal. This error is converted to positional and navigational errors by the coordinate conversion procedure.

- Flight technical errors of about 0.4nm (2σ) were measured on both enroute and calibration flights.

- Alongtrack and crosstrack computational errors were negligible throughout the test.

- Cycle errors were observed on three separate occasions during this test. Two of these occurrences happened in good Loran-C signal coverage areas near London, KY and Lafayette, LA. One occurrence happened in a poor signal coverage area near Albuquerque, NM. The flight crew was not aware of these errors during the test as the navigation system indicated normal operation.

- The navigation system produced very large errors in the
Table 2 Loran-C Area Calibration Accuracy

<table>
<thead>
<tr>
<th>ERROR QUANTITY</th>
<th>MEAN (X)</th>
<th>MEAN STANDARD DEVIATION (σ)</th>
<th>X-2σ</th>
<th>X+2σ</th>
<th>AC 70-45A REQUIREMENTS FOR NON-PRECISION APPROACH</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>X-2σ</td>
<td>X+2σ</td>
<td>X-2σ</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(A)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>London Area Calibration</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DRMS</td>
<td>0.21</td>
<td>0.06</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>TSCT</td>
<td>0.21</td>
<td>0.47</td>
<td>10.60</td>
<td>0.23</td>
<td>0.13</td>
</tr>
<tr>
<td>TSAT</td>
<td>-0.05</td>
<td>0.15</td>
<td>0.25</td>
<td>0.30</td>
<td>0.30</td>
</tr>
<tr>
<td>FTE</td>
<td>0.01</td>
<td>0.17</td>
<td>0.35</td>
<td>0.33</td>
<td>--</td>
</tr>
<tr>
<td>TD-A</td>
<td>1.00</td>
<td>1.37</td>
<td>-1.74</td>
<td>1.74</td>
<td>--</td>
</tr>
<tr>
<td>TD-B</td>
<td>-1.09</td>
<td>0.43</td>
<td>-1.95</td>
<td>-0.23</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>Burlington Area Calibration</td>
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<tr>
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<td>TSAT</td>
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<td>0.17</td>
<td>0.17</td>
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<tr>
<td>FTE</td>
<td>0.15</td>
<td>0.42</td>
<td>0.56</td>
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<td>--</td>
</tr>
<tr>
<td>TD-A</td>
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<td>-1.68</td>
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<tr>
<td>TD-B</td>
<td>0.47</td>
<td>0.80</td>
<td>-1.13</td>
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<tr>
<td>Muskegon Area Calibration</td>
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<tr>
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<td>0.06</td>
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<tr>
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<tr>
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<tr>
<td>TD-B</td>
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<td>0.51</td>
<td>-0.10</td>
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<tr>
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</tr>
<tr>
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<tr>
<td>TD-B</td>
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<td>-2.32</td>
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<tr>
<td>Lafayette Area Calibration</td>
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<td>DRMS</td>
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</tr>
<tr>
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</tr>
<tr>
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<td>0.66</td>
<td>-1.53</td>
<td>1.11</td>
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</tr>
<tr>
<td>TD-B</td>
<td>-0.20</td>
<td>0.30</td>
<td>-0.80</td>
<td>0.40</td>
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</table>

NOTE: All values are in nautical miles.
Table 3  Loran-C Area Calibration Accuracy Aggregation

<table>
<thead>
<tr>
<th>ERROR QUANTITY</th>
<th>MEAN (X)</th>
<th>STANDARD DEVIATION (σ)</th>
<th>X-2σ</th>
<th>X+2σ</th>
<th>AC 90-45A LIMITS (Non-Precision Approach)</th>
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<tbody>
<tr>
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<td></td>
<td></td>
<td></td>
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<tr>
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<td>0.08</td>
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<td></td>
<td></td>
<td></td>
<td>TSCT</td>
</tr>
<tr>
<td></td>
<td>0.06</td>
<td>0.23</td>
<td>-0.40</td>
<td>0.52</td>
<td>±0.60</td>
</tr>
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<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>-0.03</td>
<td>0.14</td>
<td>-0.31</td>
<td>0.25</td>
<td>±0.30</td>
</tr>
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<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>FTE</td>
<td></td>
<td>-0.34</td>
<td>0.38</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.02</td>
<td>0.18</td>
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<td></td>
<td>TD-B</td>
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<td>-1.95</td>
<td>1.81</td>
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<td></td>
<td>-0.07</td>
<td>0.94</td>
<td></td>
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<td></td>
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</tbody>
</table>

NOTE: All values are in nautical miles except TD-A and TD-B which are in microseconds.

Figure 4  Mean ±2σ Errors for the Calibration Flights
baseline extension areas. These errors were recognized by the flight crew by comparing Loran-C position with information from VOR/DME receivers. In many instances, the Loran-C navigation system did not produce any indication to the crew that its information was not accurate during operations near the baseline extensions.

- Momentary system outages occurred during thunderstorm and rain activity. These outages are believed to have been caused by atmospheric noise and/or precipitation static. The outages were not operationally significant in most instances.

- System outages occurred during times when Loran-C transmitters were experiencing momentary or longer outages. In one instance, a momentary outage on the Dana station appears to have triggered a cycle error in the navigator.

ACKNOWLEDGEMENTS

Much of the material for this paper was derived with the aid of associates at the Champlain Technology Industries Division of Systems Control Technology, Inc. Dr. Donald W. Richardson, Vice President, Director of Eastern Operations, provided overall program management. Mr. Eric H. Bolz, Senior Engineer, provided technical expertise in the instrumentation coordination of the aircraft.

Mr. Harvey Barnett and Mr. Howard Meyers were contracted to participate as the primary subject pilots on the project.

REFERENCES


LORAN-C NAVIGATION AS AN AID TO AERIAL PHOTOGRAPHIC OPERATIONS

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ABSTRACT

New and improved state-of-the-art Loran-C receivers interfaced to navigation computers are now available to assist in aerial photographic operations. Loran-C navigation systems are compatible for installation in all types of aircraft at a price comparable to other navigation systems without Loran-C capabilities and accuracy.

The efficiency of conventional photogrammetric mapping projects can be increased and aerial survey costs can be substantially reduced when aided by Loran-C guidance. Aerial photographic mission design and flexibility in mission planning can be enhanced with Loran-C navigation. Aerial photographic sampling procedures and sequential aerial photography can now be accomplished with greater accuracy and reduced costs. The USDA Forest Service, Forest Pest Management, Aerial Survey Team evaluated the Loran-C system for use in aerial photography and other aerial operations requiring precision navigation. The accuracy and operational characteristics of the Loran-C systems are well suited for aerial photographic operations. A wide variety of additional aviation applications using Loran-C guidance have also been evaluated.

INTRODUCTION

One of the new developments in aerial surveys and aerial photography in the USDA Forest Service has been the utilization of Loran-C airborne navigation systems. Loran-C can be used to increase the efficiency of aerial photographic operations, decrease the effort by ground crews in ground truth data collection and ultimately reduce costs. Loran-C navigation systems also increase the flexibility of aerial photographic survey design for a variety of custom, user-oriented aerial photographic missions. These missions include aerial photographic sampling, sequential aerial photography to measure and detect changes over a given period of time, accurate aerial photographic point sampling of predetermined locations, as well as greater control over conventional parallel flight-line navigation, (Dull, 1980). Loran-C system characteristics include easy installation in most types of aircraft, small size and light weight, relatively low cost, and extended area of operation make it an ideal navigation aid for aerial photographic operations. This evaluation reviews the navigational accuracy obtained during a wide variety of operational aerial photographic missions utilizing a Loran-C TDL-424 Navigator manufactured by Teledyne Systems.*

NAVIGATION ACCURACY EVALUATION

Loran-C flight tests were incorporated into operational photographic missions and aerial surveys. These flight tests have been divided into four different categories; (1) parallel flightlines spaced at predetermined intervals; (2) comparison of an aerial photographic mission with and without Loran-C guidance; (3) return flight accuracy to predescribed flightline; and (4) overflights of predetermined exposure stations. An assessment of total system error in aerial surveys was based upon the methodology found in Adams, 1976 and Hughes and Adams, 1977.

Aerial operations utilizing the airborne navigator have been performed in 13 southeastern states and most of the northern United States. The evaluation of the Loran-C performance was based on aerial photographic measurements and flight log entries. An RC-10 camera mounted in an Aero Commander was used to obtain aerial photographic reference data. The principle points of a series of vertical aerial photographs were

*Mention of a proprietary or commercial product does not constitute recommendation or endorsement of the product by the U. S. Department of Agriculture and does not imply its approval to the exclusion of other products that also may be suitable.
transferred to 1:24,000 scale USGS topographic maps to define the aircraft's true ground track. The following is a partial list of data required for the aerial operational evaluation of the Loran-C airborne navigation system:

1. Actual aircraft position (from aerial photographs).
2. Loran-C system position (from digital readout or cassette tape via the data link system).
3. Cross track deviation (CDI needle deflection and digital readout).
4. Waypoint in use or digitized base leg end points.
5. Desired track.
6. From/to indication.
7. Along track distance (nmi).
8. Loran-C operation mode.
9. Repeat work over (communications, weather, traffic, etc.).
10. Status of equipment (aircraft, photographic, Loran-C system, etc.).
11. Loran-C chain and secondaries utilized.

Parallel Flightline Navigation Evaluation

The navigation requirements of parallel track steering are ideally suited to the TDL-424 system. Parallel track steering provides the ability to fly along a course parallel to a given course at a selected distance from it. Once the offset has been entered, all steering and other navigational data are with reference to the artificial destination (Anon., 1976). Given the scale, percent end lap and side lap, as well as the area boundaries, navigation coordinates for Loran-C system input could be obtained by digitizing for latitude and longitude coordinates, 1:24,000 USGS topographic maps or the aerial survey map to be utilized. A base leg was established within the survey boundary with parallel flightlines positioned to accommodate side lap and scale requirements.

Direct navigation to the target area is provided by the Loran-C navigator. Once on the first photographic leg of the flight the pilot would position the aircraft on track prior to initiating photography. The Loran-C steering indications on the course deviation indicator and the horizontal situation indicator, providing distance to go, as well as digital readout on the control indicator box provided the necessary navigational data along each flightline and indicating when to begin and terminate each sequence of photographs. After each flightline was completed the Loran-C navigator, reprogrammed for the next parallel offset, would provide steering direct to the next flightline.

An acceptable error budget for aerial photographic missions would vary with the desired scale of the imagery and the desired percentage of sidelap. For this evaluation maximum acceptable error was defined as the ground distance represented by one-half the desired sidelap. This is compatible with standard requirements for aerial photographic mapping missions (Thompson, 1966; Anon, 1979).

The desired ground track and the actual aircraft track based on the principle point of successive photographs along each flightline were plotted on 1:24,000 topographic maps. Cross track error was determined by measuring the distance between the actual and desired flightlines at 1.0 nautical mile (nmi) intervals. The distance between adjacent flightlines was measured at 1.0 nmi. Intervals and subtracted from the desired sidelap to determine sidelap error.

In each of the photographic missions requiring parallel flightline navigation included in this evaluation both the cross track error and the difference between actual gain per line and the desired gain per line were analyzed. In all of the flight tests a highly trained three man flight crew was utilized. These missions were conducted over extensively forested, remote areas where visual checkpoints for ground to map reference were lacking and maps to track by were outdated.

Table 1 illustrates the guidance accuracy of the Loran-C navigation system during three aerial photographic missions. Dozens of aerial photographic missions have been conducted by the USDA Forest Service, Forest Pest Management, Aerial Survey Team with similar results, relying upon Loran-C guidance for primary navigation and steering indications. The ability to fly parallel flightlines at specific offsets is one of the most critical demands of aerial surveys and aerial photographic missions. The results of the three missions in Table 1 illustrate that the Loran-C system performed within the error tolerance limits for accepting the aerial photography. The punctual accomplishment of each mission, savings in flight time and film, and reduction of resflights are additional benefits not directly reflected in the analysis of navigational accuracy. These factors and limiting conditions mentioned previously become increasingly important in areas where flight time available for aerial photography is restricted.
Table 1 - Performance Evaluation of Loran-C Guidance for Parallel Flightline Navigation in Operational Aerial Photographic Missions

<table>
<thead>
<tr>
<th>Mission</th>
<th>Oconee National Forest, GA</th>
<th>Linville Gorge Wilderness, NC</th>
<th>Great Smoky Mountains National Park, NC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desired scale</td>
<td>1:8,000</td>
<td>1:20,000</td>
<td>1:12,000</td>
</tr>
<tr>
<td>Gain/line (nmi)</td>
<td>0.7</td>
<td>1.7</td>
<td>0.9</td>
</tr>
<tr>
<td>Number flightlines</td>
<td>65</td>
<td>7</td>
<td>16</td>
</tr>
<tr>
<td>Total linear flightline length (nmi)</td>
<td>605</td>
<td>152</td>
<td>193</td>
</tr>
<tr>
<td>Cross track error (nmi, meters)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>.05;92.6</td>
<td>.13;240.5</td>
<td>.15;277.7</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>.09;166.7</td>
<td>.15;277.7</td>
<td>.20;370.3</td>
</tr>
<tr>
<td>Difference in distance (nmi, meters)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>.06;111.3</td>
<td>.13;240.5</td>
<td>.07;129.5</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>.07;129.5</td>
<td>.23;425.8</td>
<td>.14;259.4</td>
</tr>
<tr>
<td>Tolerance</td>
<td>.15;277.7</td>
<td>.37;685.2</td>
<td>.22;407.5</td>
</tr>
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</table>

Comparison of an Aerial Photographic Mission With & Without Loran-C

Aerial photographic coverage of the Oconee National Forest and surrounding area was completed in the spring and fall of 1979. The same predetermined flightlines were used on each mission. Two Aero Commanders each equipped with a Wild RC-10 camera flew simultaneously to acquire the photography over a two day period. One aircraft was equipped with a Loran-C TDL-424 navigation system, the other relied on visual line of site to fly the flightlines.

This test was designed to compare the parallel flightline navigation accuracy between visual and Loran-C guidance. The results obtained from the spring flight with Loran-C were compared with the results of the same flightlines flown with Loran-C in the fall. In the fall the pilot relied solely on the Loran-C readout as programmed by the navigator/tracker to position the aircraft along the flightline. The pilot of the aircraft relying on visual navigation had ten years of aerial photography experience. The results of this test are illustrated in Table 2. The Loran-C outperformed an experienced flight crew in

Table 2 - Comparison of Parallel Flightline Navigation With & Without Loran-C Guidance, Oconee National Forest, Georgia, 1979

<table>
<thead>
<tr>
<th>Desired scale</th>
<th>1:8,000</th>
<th>1:8,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desired gain/line (nmi)</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>Area (acres)</td>
<td>175,800</td>
<td>175,800</td>
</tr>
<tr>
<td>Number flightlines</td>
<td>27</td>
<td>27</td>
</tr>
<tr>
<td>Linear flightlines length (nmi)</td>
<td>234</td>
<td>234</td>
</tr>
<tr>
<td>Cross track error (nmi, meters)</td>
<td>.04;64.8</td>
<td>.08;140.7</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>.08;114.8</td>
<td>.14;251.9</td>
</tr>
<tr>
<td>Difference in distance (nmi, meters) between actual gain/line and desired gain/line</td>
<td>.05;98.1</td>
<td>.09;174.1</td>
</tr>
<tr>
<td>Mean</td>
<td>.08;155.6</td>
<td>.16;292.6</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>.15;277.8</td>
<td>.15;277.8</td>
</tr>
<tr>
<td>Tolerance</td>
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both the cross track and gain per line analysis. The mean and standard deviations for Loran-C guidance in the cross track error analysis were less than one-half those for visual navigation. In the gain per line analysis, the mean and standard deviation were again almost one-half the visual navigation values.

The results of a T-test indicate that the means for cross track error were significantly different \((t=6.9; df=454)\) at the 99 percent level. Results of a T-test to evaluate the means of with and without desired gain per line were also significantly different \((t=8.6; df=517)\) at the 99 percent level. The average flightline length in this test was only 8.7 nmi with a range of 2.3-13.7 nmi. If the flightlines had been longer a greater cross track error and variance in gain per line would be expected.

Return Flight Accuracy for a Predescribed Flightline

The objective of these tests were to determine if the Loran-C navigator could accurately direct an aircraft precisely over a flightline which had been flown previously. This capability is essential for accurate sequential aerial photography.

A flightline over the target was drawn on a map. The Loran-C indicated coordinates for beginning and end points of the flightline were recorded in latitude and longitude following the first overflight. This flightline was then reflying utilizing Loran-C guidance.

Table 3 - Reflight Accuracy of a Loran-C System During an Aerial Photographic Mission at Various Altitudes

<table>
<thead>
<tr>
<th>Line #</th>
<th>ASL</th>
<th>Scale</th>
<th>Mean X-track Error (nmi)</th>
<th>Range X-track Error (nmi)</th>
<th>Standard Deviation (nmi)</th>
<th>Width of Neg. Error (nmi)</th>
<th>Calculated Error Tolerance Limit (nmi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9500</td>
<td>1:18,000</td>
<td>.04</td>
<td>.01-.09</td>
<td>.09</td>
<td>2.25</td>
<td>.13</td>
</tr>
<tr>
<td>2</td>
<td>9500</td>
<td>1:18,000</td>
<td>.09</td>
<td>.06-.13</td>
<td>.08</td>
<td>2.25</td>
<td>.17</td>
</tr>
<tr>
<td>3</td>
<td>3500</td>
<td>1:6,000</td>
<td>.07</td>
<td>.03-.12</td>
<td>.06</td>
<td>.74</td>
<td>.13</td>
</tr>
<tr>
<td>4</td>
<td>3500</td>
<td>1:6,000</td>
<td>.14</td>
<td>.12-.16</td>
<td>.03</td>
<td>.74</td>
<td>.17</td>
</tr>
<tr>
<td>5</td>
<td>3500</td>
<td>1:6,000</td>
<td>.16</td>
<td>.10-.17</td>
<td>.07</td>
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<td>1:6,000</td>
<td>.15</td>
<td>.11-.19</td>
<td>.07</td>
<td>.74</td>
<td>.22</td>
</tr>
<tr>
<td>7</td>
<td>3500</td>
<td>1:6,000</td>
<td>.03</td>
<td>.01-.04</td>
<td>.03</td>
<td>.74</td>
<td>.06</td>
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<tr>
<td>8</td>
<td>3500</td>
<td>1:6,000</td>
<td>.09</td>
<td>.03-.11</td>
<td>.07</td>
<td>.74</td>
<td>.16</td>
</tr>
<tr>
<td>9</td>
<td>1700</td>
<td>1:2,400</td>
<td>.05</td>
<td>.05-.08</td>
<td>.04</td>
<td>.30</td>
<td>.09</td>
</tr>
<tr>
<td>10</td>
<td>1700</td>
<td>1:2,400</td>
<td>.09</td>
<td>.05-.11</td>
<td>.03</td>
<td>.30</td>
<td>.22</td>
</tr>
</tbody>
</table>

The principal points of the aerial photographs obtained during these flights were plotted on 1:24,000 scale maps. Cross track error for each reflight was measured from the maps for each frame. Therefore, the deviation from the original flight could be determined for each subsequent reflight. In this evaluation two separate tests were conducted to measure the reflight accuracy of the Loran-C system. Test A measured the reflight accuracy over the same flightline at various altitudes. Test B was a comprehensive evaluation of reflying different flightlines at the same altitude. These two tests will be discussed separately.

Aerial photography in Test A was acquired at three different scales: 1:18,000; 1:6,000; and 1:2,400. Different film and filter combinations utilized in the test necessitated reflying the flightline ten times at the various altitudes. One east to west oriented flightline 2 nmi long provided coverage for the target area at all altitudes.

Table 3 illustrates the mean cross track error for each of the ten subsequent overflights. A tolerance limit for error was defined as 15 percent of the negative width at each of the three scales. The standard deviation was also computed for each overflight. The mean plus its standard deviation error were combined and compared to the tolerance limit.

It can be inferred from these results that as you increase in altitude the greater the likelihood of remaining within the specified error tolerance limits. This can be explained due to the fact that as the scale gets smaller the corresponding tolerance for error gets larger, while the error of the airborne Loran-C navigation system would remain constant. Both reflights at the scale of 1:18,000 were well within the tolerance limit.
An analysis of variance displayed significant differences among the means for cross track error. The greatest amount of variation between two flightlines occurred at the same altitude. This variation may have been influenced by atmospheric turbulence. Turbulence generally would tend to increase the cross track error more at the lower altitude and become a more influential factor in relation to the tolerance for error.

A tolerance limit of .05 nmi (304 ft.), as specified at a scale of 1:2,400 would be very difficult to maintain on a single overflight. Errors greater than 15 percent of the area covered by the negative width should be expected at the larger scale.

Table 4 illustrates the navigational performance of adherence to a predetermined flightline in Test B. In order to obtain the maximum accuracy during subsequent reflights, the same secondary stations must be in track. In-track status could not always be obtained for previously utilized stations during reflights due to a reconfiguration of the Loran-C chain during a subsequent flight. Therefore, data were obtained for 67 visual lines flown as opposed to 40 utilizing Loran-C guidance. The navigational performance of the aircraft utilizing Loran-C allowed better adherence to a predetermined flightline.

At a scale of 1:8,000 the width of a negative is 0.98 nmi. The means for cross track error with Loran-C guidance were below the tolerance level. However, the calculated error for tolerance compliance (standard deviation plus the mean) was above the error tolerance limit for both with and without Loran-C guidance as specified in conventional aerial photographic contracts.

In this test the Loran system relied upon previously recorded coordinates for subsequent flights. The first flight performance was compared to the predetermined flightlines. All subsequent flights were analyzed in reference to lines actually flown initially. The amount of flight time required to obtain coverage of the photo sample plots was reduced by 40 percent using Loran-C guidance. Loran-C navigation allowed direct navigation to each site with electronic guidance along each flightline.

Overflights of Predetermined Exposure Stations

Aerial photography at a scale of 1:12,000 was acquired on forty sites in west central South Carolina. Each sites covered only one acre. The center location for each site was plotted on 1:24,000 scale USGS topographic maps. A digitizer containing software capability to determine latitude and longitude for each site was used to obtain the coordinates for each site. These coordinates were used to program the Loran-C system to obtain guidance for overflights on each at a 360 bearing. An Aero Commander 5008 equipped with a Wild RC-10 camera and a TDL-424 Loran-C system was used to acquire the imagery.

Table 4 - Return Flight Accuracy Utilizing Loran-C Navigation During an Aerial Photographic Mission

<table>
<thead>
<tr>
<th>Without Loran-C</th>
<th>With Loran-C</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. flightline plots flown</td>
<td>67</td>
</tr>
<tr>
<td>Mean cross track error (nmi)</td>
<td>0.12</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.20</td>
</tr>
<tr>
<td>Maximum cross track error (nmi)</td>
<td>0.48</td>
</tr>
<tr>
<td>(average per flightline plot)</td>
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</tr>
<tr>
<td>Standard deviation &amp; mean for tolerance compliance (nmi)</td>
<td>0.32</td>
</tr>
<tr>
<td>Error tolerance limit (nmi)</td>
<td>0.15</td>
</tr>
<tr>
<td>Photographic scale</td>
<td>1:8,000</td>
</tr>
<tr>
<td>Width of negative (nmi)</td>
<td>0.98</td>
</tr>
</tbody>
</table>
ADDITIONAL LORAN-C APPLICATIONS IN
NATURAL RESOURCE MANAGEMENT

A variety of additional applications for Loran-C guidance used in aviation for natural resource management have been evaluated. The precise location of forest fires in remote areas must be determined for dispatchers to route fire crews with a minimum of wasted travel. Air tankers used to deploy fire retardant can be equipped with Loran-C systems to record the actual locations of each drop, and if additional drops are required on the fire, Loran-C can direct the pilot back to that location with a minimum of turn around time.

Insect and disease specialists need to know exactly where infestations of timber killing agents are occurring. Loran-C is used in aerial detection surveys to pinpoint the locations of standing dead timber to efficiently salvage the timber and reduce subsequent losses caused by the timber killing agents. Systematic aerial surveys to detect insect and disease losses require that a series of parallel lines be flown to provide the proper coverage of an area. If the aircraft accurately fly extended flightlines, the observers can plot the locations of these infestations more accurately.

The aerial application of pesticides is becoming more and more a public issue. Resource managers need to more accurately direct pesticides to their predetermined targets once the decision to spray has been made. Spray craft flight line guidance using the Loran-C has been evaluated. In general, if flight lines are spaced too far apart, untreated areas allow an insect population to remain uncontrolled and allow the insects to reoccupy the spray areas. If flight lines are flown too close together, too much pesticide is applied creating an environmentally hazardous situation, increasing application costs. In order to apply less pesticide and avoid environmentally sensitive areas, small spray blocks may be established where the pesticide is used more effectively. Loran-C guidance helps the pilots locate the spray blocks and their boundaries. The entire spray operation can be recorded on cassette tape and monitored from a remote location through the data link flight following system to evaluate the effectiveness of the operation and avoid applying materials where unwanted.

Loran-C guidance can also assist in aerial fertilization and aerial seeding operations. Remote heliports can also be located more easily. Aerial ignition may prove to be the answer to high cost of prescribed burning, but precise delivery of the fire is necessary to avoid the expensive embarrassment of burning the wrong track and to evenly apply the fire across the desired area.

These are just a few examples of the use of Loran-C guidance in aerial operations in the USDA Forest Service. The potential uses for Loran-C navigation and positioning equipment may have a far ranging effect on the natural resource manager, especially in forestry applications.

CONCLUSIONS

Several Loran-C systems have been evaluated for accuracy and utility during operational aerial photographic missions. Thousands of aerial photographs from a variety of missions with various objectives have been reviewed. The results of these evaluations indicate that the Loran-C navigation system is ideally suited as an aid to aerial photographic operations. Navigation accuracy was acceptable at scales of 1:6,000 and smaller for parallel track navigation. Sequential aerial photography at scales of 1:12,000 and smaller were acceptable utilizing Loran-C for primary navigation.

Loran-C enables the flight crew to fly extended flightlines more accurately, especially in areas with few landmarks. A major advantage of Loran-C is the reduced time needed to position the aircraft on a flightline prior to entering the target area. The increased accuracy of flying parallel flightlines also provides greater control of sidelap. Loran-C also helps control sequential photography for sampling loss assessment and trends over time. Using it reduces survey fatigue to the flight crew. Freed from continually referring to the flight map the pilot can direct his attention to the flight path, thereby increasing safety of the operation.

The total system accuracy presented in this evaluation illustrates the Loran-C utility in actual photographic missions. These results reflect several sources of error, such as airborne equipment error which would include Loran-C signal propagation anomalies, signal filtering, processing, computational, and output and display errors. Flight technical error or the quantitative assessment of manual or auto-pilot steering performance were also a contributing error factor. Finally, errors associated with aircraft tilt as the time of exposure are taken into account in this analysis. The methodology used to assess the Loran-C system accuracy in
these evaluations included all of the
er error sources mentioned above and reflect
constraints present in most aerial photo-
graphic missions. The Loran-C system
provided navigational accuracy within
an error tolerance specified in conven-
tional photogrammetric mapping contracts.

ACKNOWLEDGEMENTS

The authors extend grateful apprecia-
tion to the U. S. Coast Guard and Teledyne
Systems, Inc.

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APPLYING THE "ORD" MODEL TO INLAND AIRPORTS

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ABSTRACT

The certification of Loran-C for non-precision approaches can be enhanced by using the (Double Range Difference) DRD model. By collecting data at a selected number of locations, it is possible to model the expected error ellipses at any number of locations within the constraints of the model. This paper utilizes the existing U.S. Coast Guard's Loran-C database to generate the error ellipses which can be expected at five New England airports. The USCG R&D Center has recently installed Loran-C monitors at these five airports, thus providing an excellent opportunity to validate the effectiveness of the DRD model on inland locations.

INTRODUCTION

The current Continental United States (CONUS) Loran-C system was configured to provide 1/4 nautical mile or better accuracy for the Coastal Confluence Zone (CCZ). However, the use of Loran-C by the aviation community has extended its use to now include the entire United States. The use of Loran-C in this new capacity has raised valid questions concerning its capability to meet the requirements set forth in AC-90-45A (Reference 1).

Whether Loran-C is to be used in the repeatable (waypoint navigation) mode, or the absolute accuracy (Lat/Lon conversion) mode, there is a definite need to fully understand the effects of seasonal variations. The U.S. Coast Guard's Loran-C database shows variations in the signal from minimal at the System Area Monitor (SAM), to as much as 2 usec peak-peak in some areas. These variations along with the GDPD can result in the repeatability of Loran-C exceeding the requirements of AC-90-45A for nonprecision approaches. To collect data at every airport for a year to determine the extent of the seasonal variations is obviously not economically feasible. Therefore this paper is directed towards showing the repeatability of Loran-C in both the TD and XY positioning, and applying the DRD model to determine the seasonal variations expected at five airports.

REPEATABILITY

The repeatability of Loran-C is the key concept in understanding the effectiveness of waypoint navigation or "calibration techniques". Therefore, the following plots are presented to show that Loran-C indeed has annual repeatability. Figure 1 shows the 9960 Xray data collected at Massena, New York; for the years 1982, 1983, and 1984. The mean value used for plotting purposes is the data mean for 1982. As this figure shows, Loran-C has excellent repeatability from year to year at this northern location.

From a more temperate area is the plot of Figure 2, which shows the 7980 Yankee data collected at St. Petersburg, Florida, for the same 3 year period. While the scale has been changed for presentation purposes, there is again excellent repeatability, only the magnitude of the seasonal component has changed.

Figure 1 Massena NY 9960 Xray 1982-1984

Figure 2 St. Petersburg, FL 7980 Yankee 1982-1984

The repeatability of the TD's is important, but the bottom line is how well this translates to position. Figure 3 is the 95% probability error ellipses for the 9960 Whiskey and Xray data at Massena, NY, for the years 1982 through 1984. The origin of this plot is the dataset means for the 1982 data, with the 1983 and 1984 ellipses offset by their appropriate mean differences from 1982. As expected, Figure 3 shows that Loran-C also has excellent positional repeatability.

Figure 3 1982 - 1984 Error, Ellipses Massena NY
Figures 1 through 3 are extracts of the extensive data base which the USCG R&D Center has collected. Within this database, there are over 60 locations throughout the United States and Canada. This multi-year program of Loran-C data collection supports the repeatability which is inherent to the system.

THE MODEL

There are numerous references on the ORD model, with References 3 and 4 presenting the concepts in detail. Here we will briefly review the model, and refer those with a more extensive interest to References 2, 3, and 4. The ORD model is basically a linear approximation used to model behavior in a nonlinear world. This does not prohibit the use of the model, it merely limits its applicability, depending on the exactness required of it. In fact, References 3 and 4 showed that refinements to the ORD resulted in a significant improvement to the model. The ORD model has been used by the U.S. Coast Guard to model the expected seasonal variations for the CCZ and Harbor Entrance (HHE) areas. For this purpose, coastal monitors were used within the model to determine the signal variations at sea. Here an attempt will be made to model expected seasonal variations at inland airports, where changes in conductivity and the index of refraction vary greatly.

Figure 4 shows the signal paths from the transmitters (Master & Secondary), the SAM, and the point of interest. Since Rs-sam - Rm-sam is a range difference which defines the SAM's hyperbola, and Rs-p - Rm-p is also a range difference defining the hyperbola of the point of interest, Equation (1) is then a "Double Range Difference" which is the hyperbolic distance between the point of interest and the SAM.

DRD = Rs-p - Rm-p - Rs-sam + Rm-sam (1)

To obtain the expected variations in the time differences at the point of interest, equation 2 is used, where the terms are:

- \( z(n) \) = modeled observations
- \( A \) = Double Range Difference in Kilometers
- \( \Delta TD(n) \) = estimated TD variations in nanoseconds/kilometer
- \( C(n) \) = common variations throughout the area
- \( e(n) \) = errors within the model (noise)

\[
z(n) = A \Delta TD(n) + C(n) + e(n)
\] (2)

The \( \Delta TD(n) \) and \( C(n) \) terms used in Equation 2 are obtained from Equation 3 which uses the minimum mean square estimate (MMSE) method. In Equation 3, however, the \( z(n) \) terms are the actual monitor data.

\[\\begin{bmatrix}
\Delta TD(n) \\
C(n)
\end{bmatrix} = (A^T A)^{-1} A^T z(n)
\] (3)

Figure 5 shows the locations of the five airports where the R&D Center installed the monitors. The locations are Jackman, Maine; Newport, Vermont; Rutland, Vermont; Burlington, Vermont; and Pittsfield, Massachusetts. Also shown are the locations of the three Coast Guard monitors selected to serve as input data for Equation 3. The three datasets to be used are Bass Harbor, Maine; Massena, New York; and Avery Point, Connecticut.
Having obtained the estimated $dTD(n)$ and $C(n)$ records for each secondary, the TD variations for the five airports can then be estimated using Equation 2. Figure 8 shows the estimated TD variations for Burlington, Vermont 9960 Whiskey and Xray, which were obtained from Equation 2. These TD variations are then used to calculate the standard deviations and correlation coefficient.

Using the statistics of the data in Figure 8, the 95% probability error ellipse for Burlington, Vermont can then be generated. The ellipse for Burlington VT is shown in Figure 9, along with the calculated Alongtrack Error (ATE) and the Crosstrack Error (CTE). The ATE and CTE are calculated with respect to direction of the runway which is shown as a solid line. The estimated TD variation plots along with the 95% probability error ellipses for all five airports are included in appendix A.
When Loran-C is used in the hyperbolic mode, two or more TD's are required which are not statistically independent. There is, therefore, a correlation coefficient which is not zero, and must be taken into consideration when generating probability error ellipses. Figure 10 is the 95% probability error ellipse for Massena, New York which was computed from the actual monitor data for the year 1984. Also included in the plot are the XY positions of each sample period (4 per day), which are marked with a **. As Figure 10 shows, approximately 95% of the samples are within the error ellipse. In Figure 11, the data set is the same as the one used for Figure 10, with one exception. Prior to calculating the error ellipse, the correlation coefficient was changed to zero. As this figure clearly shows, the error ellipse is no longer a valid 95% probability error ellipse. Any attempt to define the ATE or CTE from it would be misleading.

![Figure 10 Massena NY Actual Error Ellipse](image)

**Figure 10** Massena NY Actual Error Ellipse

![Figure 11 Massena NY Error Ellipse, Rho = 0](image)

**Figure 11** Massena NY Error Ellipse, Rho = 0

**CONCLUSIONS**

Loran-C offers several advantages for aircraft navigation which should not be discarded lightly. The monetary advantages are significant in several areas, the first of which is the cost of providing the signals. Loran-C already provides good coverage over large areas of the United States with its existing transmitters. The use of these signals for navigation should entail little to no additional cost in providing them. In addition, many of the smaller airports which currently are not covered by the conventional aircraft navigation systems, are covered by Loran-C. The cost of Loran-C receivers to use in these areas, while not down to the price of a pocket calculator, are quite reasonable, and further reductions are foreseen. Enroute navigation by Loran-C has the additional advantage of being direct path, which can result in significant savings in manhours, engine hours, and fuel costs.

The DRD model has served the Coast Guard well in estimating the variations of Loran-C for the CCZ and HME of the Northeast and Southeast United States. What has yet to be determined is how well it will work for the Federal Aviation Administration (FAA) in their process of certifying Loran-C for aviation. The application of the DRD model on extensive inland locations may require further refinement of the model's input parameters. Should the requirements on it prove to be too stringent, adoption of a more complex model may prove necessary. To obtain the estimated ATE and CTE for Loran-C, it is necessary to know both the standard deviations and the correlation coefficient at the point of interest.

Several methods of using Loran-C for non-precision approaches have been proposed to the FAA. Of these, the most efficient use of Loran-C for non-precision approach navigation is in the repeatable (waypoint) mode. ASF corrections, area calibration techniques and Lat/Lon conversions, while all viable candidates, are not as effective as waypoint navigation. Determining the TD's for a particular runway is not difficult. A mobile unit can be used to record these time differences at the various airports. These TD's can then be extended out to the approach points, and once verified, made available to the users and the receiver manufacturers. Should the receiver manufacturers choose to put this information in their receivers, it is possible that a pilot could call up a specific airport with a designation code, rather than inputting a long series of numbers. A three letter designation code (17,576 locations) would be less susceptible to error, and require less pilot attention.

**References**


APPENDIX A

Figure A1 Pittsfield, MA

Figure A2 Burlington, VT
Figure A3 Rutland VT

Figure A4 Newport VT
MODEL FOR FORECASTING LORAN-C COVERAGE

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PAPER PRESENTED BY
JANIS VILCANS

ABSTRACT

This paper describes a computational procedure for predicting the potential improvement in LORAN-C coverage in the conterminous United States (CONUS).

System coverage, defined by a set of usable triads from a LORAN-C chain configuration, is estimated by locating a receiver at regularly spaced intervals (0.5 degree by 0.5 degree) throughout the CONUS. Signal and geometric characteristics are determined at each location. This technique, designed to be run on a computer, was developed by MITRE Corporation for the Federal Aviation Administration (FAA). The MITRE model, modified for forecasting by the Transportation Systems Center (TSC), is described in this paper.

LORAN-C coverage is said to exist at a specific geographic location if signals can be received from at least three LORAN-C Stations (LORSTAs) and satisfy two criteria:

a. The signal strength from each of the three LORSTAs must be equal to or exceed a specified minimum signal-to-noise ratio (SNR) at the receiver. This value is the minimum SNR at which a receiver is assumed to be capable of tracking a signal. The noise source is atmospheric radio noise.

b. The geometric relationships between the receiver location and the three LORSTAs must be satisfactory. This relationship is known as satisfying the Geometric Dilution of Precision (GDOP) requirement.

The criteria for determining the optimum triads are based on maximizing SNR and minimizing the GDOP value.

To evaluate the first condition, the strengths of the signals from all LORSTAs are computed at the receiver location. This requires the computation of the loss in LORAN-C signal strength during propagation of the ground wave from its transmitter location to the receiver location. It is assumed in the MITRE model that signal attenuation depends only on the ground conductivity of the CONUS. This assumption has not been changed, although the resolution of the CONUS conductivity grid has been increased in the modification. Since the propagation path is over cells of mixed conductivity values, the Millington method of calculating the attenuation is used in the model.

Analysis of the coverage is dependent on the location of a receiver within the CONUS. Therefore, the coverage forecast requires analysis at individual locations within the CONUS. The location matrix chosen for the analysis includes the area from 124 degrees west to 66 degrees west and from 22 degrees north to 50 degrees north in 0.5 degree increments. The matrix contains 6496, i.e., 116 by 56, locations. The coverage improvement is determined from the percentage increase in the number of locations (with good signal and geometric characteristics) gained by a LORSTA configuration when compared with the coverage obtained with the 1984 configuration. Results of the coverage evaluation, i.e., the coverage assessment, are graphically overlaid on a CONUS outline, and statistically tabulated as cumulative distributions and percentage increase in coverage.

INTRODUCTION

Buoyed by the availability of LORAN-C signals for air navigation, general aviation pilots are expending considerable amounts of money purchasing airborne receivers. These receivers provide navigation capabilities in off-shore, mountainous, and low altitude areas where coverage from VOR/DME is not available. It is expected that both users and manufacturers will want to be able to operate their receivers everywhere in the CONUS. To provide coverage in the approximate one-third of the CONUS that does not have coverage, additional LORAN-C chains and LORSTAs are needed. The FAA is evaluating LORSTA configurations for optimizing coverage in areas where there is an aviation user group and where there are no LORAN-C signals available or the available signals cannot be used with confidence. Areas of these characteristics are the Gulf of Mexico and the "midcontinent gap". This evaluation is a joint FAA/U.S. Coast Guard (USCG) effort.

MODEL ORGANIZATION

The model for forecasting LORAN-C coverage consists of three interrelated parts: input, processing, and output. The inputs are the
The ability of the MITRE model to vary the receiver parameters attracted the attention of TSC. A way to graphically display the benefits gained by using a state-of-the-art LORAN-C receiver was needed. The model answered the question of gained benefits in terms of additional coverage, that is, more areas in the CONUS where the pilot could use LORAN-C signals for navigation.

After serving this initial function, it seemed natural to improve the model by incorporating a denser conductivity grid (Figure 1) and using it to support the FAA/USCG Program. This grid is a closer representation of the CONUS conductivity values.

All geographic inputs are in latitude and longitude. This assures a realistic representation of the coverage when the output is overlaid on a map or chart. The parameters for CONUS inputs are shown in Table 1. Initial computer runs are done at 2 degree intervals to reduce the cost of the processing. Final runs are done at 0.5 degree intervals because one can see contours of GDOP values at this resolution.

The atmospheric noise grid (Figure 2) is partitioned into four quadrants: north, south, east, and west. To represent the worst case, the average noise values (of the rms noise field strength at 100kHz for a receiver bandwidth of 20kHz) for the four daily six-hour periods in the summer season are used. Noise levels are at their highest at these times.

![Figure 1. CONUS Conductivity Grid](image)

![Figure 2. CONUS Atmospheric Noise Grid](image)

**Table 1. CONUS Input Parameters**

- **Geographic Area (LAT, LON, INC-0.5 degrees)**
- **Conductivity Grid (mmho/m)**
- **Atmospheric Noise Grid (LAT, LON, dB)**
The station data entered as input are location, radiated power, chain, function within the chain (master or secondary), and additional GRIs supported. An example of this input is listed in Table 2.

The receiver parameters are listed in Table 3. For most of the data collected to date, the receiver mode used was the master dependent mode. However, the capability of the software to model master independent and cross chain operation is available in the program.

The two values that are calculated in the processing section are SNR and GDOP. Before these two values are computed, several subroutines are used. The first is the calculation of the distance from the receiver location to each of the transmitters. The equations used to compute the distance between two points on the surface of the earth were developed by Sodano. The parameters are listed in Table 4. Using the distance calculation and conductivity values, the signal attenuation is obtained using the Millington method. The SNR is then calculated for the receiver location. The angle subroutine calculates the angles defined in Figure 3, which in turn are used to determine the GDOP value. The expression used for the GDOP calculation is also shown in Figure 3.

The results of the input data and the processing are displayed on maps of the CONUS. The coverage diagrams are the most useful output for the present task—filling the midcontinent gap. The blank areas indicate the areas with satisfactory coverage, as defined by the input values of SNR and GDOP. Preliminary analysis indicates that either five 400kw LORSTAs or four 800kw LORSTAs, properly located, will provide the required signals for navigation throughout the CONUS.

### Table 2. LORSTA Input Parameters

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<th>#</th>
<th>Location</th>
<th>Lat</th>
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<td>1600</td>
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<td>FALSE</td>
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<tr>
<td>27</td>
<td>FOX HARBOUR, LB, CAN</td>
<td>52.376</td>
<td>-55.708</td>
<td>800</td>
<td>7</td>
<td>22</td>
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<tr>
<td>28</td>
<td>ANQUISSOQ, GREENLAND</td>
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<td>760</td>
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<td>FALSE</td>
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<td>CAPE RACE, NF, CAN</td>
<td>46.776</td>
<td>-53.2</td>
<td>1500</td>
<td>7</td>
<td>20</td>
<td>FALSE</td>
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**Chain No.**

<table>
<thead>
<tr>
<th>NAME</th>
<th>GRI No.</th>
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</thead>
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<tr>
<td>NORTHEAST U.S.</td>
<td>9960</td>
</tr>
<tr>
<td>SOUTHEAST U.S.</td>
<td>7980</td>
</tr>
<tr>
<td>GREAT LAKES</td>
<td>8970</td>
</tr>
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<td>U.S. WEST COAST</td>
<td>9940</td>
</tr>
<tr>
<td>CANADIAN EAST COAST</td>
<td>5930</td>
</tr>
<tr>
<td>CANADIAN WEST COAST</td>
<td>5990</td>
</tr>
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</table>
TABLE 3. RECEIVER INPUT PARAMETERS

• DYNAMIC RANGE (120dB)
• SIGNAL-TO-NOISE RATIO (-10dB)
• NOISE EQUIVALENT BANDWIDTH (20 kHz)
• GDOP VALUE (7700 feet/microsecond)
• OPERATIONAL MODE (MASTER DEPENDENT)

TABLE 4. SIGNAL PATH DISTANCE CALCULATION

\[
D = 2 \sin^{-1} \left( \sin^2 \left( \frac{a-b}{2} \right) \right) \sin \left( \sin \left( \frac{a+b}{2} \right) \right) \sin \left( \sin \left( \frac{(\text{LON1}-\text{LON2})/2}{2} \right) \right) \right)^{1/2}
\]

\[
D = \text{GREAT CIRCLE DISTANCE (nmil)}
\]

\[
a = 1.5708 - \text{LAT1}
\]

\[
b = 1.5708 - \text{LAT2}
\]

LAT1, LON1 = RECEIVER LOCATION COORDINATES
LAT2, LON2 = TRANSMITTER LOCATION COORDINATES

FIGURE 3. RECEIVER TO TRIAD GEOMETRY
Figures 4, 5, and 6 demonstrate the coverages forecast by the model for 1986 (including new power values projected by the USCG), and by the five station and four station configurations. Two other engineering considerations come into the analysis at this stage: redundancy in case of a LORSTA failure and cost.*

The model will generate data to plot the redundant coverage for all configurations. The model provides two additional plots for diagnostic use: one contains GDOP values for all the receiver locations in CONUS, and the other contains GDOP values for only those locations that meet the SNR limits. In addition to the plotted output, several tables can be generated to provide numerical values for the configurations. As an example of this output, the following scenario can be considered: An additional station in the Gulf of Mexico area would improve the LORAN-C signal characteristics for helicopter operations to oil platforms. Two locations being considered are Brownwood, TX and Merida, Yucatan Peninsula, Mexico. (See Figures 7 and 8). The advantage of locating the station in Brownwood is shown in Table 5, the coverage improvement table. The most useful output is the additional coverage provided in terms of numbers of airports and general aviation aircraft located in the area. The number of airports and aircraft currently covered by LORAN-C signals are listed in Table 6 and the same type of data, produced with an additional transmitter in Brownwood, TX, are listed in Table 7.**

**NOTE: The data contained in Tables 6 and 7 are not generated by the forecast model.

REFERENCES


FIGURE 5. MIDCONTINENT COVERAGE WITH FIVE NEW STATIONS

FIGURE 6. MIDCONTINENT COVERAGE WITH FOUR NEW STATIONS
FIGURE 7. GULF COVERAGE - STATION BROWNWOOD

FIGURE 8. GULF COVERAGE - STATION YUCATAN

TABLE 5. COVERAGE IMPROVEMENT

<table>
<thead>
<tr>
<th>COVERAGE CATEGORY</th>
<th>NUMBER OF LOCATIONS FOR STATION CONFIGURATION</th>
<th>CHANGE FROM BWD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BWD</td>
<td>YUC</td>
</tr>
<tr>
<td>GOOD SNR AND GDOP</td>
<td>1388</td>
<td>1312</td>
</tr>
<tr>
<td>BAD SNR</td>
<td>316</td>
<td>367</td>
</tr>
<tr>
<td>BAD GDOP</td>
<td>70</td>
<td>34</td>
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<tr>
<td>BAD SNR OR GDOP</td>
<td>79</td>
<td>22</td>
</tr>
<tr>
<td>BAD SNR AND GDOP</td>
<td>314</td>
<td>382</td>
</tr>
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</table>
### TABLE 6. GA ACTIVITY CURRENTLY COVERED BY LORAN-C

<table>
<thead>
<tr>
<th>Description</th>
<th>Airports</th>
<th>Airports with Instrument Approaches</th>
<th>1983 Active GA Aircraft Registered (000)</th>
<th>1983 GA Hours Flown (000)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAST totals</td>
<td>5602</td>
<td>2206</td>
<td>213.3</td>
<td>35,249</td>
</tr>
<tr>
<td>Amount included within current Loran-C coverage</td>
<td>4308</td>
<td>1701</td>
<td>171.1</td>
<td>28,145</td>
</tr>
<tr>
<td>Percentage of total coverage by Loran-C</td>
<td>77%</td>
<td>77%</td>
<td>80%</td>
<td>80%</td>
</tr>
</tbody>
</table>

*These are public-use airports with paved runways.

### TABLE 7. GA ACTIVITY CURRENTLY COVERED BY LORAN-C WITH ADDITIONAL GULF TRANSMITTER

<table>
<thead>
<tr>
<th>Description</th>
<th>Airports</th>
<th>Airports with Instrument Approaches</th>
<th>1983 Active GA Aircraft Registered (000)</th>
<th>1983 GA Hours Flown (000)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAST totals</td>
<td>5602</td>
<td>2206</td>
<td>213.3</td>
<td>35,249</td>
</tr>
<tr>
<td>Amount within expanded Loran-C coverage</td>
<td>4818</td>
<td>1958</td>
<td>194.5</td>
<td>31,801</td>
</tr>
<tr>
<td>Percent of total covered by expanded Loran-C</td>
<td>86%</td>
<td>89%</td>
<td>91%</td>
<td>90%</td>
</tr>
</tbody>
</table>
SESSION III
THE MARITIME ENVIRONMENT

SESSION CHAIRMAN:
Mr. W. Mooney, DOT TSC
SESSION III SPEAKERS

Charles R. Edwards

Ralph Johler

J. R. McCullough

LT Doug Taggart

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AAPS: AUTOMATED AID-TO-NAVIGATION POSITIONING SYSTEM - INTEGRATION OF LORAN-C AND DIGITAL SEXTANTS

Glen E. Baer and Charles R. Edwards
The Johns Hopkins University Applied Physics Laboratory
Laurel, Maryland 20707

ABSTRACT

The Automated Aid-to-Navigation Positioning System (AAPS) is the product of a long evolution of special-purpose loran processors developed at the Applied Physics Laboratory for the U.S. Coast Guard. The design objectives of the AAPS were to improve the aid-to-navigation (AN) positioning accuracy, to improve the integrity of the AN positioning records, and to provide the features of a PILOT system for underway piloting. Horizontal sextants are the primary instrument for positioning aids to navigation, with loran data as a backup. Data logging and report generation are an integral part of the aid positioning process. For piloting, loran and ship gyro data are combined with color chart graphics and presurveyed way points to present relative position. The AAPS hardware consists of a Hewlett Packard 9836C color computer, a graphics printer, a remote CRT, and a loran receiver. The AAPS algorithms, hardware, and software are described, and the results of preliminary testing on the Delaware River are given.

BACKGROUND

Positioning Aids-to-Navigation (AN) is a multifaceted task using all reasonable means for determining position. Horizontal sextants measuring angles between known fixed objects provide primary reference because of their high accuracy. Other measurements such as loran time differences (TDs), ranges and bearings to known objects, water depth, wind, current, etc. are recorded for reference. With insufficient sextant data (e.g., positioning aids offshore) the other measurements must be weighted and entered into the position determination process. Before an aid can be accepted as "on station," the statistical errors in the position determination must be combined with the buoy watch-circle radius (in the case of a floating aid) to verify that the aid is within the assigned tolerance. Care, precision, and documentation must be maintained at all steps of the process to ensure vessel traffic safety.

Currently, manual plotting grids and programmable calculators are used to determine position from the sextant data while maneuvering the vessel to the assigned position for the aid. These plotting grids are precomputed and drawn at the District Headquarters for each aid using preassigned reference objects and do not provide for loran, range, or bearing information.

Using manual plotting grids presents several problems. The objects to be sighted are first selected by the ship personnel, then the list of selections are sent to District Headquarters where the grids are computed and plotted, after which the selections are returned to the ship. If, at the time the aid is to be placed or checked, some of the objects are no longer usable, then fewer objects must be used or new plotting grids must be prepared. It is possible to prepare grids aboard ship, but it is a tedious process. Also, plotting a position on these grids requires considerable data interpolation during the final maneuvering of the vessel. Better error analysis and better documentation are two other tasks that could be improved.

INTRODUCTION

The USCG has asked APL to use the PILOT (Refs. 1, 2, 3, 4) technology to develop a new system that would provide both underway piloting and improve the AN positioning process. The new system, AAPS, when operating in the PILOT Mode determines position continuously, using two or three loran TD; and when operating in the AN POSITION Mode determines relative position on demand, using any combination of digital sextants, loran TDs, ranges, and bearings. Loran TDs are used only in the REPEATABLE Mode and the DIFFERENTIAL Mode. In the AN POSITION Mode, each position fix includes a complete error analysis with a plot of the most probable position (MPP) relative to the assigned position (AP), an error ellipse of 90% position probability, and a circle showing the allowable position tolerance. A printed Aid Position Record and a service record stored on a floppy disk provide full documentation.

AAPS consists of an HP 9836C Desktop Computer, a remote display screen, an LC 404 loran receiver, three digital horizontal sextants, interface chassis, printer, and an optional XY plotter (Figs. 1 and 2). Most of the operator interface with the HP 9836C computer is via the programmable softkeys at the base of the display screen. These keys provide easy access to multilayer menus and minimize operator training. The softkey labels are updated during each process so as to present only the choices pertinent to the next step.

PILOT MODE

Piloting information is presented on the display screen as a color chart with the ship superimposed (to scale) in the center of the display. An interface to the ship gyro allows the vessel symbol to be drawn with the correct heading. Distance and speed both along a track line and across the track line to a predefined way point (WP) are shown across the top of the display. Each chart disk (5½ inch floppy disk) contains a representation of one NOAA chart, 50 presurveyed waypoints, and up to 10 routes defined by the operator. A route consists of a se-

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The primary function of the AN Position Node is to integrate AAPS to as many ship's sensors as possible in order to automate the placement of aids to navigation. In this version of AAPS, data are collected automatically from digital sextants, a loran receiver, and ship's gyro. Other data are entered manually by the operator. AAPS uses Coast Guard proven algorithms and techniques to place an aid. The resultant product for aid placement is still the same, i.e., an aid service report.

The primary instrument used to place an aid is a standard Weems and Plath sextant. AAPS uses this same sextant with one minor modification, a shaft encoder has been added to make it possible to read the angle electronically. This addition does not alter the operation of the sextant. The shaft encoder, added by Teledyne Gurley, ensures that all optical properties remained unchanged.

The procedure currently used by the Coast Guard (Ref. 5) for aid placement consists of the following steps:
1. Select aid.
2. Select objects to be used to place aid.
3. District generates plotting grids.
4. Use sextants to determine correct location of aid.
5. Place aid in correct location based on available information.
6. Record information as to where aid is placed.

AAPS follows the same procedure to assist in aid placement.

All reference data about aids are stored on floppy disks. Up to fifty aid data files are stored on one floppy disk. AAPS permits the operator to view the aids stored on a disk and to select an aid to be placed.

When an aid is selected, all reference data are displayed. The operator selects which objects the sextants will use to place the aid. The selection of the objects enables AAPS to compute the on-line data required to place the aid. Before the existence of AAPS this set of calculations known as "precompute" was performed only at Coast Guard headquarters; however, with AAPS it is now performed aboard ship.

When the vessel is near the desired location of the aid, the sextants are used to determine accurately the location of the vessel. With AAPS, the sextant operators accomplish this by pressing their trigger button whenever they have a valid reading. Ranges and bearings to any of the reference objects may be entered at the keyboard. The AAPS operator selects from all available lines of position (LOP), consisting of up to three loran TDs, and nine angles, bearings, or ranges, all of which are believed to be valid entries.

AAPS utilizes all selected data to compute the NPP of the aid. A plotting grid is used to show the location of the vessel relative to the AP for each NPP determination (see Fig. 3). A complete error analysis may be requested for each position fix. The error analysis is shown graphically with a plot of the NPP, error ellipse, buoy station dimension circle, and a grid scale (see Fig. 4).

\[
\begin{align*}
\text{SEMI MAJOR AXIS} & : 6 \text{ yd} \\
\text{SEMI MINOR AXIS} & : 0 \text{ yd} \\
\text{ELLIPSE ANGLE} & : 133^\circ \\
\text{STD DEVIATION} & : 0 \text{ min} \\
\text{T 30 BIV} & : 5 \text{ yd} \\
\text{NO LOPs} & : 4
\end{align*}
\]

Fig. 4 AN ERROR plot.

After an aid has been set, the operator may request that an Aid Positioning Record (similar to CG-5716 14-80) be printed. An aid service record can also be recorded on the floppy disk at this time. Up to 500 aid service records may be stored on each floppy disk along with the reference data on the fifty aids.

FIELD TEST RESULTS

Field testing of AAPS is scheduled to begin in late October. Preliminary results will be available and presented at the conference.

Using a loran simulator built by the Coast Guard, laboratory testing of the AAPS operated in the PILOT mode indicates an accuracy equal to that obtained with PILOT units.

THE FUTURE

The immediate future for AAPS will be to use loran to place aids-to-navigation. AAPS will provide the link between sextants as they are currently used and loran as it will be used. Other ship sensors will be integrated into AAPS to make possible automatic recording of data from these sensors. Sensors being investigated are radar, depth sounder, and global positioning system (GPS) data.

CONCLUSIONS

AAPS provides Coast Guard buoy tenders with a real-time aid for piloting vessels and a real-time system for placing aids-to-navigation.

ACKNOWLEDGMENT

The Johns Hopkins University Applied Physics Laboratory acknowledges the cooperation and assistance provided by the United States Coast Guard in the development and testing of AAPS.
REFERENCES


ACCURATE POSITION DETERMINATION IN THE BERING SEA USING LORAN-C

J. Ralph Johler and Alan R. Cook
Colorado Research and Prediction Laboratory, Inc.
4801 North 63rd Street
Post Office Box 1056
Boulder, Colorado 80306

ABSTRACT

Alaska and its adjacent waters are becoming of increasing economic importance to the world in which we live. The successful and efficient exploitation of natural resources of the area is vastly enhanced with precise positioning capability as can be provided with Loran-C. In this paper the authors discuss their accomplishments in accurate spatial calibration of the North Pacific Loran-C chain in areas of southwest Alaska and the Bering Sea. The case of the Saint Paul-Narrow Cape transmitter pair is used to illustrate the calibrated TOA coverage of the Shelikof Strait and the Saint George Basin area of the Bering. Calibrated TOAs in the areas are discussed in terms of the overland propagation corrections resulting from irregularities and inhomogeneities along propagation paths of Kodiak Island and the Alaskan Peninsula.

An example is provided which describes TD and TOA variations along a line south of the Pribilof Islands and far removed from the Alaskan Peninsula. Variations of the loran phase along the line are presented for the effects produced by the Pribilofs and Alaskan Peninsula land masses.

The calibration procedures are universal and will remove sufficient propagation bias such that present day receiving equipment is limited only by noise. With the removal of grid warpage Kalman type filter methods are suitable to map a calibrated area anywhere in the world.

1. INTRODUCTION

Position location is defined herein as the precise determination of geographic coordinates (latitude, \( \phi \), and longitude, \( \lambda \)) from the radio navigation coordinates such as \( y_{i} \) of the time differences representing hyperbolic lines of position. Also, the signal propagation time or time of arrival, \( r_{i} \), of each of the signals from at least two Secondaries and a Master. The time difference, \( y_{i} \), between one such Secondary and the Master plus the emission delay, \( C_{s} \), of the Secondary determines the fundamental navigation quantity called the time difference, \( y_{1} \). Thus,

\[
y_{1} = \text{constant} \quad (1)
\]
defines a hyperbolic line of position. The radio navigation fix is determined by only two such numbers, \( y_{i} \), say \( i = X,Y \). Each line of position and hence, each radio navigation fix is related to the latitude, \( \phi \), and the longitude, \( \lambda \), through the fundamental time difference equation:

\[
y_{i} = \frac{r_{i}}{c} \left[ d_{s}(\phi, \lambda) - d_{m}(\phi, \lambda) \right] + \frac{C_{s}}{c} (\phi, \lambda) - C_{m}(\phi, \lambda) + C_{s} \quad (2)
\]
The problem of finding the secondary phase correction for overland propagation becomes an almost universal problem for precise positioning since most Loran-C chains involve considerable land mass in the chain service area. Such ground causes forward scatter of the electromagnetic fields which in turn generates the non-linear behavior of the secondary phase correction both as a function of distance from the transmitter and as a function of the angular distance about the transmitter. The physical mechanism for radio wave propagation involves the topography of mountain ranges, soil structure between the mountains and along coastlines, geology of the rock underlay­ment, and numerous other geophysical features. Both the electrical properties and the form or shape of the land surface affect the radio wave propagation mechanism.

It is apparent that an almost infinite amount of such information could be sought out and collected in a great data base. This may discourage or dismay the user of Loran-C for accurate navigation. Indeed, it soon becomes evident that great data bases are not really necessary for precise coordinate conversion. Nor is it necessary for the data to be exactly correct. Even small amounts of data inserted into the rigorous propagation model will cause substantial error reduction. In fact, the amount of data required for precise coordinate conversion is quite minute when compared with the vast number of expensive measurements required to obtain commensurate results. It has been estimated that $100.00 worth of geophysical data obtained from geophysical libraries of the world are equivalent to $100,000.00 worth of measured Loran-C data and probably produces results which are an order of magnitude more accurate. This is not meant to say that one should not use measured data. In fact, strategically located observations at precisely known geographic locations are the fundamental requirement for a precision calibration of a Loran-C service area. In this manner the calibration is placed in the context of a systematically structured, physically real model of the propagation mechanism.

The authors have been involved with the calibration of an area of the North Pacific Loran-C chain. In particular, a rather interesting anomaly seems to persist in the Bering Sea south of the Pribilof Islands. In this region the time differences or $\gamma_i$'s generated by the Narrow Cape Secondary and the Saint Paul Master transmitters exhibit an enhancement in what appears to be the "radio shadow" just to the south of Saint George Island. In this paper the physical explanation of the phenomena is discussed in detail.

2. PROPOSITION MODEL

For many years the authors have accumulated an organized ensemble of data representing the elements of nature that affect radio frequency electromagnetic groundwave propagation. These data can be convolved with rigorous propagation models derived from Maxwell's equations and conforming to the boundary conditions at the surface of the ground, in the ground and, in the atmosphere to predict the phase in a radio navigation phase type positioning measurement. This rigorous propagation model is the collective convolution of propagation theory and data. Such a model can be used both for prediction and analysis of the groundwave signal. The former is used for very accurate navigation while the latter is used to gain under-
standing of the propagation phenomena of the radio navigation system and to optimize the effective management of the system. Much of the information used in the model has been accumulated during the course of Loran-C measurements observed and recorded throughout the world. The technique of modeling is based upon the foundations of radio metrology (theory of measurement), electromagnetic theory, and a collective knowledge of the electrical properties of the soil, subsoil (hardpan), bedrock (geological structure), and the nature of the atmosphere. This detail is important since the groundwave travels from the transmitter to the receiver through a multiplicity of media. All of these media affect the propagation time, $t_p$, of the wave crests, troughs and zeros as they recede from the transmitter. An introduction to our propagation model is given in reference [1]. In this paper we shall apply this model to analyze the behavior of Loran-C in the Bering Sea.

The fundamental measurand in a radio navigation system is the phase, $\Phi$. Thus radio navigation is accomplished by a phase comparison scheme that tags points in time at or near the crests, troughs or zeros of the wave train sent out by the transmitter. Modulation may be used to resolve specific unambiguous points in time. Indeed, the modulation envelope can be tagged in time. In the particular case of Loran-C the wave is modulated as a pulse. The consequences of pulse modulation have been studied in detail in our previous paper [1], with particular reference to the Loran-C pulse. The work in this reference employs the rigorous and unique structure of Maxwell's equations solved for boundary conditions at the surface of both regular and irregular ground with appropriate boundary in the ground and in the atmosphere. This is shown diagramatically in Figure 2.1. The propagation filter convolves topographic data of land masses, geological data, soil data (both on the surface and at depth) with propagation theory to calculate the time of arrival, $t_c$, or a time difference, $y_i$, to an accuracy unmatched by previous technology. More specifically, an analytic field, $\xi_r$, can be calculated for each propagation path from a transmitter to an observer. This field has the form:

$$\xi_r = |\xi_r| \exp \left[ i\omega t - ik_1d - i\phi_c \right] \quad (2.1)$$

where,

$\omega = 2\pi f$,  
$f =$ frequency, Hertz,

$k_1 = \frac{\omega}{c} n_1$, the wave number in an atmosphere of infinite extent,

$n_1 = 1.000338$, a constant,

$\phi =$ secondary phase correction,

$C =$ radians

$d =$ distance from the transmitter, meters,

$t =$ time, seconds,

$c = 2.99792458 \times 10^8$ meters/second,

$i = \sqrt{-1}$

The total phase, $\Phi$, is therefore:

$$\Phi = \omega t - k_1d - \phi_c \quad (2.2)$$

where a complex space-time function,

$$\exp(\omega t - ik_1d - i\phi_c)$$

has been used, the real part of which is:

$$\cos(\omega t - k_1d - \phi_c).$$

Thus, $k_1d$ and $\phi_c$ are phase lags or phase slowness terms. The term $k_1d$ has been called the Lorentz term. It is caused by the physical separation, $D$, of the transmitter and the receiver and in the curved spherical system space domain can be resolved as the great circle distance, $d = a\theta$ where $a$ is the radius of the sphere and $\theta$ is the angular distance between transmitter and receiver. The phase $k_1d$ is obviously a linear function of distance from the transmitter and describes the phase slowness of an equivalent plane wave in free space, $n_1$, or a non-absorbing, homogeneous medium ($n_1 > 1$ but real) of infinite extent. Obviously, while $k_1d$ is a large number at great distance from the transmitter, it does not suffice to describe propagation at or near the earth's surface or in the earth's atmosphere. This is true for all waves encountered in radio science at frequencies between low frequencies through microwaves to optics. Thus, in general the phase quantity, $\phi_c$, is finite and indeed is the fundamental source of propagation "error" in any radio navigation system. We enclose error in quotes since such error in the system is not stochastic in nature but, indeed, is quite systematic and follows known natural laws such that it is exactly predictable. Throughout the history of Loran-C, $\phi_c$ has been called the secondary phase correction. It can be converted into time, $t_c$, usually expressed in microseconds instead of the MKS seconds as follows:

$$t_c = \frac{\Phi}{\omega} \times 10^6 \text{ usec.} \quad (2.3)$$

Then, the propagation time, $t_i$, becomes for a Master (M) or a secondary (S) transmitter:

$$t_i = \frac{n_1 d_i}{c} + t_c(d_i) \quad (2.4)$$

and the Loran-C time difference, $y_i$, becomes:

$$y_i = t_i - t_m + C_s \quad (2.5)$$

where $C_s$ is the emission delay constant of the secondary, and $s = W, X, Y$, or 2 for a particular secondary.
The scheme used for the propagation model is given in Figure 2.1. This system will usually reduce error to the receiver noise level without iteration. However, accurate positioning may require the adjustment of one or two major propagation parameters using precisely known locations, preferably on land. The time difference measurement at the monitor can be considered as one of these measurement sets. In fact any number of measurements can be used for adjustment but only a small number are required. The savings in time and effort instituted by this propagation model is rather enormous through the obviation of extensive and expensive measurement programs. Moreover, accuracy and reliability of calibrations are enhanced by eliminating the majority of measurement errors which tend to degrade the system for various reasons, some of which are discussed in Appendices I and II.

* By grid warpage is meant the distortion or deformation of the hyperbolic lines of position by propagation enhancement of the secondary phase correction, τ, in the area.

3. THE BERING SEA PROBLEM

Our story begins in the Alaskan frontier where, for several years, numerous natural resource explorers have reported to us of severe Loran-C grid distortions in southwestern Alaskan waters and the Bering Sea. Grid warpages* in these waters have been reported to be so extreme as to render Loran-C unusable as a positioning system or for precision radio navigation. A specific area of consequence lies in the southeastern Bering Sea just south of the Pribilof Islands where the Loran-C is observed to exhibit extreme variations in the TDs and TOAs of the signals from the Saint Paul Master and Narrow Cape Secondary transmitters. The extreme loran signal variations throughout the area are reasonably attributed to anomalous propagation over the land masses in the area, i.e. the Pribilof Islands, Kodiak Island and the Alaskan Peninsula. Calibration of the region to remove the grid warpage obviously requires a detailed examination of the loran signals as they transit these land masses. For this purpose our adventure will travel the crest of a loran wave as it progresses over Kodiak Island, the Shelikof Strait, Alaskan Peninsula, and into the far reaches of the Bearing Sea.

The area of the Bering chosen for precision calibration and described in this report lies amidst some particularly exasperating variations in the loran grid. The area, shown in Figure 3.1, encompasses a line which was the object of calibration and spoken of in this report as the calibrated line. The southwestern part of the line passes through what is termed the "radio shadow" of Saint George Island where it has been tacitly assumed that propagation over the island is the major contributor to the propagation errors observed. On the surface it would seem that this notion is quite valid since the area is several hundred miles removed from the Alaskan Peninsula land mass lying along the signal propagation path. As will be demonstrated in our journey, the Alaskan Peninsula is the major perturbing source of gridwarpage along this line.

The propagation model described earlier was used to quantitatively identify the causes of grid warpage in the Bering Sea. Calibration of the shaded area shown in Figure 3.1 was effected by studying the loran propagation over Kodiak Island, the Shelikof Strait, and the Alaskan Peninsula.

The calibrated line was constructed across...
the trapezoidal area from the northeast corner to the southwest corner connecting the points: \(56^\circ 45'\ N;\ 165^\circ 45'\ W\) together with \(54^\circ 15'\ N;\ 168^\circ 15'\ W\). The line is 320 kilometers in length and far removed at sea from the land masses affecting the propagation from the Narrow Cape transmitter.

Figure 3.1. Map depicting the Bering Sea and Shelikof Strait in relation to the Narrow Cape and Saint Paul transmitters with area of interest indicated as a shaded trapezoid. Dotted line across the trapezoid from the northeast corner to southwest corner is used as a sample calibrated navigation line.

Table 3.1 defines the navigation line in greater detail by providing calibration data at points along the line at separations along the line of approximately 35.5 kilometer increments. The northeastern point, or the starting point, was located 813 kilometers from the Narrow Cape transmitter or Secondary transmitter and 278 kilometers from the Saint Paul or Master transmitter. The southwestern point, No. 10, was 1053 kilometers from the Narrow Cape transmitter and 347 kilometers from the Saint Paul transmitter. In the analysis of an at sea problem, such as is indicated by the geodetic line on the map in Figure 3.1, one

Table 3.1. Detailed definition of the navigation line in the area of interest with definition of calibration points along the line.
can assume that the radio wave propagation is "well behaved" at great distances out to sea. This is quite true along a radio geodetic from the transmitter. But navigators should not be constrained to navigate along radial geodetics, to wit, the lines which have been selected for our study. Hence, to ascertain changes in phase propagation along the select navigation line, the path from each point along the line to both the Master (Saint Paul) and the Secondary (Narrow Cape) are examined in considerable detail. The behavior of the phase along the path from Narrow Cape to point No.1, a distance of 813 kilometers as defined in Table 3.1 is depicted in Figure 3.2 as the secondary phase correction or propagation error in meters. Hence, in the figure the secondary phase correction, was converted into a distance correction in meters, \( d_c \), from:

\[
d_c = \frac{c}{n_1} t_c
\]

This represents the propagation error in meters in the absence of geometric dilution of error, i.e., the actual error will be greater by an amount which depends upon the geometry of the Loran-C chain.

Two major land masses are involved in the propagation path: Kodiak Island and the Alaskan Peninsula. Both of these land masses exhibit severe geologic and topographic features such as mountain ranges, ice fields, swamps and tundra, and patches of permafrost. The features were modeled in some detail as to both topography and electrical properties on the surface of the ground and at depth in the ground.

Let us now follow the recession of the crests, troughs and zeros of the wave propagating away from the transmitter at Narrow Cape. Although the transmitter is located on land, between distances of 5 and 22 kilometers from the transmitter, the signal passes over Ugak Bay. At this point in the wave travel, the phase lag in meters as given by equation (3.1) passes through a minimum propagation error partially because of the salt water of Ugak Bay and partially due to the phase recovery from the induction and electrostatic field perturbations of the transmitter. This then is a phase advance relative to a plane wave propagated in a homogeneous and non-dispersive space of infinite extent. Before the recovery is complete, land (Kodiak Island) is encountered at nearly 22 kilometers. At this point the observer on the ground is 70 meters below the ground plane of the transmitting antenna. The terrain immediately increases to elevations between 300 and 500 meters above the trans-

![Figure 3.2](image-url)  
**Figure 3.2.** Secondary phase correction, or propagation error relative to the propagation time for a free space plane wave propagation time, expressed in meters error for a radial geodetic path from the Narrow Cape transmitter to point No.1 on the navigation line.
mitting antenna and an inflection in the curve is evident at 40 kilometers as the -70 meter level is again encountered for an arm of Ugak Bay. At 45 kilometers from the transmitter an ice field is found at the 900 meter level followed by a rise in the elevation to the 1000 meter level. The propagation error has now climbed to 440 meters. As the wave progresses the elevation abruptly drops to 84 meters at 69 kilometers accompanied by a phase lag decrease to 324 meters. At this point we have a valley or river mouth to 800 meters. A 50 meter error increase is then caused by a series of ridges followed by a swamp and the coast line at 143.5 kilometers.

The wave now recedes across the Shelikof Strait, and the characteristic seawater phase recovery noted. The phase continues to advance (negative phase lag change) until the land is encountered at 241 kilometers. Here the Alaskan Peninsula begins after traversing the Strait and what is known as Wide Bay.

Ridges between 270 and 280 kilometers from the transmitter have elevations of 450 and 526 meters and produce an inflection in the curve of secondary phase correction. Between 300 and 310 kilometers a swamp is crossed with a characteristic phase lag recovery similar in form to salt water. At a distance of 352 kilometers the wave enters Bristol Bay and the Bering Sea. The recovery to the characteristic salt water phase slowness increase occurs at approximately 200 kilometers at sea. The sea water characteristic curve of secondary phase correction is quite regular monotonically increases at great distance out to sea.

The total phase is of course enhanced by the scattering of fields from the land and any changes in this scattering mechanism over the land mass can produce changes at sea. This can be studied by the sequence of propagation paths from the Narrow Cape transmitter to the Bering Sea as depicted in Figures 3.2 through 3.11. As the observer moves southwestward along the line depicted in Figure 3.1, the sequence of radial propagation paths through each end point out to sea depicts this variation more commonly known as the antenna phase pattern. Distances to the point on the navigation line are given in Table 3.1. Also the distances along the navigation line relative to the first point or point No.1 are also given and these are in approximately 35.5 kilometer increments.

Figure 3.3 shows similar but distinct propagation features in the secondary phase correction again expressed in units of meters. The Shelikof Strait and a large swamp near the Bering Sea coast line are evident in the propagation modeling. Several small undulations appear in the curves for out to sea distances as much as 200 kilometers from the coast line. This is caused by the forward scattering mechanism resulting from the irregular growth of the land just crossed. In Figure 3.3, several 200 to 500 meter ridges are crossed. These ridges are interspersed with swamp land and, indeed, the topography ends in a rather large swamp before the coast line is crossed.

From the following sequence of secondary phase correction graphs for propagation paths No.2 through No. 10, it becomes clear that the Alaskan Peninsula is largely responsible for the perturbations observed at sea. For example, Figure 3.6 depicts a variety of features characteristic of the Alaskan Peninsula. Thus, after the Shelikof Strait has been crossed, a perturbation of the phase is noted as the slopes of Mount Chugunagak are transited. This is followed by another ridge and Cinder River. Another perturbation is noticed as Jaw Mountain is crossed followed by recovery at Lava Creek. Then a rather severe perturbation is noted 30 kilometers inland from the Bering Sea as the 898 meter Aviakchak Crater is crossed. This rather severe perturbation is distinctly evidenced by ripples in the phase that extend at least 200 kilometers out to sea from the coast line. The Crater as well as Aviakchak Peak are crossed by path No. 6 at the 1070 meter level relative to the transmitter. Here a swamp and mud flat are crossed before the wave enters the Bering Sea.

Effects due to Kodiak Island are also not negligible. Suppose the time of arrival, $t$, is studied along lines perpendicular to the radials in the Shelikof Strait in the area between Kodiak Island and the Alaskan Peninsula, Figure 3.1. A sampling of the data from our propagation model is made at 150, 200, 250, and 300 kilometers from the transmitter for azimuthal arcs.

The configuration is depicted in Figure 3.12 with the travel from north to south in the Strait. The corresponding error for the Shelikof Strait is given in Figure 3.13. As the distance is increased from the transmitter the perturbations spread due to the divergence of the radials from the transmitter. The error or secondary phase correction, $e$, ranges to over 400 meters in this region. It is, however, completely predictable with the aid of our propagation model.

To synthesize a time difference, $y$, along the at sea navigation line depicted in Figure 3.1 it was also necessary to account for propagation from the Saint Paul (Master) transmitter to our navigation line. Some Perturbations were evident due to Saint Paul Island on which the transmitter was
Figure 3.3. Secondary phase correction or propagation error relative to the propagation time for a free space plane wave propagation time, expressed in meters of error for the path from the transmitter at Narrow Cape to point No. 2 on the navigation line.

Figure 3.4. Secondary phase correction or propagation error relative to the propagation time for a free space plane wave propagation time, expressed in meters of error for the path from the transmitter at Narrow Cape to point No. 3 on the Navigation line.
Figure 3.5. Secondary phase correction or propagation error relative to the propagation time for a free space plane wave propagation time, expressed in meters of error for the path from the transmitter at Narrow Cape to point No. 4 on the navigation line.

Figure 3.6. Secondary phase correction or propagation error relative to the propagation time for a free space plane wave propagation time, expressed in meters of error for the path from the transmitter at Narrow Cape to point No. 5 on the navigation line.
Figure 3.7. Secondary phase correction or propagation error relative to the propagation time for a free space plane wave propagation time, expressed in meters of error for the path from the transmitter at Narrow Cape to point No. 6 on the navigation line.

Figure 3.8. Secondary phase correction or propagation error relative to the propagation time for a free space plane wave propagation time, expressed in meters of error for the path from the transmitter at Narrow Cape to point No. 7 on the navigation line.
Figure 3.9. Secondary phase correction or propagation error relative to the propagation time for a free space plane wave propagation time, expressed in meters of error for the path from the transmitter at Narrow Cape to point No. 3 on the navigation line.

Figure 3.10. Secondary phase correction or propagation error relative to the propagation time for a free space plane wave propagation time, expressed in meters of error for the path from the transmitter at Narrow Cape to point No. 9 on the navigation line.
Figure 3.11. Secondary phase correction or propagation error relative to the propagation time for a free space plane wave propagation time, expressed in meters of error for the path from the transmitter at Narrow Cape to point No. 10 on the navigation line.

Figure 3.12. Locations for the azimuthal arcs in the Shelikof Strait and western Kodiak Island for describing secondary phase corrections when moving north to south along the arcs and perpendicular to the radio geodetics from the transmitter at Narrow Cape.
located; more interesting was the effect on the propagating wave phase as it crossed Saint George Island on its journey to our navigation line. The paths which crossed Saint George Island were located so as to affect the time differences at point Nos. 8 and 9 on the line.

Figure 3.14 depicts the perturbation of the secondary phase correction, \( d_c \) as the wave transits the island. Whilst the perturbation is not so great in magnitude compared with those generated by the Alaskan Peninsula, it is none the less not negligible. In fact the perturbations cause a permanent pattern offset of about 40 meters which is reflected in the time difference, \( \gamma_i \), and time of arrival at the points on our navigation line.

Finally, Figure 3.15 shows the variation of the time differences along our navigation line relative to the starting point located at point No. 1. Thus the error is a \( \gamma_i \) error due to propagation normalized to point No. 1:

\[
\text{ERROR} = (d_{cs} - d_{cm}) - (\gamma_{cs} - \gamma_{cm})
\]

where,
\[
\begin{align*}
  d_{cs} & \quad \text{is the distance error from the Secondary to the point,} \\
  d_{cm} & \quad \text{is the distance error from the Master to the point,} \\
  \gamma_{cs} & \quad \text{is the distance error from the Secondary to the reference point,} \\
  \gamma_{cm} & \quad \text{is the distance error from the Master to the reference point.}
\end{align*}
\]

Thus the total error involves the total secondary phase corrections between both the Secondary and Master transmitters. Much of this error is due to the normal propagation over sea water. Removal of the error due to sea water gives the second curve in Figure 3.15 marked "Relative to Sea Water."

Suppose the geographic location of point No. 1 is known with the aid of an independent position locator. Then one could operate Loran-C in the differential or relative Loran-C mode. However, as we travel along the line our error would again become quite finite and certainly not negligible for accurate positioning. This
is a consequence of the velocity or "speed of propagation" concept discussed in Appendix I. It is interesting to note that the apparent shadowing effect due to Saint George Island is actually caused by the Alaskan Peninsula.

Table 3.1 gives the absolute propagation phase error or secondary phase correction in meters. This value varies from 713.0 meters for point No. 1 to 949.4 meters for point No. 10. The predicted time difference \( y_i \), in microseconds is also given for each point. These values were obtained without the parameter adjustments indicated in Figure 2.1. The values given are guaranteed to 100 nanoseconds or 15 meters. Greater accuracy can be obtained by fine tuning the adjustable parameters in the propagation filter. It is of interest to note that a strong enforcement of propagation error occurs as the propagation path to the Narrow Cape transmitter intercepts the Aniakchak Crater on the Alaskan Peninsula as indicated in the graph of Figure 3.15.

In Table 3.1 the emission delay, \( C_o \), for the Narrow Cape transmitter is reported. This was deduced as consistent with the value of the Monitor time difference, \( y_i \), and determined upon application of our propagation filter to the monitor propagation paths. The values reported in reference[2] represent a "sea water" value and hence are incorrect. It is of interest to note that an accurate emission delay can be deduced from our model without the necessity of determining the constant with numerous elaborate and expensive baseline extension measurements.

It is concluded from the sequence of Figures 3.2 through 3.11 comprising propagation paths No. 1 through No. 10 in Table 3.1 and from Figures 3.13, 3.14, and 3.15 that the at sea state of the phase measured for Loran-C is a function of the details of the propagation over Kodiak Island, the Shelikof Strait, and the Alaskan Peninsula as well as to some extent the Pribilof Islands.

Supplying such details is the function of
our propagation model which provides a data base on the natural land features that affect wave propagation over a land mass like that depicted in Figure 2.1. The model then convolves the specific information with Maxwell's equations and the propagation media boundary conditions to provide a unique prediction for Loran-C values in the service area. Without such modeling it is doubtful and uncertain if uniqueness can be obtained. It is true that one can find areas where such errors are fortuitously small but for each such area another can be cited where propagation errors are unacceptably large.

4. CONCLUSIONS

Loran-C has been developed and is maintained as one of the more splendid navigation systems ever conceived. The stability of the radio groundwave is remarkable and provides to the Loran-C user a system which is inherently of high reliability and with a potential for very high accuracy in all types of environments. In the radio groundwave radio science and metrology have given a "state of the art" for prediction and calibration of the loran system which, when used, will establish Loran-C as a "stand alone" system or as a reference for the integrated navigation system concept. However, to reach this state of positioning the foundations of radio science are required to resolve propagation problems for both sea water as well as irregular and inhomogeneous earth. Such is the case in the Bering Sea discussed in this paper.

In our journey across Kodiak Island and the Alaskan Peninsula, we have described the calibration of an area in the Bering Sea in the face of a hostile positioning and navigation environment. The Kodiak Island and Alaskan Peninsula land masses are representative of the rugged earth surface features found in numerous Loran-C service areas. As has been demonstrated here, the Loran-C solution to the most difficult of
positioning applications is viable even under what once was considered unfavorable signal propagation conditions. With the technology now available to calibrate the radio groundwave, 100 nanosecond accuracy is readily achievable for a loran service area at any place in the world without a requirement of expensive measurement programs. Indeed, with a limited number of measurements at strategic locations in a service area the accuracy can be enhanced to 10 meters or better for 95 percent of the position determinations.

The marine environment is deceptively oversimplified for many of the currently used positioning systems, particularly those relying on tropospheric propagation. The stability afforded by the radio groundwave makes Loran-C exploitable for numerous economic, political, and defense purposes. Exploratory geophysical surveys have as a primary aim the detection of oil bearing geological structures with typical dimensions on the order of hundreds of meters and where tens of meters in positioning error could mean the success or failure of a seismic survey. Observation of international borders, resolution of border disputes, avoidance of marine hazards, and safety in navigation are but a few of a seemingly boundless list of benefits to be realized from accurate Loran-C.

Common practice in the Loran-C community is to use a concept of radio wave velocity or speed of propagation to solve practical problems in positioning. These concepts are discussed in Appendices I and II of this paper. While ad hoc concepts such as these find suitable application in some instances of ordinary navigation, they lack the rigor necessary to obtain positioning accuracies of which Loran-C is capable. On the other hand, as demonstrated in the Bering Sea case described in this paper, radio science and metrology offer the systematic analytical approach and the universality which is necessary for the science of positioning. There is no shortcut. To use Loran-C to its fullest potential it is necessary to "sweat the details" of radio science as cited here for the Bering Sea.

If Loran-C is to become the accurate and reliable positioning or navigation system of which it is capable, the calibration problems will be resolved with the theory of radio science and the judicious use of meaningful measurements. Indeed, for ordinary navigation the tenets of radio science cannot be ignored if reliability and user confidence in the system are to be maintained. As has been shown here, the use of a velocity concept to determine the range of a radio navigation system, and more precisely the ersatz velocity, is not in keeping with the fundamentals of radio theory.

RECOMMENDATIONS
1. The U.S. Coast Guard has done an outstanding job at stabilizing the Loran-C chain and should continue to do the same,
2. Emission delays are irrelevant and misleading and should be replaced or at least supplemented with TD's or TOA's of the monitor,
3. Baseline extension measurements are unnecessary to determine the emission delay and can be eliminated for economy of operation,
4. The burden of calibration should be left to the user, since this paper demonstrates economic methods for its accomplishment.
5. Loran-C should be put forth as a stand alone system and, indeed, as a standard with which to compare other radio positioning systems.

ACKNOWLEDGEMENTS

It is with deep appreciation that we thank Mr. Walt Dean, ARNAV Systems, Inc. for his technical review of this paper.

REFERENCES

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APPENDIX I: PHASE VELOCITY

Since the pioneering work of Sommerfeld during the very early part of this century, and even earlier, it has been recognized that the phase velocity of an electromagnetic wave is not a measurand for a radio system. The radio wave phase velocity cannot be determined experimentally and is considered void of any direct physical significance. This is particularly the case with the electromagnetic groundwave where the phase velocity frequently exceeds the speed of light and can oscillate wildly about the speed of light when traversing irregular and/or inhomogeneous ground. A particular case in point is the elementary example of a groundwave signal passing over a smooth earth land-sea interface. Upon transiting the boundary the instantaneous phase velocity exceeds the speed of light and continues to exceed that value for great distances at sea. Clearly in this case the phase velocity is not measurable and it is easy to imagine how the problem is compounded when the propagation path is neither smooth nor homogeneous.

For a long time it has been the practice of the radio navigation and positioning industry to use the concepts of average velocity, speed of propagation, or velocity over average land to determine the range for the radio groundwave navigation systems. In view of the behavior of the radio phase velocity and its lack of physical meaning, it is appropriate to ask if a number can be assigned for a speed of propagation which will represent that quantity sufficiently to be used for precision navigation and/or positioning. That subject is explored here for the Loran-C groundwave. It should be noted that the arguments presented here for the phase velocity are extended to the wave velocity, signal velocity, and the group velocity.

The model used for the groundwave analysis is that of a spherical coordinate system and is displayed in Figure A1.1.

The analytic groundwave field, $\phi$, radiated from a transmitter $T$, to an observer, $O$, has for the particular field component in the $r$-direction (vertical electric field) the form:

$$\phi_r = |\phi| \exp \left( i \omega t - i \frac{k_1}{c} |D|^{-1} \cdot \delta s - i \phi_c(s) \right)$$

(A1.1)

where,

- $k_1 = \frac{\omega}{c} n_1$,  
- $c = 2.99792458 \times 10^8$ m/sec.,  
- $n_1 = 1.000338$,  
- $\omega = 2\pi f$,  
- $f = \text{frequency (Hertz)}$,  
- $|D|^{-1}$,  
- $\delta s$ a position vector for fields radiated from the transmitter $T$,  
- $r = a + h$, the distance along the spherical surface,  
- $a = 6.36739 \times 10^6$ meters,  
- $h$ altitude above the earth’s surface,  
- $\hat{r}$ $\hat{\delta}$ unit vectors of the spherical system,  
- $a = \text{effective earth radius}$.  

The universal constant, $c$, as determined by the National Bureau of Standards [4] has a value of $2.99792458 \times 10^8$ meters/second. This constant is dimensioned as a velocity and hence is referred to as the speed of light or even as the velocity of light. Obviously the value for $c$ is determined as the speed of light in free space and in the determination of this constant great precautions are taken to ensure that the $\phi_c$ of equation A1.1 or the quantity secondary phase correction is identically zero ($\phi_c = 0$). Accordingly, with the secondary phase correction zero the determination of the constant can be made precisely by measurement of a plane wave in free space. It is readily recognized that the measurement of $c$ is a separate and distinct case from the determination of radio wave velocities as used in practice. In the latter case the secondary phase correction assumes a finite value, particularly the radio groundwave which is attached to the surface of the earth and especially over the land masses of the earth’s surface.

The quantity, $\phi_c$, is the phase of the complex field, $\phi$, that satisfies Maxwell’s
equations at a point source of radiation on or near the surface of the earth. The effects of ground conductivity, dielectric constant, permeability, and topography of the ground are introduced into through satisfying the boundary conditions at the surface of the earth. Thus the secondary phase correction is the fundamental physical quantity that accounts for the diffraction mechanism of the groundwave.

The advancing groundwave that has been radiated along the surface of the earth can be measured in the time domain by tagging the surfaces of constant phase, \( \phi \) via

\[
\phi = \text{Arg} e^{i \omega t} \text{ = constant} \tag{Al.2}
\]

or, \( \phi = \omega t - k s - \phi_c(s) = \text{constant} \tag{Al.3} \)

and the differential phase, \( d\phi \), for the surfaces of constant phase must vanish:

\[
d\phi = \frac{\partial \phi}{\partial t} dt + \frac{\partial \phi}{\partial s} ds = 0 \tag{Al.4}
\]

Using vector notation for the gradient, \( \vec{\nabla} \), one can write:

\[
\vec{\omega} t + \vec{\nabla} \phi \cdot \vec{a} ds = 0 \tag{Al.5}
\]

If \( \frac{ds}{dt} \) is interpreted as the speed at which such constant phase surfaces recede from the transmitter, one has then identified a phase velocity, \( v_c \), that can be written from equation Al.4 as:

\[
v_c = -\frac{\partial \phi}{\partial s} \tag{Al.6}
\]

or, as given in NBS Circular 573, reference [3]:

\[
v_c = \frac{n_1}{c} + \frac{\partial \phi_c}{\partial s} \tag{Al.7}
\]

where,

\[
t_c = \frac{\phi_c}{\omega} \tag{Al.8}
\]

In the time domain the time of arrival, \( t \), can be calculated from the phase slowness for a distance, \( d \), from the transmitter:

\[
\frac{dt}{ds} = \frac{n_1}{c} + \frac{\partial t_c}{\partial s} \tag{Al.9}
\]

or,

\[
t_i = \frac{n_1 d}{c} + t_c(d) \tag{Al.10}
\]

the time of arrival. Thus, the times of arrival as implied in the time difference equation:

\[
y_i = t_m - t + C_s \tag{Al.11}
\]

is the component of a vector in the \( \hat{\phi} \) direction and is a quantity that can be measured.

The notion of an average velocity, speed of propagation, or velocity over average land as commonly used by the navigation industry for navigation and positioning applications is not as clearly defined for the radio groundwave as is the definition for the phase velocity, \( v_c \). In view of the lack of significance attached to the phase velocity it is legitimate to question if a meaning can be ascribed to "average velocity" type concepts which will permit accurate and reliable positioning applications. "Average" is a stochastical concept usually given in a discrete form such as:

\[
v_{av} = \frac{\sum_{n=1}^{N} p(n)v_c(n)}{N} \tag{Al.12}
\]

where \( p(n) \) is a probability and \( v_c \) is the discrete phase velocity. In the continuous form:

\[
v_{av} = \frac{1}{d} \int_{0}^{d} v_c(s) ds \tag{Al.13}
\]

where at some distance, \( d \), all values over the distance are averaged. The lower limit need not be zero or one can write:

\[
v_{av} = \frac{1}{d-d_0} \int_{d_0}^{d} v_c(s) ds \tag{Al.14}
\]

Upon introducing equation (Al.7) into (Al.14), the expression for the average velocity is found to be:

\[
v_{av} = \frac{1}{d-d_0} \int_{d_0}^{d} \frac{ds}{\frac{n_1}{c} + \frac{\partial t_c}{\partial s}} \tag{Al.15}
\]

Clearly the integrand for \( v_{av} \) is a function of the rate of change of the secondary phase correction with respect to distance and is subject to the non-linearities that are characteristic of the rate of change of \( t_c \). To illustrate the non-linear character of \( v_{av} \) consider the special and elementary
case of the secondary phase correction over smooth and homogeneous earth media such as seawater and a typical type land. For the examples to follow, seawater has a ground impedance of |x|=0.001055 and the typical land chosen assumes a ground impedance of |x|= 0.03. For a smooth spherical, earth tc assumes the non-linear form:

\[ t_c = a_1 s^{-1} + a_3 + a_1 s + a_2 s^2 \quad (A1.16) \]

where the coefficients, \( a_i \), are given in Table A1.1. Upon integrating the expressions for \( v_{av} \) from equations (A1.13) and (A1.15) one finds for the case 10 ≤ d ≤ 500:

For \( d_0 = 0 \),

\[ v_{av} = \left( \frac{n_1}{c} + a_1 \right)^{-1} \left\{ 1 + \frac{\sqrt{a_1}}{2d} \ln \left[ \frac{1 - (a_{1})^{-\frac{1}{2}} \sqrt{\frac{n_1}{c} + a_1}}{1 + (a_{1})^{-\frac{1}{2}} \sqrt{\frac{n_1}{c} + a_1}} \right] \right\} \quad (A1.17) \]

For finite \( d_0 \),

\[ v_{av} = \left( \frac{n_1}{c} + a_1 \right)^{-1} \left\{ 1 + \frac{\sqrt{a_1}}{2d} \ln \left[ \frac{1 - (a_{1})^{-\frac{1}{2}} \sqrt{\frac{n_1}{c} + a_1}}{1 + (a_{1})^{-\frac{1}{2}} \sqrt{\frac{n_1}{c} + a_1}} \right] \right\} + \]

\[ - \ln \left[ \frac{1 - (a_{1})^{-\frac{1}{2}} \sqrt{\frac{n_1}{c} + a_1}}{1 + (a_{1})^{-\frac{1}{2}} \sqrt{\frac{n_1}{c} + a_1}} \right] \quad (A1.18) \]

For cases when d ≥ 500 km.

\[ v_{av} = \frac{1}{2a_2 d} \left( \ln \left[ 1 + \frac{2a_1 d}{n_1 + a_1} \right] + \right. \]

\[ - \ln \left[ 1 + \frac{2a_1 d_0}{n_1 + a_1} \right] \quad (A1.19) \]

The non-linear characteristic of the average velocity is illustrated by the logarithmic forms of equations (A1.17), (A1.18), and (A1.19). The computations for \( v_{av} \) are displayed in Table A1.2 for seawater and typical land propagation paths and for varying \( d_0 \).

Table A1.2 demonstrates that the value obtained for an average velocity in an area is dependent upon the points where the measurements are made. It is easily shown that in the limit

\[ \lim_{d \rightarrow d_0} v_{av} = \frac{v_c}{d} \]

or, as d approaches \( d_0 \) the value for the average velocity approaches that of the phase velocity, a quantity which is not measurable. The phase velocity can exceed the universal constant c and frequently does over irregular land paths as well as over path inhomogeneities. Such is the case for land-sea interfaces as can be inferred from Table A1.3 where the phase velocity for the Loran-C signal exceeds the speed of light for distances of 10, 20, and 50 kilometers for the simple case of smooth earth seawater paths.

At this point it is instructive to estimate the errors associated with the use of an average radio wave velocity type concept. For this purpose assume that a measurement is made at 200 kilometers with a precision satellite such that the error due to the use of the velocity concept at this point is zero. Then using equation A1.9 and neglecting the geometrical dilution of error, the average velocity concept error relative to the known position can be calculated from:

\[ \frac{d}{v_{av} \cdot \frac{c}{n_1}} = \text{error (meters)} \]

Similarly for the instantaneous phase velocity:
defined as:
\[
\frac{d}{\varepsilon} = \frac{c}{n_1} = \text{error (meters)}.
\]
The errors thus calculated for distances corresponding to the values for velocities given in Table A1.2 appear in Table A1.5.

Appearing in the literature there is still another type of velocity which evidently\(^5\)

\[
\varepsilon_c = \frac{d}{c + t_c}
\]

\[\text{(Al.19)}\]

\begin{center}
\textbf{TABLE A1.1}
\end{center}

\textbf{COEFFICIENTS}

\textbf{SMOOTH, SPHERICAL GROUND}

\begin{tabular}{|c|c|c|c|}
\hline
\textbf{\(x\)} & \textbf{\(a_1\)} & \textbf{\(a_2\)} & \textbf{\(a^{-1}(a_2)\)} & \textbf{\(\text{RANGE}\)}
\hline
0.001055 & 0.0657216594 & 0.0015870425 & 2.68655794 & 10 \(\leq s \leq 500\) \textbf{kms} \\
0.001055 & 0.311244450 & 0.0021263440 & 3.1448 \(10^{-8}\) & 500 \(\leq s \leq 2400\) \textbf{kms} \\
0.03 & 0.4514695120 & 0.0046543380 & -0.92728794 & 10 \(\leq s \leq 500\) \textbf{kms} \\
0.03 & 0.394881340 & 0.0042737924 & 3.3940 \(10^{-8}\) & 500 \(\leq s \leq 2400\) \textbf{kms}
\hline
\end{tabular}

where,

\[
t_c = a_0 + a_1s + a_2s^2
\]

10km \(\leq s \leq 500\) km

\[
t_c = a_0 + a_1s + a_2s^2
\]

500km \(\leq s \leq 2400\) km

\begin{center}
\textbf{TABLE A1.2}
\end{center}

\textbf{AVERAGE VELOCITIES}

\textbf{(SMOOTH EARTH)}

\[\text{(a) } |x| = 0.001055; \ 10 \leq d \leq 500\]

\begin{tabular}{|c|c|c|c|c|c|}
\hline
\textbf{d} & 10 & 20 & 50 & 100 & 200 \\
\hline
20 & 300255. & & & & \\
50 & 299620.21 & 299635.83 & & & \\
100 & 299564.65 & 299565.10 & 299573.57 & & \\
200 & 299552.48 & 299552.34 & 299552.85 & 299554.81 & \\
500 & 299549.28 & 299549.24 & 299549.58 & 299549.30 & 299549.50 \\
\hline
\end{tabular}

\[\text{(b) } |x| = 0.001055; \ 500 \leq d \leq 2400\]

\begin{tabular}{|c|c|c|}
\hline
\textbf{d} & 500 & 1000 \\
\hline
1000 & 299496.08 & \\
1500 & 299494.67 & 299493.26 & \\
2000 & 299493.26 & 299491.84 & \\
\hline
\end{tabular}

\[144\]
Although the expression of equation (Al.19) is dimensioned as a velocity (speed), it is not representative of either the average nor instantaneous phase velocity. Comparing equation (Al.7) with equation (Al.19) demonstrates a restrictive condition of linearity upon the rate of change of the secondary phase correction with respect to distance. Consider, for example, a case where it might be possible to represent the secondary phase correction as a linear function of distance, or:

\[ \tau_c = a_0 + a_1s \]
\[
\frac{\Delta t_c}{\Delta s} = a_1,
\]
which infers that the rate of change of \(t_c\) with respect to \(s\) is a constant, \(a_1\). Further, it follows that:
\[
a_1 = \left[ \frac{1}{s} (t_c(0) - a_2) \right]_{s=d_0}
\]
where \(a_1\) is evaluated at a reference point \(d_0\) and \(t_c(0)\) is the corresponding secondary phase correction at that point. Therefore,
\[
\vec{v}_c = \frac{d_0}{a_1d_0 + t_c(0) - a_2} \quad (A1.20)
\]

Equation (A1.19) follows when \(a_1\) is made to be identically zero. Equation (A1.19) has been used to estimate average velocities for the radio groundwave and aside from the presumption of linearity to represent the secondary phase correction the equation neglects the constant term \(a_2\). Experiment has verified that the secondary phase correction requires higher order polynomials for its representation even in the case of smooth homogeneous earth. Thus, there is no justification for equation (A1.19) and accordingly the authors will refer to this quantity as an "ersatz" velocity.

As stated earlier, the velocity of a radio wave is not measurable and is considered void of direct physical significance. The velocity concept takes on meaning only when the velocity is structured by the characteristics of the media through which it propagates. This structuring process, whether it is accomplished by measurement or by computer simulation is the process of determining the rate of change of the secondary phase correction, a quantity more difficult to assess than the secondary phase correction itself.

The error in the ersatz velocity as given in equation (A1.19) is evident by observing that the rate of change of the secondary phase correction with respect to distance appearing in the expression for the velocity of equation (A1.7) is the tangent to the non-linear secondary phase correction curve when plotted as a function of distance. The ersatz velocity approximates the tangent with a secant through the origin. Table A1.4 gives the values of the ersatz velocity over a smooth spherical surface for both seawater and the typical land propagation. Errors for this velocity are also included in Table A1.5.

### Table A1.4
ERSATZ VELOCITIES (SMOOTH EARTH)

<table>
<thead>
<tr>
<th>(d(\text{kms}))</th>
<th>SEA WATER</th>
<th>LAND</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>299494.82</td>
<td>296196.16</td>
</tr>
<tr>
<td>20</td>
<td>299691.16</td>
<td>297159.95</td>
</tr>
<tr>
<td>50</td>
<td>299583.60</td>
<td>298534.11</td>
</tr>
<tr>
<td>100</td>
<td>299583.60</td>
<td>298962.51</td>
</tr>
<tr>
<td>200</td>
<td>299572.15</td>
<td>299170.46</td>
</tr>
<tr>
<td>500</td>
<td>299559.52</td>
<td>299293.58</td>
</tr>
<tr>
<td>1000</td>
<td>299531.05</td>
<td>299352.00</td>
</tr>
<tr>
<td>2000</td>
<td>299512.86</td>
<td>299375.21</td>
</tr>
</tbody>
</table>

It should be re-emphasized that the errors appearing in Table A1.5 are those for a smooth spherical surface without perturbing influences such as land mass topography and

### Table A1.5
DISTANCE ERROR FROM VELOCITY CONCEPT (METERS)

<table>
<thead>
<tr>
<th>(d(\text{kms}))</th>
<th>SEA WATER</th>
<th>LAND</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>-80.7</td>
<td>27.7</td>
</tr>
<tr>
<td>20</td>
<td>-40.6</td>
<td>13.7</td>
</tr>
<tr>
<td>50</td>
<td>-41.7</td>
<td>5.2</td>
</tr>
<tr>
<td>100</td>
<td>-10.1</td>
<td>2.1</td>
</tr>
<tr>
<td>*200</td>
<td>000.0</td>
<td>000.0</td>
</tr>
<tr>
<td>500</td>
<td>75.5</td>
<td>-2.9</td>
</tr>
<tr>
<td>1000</td>
<td>160.4</td>
<td>41.6</td>
</tr>
<tr>
<td>2000</td>
<td>358.3</td>
<td>624.2</td>
</tr>
</tbody>
</table>

\(*d_0 = 200 \text{ kms.}\)
propagation path inhomogeneities. As will be seen in the following parts of this appendix, such features of the earth surface render the velocity type concept unusable for applications of accurate positioning.

The influence of topographic relief and its deleterious effect when using a velocity type concept for positioning with a radio groundwave system is vividly demonstrated in the case of the Narrow Cape transmitter of the North Pacific Loran-C chain. When using this transmitter for positioning in the Shelikof Strait or the Bering Sea, the loran signals must propagate over the irregular terrain of Kodiak Island and, in the latter case, the Alaskan Peninsula. Both of these land masses are characterized by rugged topographic relief and are quite similar to much of the relief encountered in the West Coast Loran-C service area.

The examples discussed heretofore which described errors associated with velocity calculations on a smooth, homogeneous earth involved only the perturbation zone of the antenna along a geodetic from a transmitter, T, to an observer at point O. In these cases the antenna pattern in both the near field and the far field of the transmitter is azimuthally uniform and well behaved and, as has been demonstrated, the errors due to a velocity concept are a function of distance from the transmitter. Such is not the case when irregular and inhomogeneous propagation paths are involved in the groundwave signal transmission to the point O. In this latter instance, the secondary phase corrections at points along nearby geodetics intersecting the same azimuthal arc can differ in value from each other by hundreds and even thousands of nanoseconds. The resulting antenna pattern variations cause hundreds of meters in displacement of apparent position from its true value which must be accounted for if the radio groundwave is to be used for accurate positioning.

Three areas in the field of the Narrow Cape transmitter are used to scrutinize the velocity type concept. These areas are: the western portion of Kodiak Island and the effect of the land inhomogeneities and topographic relief on positioning in the Shelikof Strait. The Alaskan Peninsula and its land mass effect offshore in the Bering Sea, and, a calibrated line in the Bering Sea south of the Pribilof Islands and far removed from the Alaskan Peninsula and Kodiak Island.

Case I: Kodiak Island and the Shelikof Strait.

Figure Al.2 depicts the area around western Kodiak Island where phase velocity and ersatz velocity calculations were made. Ten calibrated geodetics pass through the area to the calibrated line in the Bearing Sea. The geodetics are numbered through ten. Azimuthal arcs intersect the geodetic lines at 130, 150, and 200 kilometers from the transmitter. The approximate arc distances between the geodetic lines are given in Table Al.6.

<table>
<thead>
<tr>
<th>Line</th>
<th>130kms</th>
<th>150kms</th>
<th>200kms</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>j</td>
<td>4.0</td>
<td>4.0</td>
<td>6.8</td>
</tr>
<tr>
<td>j+1</td>
<td>4.0</td>
<td>4.0</td>
<td>6.8</td>
</tr>
</tbody>
</table>

where,

\[ j = 2 \text{ to } 10 \]

Values for the phase velocity, \( v_p \), and the ersatz velocity, \( v_e \), under the influence of topography and ground inhomogeneities are given for 10 kilometer increments from 130 kilometers to 200 kilometers along line 3 in Table Al.7. As is evident from the table, both velocities are ill-behaved on both Kodiak Island and in the Shelikof Strait. Figure Al.3 is a graph depicting the errors for both velocities at the incremental distances while establishing a reference velocity at the 130 kilometer point.

Table Al.8 provides values for \( v_p \) and \( v_e \) in the direction normal to the geodetic lines along the azimuthal arcs at 130, 150, and 200 kilometers while Figures Al.4(a,b,c) illustrate the errors associated with velocity calculations for each arc while a reference point as the intersection of line 3 with each arc.
TABLE A1.7
PHASE AND ERSATZ VELOCITIES
ALONG GEODETIC LINE 3
(kms/sec.)

<table>
<thead>
<tr>
<th>d(kms)</th>
<th>( v_c )</th>
<th>( \bar{v}_c )</th>
</tr>
</thead>
<tbody>
<tr>
<td>130</td>
<td>302226.89</td>
<td>298559.50</td>
</tr>
<tr>
<td>140</td>
<td>300260.16</td>
<td>298727.04</td>
</tr>
<tr>
<td>150</td>
<td>300053.01</td>
<td>298824.23</td>
</tr>
<tr>
<td>160</td>
<td>299909.21</td>
<td>298896.11</td>
</tr>
<tr>
<td>170</td>
<td>299823.43</td>
<td>298953.00</td>
</tr>
<tr>
<td>180</td>
<td>299766.27</td>
<td>298999.67</td>
</tr>
<tr>
<td>190</td>
<td>299725.30</td>
<td>299038.89</td>
</tr>
<tr>
<td>200</td>
<td>299684.40</td>
<td>299072.42</td>
</tr>
</tbody>
</table>

As is evident from Figure A1.3, the error functions for both the phase velocity and ersatz velocity exhibit the logarithmic characteristic which would be expected from previous discussion. It is emphasized that for the construction of these curves the velocities were structured for the specific geographical area under discussion. Since the velocities require structuring by the physical medium through which the signal propagates, the error curves do not possess universality and would exhibit different error magnitudes for other areas as well as for other reference points along the geodetic line.

Because of the logarithmic form for the error curves, the most rapidly changing portion of the curve is in the vicinity of the reference point where the reference velocity is measured. Accordingly, the assumption of an area around the reference point wherein the velocity can be assumed to be constant places severe and unrealistic limitations upon the groundwave signal. As the distance from the reference point is increased toward a more linear portion of the curve, it is very difficult if not impossible to assess the error which would have accumulated in the non-linear part of the curve.

Examples of the antenna pattern distortion in the area are seen when moving along the azimuthal arcs in a direction perpendicular to the geodetic lines. The following tabulated velocities indicate the effect of the terrain:

<table>
<thead>
<tr>
<th>line</th>
<th>( v_c )</th>
<th>( \bar{v}_c )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>284066.50</td>
<td>298538.56</td>
</tr>
<tr>
<td>2</td>
<td>307419.09</td>
<td>298362.87</td>
</tr>
<tr>
<td>3</td>
<td>302226.89</td>
<td>298559.50</td>
</tr>
<tr>
<td>4</td>
<td>233924.13</td>
<td>298735.78</td>
</tr>
<tr>
<td>5</td>
<td>474958.66</td>
<td>298245.24</td>
</tr>
<tr>
<td>6</td>
<td>299460.70</td>
<td>298427.87</td>
</tr>
<tr>
<td>7</td>
<td>311473.85</td>
<td>298491.02</td>
</tr>
<tr>
<td>8</td>
<td>300223.63</td>
<td>298493.34</td>
</tr>
<tr>
<td>9</td>
<td>277716.34</td>
<td>298481.81</td>
</tr>
<tr>
<td>10</td>
<td>301111.73</td>
<td>298483.11</td>
</tr>
</tbody>
</table>

Table continued next page.
### TABLE A1.8 (cont)

<table>
<thead>
<tr>
<th>line</th>
<th>150 kms</th>
<th>200 kms</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>300692.52</td>
<td>299740.93</td>
</tr>
<tr>
<td>2</td>
<td>300511.80</td>
<td>299742.37</td>
</tr>
<tr>
<td>3</td>
<td>300053.01</td>
<td>299694.40</td>
</tr>
<tr>
<td>4</td>
<td>300722.72</td>
<td>299748.65</td>
</tr>
<tr>
<td>5</td>
<td>300507.82</td>
<td>299746.32</td>
</tr>
<tr>
<td>6</td>
<td>300255.90</td>
<td>299729.97</td>
</tr>
<tr>
<td>7</td>
<td>300261.13</td>
<td>299726.19</td>
</tr>
<tr>
<td>8</td>
<td>300168.12</td>
<td>299713.08</td>
</tr>
<tr>
<td>9</td>
<td>300177.67</td>
<td>299712.36</td>
</tr>
<tr>
<td>10</td>
<td>300307.66</td>
<td>299738.41</td>
</tr>
</tbody>
</table>

The error curves along the azimuthal arcs are given in Figures A1.4 (a,b, and c).

![Figure A1.4(a). Phase velocity distance error for an azimuthal arc located 130 kilometers from the transmitter.](image)

![Figure A1.4(b). Phase velocity distance errors for azimuthal arcs located 150 and 200 kilometers from transmitter.](image)

![Figure A1.4(c). Ersatz velocity distance errors along azimuthal arcs located 130, 150, and 200 kilometers from the transmitter.](image)

It can be observed in Figure A1.4(c) that the error associated with the ersatz velocity along the arc at 150 kilometers has a value less than those along the arc at 200 kilometers. Since both arcs lie in the Shelikof Strait one would expect the arc at greater distance from the transmitter to exhibit less error than the arc closer to the shoreline. Reference to Figure A1.2 demonstrates that the discrepancy is a fortuitous choice for the location of the arc with respect to the irregular shore.
Here again is another example for pitfalls resulting from the use of an unstructured velocity concept.

It should be remarked that the specific error realized from the use of the velocity concept is bounded by the error computed from the phase velocity and those assessed by the ersatz velocity. It is noticed from Figure A1.4(a) that in the case of irregular terrain the realizable error due to the use of the velocity concept is for all practical purposes unbounded.

**Case II: The Alaskan Peninsula and offshore into the Bering Sea.**

Figure A1.5 exhibits the calibration areas across the Alaskan Peninsula and in the Bering Sea. Line 5, depicted in the figure, was chosen to illustrate the randomness of the ersatz velocity as the loran signal propagates over the peninsula. Two cases are shown in the Figure A1.6, one where the reference velocity is measured in the Shelikof Strait near the eastern shore of the peninsula (d_0 = 240 kms.), and the second case with the reference velocity made off the western shore of the peninsula in the Bering Sea (d_0 = 600 kms.). Plots of the ersatz velocity for the two cases in the region appear in Figure A1.6.

Reference to Figure A1.6 demonstrates the disorderly behavior of this velocity as the signal passes over the peninsula. It is interesting to note that the effects of the land mass are manifested in the velocity for great distances at sea. Prominent perturbations appear in the curve at near 40 and 160 kilometers from the western shore of the peninsula and in the Bering Sea. These "ripples" far at sea are caused by a forward scatter of the signal by the land mass of the peninsula. An interesting feature of these perturbations is that as the receiving antenna is raised above the surface of the earth, the perturbations will become more and more prominent and move further from shore.

**Case III: The calibrated line in the Bering Sea.**

Figure A1.5 depicts a line in the Bering Sea which was calibrated to high precision for both TOAs and TDs for the Saint Paul-Narrow Cape transmitter pair. The points along the line discussed in this case are equally spaced with point number 1 lying at the extreme northeasterly tip of the line and point number 10 at the southwestern tip. Cases I and II have discussed the ersatz velocity as the signal propagates over the land masses of Kodiak Island and the Alaskan Peninsula. To discuss the error in the velocity concept along the line it is first instructive to discuss velocities of the signals as they propagate from the Saint Paul transmitter to the line.

In the field of the Saint Paul transmitter, Saint George Island is the only land mass distorting the loran signal on the calibrated line. Saint George is characterized by relatively high bluffs rising sharply out of the sea with topographic relief on the island of between 400 and 600 feet elevation. The radio geodetic which is described for this case passes over the main part of the island which represents...
Figure A1.6. Behavior of the ersatz velocity over the Alaskan Peninsula and into the Bering Sea. Two cases: \(d_0 = 240\) kms. and \(d_0 = 600\) kms.

approximately 7.9 kilometers of land path for the loran signal. The radio geodetic intercepts the calibrated line at point 8 as implied in Figure A1.5. Figure A1.7 shows the error for the ersatz velocity as a function of distance along the signal path from 60 kilometers to the calibrated line at a distance of 300 kilometers. The reference velocity was assumed to be measured north of Saint George Island at a distance of 60 kilometers from the Saint Paul transmitter. As would be expected, the figure indicates a permanent bias for the signal after transiting the island.

Figure A1.7. Error in ersatz velocity for a loran signal geodetic from Saint Paul Island to the calibrated line and passing over Saint George Island.
Reference to Figure A1.5 will show that the calibrated line is skewed with respect to the radio geodetics from both Saint Paul and Narrow Cape transmitters. Accordingly, measurements along the calibrated line are necessarily involved with variations in the antenna pattern. In Figure A1.8 the error due to velocity calculations is plotted as a function of reference points along the line by assuming a reference measurement is made at point 1. Figure A1.9 provides a similar variation in TDs along the line.

The foregoing discussion with examples of the errors involved with a velocity type concept demonstrate explicitly that the radio wave velocity concept is inadequate for applications of radio positioning or accurate navigation. Clearly a number cannot be assigned to the velocity or speed of propagation which will represent the average value of that quantity over land or seawater. Moreover, the systematic nature of the secondary phase correction as well as its rate of change with respect to distance prevent the satisfactory use of minimization techniques to evaluate a position.

It should be noted at this point that the fundamental time difference equation has been given incorrectly in the WGA RADIO NAVIGATION JOURNAL* [2] as follows:

\[ y_i = \frac{d_s}{v_{cs}} - \frac{d_m}{v_{cm}} + C_s \]  
(A1.21)

where \( v_{cs} \) and \( v_{cm} \) are the "speed of propagation associated with the Secondary-Observer and Master-Observer signal paths respectively. Now "speed of propagation is defined by the dictionary to be the magnitude of the velocity. In NBS Circular 573 (1956), reference [3], the phase velocity of a radio signal, \( v_c \), is derived leading to the expression:

\[ v_c = \left[ \frac{n_i}{c} + \frac{3t_c}{3S} \right]^{-1} \]  
(A1.22)

or, rewriting equation (A1.22)

\[ y_i = \frac{n_i}{c} (d_s - d_m) + \left[ \frac{3t_c}{3S} d_s + \frac{3t_c}{3S} d_m \right] \]

\[ s = d_s \]  
(A1.23)

Now the fundamental time difference equation is given as:

\[ y_i = \frac{n_i}{c} \left[ d_s(\phi, \psi) - d_m(\phi, \psi) \right] + \]

\[ + t_c^S(\phi, \psi) - t_c^M(\phi, \psi) + C_s, \]

(A1.24)

(continued next page)

where,

\[ i = \{W,X,Y,Z\} \] (minimum of two for a fix),

\[ n_1 = 1.000338 \]

\[ c = 2.99792458 \times 10^8 \text{ meters/second}, \]

and,

\[ d_s \] the geodetic distance from the Secondary to the Observer in meters,

\[ d_m \] the geodetic distance from the Master to Observer in meters,

\[ t_{c,s,m} \] the secondary phase correction in seconds for the Master(m) or the Secondary(s) propagation path associated with each of the above geodetics,

\[ C_s \] the emission delay of the Secondary in seconds.

Upon comparing equation (Al.23) with equation (Al.24) one notices that:

\[ t_c \neq \left[ \frac{3t_c}{3s} \right] d \]

(Al.25)

a contradiction! Equation (Al.21) is therefore incorrect because it contains an error in calculus.

More explicitly, for example, an accurate approximation for the secondary phase correction, \( t_c \), is given by (seawater):

\[ t_c = a_1 s^{-1} + a_2 s + a_3 s^2 \]

(Al.26)

\[ \left[ \frac{3t_c}{3s} \right] d = -a_4 s^{-2} - a_1 + 2a_3 s \]

(Al.27)

\[ \left[ \frac{3t_c}{3s} \right] s = d \]

(Al.28)

A contradiction! Of course, over smooth ground with higher resistivities and in the presence of irregular or non-homogeneous ground, \( t_c \) is even more non-linear and may require higher order polynomials for accurate representation. Thus it is clear that the use of velocity in equation (Al.13) is incorrect irrespective of the form for the representation of \( t_c \). It is to be noted that the arguments given apply equally well to such notions as the "wave velocity", "group velocity", and "signal velocity". Indeed, the use of a velocity type concept for precision radio navigation and positioning is an incorrect notion. It fails as an engineering approximation since it is without structure of radio science, electromagnetic physics, or radio metrology.

**APPENDIX II: ERSATZ VELOCITY**

The phase velocity and the group velocity can be calculated from the phase and group propagation time, \( t_{c,g} \), respectively. Thus, using \( s \) for distance and reference [3]

\[ t_{c,g} = \frac{n_1 s}{c} + t_c + \omega \cdot \frac{d t_c}{d \omega} \]

(A2.1)

\[ t_{c,g} = \frac{n_1 s}{c} + \frac{dt_c}{d} \]

(A2.2)

where \( t_{c,g} \) is the secondary phase correction for the group. The phase, \( \phi \), crests, troughs or zeros can be tagged as the constant,

\[ \phi = \omega t - ks - \frac{\phi_{c,g}}{c} \]

(Al.2.3)

\[ = \text{constant} \]

where \( \phi_{c,g} \) is the radian phase correction for the phase or the group propagation time, i.e., the secondary phase correction in radians. Thus,

\[ \frac{d \phi}{d k} = \frac{d \omega}{d k} - \frac{s}{c} - \frac{1}{c} \frac{d t_c}{d \omega} = 0 \]

(A2.4)

\[ d \omega = \frac{s}{c} \frac{d k}{d \omega} + \frac{1}{c} \frac{d t_c}{d \omega} \]

(A2.5)

\[ \frac{s}{c} = \frac{\omega}{k} - \frac{1}{c t_c} \frac{d t_c}{d \omega} = \frac{1}{c \phi_{c,g}} = \bar{v}_c \text{ as defined} \]

Then, one finds:

\[ \bar{v}_c = \left[ \frac{n_1}{c} + \frac{t_{c,g}(s)}{s} \right]^{-1} \]

(A2.6)

the ersatz velocity for either the phase propagation time or the group propagation time. But \( t_{c,g}(s) \) is a function of distance, \( s \), and \( t_{c,g} \) is not constant; thus, \( \bar{v}_c \) is not a constant. Hence, using \( \bar{v}_c \) at a point as a constant for an area results in the errors described in Appendix I. Whilst \( s/t \) may identify a precise crest, trough or zero on the cycle or envelope, there is slippage in time as the distance is increased such that the precise point (crest, trough or zero) no longer corres-
ponds to the same s/t since,

$$s + \Delta s \neq \frac{s}{t} + \Delta t$$

(A2.7)

Thus, one finds that:

$$t_c \neq \left[ t_c(s) \right]_{s=d} = \text{constant}$$

(A2.8)

Therefore using $\bar{v}$ in equation (A1.21) again leads to a contradiction! As shown numerically in Appendix I, the redefinition of velocity to the quantity $s/t$ instead of $ds/dt$ is not much of an improvement. Again it is obvious that none of the velocities cited can be measured. Again it is noted that the use of a velocity type concept for accurate radio navigation or positioning is an incorrect notion. It fails as an approximation since it is without structure.

**GLOSSARY**

TD $\triangleq$ time difference, Loran-C coordinate in seconds or microseconds.

$v_i$ $\triangleq$ time difference, Loran-C coordinate in seconds or microseconds.

$\eta_1 = 1.000338$, a constant.

c $= 2.99792458 \times 10^8$ meters/second, a universal constant of nature.

d $= \text{distance, meters.}$

d$_s$ $= \text{distance to a Secondary transmitter in meters.}$

d$_m$ $= \text{distance to a Master transmitter in meters.}$

t$_c$ $= \text{secondary phase correction (seconds or microseconds); phase slowness relative to a free space plane wave.}$

t$_{cs}$ $= \text{secondary phase correction for a propagation path from the Secondary transmitter to an observer, (seconds or microseconds).}$

t$_{cm}$ $= \text{secondary phase correction for a propagation path from the Master transmitter to an observer, (seconds or microseconds).}$

$c_s$ $= \text{emission delay, (seconds or microseconds).}$

i $= \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$ designations for Secondary transmitters.

i $= N$ designation for Master transmitter.

$\phi_c$ $= \text{secondary phase correction, radians.}$

$k_1 = \frac{w}{c \eta_1}$

$w = 2\pi f$

f $= \text{frequency, Hertz.}$

$\vec{u}_d \triangleq \hat{\delta} |\hat{\delta}|^{-1}$, unit vector.

$\vec{\delta}$ $= \text{a position vector for fields which are radiated from a transmitter,}$

$r = a + h$, $h$ is the altitude above the surface of a spherical earth.

$\theta$ $= \text{angle at the center of the sphere,}$

$a = 6.36739 \times 10^6$ meters,

$a = 0.85$, effective earth radius conversion, $a_e = a/a$.

$r$ $= \vec{\delta}$ $= \text{unit vectors of a spherical earth,}$

$\phi$ $= \text{phase of the field in radians,}$

$v_c$ $= \text{phase velocity, m/s,}$

$v_{av}$ $= \text{average phase velocity,}$

$\bar{v}_c$ $= \text{ersatz velocity,}$

$s$ $= \text{distance, meters,}$

d $= \text{specific distance in meters,}$

d$_0$ $= \text{reference distance in meters,}$

t$_i$ $= \text{time of arrival (seconds, microseconds),}$

$t_s$ $= \text{time of arrival for Secondary,}$

$t_m$ $= \text{time of arrival for Master,}$

d$_s$ $= \text{velocity } v_c \text{(Newton, Leibnitz def.)}$

$s$ $= \text{ersatz velocity, } \bar{v}_c$, not really a velocity.

$(\phi, \psi) = \text{(latitude, longitude),}$

In general the MKS system of units is employed except for trivial items of convenience such as the conversion of meters to kilometers and seconds to microseconds.
USCG R&D DIFFERENTIAL LORAN-C STUDY

(Maritime Session)

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Information About the Author

LT Doug Taggart graduated from the U.S. Coast Guard Academy in 1976 with a B.S. degree in Electrical Engineering. After graduation, he was assigned to the U.S. Coast Guard Cutter Hamilton as Communications Officer. Next came a tour at the Department of Transportation's Transportation Systems Center in Cambridge, Massachusetts. LT Taggart was then accepted in the Coast Guard's Electronics Engineering post-graduate study program. Upon graduation from Purdue University in 1980 with a Master's degree in Electrical engineering, LT Taggart was assigned to the Electronics Branch of the U.S. Coast Guard Research and Development Center in Groton, Connecticut. Since being assigned to the Center, he has been project engineer for Loran-C Harbor/Harbor Entrance Surveying, the Loran-C Stability Study and the Loran-C Guidance Equipment project.

Abstract

The U.S. Coast Guard Research and Development Center (R&D) is currently engaged in a project to develop techniques for the operation of a real time differential Loran-C system in harbor areas that require improved navigational performance. Present project efforts are dedicated to the generation of an automated marine band VHF-FM digital and synthesized voice update message. Variations induced on the Loran-C signals can be attributed to changing characteristics, weather conditions, chain control procedures and diurnal effects.

The project is divided into five separate tasks. The first task includes the development of hardware and software to output the automated synthesized voice and digital update message. The second task is concerned with the development of a redundant network of monitors for a specific harbor. The third task will address the survey of the subject harbor. The fourth task is concerned with the modification of the Johns Hopkins University Applied Physics Laboratory (JHU/APL) Precision Intracoastal Loran-C Translocator (PILOT) to allow automated input of the digital updates. The fifth task is dedicated to investigation of problems that will most likely be encountered should the system become operational. Areas to be addressed in this final task include: the message format, the update interval, the generation of the update TO values, differences between various receiver types and the addition of differential information on navigational charts (reference TDs, waypoint locations and TDs, VHF-FM update channel and frequency of messages, etc.).

Anticipating the implementation of NAVSTAR GPS, the Coast Guard is also involved with Differential GPS. Much of the knowledge gained during the operation of the Differential Loran-C system will be directly applicable to the development of a GPS Differential network.

Introduction

It is accepted that the Loran-C system offers much better navigational information when used in the repeatable mode, compared to the absolute accuracy mode. Although this fact is well known by many mariners, the reasons behind it may not be understood, or in a more general sense, of no real concern to a majority of the "unsophisticated" users. ("Unsophisticated" refers to those users that rely on their Loran-C receiver for navigational information solely on the assumption that, "That's what it's supposed to do; I don't care how or why, but it works."). However, these users, given the present state-of-the-art microprocessor based Loran-C receivers, are capable of observing deviations in the repeatable mode of operation that before this point in time most likely went unnoticed. Loran-C receivers possessing the capability to store waypoint data are driving the use of Loran-C in the repeatable mode.

If the variations in the Loran-C TD signals could be measured and made available to users, it would then be possible to improve the navigational accuracy associated with the use of Loran-C in the repeatable mode. Based on this assumption, which has been clearly demonstrated in a number of implemented systems (see references 1 and 2), the U.S. Coast Guard's Research and Development Center is investigating the application of these corrections to various receivers and is also developing the necessary equipment and procedures that could be implemented to transmit differential corrections to the user community.

TD Data Collection

In addition to the differential Loran-C project, the USCG R&D Center is also engaged in a project dedicated to the investigation and modeling of Loran-C signal stability characteristics throughout the continental U.S. This project was initiated in the spring of 1980. Specific information about this project can be found in Reference 3. All work conducted during the course of the stability analysis study is based on time difference (TD) data obtained by the U.S. Coast Guard's Harbor Monitor System (HMS) network. This network is comprised of remote data collection units located throughout the Loran-C coverage areas of the continental U.S. and parts of Canada. Each of these collection units is designed to automatically collect and store TD measurements. Commercial grade telephone lines are used for automatic retrieval of each site's collected data. The Loran-C receivers used in this project are the Internav LC-404, Megapulse Accufix 500 and where possible, operational chain control data is collected from the chain monitor Austron 5000 receivers. The present network of monitors is shown in Figure 1.
Data collected demonstrates that natural variations observed in the repeatable accuracy (excluding installation and interference offsets) can be categorized as follows:

- seasonal variations effects
- weather effects (i.e. storms, cold fronts)
- chain control equipment effects
- chain transmitter effects
- diurnal effects

Figures 2 through 4 present data collected from various harbor monitor sites. Each of these plots contain deviations from the long term time difference (TD) averages that can lead to significant errors when converted to position. Deviations of this type can be removed by transmitting a correction from a fixed monitor (or network of monitors) in areas where improved navigational information is necessary to meet the needs of particular users.

Figures 2a, 2b and 2c present TD data collected at the Avery Point, Connecticut (USCG R&D Center) harbor monitor site. These plots present three years (1982 through November of 1984) of 4-sample-a-day (90 independent samples averaged over a one hour period) TD observations for the Northeast U.S. (9960) Chain, secondaries Whiskey, Xray and Yankee, respectively.

Figure 2a
9960 Whiskey TD Plot Avery Point, CT
(Seasonal Variation)
January as the reference will be more positive in the summer months. The X-ray measurement for a mixed path: see References 4.

The sinusoidal pattern that is observed is caused by the change in propagation speed experienced over an annual period. The direction of the swing (1 January as the reference) is determined by the site's location with respect to the system area monitor (SAM) and the secondary transmitter site (taking into account the corrected Double Range Difference (DRD) measurement for a mixed path: see References 4 through 6 for further details). The amplitude of the swing is directly proportional to the magnitude of the DRD. As Figure 2a demonstrates, Avery Point's location with respect to Cape Elizabeth, Maine (SAM for 9960 Whiskey) and Caribou, Maine (9960 Whiskey transmitter site), is hyperbolically located on the Master side of the SAM; therefore, the seasonal swing will be more positive in the summer months. The X-ray and Yankee TDs, as observed from Avery Point, are both hyperbolically located on the secondary side of the SAM (Sandy Hook, New Jersey). Therefore, the characteristics of these TDs will be more negative during the summer months, a result that can be seen in Figure 2b and 2c, respectively.

The data presented in Figure 3 was taken at the Folly Island, South Carolina harvest monitor site. The data presents time difference (TD) observations for the Southeast U.S. (7980 Zulu) secondary located at Carolina Beach, South Carolina. The data is one full year (1983) of 4-sample-a-day observations. This plot demonstrates three of the TD offsets: chain control effect, chain transmitter effects and weather effects (These are in addition to the slight seasonal component that can be seen.)

The chain control effect is the data spike (three day duration) that occurred on Julian days 14 through 16. During this period, the Alpha 1 SAM located at Mayport, Florida was inoperative. The Alpha 2 monitor located at Destin, Florida was used to control the chain. Offsets of this type can be removed with real time differential updates.

The square wave pattern that has a period of 28 days represents the chain transmitter effect. The offset is produced by routinely changing the on-line transmitters every 14 days. The equipment at Carolina Beach is a pair of AN/FPN-42 tube type transmitters. This type of effect has been observed on other chains that use AN/FPN-42 and AN/FPN-44 transmitters. Note that operational chain control records indicate that this offset, although still attributed to a transmitter switch, is actually induced at the SAM control sites. In an effort to maintain the Control Standard Time Difference (CSTD), the SAM Austron 5000 receiver reacts to transmitter changes with phase adjustments to the secondary's emission delay. These timing adjustments are on the same order of magnitude as the peak to peak values observed in this data set.

The data spike observed toward the end of the calendar year is a result of severe cold weather that affected the entire southeast portion of the country. This offset, which was dramatically seen at this site, was also visible in other HRS data sets distributed throughout the Southeast U.S. chain.

Data presented in Figures 4a and 4b shows the effects of diurnal variations. These two plots, which are examples of high density HMS data, were obtained from a site located at Iroquois Lock, Ontario Canada. HMS equipment operating in the high-density mode is collecting data 24 hours per day. Each data point is the result of 22 averaged samples taken over a 15 minute period. The data presented in Figures 4a and 4b cover 14 days (Julian Day 253 to 267 of 1983). Position offsets, although clearly dependent on geometry, can vary considerably over a 12 hour period. Again, a fixed monitor could correct for these variations if a method of disseminating the information were implemented.

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making use of real time digital information transfer are examples of vessel traffic systems. Studies that have either investigated or taken on the vessel are transferred to the shore based control site using VHF/FM communications. To calibrate the TD grid, a local survey of the test area has been conducted and various waypoint TDs have been tied to simultaneous data. To test the differential concept, a synthesized voice message is periodically transmitted from the differential site using VHF/FM communications equipment. This correction is applied at the user receiver, either manually or automatically, and the results are recorded and evaluated.

The block diagram shown in Figure 5 details this project approach.

Although many of the concepts that exist in these two systems are applicable to the US Coast Guard's differential project, two major differences exist, as follows.

1) in the R&D project, differential corrections will be transmitted to users on a non-interrogation/non-restricted basis;

2) the user equipment (receiver) need not (and most likely will not) be the same as the shore based monitor receiver being used to compute the update.

These two items pose a number of problems. First, to offer a differential correction, a reference must be established and maintained. This requires the need to survey the area of interest and relate the waypoint TDs to an arbitrary set of reference TDs. The reference TDs chosen become the differential monitor reference numbers and all future offsets must be relative to those numbers. This immediately creates an implementation problem since potential users must have knowledge of the reference data. This is complicated even further if we induce an additional unknown, and that is the differences that may exist between the monitor receiver and the user receivers. In general, two different receivers placed side by side will more times than not give different reading for identical TD pairs (at least in the sense that deviations between the two may be on the same order as the differential correction being proposed). These differences can be attributed to any number of items relating to the receiver characteristics such as: pass band, notch filters, master oscillator frequencies, installation peculiarities, tracking loops, etc.).

Keeping in mind that these problems must be overcome, the following approach for implementation of a differential system is now underway. As a "first cut", the system is being developed using the same shore base monitor receiver as the underway test receiver. To calibrate the TD grid, a local survey of the test area has been conducted and various waypoint TDs have been tied to simultaneous observations taken at the fixed differential site. To test the differential concept, a synthesized voice and digital message is periodically transmitted from the differential site using VHF/FM communications equipment. This correction is applied at the user receiver, either manually or automatically, and the results are recorded and evaluated.

The USCG R&D Center Approach to Differential

References 1, 2 and 7 are examples of three studies that have either investigated or taken advantage of the improved navigational performance that can be achieved through the use of differential Loran-C. The systems described in References 1 and 8 are examples of vessel traffic systems that are making use of real time digital information transfer in conjunction with navigational data supplied by Loran-C. These two systems are the Suez Canal Traffic Control System and the Lake Pontchartrain Collision Avoidance System. To implement the Suez Canal Vessel Traffic System, the following action was required:

- A survey of the area to be serviced by the system to calibrate the TD grid,
- The development of fixed monitors to observe variations in the TD grid,
- The development of user equipment to be installed on the vessels with real time communication to a shore based control site,
- A communication link between shore based monitors and the control sites.

Again, the Suez Canal System is a vessel traffic system. In this system, time difference measurements taken on the vessel are transferred to the shore based control site, where differential variations are applied to improve the position information. This is an appealing application of differential Loran-C since the user and update monitor equipment are uniquely defined by the vessel traffic system. Although, the Lake Pontchartrain system does not rely on differential corrections for improved accuracy, the communications link between vessels and the shore based control site does exist and has proven reliable.
was accomplished using the trackline survey technique developed by the USCG's Office of R&D during the Saint Mary's River Mini-Chain project (see Reference 9). Modification of the Johns Hopkins University/Applied Physics Laboratory (JHU/APL) Precision Intercoastal Loran-C Translocator (PILOT) was desired to graphically demonstrate the effects of digital data entry. Fortunately, when the PILOT device was built in 1979-80, a 1/0 port was included for differential inputs. Therefore, the only task necessary to demonstrate automatic digital input was to meet data format requirements. The PILOT system is documented in references 10 through 12.

The remaining two project elements - Develop the Differential Monitor Operating System and Develop the Operation Management System, are more involved and are broken down separately. Development of the Differential Monitor Operating System is as follows:

- Develop a communications network to allow for more than one fixed site to offer system redundancy and to reduce the possibility of localized site dependent anomalies.
- Given a multiple site network, develop guidelines for update calculation and network operation.
- Determine the data update rate and determine, for example, if this rate should be fixed (dependent on the rate of signal change). Presently, the update interval can be changed from 3 to 5, 7.5, or 15 minutes. All tests to date have been done using the shortest interval which is 3 minutes.
- Investigate the receiver to receiver problem and determine how this may influence the update rate and magnitude.

The last subelement, Develop the Operational Management System, consists of the following areas:

- Determine what, if any, action should be taken if the differential network determines that the chain may be off-air or unusable.
- Determine the usefulness and feasibility of publishing monthly updates to account for seasonal-variations.
- Determine the user community (Navy Minesweeping, Buoy Positioning, Survey Craft, Off Shore Oil Rigs, Terrestrial Users, FAA, etc.)
- Specify update formats (digital) that could be incorporated as additional inputs to receiver navigation loops.
- Specify those areas where differential Loran-C should be implemented.

Differential Update Equipment

Figure 6 shows the block diagram of the present differential transmitter/monitor hardware recently demonstrated in New London, Connecticut. The left portion of the diagram represents the Harbor Monitor System (HMS). This portion of the system remained virtually unchanged with regard to the system hardware. As previously mentioned, the HP9915 processor monitors the receiver (LC-404 or Accufix 500), collects and then stores that data for remote access via commercial grade telephone lines. The HMS software was slightly modified to default the system to the 24 hour-per-day data collection mode. In addition to this change, additional software was added to allow for I/O to the second processor, which is dedicated to the control and generation of the differential update message. This portion of the system is shown on the right side of the dashed line.

The second processor was added for two reasons. First, the project directive stated that the Harbor Monitor System remain as complete as possible. Secondly, by adding the additional processor it was possible to separate the number of tasks that must be handled simultaneously for normal operation of the system. For example, at any given instant the HMS processor must monitor the receiver and determine that it is functioning correctly, keep track of time for data sampling, keep track of the time for a differential update to the differential processor, and monitor the telephone line for incoming phone calls. At the same time, the differential processor must monitor the interface line for update from the HMS processor; monitor the communication link for incoming requests for data (this is assuming a network configuration), and once a request has been received or the update time is reached, initiate an update either by voice, digital or both.

Network Operation

To avoid transmitting TD updates that are related in part to localized peculiarities that may exist at the differential monitor site, a network of monitors is being installed at the New London test site. For purposes of discussion, the following terminology will apply. The site responsible for transmitting an update will be referred to as the "master". The sites that are geographically located some distance away from the master unit will be referred to as: slave 1, slave 2, etc. The New London network is shown in Figure 7.

The network of monitors can individually be contacted by the system control personnel using commercial grade telephone lines. Using this communication means, site parameters can be edited (i.e. update interval change, receiver status manually checked, transmissions terminated, reference TDs changed or checked, polling TD changed). At the New London test site, the communication link used for real time network operation is the marine band channel 83 (157.175 MHz) VHF-FM. This is also the same frequency used for the update message. Referring to Figure 7, the following example is used to describe the operation of the system utilizing a 3 minute update interval.
At time $t_0$ each of the monitor sites begin a sample period. Time correlation between sites is monitored during each 3 minute period and collection times for all sites are automatically synchronized every 24 hours. At time $t_0 + 100$ seconds, the differential processor at the master site will receive an update from its HMS processor. This update is comprised of: the number of sample points (four samples for a three minute period based on a 10 second receiver interrogation interval), an average TD; maximum and minimum TD relative to the average, a standard deviation, and an average signal to noise ratio (SNR) reading for each monitored TD. Immediately following the master update, the master unit will interrogate the slave 1 site for its data. Based either on slave 1's response or on the recognition of the master's interrogation of slave 1, slave 2 will output its corresponding update at a fixed delayed interval (used to avoid simultaneous transmission of data). Upon receipt of the updates from all sites, the master site will correlate the reading and make a determination as to the validity and magnitude of the update and will then transmit that update to all potential users. Note that in the prototype system, which consisted of a single transmitter, the update message was done using synthesized voice and also a 200 baud digital message. Present plans for the network configuration call for the elimination of the voice message and the digital communication speed will be increased to 1200 baud.

The previous scenario assumes that there were no abnormalities existing either in the Loran-C System or in the differential network operation. However, even though the Loran-C system offers approximately 99.7% triad availability and differential hardware failures can be minimized by implementing redundancy and error checking, there are always those special cases of "Murphy's Law" with which to contend. To develop checks and balances to meet every deviation from the perfect scenario is the area of most effort.

Approaching this problem from two different areas, Loran-C system abnormalities and differential network failures, the following system checks are presently being conducted. The first problem, loss of the Loran-C signal, is handled by the HMS processor. For example, if the receiver loses the Loran-C signal in the middle of a sample period, data collection is interrupted until the signal is regained. If at least one valid data point were already obtained, that point or the partial set of data points is provided as the correction for that interval. Associated with this update, however, is a flag that informs the user that the update should be treated as suspicious. If the signal outage lasts longer than the update interval (i.e., 3 minutes), the user is indirectly made aware of a problem by the absence of an update. Further evidence of a possible chain problem is especially obvious if the last update (prior to a missed update interval) contained a flag and the user has also lost the Loran-C signal.

Addressing the possibility of a differential network failure or the loss of a portion of the network, the following actions are automatically taken. If one of the network slaves fails to acknowledge three interrogations from the master, the network will remain in operation using the two remaining sites. Operation in this mode will continue until there is a disagreement between the two remaining sites. Should this occur, the network will be placed in standby and no updates will be made until the problem is discovered and corrected. If the master unit fails to interrogate the slaves over three consecutive update intervals then the slave that is designated "slave 1" will assume the role of the master and the network will continue to function until there is a disagreement between the two remaining units.

PILOT Tests

To demonstrate the automatic and manual inputs of real time differential updates, the PILOT system was used. A very simplified description of PILOT is:

PILOT is a precision navigator which utilizes Loran-C time difference (TD) readings to graphically position own ship on a digitized chart which is displayed on a CRT. Position information is relative to surveyed waypoints. Two and three TD navigational solutions are possible. The Loran-C receiver used is an Internav LC-404.

As previously mentioned the surveyed waypoints were measured in conjunction with simultaneous shore-based measurements. In underway tests during a three month period of operation, three PILOT systems were tested side by side. One unit was used as a control for navigational information with no differential, the second was used for manual update, and the third unit was used for real time application of digital information. At no time was the solution degraded either through the application of manual or automatic corrections. The tests were conducted between October and December of 1984. Based primarily on the growing seasonal effect, when the time difference corrections were converted to position, they corrected the unaided position by 20 meters in October to 100 meters in late December.
Test Results

The differential monitor system that was first demonstrated in New London, Connecticut in October of 1984 consisted of a single fixed monitor site. A VHF-FM synthesized voice message and a 200 baud digital message were used to convey corrections to an underway test vessel. The update interval was chosen as 3 minutes. Whiskey, Xray and Yankee of the East Coast Loran-C Chain (9960) were monitored and appropriate corrections were made. The primary contributor to position offset was the Carolina Beach (Yankee) secondary. The azimuth of the lines of positions (LOPs) and the gradients for the three TDs at the New London test site are shown in Table 1.

Secondary  LOP  Gradient
Whiskey (Caribou, ME)  340.1 deg  672 ft/usec
Xray (Nantucket, MA)  12.4 deg  500 ft/usec
Yankee (Carolina Beach, SC)  253.8 deg  776 ft/usec

The update was comprised of at most four statistically independent receiver TD observations that were averaged and compared to an arbitrary set of reference TDs. Deviations from these averages were then transmitted to the user. The least significant value of the update was one nanosecond. The voice correction specified the sign of each correction (plus or minus) and identified the appropriate TD (i.e. Whiskey, Xray or Yankee). The digital message included the TD identifier, the update and the appropriate sign for the correction and a flag to characterize the quality of the update. The voice message was used as a source for manual input of corrections, while the digital message demonstrated the automatic application. Tests were conducted in the manual mode by rounding the corrections to the nearest 50 and 100 nanosecond intervals. Results of rounding the correction, although favorable, did not offer the same accuracy that was available from those obtained with the more precise digital update. In addition to this, the voice message was useful for purposes of keeping "tabs" on the correction but it was time consuming to apply and unnecessarily complicated the overall concept.

In the development of the three station network, the voice message has been eliminated. The digital message has been increased to 1200 baud and in addition to the added speed, the format of the message has been modified to include the time (Zulu), Julian day, a network identification code and chain GRI. Since the digital correction can be done transparent to the user, updates are to the nearest nanosecond. The update interval, although variable, has remained at three minutes.

References 1 and 2 state that the accuracy that can be achieved with real time differential is 15 meters or better. Reference 4 states that an improvement of 2 to 4 times that of unaided Loran-C can be expected assuming that the update interval is chosen correctly. Obviously, the geometry of the Loran-C signals in the area being considered plays an important role in the resulting accuracy. For example, the use of Differential Loran-C in the western portions of the Gulf of Mexico may improve the position by a factor of two or more but the resulting accuracy does not approach 15 meters. Figures 8a, 8b and 8c show the effects of applying 15 minute time correlated updates from Morgans Point, Texas to Galveston, Texas. These two sites are approximately 20 miles apart.
Going to the other extreme, installation of a differential system in an area such as New York Harbor would have no observable effect assuming that the TDs being used for the navigational fix information were Xray and Yankee (the SAM is located at Sandy Hook, NJ). Figure 9 shows the scatter plot for the entire 1983 calendar year using these two TDs.

In areas such as New London, Connecticut, where the seasonal components are large enough to create significant deviations in position, the following results have been recorded. The scatter plot shown in Figure 10 represents a five hour period of data observations showing the unaided and 3 minute update corrected position relative to a fixed survey point as perceived by an Internav LC-404. The scatter plot is generated by converting the receiver TDs to X and Y coordinates relative to a fixed set of TDs. The TDs used to generate this plot were Whiskey, Xray and Yankee. The data shown in Figure 11 represents the deviations recorded during that same five hour period.

The range over which a differential update remains valid can be many hundreds of miles as stated in Reference 13. This assumes that the primary component being removed is the seasonal offset. If a single correction could be transmitted throughout the coverage area, scaling factors applied at each user receiver could be incorporated to account for the localized seasonal component. In this type of application, the Loran-C signal itself could be used to convey the differential update.

Obviously, the present R&D project does not concern itself with this type of approach. References 2 and 4 show that there is no sign of distance dependence up to 150 kilometers and 69 miles, respectively. The differential updates being considered in this project are not limited by the Loran-C geometry but rather by the VHF-FM communications link.

Modification of User Equipment

Many receivers available today offer the capability to account for Latitude/Longitude conversion error by incorporating an Additional Secondary Phase Factor (ASF) correction. This correction is designed to compensate for the difference between actual TD observations versus those predicted for an all sea-water path. This term has incorporated in it (by the pure nature of the means used to measure it) variations in the repeatable accuracy as well as the Latitude/Longitude conversion error. Figure 12 is a block diagram of the ASF calculation and application scheme being used by a number of present day Loran-C receivers.
The highlighted portion of this diagram represents an input of differential corrections. A user that calculates an "ASF" correction at a known geographic location during a specific time of the year, stores that information in the form of a waypoint (Lat/Long and TD), and then attempts to return to that same geographic point some time later (e.g. 6 months) will see an error that can be attributed to a TD variation caused by a combination of those factors highlighted in Figure 12 (assuming the same receiver and installation). If the variations could be measured and made available to that particular user (real time or via a table), his ability to return to a point when using Loran-C would be improved. If the receiver could be modified to allow for automatic input of differential corrections the entire process would be transparent to the user.

To further expand the user population, efforts are currently being considered within the Coast Guard's Office of R&D to have Coast Guard owned receivers modified by their respective manufacturers to allow for digital input of differential corrections.

For the differential concept to assume a useful role in precision navigation, user equipment must be available and potential users must be educated with regard to the systems operation. An optimistic view of a partial system would be a totally automatic system with all operations being conducted at the receiver level. In this situation, data update rates could be as often as the communication network and receiver interface dictate.

Conclusions

The Loran-C system has been in operation for approximately 30 years. Upgrades to chain equipment as well as improvements in the receiver community have resulted in improved navigational accuracy for all users. In the near future, the civilian community will have a 100 meter randomly degraded Global Positioning System (GPS) to utilize for their navigational needs. Already, plans are being made to remove the generated dither and allow for improved navigational information through the use of Differential GPS. An immediate question to be asked is: Why is this portion of the government intentionally degrading a navigational system while other government funded organizations are dedicated to the removal of that contamination? Another question may be: Why 100 meters? Is this based on the repeatable Loran-C accuracy that can be expected in many portions of the existing coverage areas?

If this be the case, reference 6 shows that much better accuracy than 100 meters can be expected in many areas of Loran-C coverage. In this case, if a few dollars (relative to the cost of degrading and correcting the GPS system) could be spent on the implementation of differential Loran-C systems in selected areas to demonstrate the improved capabilities of Loran-C, it is quite possible that the intentional degradation of the GPS signal could be avoided and the costly task of implementing a Differential GPS system could be eliminated altogether.

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SESSION IV
LORAN-C TECHNOLOGY

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CHART LATTICING: A CANADIAN PERSPECTIVE

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Abstract

Canada is a country of few people and a very long coastline where the radio navigation aids such as Loran-C cover only the heavily travelled routes. The available resources for charting are limited, many charts are antiquated, and only the most essential work gets done. The Canadian Hydrographic Service (CHS) has seen to the publishing in advance of latticed editions of the small scale charts for each new Loran-C chain commissioning, but the medium and large scale charts have had to wait for the resources and for Loran-C survey data. Now, with the Loran-C system deployment stabilized for the foreseeable future, the chart latticing emphasis is switching to the larger scale charts. Over the next five years more than 175 charts are scheduled to be latticed, including some as large as scale 1:36,000.

The paper describes the problems, the surveys, the charts and the future for Loran-C latticing as seen by CHS.

Canada

Canada......what do YOU know about it?

In sheer size Canada is an immense land, the second largest nation in the world. Canada is one of the least densely populated, with about a tenth of the population of the United States of America and about two thirds of the people living within 100 miles of the United States. Canada has the longest coastline of any nation, with essentially three inland seas, the Great Lakes, the Gulf of St. Lawrence and Hudson Bay.

Canada has abundant natural resources: lumber and coal in British Columbia; gas, oil, grains and potash in the three Prairie Provinces; hard rock mining and heavy industries in Ontario; paper and oil refining in Quebec; potatoes and fish in the three maritime provinces; fish and hydro-electricity in Newfoundland and minerals and furs in the Yukon and Northwest Territories. Most of these resources, and others, require shipping from the source location to market by ships following established trade routes: Vancouver to the Orient, Halifax and St. John New Brunwick to Europe, Montreal to Europe via Strait of Belle Isle; internally within the Great Lakes - grain east bound and coal or iron ore west bound. In the Arctic islands where the shipping season lasts only a few months, ships are assisted by ten Canadian Coast icebreakers. To get there, ships either hug the north shore of Alaska or follow the Greenland side of the Labrador Sea before entering Hudson Strait or Lancaster Sound.

Canada makes and will make a living from the sea. The Grand Banks of Newfoundland and several other prosperous fishing banks are all within Canada's Exclusive Economic Zone and have been fished, and overfished, for centuries by many nations. In the past fifteen years, offshore oil exploration has struck vast reserves of gas and oil on the Atlantic and Arctic continental shelves.

Canadian Hydrographic Service (CHS) maintains about 1000 charts to cover all the vast coastline of Canada. Some charts are very thoroughly surveyed, presented in a modern style and frequently printed, but some are based on the sketchiest of old survey data presented in the original copper-plate style and were last printed 20 or more years ago. There are 85 charts that are
latticed with Loran-C and another 175 are planned to be latticed in the next five years.

Positioning Systems

Loran-A...why should I say anything more?

A U.S. developed system - by some of the people in this Association - that had its first operational deployment in Canada to help wartime convoys to Great Britain. Later deployment, as a U.S. military need, saw Loran-A along the east and west coasts of Canada including as far north as Baffin Bay. Canada had the distinction of maintaining and funding the last two Loran-A rates until December 1983. No chart at the scale larger than 1 : 250,000 was latticed.

The Decca Navigator system was installed in Nova Scotia, Cabor Strait, Gulf of St. Lawrence and Newfoundland in the 1950's. Later the chains were refugured and only recently three of the four chains have been decommissioned with the withdrawal of Loran-C service. Because large scale Decca charts existed, mariners are requesting that Loran-C replacements be made available. Originally, we at CHS said that 1 : 75,000 would be the largest scale for Loran-C, but we have relented, albeit on an individual chart assessment, to lattice at larger scales. A Loran-C version of the Halifax Approaches chart (1 : 36,000) has been printed recently.

CHS has both 6-f and 12-f Decca Survey chains in its equipment stores. They can run both in the hyperbolic or range-range modes.

In 1969, CHS carried out over seawater velocity studies (1) and proved Johler et al. NBS Publication 573 (33) correct for various distances for Decca frequencies. In 1972, fresh water velocity (2) was verified with a Decca chain in Lake Ontario. In 1973, over sea water and over sea ice velocities were determined for a single distance in the Arctic with Decca (19). The sea water velocity compared favourably to the NBS 573 prediction, the over ice velocity did not because the ground medium was not vertically homogeneous.

Loran-C came to Canada with the "old" East Coast US Chain (9930). And it was the Canadian fisherman of Georges Bank that first used it! The first CHS chart with Loran-C was of Georges Bank where we showed the X (Cape Fear - Cape Race) and Z (Cape Fear - Nantucket) patterns. But the fishermen wanted Y (Cape Fear - Nantucket) pattern since the same hyperbola near the baseline extension went from their homeport to the fishing grounds. CHS learned its lesson: we listen to fishermen.

CHS Experience with Loran-C

Under Mike Eaton's [last year's Award of Merit winner] direction, CHS started to use rho-rho Loran-C in 1972 by predicting the instant of transmission with the aid of a cesium beam frequency standard (7,15,27). In this way CHS surveyed offshore of Nova Scotia using Nantucket and Cape Race and off Newfoundland and Labrador using Cape Race and Angissoq. Surveying in the area between the stations was aided by the then test station at Caribou and by an Accufix (mini Loran-C) or Decca station specifically installed on the Labrador coast. The attempted installation of a Decca transmitter on Resolution Island cost us a charted ship that got held by a rock pinnacle and had to be abandoned.

Since CHS was using Loran-C in a one way travel time mode to carry out hydrographic and other scientific surveys, a retired CHS staff member developed an 8-term polynomial for total phase lag (4). The constants of the polynomial have been determined for various conductivities of land, fresh water and seawater. The one polynomial is good to better than two metres from 2 to 5000 kilometres.

Mike Eaton had his ears open in 1973 to the Loran-C expansion (8) and had heard of the possibility of a station near Williams Lake. Mike and I drove from Vancouver to Alexis Lake about 100 miles past Williams Lake, and very close to the final site, and back one weekend - a distance of 1000 miles - just to see what the country was like.

In 1977 CHS was surveying the ASF from the transmitters of the Canadian West Coast Chain (9990) (24) using SatNav positioning with velocity input from rho-rho Loran-C. We learned some bitter lessons; firstly, about the poor performance of the chain itself; and secondly, about our procedures. Eighteen months later we were calibrating for the Canadian East Coast Chain (5930) using rho-rho transmissions from the Northeast USA Chain (9960) and the Eastcoast US Chain (9930) in combination with Mini Ranger and SatNav. We had sufficient data to do large scale charts even before the chain started operating. All we had to wait for was the Emission Delays to be set, so that we could relate the time difference at one location to all surveyed locations. Decca and Loran-A readings were also recorded on that cruise to provide real data comparisons for conversion of fishermen's "hang" data.(26)

We have studied the inshore phase recovery phenomenon of ASF and find it to be real and in some cases, larger than predicted by the Modified Millington's Method(25). We have used
various techniques to collect 50,000
data points of Loran-C TD’s at surveyed
locations:

1) Direct occupation of a survey point,
2) Sextant resection,
3) Mini Ranger and Trisponder,
4) Syledis,
5) Argo and HiFix,
6) Doppler Satellite (SatNav), and this year
7) Global Positioning System (GPS)

In conjunction with the Canadian
Coast Guard, we went to the western
Arctic to test the effect of sea ice on
Loran-C performance. We knew from the
Decca tests in the same area what would
happen to the velocity, the question was
what was effect on signal strength and
pulse shape caused by sea ice. The
Canadian Coast Guard now knows what
would be necessary for a Loran-C chain
for the Beaufort sea oil and gas field
and shipping corridors through the Fingo
fields. In a similar fashion, the
signal quality of the Canadian East
Coast Chain (5930) was tested before the
configuration was approved at the
technical level (10).

Loran-C Latticing

The Canadian Hydrographic Service
policy has been to publish latticed
charts at scales smaller than 1:300,
000 prior to chain commissioning.
Medium scale charts are latticed with
the benefit of regional surveys to
correct predicted ASF while large scale
charts are latticed after intense
calibration surveys in the areas of the
chart. The colour of lattices is one
area where CHS differs from the US
charting agencies. If we think there
might be a conflict in differentiating
between lattices of the same colour
(5930X and 9960X on Georges Bank) we
change one to a different colour. The
colour change is consistent on adjoining
charts.

Originally our Loran-C lattices were
quite open - typical spacing between
lines was 2 to 4 cm. After some
feedback from users (principally
fishermen), we are now providing lines
at 1 to 2 cm apart. To aid the mariner
to follow the same hyperbola from the
label to the area of his fix we are
making every fifth line heavier.

Positioning Without Lattices

Coordinate converters have been
available for five or more years now. I
remember the first ones which gave the
right TD’s but whose positions were only
generally correct (17). Modern ones do
better. Part of the reason is the
Minimum Performance Standards set up by
Special Committee 75 of the RTCM (34)
which included CHS representation. CHS
has answered the recommendation for
publication of ASF data by issuing
chartlets of surveyed ASF in "Radio Aids
to Marine Navigation" (35). The next
generation is upon us in the form of the
"Electronic Chart".

At the 1983 Canadian Hydrographic
Centennial Conference, I suggested in my
paper (20) that future charts would have
no lattices, Mike Eaton in his
co-authored paper (12) at the same
conference did one better - no paper
chart. Mike’s opening paragraph is
worth repetition.

Imagine the scene on the bridge
shortly after the year 2000. The
tanker "Concord Yemani", Light out of
Bahrein, is crossing the Grand Banks
en route to Come-By-Chance. At 2200
that night the second mate is on the
bridge getting the consolidated
Notices to Mariners for the Atlantic
coast by telex from St. John’s radio;
he records them on a diskette which he
loads into the electronic chart
Storage Controller, and thus
automatically updates the chart data
in storage. The Captain comes out of
his sea cabin, and notes that on the
real time chart video display there is
a strobe flashing on the Virgin Rocks,
with a warning that on the present
course and speed made good the ship
will pass within 2 miles of the 30 m
contour in 18 minutes time. The mate
on watch assures him he is keeping an
eye on this while he manoeuvres to
clear a group of draggers, and as has
become quite a habit with him, he
again comments on how useful it is to
have the NAVSTAR/LORAN driven
electronic chart look after position
plotting, leaving him free to
concentrate on avoiding collision.
The Captain is satisfied, and goes to
the auxiliary video display and calls
the ephemeris to display
tomorrow’s time of sunrise and sun’s
true bearing (if a noon check)
followed by tides for the day computed
from harmonic constituents included in
his Atlantic coast chart disc. He
also checks Sailing Directions for
details of reporting and traffic
regulations for Come-By-Chance. Then
he calls up the Chart at 1:5,000,000
and zooms the scale until Placentia
Bay fills the screen. He superimposes
fishing areas in green and traffic
control areas in purple, then erases
them to have a clearer look at the
depths. As he scans over the chart up
to Come-By-Chance, enlarging the scale
as he goes, he finds he cannot go
above 1:24,000 for the outer
approaches as that was the scale of
the original survey. The Captain uses
the "track-plan" routine to put on his
courses for the next day. He selects
a 10m keel clearance and 5 cables
lateral clearance; flashing danger
strokes come up on a couple of points
where these are not satisfied. Once
he is happy with his planned track he
transfers it to the chart controller.
so that it will appear on the real
time plot when the ship reaches that
area.

As the ship rounds Cape St. Mary's
next morning and approaches Argentia
traffic control, the mate on watch
superimposes the digital radar output
in green on the chart video display,
and by radar joystick he matches the
radar coastline to the chart
coastline, thus removing a small
residual ASF correction in the Loran-C
that is driving the ship position. He
confirms at a glance that there are no
Islands three miles ahead up the
coast, so these radar echoes must be
fishing boats. As the ship nears
Argentia they pick up the shore radar
re-broadcast, and superimpose that
video image on the chart in orange to
keep track of other ships in the
vicinity not yet on their own radar.
At the same time the captain puts the
"track profile" on the auxiliary
display; this shows a graph of the
under-keel clearance along his planned
track, with the ship's sounder graph
superimposed.

An hour later, in preparation for
berthing at the loading dolphins, the
Captain locks on the differential
Loran-C monitor for maximum accuracy
with respect to the dock, and switches
the real time display to docking mode.
At a scale of 1:1,000 (no soundings)
this shows the ship 15 cm long, making
it easy to judge her orientation and
distance from her berth.

Work Needed to be Done

To make the electronic chart a
reality, digital information will be
necessary, not just digitized
information from a paper chart. The
digitized information will have to be
related to WGS or NAD-83 geodetic datums
not NAD-27 or, even worse, local or
non-uniform datums. Loran-C to
geo-graphic conversions will require ASF
data, local monitoring and standardized
procedures.

Loran-C is no longer a military
system but a civilian system. It does
not get the same development
improvements that doppler satellite got.
It is up to the Wild Goose Association,
as the leading Loran-C interest
group, to see to improvement in Loran-C
quality.

So......

In this overview, I trust that you
can appreciate that CHS is an authority
on radio propagation and on Loran-C. I
have outlined our past problems and
experiments, where we are today, and the
distance we have to go to make Loran-C a
useful tool for the hi-tech future.

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THE U.S. COAST GUARD'S LORAN-C REMOTE OPERATING SYSTEM

by

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ABSTRACT

The improved Loran-C Remote Operating System (ROS) is an integrated hardware/software Loran-C control system designed by electronics engineers at the Coast Guard Electronics Engineering Center, Wildwood, N.J. The system is designed to remote the normal operation of an AN/FPN-64, AN/FPN-45, AN/FPN-44 or AN/FPN-82 Loran transmitting set to a central control site. The intent of this development is to provide an ROS to be used to reduce manning levels at transmitting stations, thereby saving money and freeing electronics technicians for other billets throughout the Coast Guard. The design employs Hewlett-Packard Series 200 microcomputers (HP9826/HP9836) under Hewlett-Packard's Pascal operating system to accomplish the primary functions of the ROS, namely, to take and process data, to monitor alarms, and to relay commands. Here we present a complete technical description of the hardware and software of this control design, highlighting operational capabilities, system performance, and impact on the Loran-C user community.

BACKGROUND

The original project to design, develop and install the first ROS at Loran-C Station Port Hardy was assigned to the U.S. Coast Guard Electronics Engineering Center in November, 1978. This design was capable of remoting the operation of a single-rated, secondary station equipped with an AN/FPN-64(V) Loran-C solid-state transmitting set (SSX). The need for this project arose when the Canadian Coast Guard proposed that Port Hardy operate with a three person complement upon completion of the station installation. ROS was installed at Port Hardy and was certified operational on 20 November, 1980. The superior operation and performance of the ROS at Port Hardy proved that this concept can work at a remote Loran-C station.

The need to further reduce operating and personnel costs associated with the operation of the Loran-C system of navigation has been a continuing problem for the U.S. Coast Guard as well as for the Canadian Coast Guard. Based on successful tests at Loran-C Station Raymondville, TX in January and February of 1980, and successful operation of ROS at Loran-C Station Port Hardy, BC, the Coast Guard elected to install the ROS at Loran-C Station Raymondville, in April 1982. By installing the ROS, the Coast Guard was able to reduce this station's personnel complement from eleven to four people, without affecting signal availability.

Since this prototype system is designed to operate only with single-rated, secondary SSX transmitters, it soon became clear that it would be cost effective to expand the capabilities of the ROS to function with dual-rated transmitters and vacuum tube transmitters as well. In this way, more stations could be considered for inclusion in the ROS program. The project to design, develop, and install this improved ROS was assigned to the U.S. Coast Guard Electronics Engineering Center in May 1981. A complete design proposal for the improved ROS was submitted to U.S. Coast Guard Headquarters in August 1982, and it was approved in November 1982.

DESIGN REQUIREMENTS

U.S. Coast Guard Headquarters imposed the following requirements on the improved ROS design:

1. The ROS must be able to operate in any single-rate/dual-rate, Master/Secondary, or tube type/SSX transmitter configuration.

2. The ROS must be capable of operating up to four single-rate/dual-rate stations in the same chain from one Remote Site Operating Set (RSOS).

3. The improved ROS design shall consider interfacing to or incorporation of the Calculator-Assisted Loran-C Controller (CALOC), interfacing to a digital pulse analyzer, and interfacing to replacement timing and control equipment.

4. The Local Site Operating Set (LSOS) must be contained in a single rack, identical at all Loran-C stations.

5. The ROS must be capable of operation at 1200 baud/300 baud modem operation with automatic dialing back-up capability.

ROS FUNCTIONAL DESCRIPTION

An ROS consists of a Local Site Operating Set (LSOS) located at a Loran-C transmitter site, and a Remote Site Operating Set (RSOS) located at a remote site, usually the control site for the Loran-C chain. The LSOS monitors transmitter site alarms and operational data, and relays the information through a communications link to RSOS.
RSOS receives, decodes and interprets the information supplied by each LSOS in the chain.

**ROS Data**

An ROS monitors the following transmitter site data parameters:

1. **Time Interval Number (TINO):** the time interval between the remote signal tracked by the Austron receiver and the local AN/FPM-65 Loran-C Timing Receiver, as monitored on the antenna current line.

2. **Local Amplitude:** the magnitude of the current in the ground return line of the transmitting antenna.

3. **Envelope-to-Cycle Difference (ECD):** the measure of the shape of the antenna current pulse, measured in microseconds.

4. **Synchronization Number (SYNC):** the time interval between the remote signal tracked by the Austron 2000C timing receiver, and a zero crossing of the locally transmitted Loran pulse as monitored on the antenna current line.

5. **Austron Amplitude:** the voltage amplitude of a half-cycle of the received signal tracked by the Austron 2000C timing receiver.

6. **Master - Local Phase (master minus local):** the phase difference between a 1 MHz signal phase-locked to the received signal tracked by the Austron 2000C timing receiver, and the local 1 MHz signal in the timer. This number provides finer resolution of TINO.

7. **Cycle Compensation (Cycle Comp):** a control loop in the timer that corrects for small changes in the transmitting station local timing signal path. The loop provides a voltage output proportional to its current state.

Also, the following data parameters are monitored at a master transmitter station for each designated Austron 2000C Bravo Control receiver:

8. **Time Interval Number (TINO):** the time interval between the remote signal tracked by the Austron 2000C Bravo Control receiver and the local time base.

9. **Master - Local Phase (master minus local):** the phase difference between a 1 MHz signal phase-locked to the received signal tracked by the Austron 2000C Bravo Control receiver and the local 1 MHz signal in the timer. This number provides finer resolution of TINO.

10. **Austron Amplitude:** the voltage amplitude of a half-cycle of the received signal tracked by the Austron 2000C Bravo Control receiver.

The data parameters 1 through 7, above, are referred to as "Normal" data, and 8 through 10 are referred to as "Bravo" data by ROS. ROS monitors a maximum of three Austron 2000C Bravo Control receivers at a master transmitter station.

For dual-rated stations, LSOS monitors data parameters for both rates. RSOS receives Normal data for both rates but receives Bravo Control data for only the designated primary rate for the RSOS.

**ROS Alarms**

An alarm monitored by ROS can have one of three conditions. The three alarm conditions are green (normal operations), yellow (indicates minor problems with equipment status or operation, although the signal is in tolerance and usable) and red (off-air, out of tolerance or a major ROS malfunction). In the following paragraphs, all alarm messages that the ROS will display are listed along with their causes. Letters in parentheses indicate the alarm color for each alarm — R = red, Y = yellow and G = green.

**Operational alarms.**

An operational alarm implies that the on-air signal quality is impaired through an equipment malfunction. These ROS alarms are listed below.

- **Blink (R):** The on-air signal is out of tolerance and blink has been started remotely.
- **Off Air (R):** This alarm occurs when the Local Amplitude falls below a preset value.
- **Data Value Out of Tolerance (R):** This alarm is generated at LSOS by comparing data received from AN/FPN-54A timing receiver, and a zero crossing of the locally transmitted Loran pulse as detected by the Austron receiver.
- **Master Blink (R):** Master is blinking via ninth pulse as detected by the Austron 2000C Receiver.

**Transmitter/Timer Equipment alarms.**

- **Operate Osc Error (R):** A primary timing error has occurred.
- **Standby Osc Error (R):** Standby timing is unstable.
- **OSC #3 Phase Error (Y):** Oscillator #3 has drifted out of phase by more than fifty nanoseconds.
- **Retard Osc #2 or #3 (Y):** At least a negative twenty nanosecond drift in one of the standby oscillators has been detected.
- **Advance Osc #2 or #3 (Y):** At least a positive twenty nanosecond drift in one of the standby oscillators has been detected.
- **Timer #1 or #2 Failure (R):** The "operate" (#1) or "standby" (#2) timer has lost timing.

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Check Timing (R)

Provided for each timer, this alarm occurs when an internal error is detected by the timer.

No Transmitter Drive (R)

Provided for each timer, this alarm occurs when timing signals from the timer are lost or drop below a set level.

Timer in Local (R)

Indicates that a timer is in local control. This alarm also indicates which rate is in local control.

Transmitter Not Auto (R)

The transmitter is not ready for automatic/remote operation.

HCG Alarm (R)

A solid-state transmitter half-cycle generator (HCG) alarm has occurred.

Remote Call (R)

The monitor/control site is requesting that transmitter site personnel contact them.

Low Power (R)

Operate transmitter has failed and the Transmitter/Coupler Control Unit cannot complete an automatic switch (approximately thirty seconds delay after an off air alarm).

PGEN Failure (R)

Provided for each Pulse Generator (PGEN) on tube-type transmitting stations. Alarm indicates lack of a drive signal.

Transmitter Not Ready (R)

Standby transmitter is not ready for operation.

Transmitter Failure (R)

Standby PGEN failure, off air at least thirty seconds, or standby transmitter not ready for operation.

Coupler in Local (Y)

The transmitting antenna coupler can only be switched from one transmitter to the other by someone in the transmitter room.

ROS program alarms.

Comms Down (R)

ROS has detected a loss of communications signal carrier.

Diagnostic Failure (Y)

LSOS has failed diagnostic test.

Diagnostic OK (G)

LSOS has passed diagnostic test. This test is run every ten data intervals or upon operator command.

Status change alarms.

If the status of the transmitter site equipment changes, a Status Change alarm will be displayed and the status on the normal display will be updated. For instance, a switch of timers will cause a local timer status change alarm. This alerts the remote operator to any equipment changes at the local site. A Request Alarms command will clear the Status Change alarm. The status alarms are:

(Y) PATCO (Solid-State Transmitter (SSX) Pulse-Amplitude and Timing Controller) status change.

(Y) Timer Status Change.

(Y) Coupling Network Switch (SSX).

(Y) Transmitter Status Change (tube-type transmitters only).

Contact closure alarms.

ROS will recognize up to twelve user-provided contact closures as alarms to the system. Alarm names and severity (red, yellow or green) are determined by software initializations at RSOS and LSOS.

Both RSOS and LSOS maintain a singly linked list of current alarms, and the time LSOS detected the alarms. A designated alarm list start pointer always points to the first (oldest) alarm, and a designated alarm list end pointer always points to the last (newest) alarm. As new alarms occur, the alarm is linked to the list, and the alarm list end pointer is updated. Dynamic memory allocation is employed so only current alarms require computer memory. Alarms in the list are constantly displayed on the RSOS and LSOS computer screen and the display is updated anytime a change occurs in the alarm list. If more than eight alarms are present at any given time, the keyboard "up" and "down" arrows may be used to increment and decrement display pointers so that alarms may be scrolled up or down for ease in viewing.

ROS Commands

The operational commands and the ROS particular commands are listed below. Since RSOS can be initialized to receive data and alarms from both rates of a dual-rated station, RSOS can also be initialized to enable commands for the control of alternate rate equipment (selecting timers, inserting LPAs and executing blink commands).

Operational Commands

Select

Switch timers.

Timer

Insert LPA Insertion of Local Phase Adjustments.

Start/Stop

Start/Stop timer blink.

Blink

Start/Stop Master blink (W, X, Y, Z, or all).

Remote Call

Reset indicators on Remote Control Interface (RCI) and Status Alarm Unit (SAU).

PATCO Select

Switch PATCOs (SSX only).

HCG Reset

Reset HCG fault (SSX only).
The RM-16D mounts in a standard 19-inch rack and is capable of handling up to 16 modem cards. For each primary communications line, a RM-2024 D/C modem card is installed in the RM-160. The RM-2024 is a 1200 baud, full duplex, 4-wire, asynchronous modem. The RM-2024 modem card is compatible with Bell Systems 202T-type modems.

The back-up communications link is a two wire, standard voice grade line capable of a 300 baud transmission rate. The redundant communications system consists of a "primary" channel and a "back-up" channel. The back-up communication line is only used when the primary communications link is not operational. The RSOS system uses a Hayes Stack Smartmodem. The Smartmodem is a 300 baud, full duplex modem, compatible with Bell Systems 103-type modems. The Smartmodem is configured for originate mode. When RSOS detects the primary communications link not operational, RSOS is capable of either autodialing LSOS on the back-up communications link or waiting for the RSOS operator to select the back-up communications link. Once the primary communications link is operational again, the RSOS operator can select the primary communications link. The LSOS system uses a Racal-Vadic Modemphone for the back-up communications link. The Racal-Vadic is compatible with Bell Systems 103-type auto answer modems.

Both LSOS and RSOS computers use an HP98626A RS232C Interface to connect to each primary and back-up modem. The HP98626A Interface is an Electronic Industries Association RS-232C standard digital interface. The HP98626A enables the computer to communicate with the serial asynchronous modem at standard baud rate settings.

**ROS Messages**

ROS uses only three types of messages between RSOS and LSOS. The three types of messages are command, alarm and data. All the message types use an ASCII character string and have the same message format. The message format is shown in Figure 1.

![Figure 1. ROS Message Format](image)

The station ID code is a character map of the station's designator, transmitter type and whether single or dual rated. The character is to insure that both LSOS and RSOS are initialized the same for each station. If there is a difference in RSOS and LSOS system initialization, the station ID codes will differ, not allowing communications between them.

---

**Switch Transmitters**

Switch transmitters (tube-type transmitters only).

**Emergency Stop**

Stop transmitters.

**Advance or Retard OSCs**

Advance/retard either of the standby oscillators.

**ROS Particular Commands**

- **Request Data**
  - Request LSOS to take a data set.

- **Request Alarms**
  - Request for all LSOS alarms (deletes status alarms).

- **Reset LSOS**
  - Restart LSOS computer.

- **Log Comment**
  - Enter watchstander comments on log.

- **Plain Talk**
  - Request TTY-like communications with both ROS computers.

- **Set Data Interval**
  - Set LSOS data set interval.

- **Last Data**
  - Print last five data sets.

- **Set Time**
  - Set time on ROS computer.

- **LSOS Maintenance**
  - Used when maintenance is in progress at transmitter site, or when the transmitter site takes local control of ROS. LSOS will reject all RSOS commands except Reset LSOS and LSOS maintenance commands.

**RSOS Commands**

- **Select Primary Comms**
  - Switch to primary communications link.

- **Select Backup Comms**
  - Switch to backup communications link.

- **Time Sync**
  - Synchronize LSOS real-time-clock to RSOS real-time-clock.

- **Reset ROS**
  - Reset both RSOS and LSOS.

- **Select Other Rate**
  - Displays alternate rate normal data (if dual-rated).

- **Select Bravo Data**
  - Displays Bravo Control data (master station only)

**Communications Protocol**

A standard ROS configuration requires two communications links between the LSOS and RSOS systems. The primary communications link is a 4-wire, unconditioned line capable of a 1200 baud transmission rate. Both LSOS and RSOS use a Universal Data Systems RM-150 direct connect multiple modem system. The RM-150 mounts in a standard 19-inch rack and is capable of handling up to 16 modem cards. For each
Command messages are only sent from RSOS to LSOS. There are two variations of text for a command message. The text for the majority of command messages is a single ASCII character which represents a character map of the command. The other variation of command text is the single ASCII character representing the character map of the command followed by a value. This command variation is used for setting data intervals, time synchronization and local phase adjustments.

Alarm messages are used by LSOS to inform RSOS of alarms at the transmitter site. The alarm message format is a set of ASCII characters followed by the time of occurrence. As in commands, each ASCII character is a character map of a single alarm. LSOS appends all the alarms that occurred at the same time in one message. The time appended to the end of the alarm string is the time LSOS detected the alarms.

There are three types of data messages that ROS uses. The first type is a Normal or Bravo Control data value. LSOS sends only one data value in each data message. The text of the message contains an ASCII character which is a character map of the data type followed by the numeric value of the data. The second data message type is a status message. The text of a status message is a single ASCII character which encodes station equipment status change occurs. The third type of data message is an end of data set. The text of this type is an ASCII character for the end of data set and the time the data set was taken at LSOS. The end of data set message informs RSOS that LSOS is finished with the data set. LSOS only sends data that has changed from the previous data round unless RSOS requests a data set. In that case, all data is sent from LSOS to RSOS.

Before a message is sent from either LSOS or RSOS, a checksum is appended to the message. When a message is received by either RSOS or LSOS, a checksum is calculated and compared to the checksum appended to the message to detect communication errors. If a communication error is detected by either LSOS or RSOS, the message is requested again.

**LSOS Hardware**

The LSOS comprises a subsystem capable of collecting analog data, performing timing measurements, monitoring digital alarms, and controlling digital devices and relays. Data is periodically collected under program control and is subsequently encoded and transmitted to the remote site with no user intervention. Alarms generate computer interrupts but are also encoded for transmission to the remote control site. Based on data and alarm information received at the remote site, the remote watchstander can analyze the situation and issue commands as required to keep equipment related casualties from continuing to affect the on-air signal. An overall station block diagram of the LSOS is shown in Figure 2. Figure 3 depicts the LSOS equipment cabinets itself and shows individual equipment locations within the rack. A brief description of each major piece of equipment of the LSOS, and an overview of the hardware used to support LSOS capabilities of taking data, monitoring alarms, and issuing commands, now follow.

Model 2055 Phase Microsteppers are the top two devices in the LSOS rack. The 5 MHz signal from the standby Cesium Beam Oscillator is routed through the top Phase Microstepper, while the 5 MHz signal from the tertiary Cesium Beam Oscillator is routed through the second Phase Microstepper. The standby oscillator provides the primary input to the standby Loran-C timer. The tertiary oscillator is patched into a Loran-C timer only upon failure of one of the other two oscillator systems. The Microsteppers are interfaced through the Multiple Microprogrammer and the ROS Interface unit to the HP9826 LSOS computer. They operate upon user command and are used to step the secondary and tertiary 5 MHz timing signals into phase with the operate 5 MHz signal. Fixed step amounts of 5 or 10 nanoseconds per command are established upon software initialization at LSOS.

The HP5300B Measuring System is installed just below the Phase Microsteppers. This system is almost identical to Time Interval Counter systems installed at all Loran-C stations, however the ROS Measuring System can pass data directly to the LSOS computer because of the addition of an HPIB (IEEE-488) interface to the system. This allows TINO and SYNC to be measured under computer control.

The Multiple Microprogrammer Interface (HP59500A) and the Multipleprogrammer (HP5940B) are installed immediately below the Time Interval Counter. The Multipleprogrammer interface converts the HPIB (IEEE-488) bus information into the 16-bit bus format required by the Multipleprogrammer, and permits bi-directional communication between the Multipleprogrammer. The Multipleprogrammer itself represents an interface between the computer and the ROS Interface unit. All alarm information is monitored by the Event Sense (HP69434A) cards installed inside the Multipleprogrammer card cage. Data is collected via Relay Output/Feedback (HP69433A) cards performing the functions of computer controlled data multiplexers installed in the Multipleprogrammer. Multiplexed analog data is routed to a plug-in High Speed A/D Converter (HP69422A) card installed inside the Multipleprogrammer, and multiplexed digital timing waveforms used to measure TINO and SYNC are routed via relay cards to the ROS Measuring System. Equipment control functions are also accomplished by closing or opening relays on relay output cards, or by controlling the Digital Output (HP69331A) card inside the Multipleprogrammer.

The ROS Interface (GFC-W-1002-ROS I/F) is a custom interface installed immediately below the Multipleprogrammer. It interfaces the existing station equipment to the LSOS monitoring and control equipment. It also provides an interface up to twelve external relay closures allowed for the detection of building security and environmental alarms. The ROS Interface has twelve card slots for interface card expansion. Only two slots are filled with custom designed boards in the current design.
Figure 2. LSOS Functional Block Diagram
The LSOS system printer (HP2571G Thermal printer) is a bi-directional, HPIB thermal printer provided for local site "hard copy" of alarms, data, and commands. The printer is capable of dot-for-dot unidirectional raster graphics copy. The print rate operating with LSOS is 190 characters per second in a compressed print mode of 16.2 characters/inch. The printer has a 2K byte ASCII buffer which serves to keep the HP9825 computer from becoming I/O bound when printing alarms during even the worst of casualties. The system printer automatically commences logging operations under software control during any red alarm condition. In addition, the RSOS watchstander can command LSOS to commence or cease logging at the local site. The RSOS watchstander cannot, however, override automatic LSOS logging during red alarm conditions. LSOS software incorporates soft-fail printing features such that printer errors or loss of paper do not affect normal operation of the LSOS.

The HP9826 LSOS Controlling Computer is the brain of the LSOS. This is the unit that collects data, monitors alarms, and issues commands to the local transmitting equipment. The computer also performs all intelligent functions associated with communications to the RSOS computer. The LSOS HP9826 computer is an MC68000 microprocessor-based machine which operates in our application under the 9826/9836 PASCAL Operating System. The HP9826 has built-in 128K bytes of RAM, 8-slot card cage for interfaces or memory, HPIB interface, 7-inch CRT display, and a single 264K byte 5-1/4 inch flexible disc drive. Under the normal LSOS configuration, serial interfaces (HP98626A) are installed in the card cage as required for communications, and two 256K byte (HP98256A) RAM boards are installed for additional memory.

The Battery Pack and Uninterruptible Power Source that provide uninterruptible 115 VAC for the entire LSOS are installed immediately beneath the LSOS computer. Under normal operations and system loading, this battery back-up configuration will supply emergency power to the LSOS for approximately 45 minutes.

The modems installed for primary and back-up communications at the LSOS are installed in available locations in existing station 19-inch racks. The modems used for 1200 baud V.H/FDX primary ROS communications are the Universal Data Systems RH-16D/C modems with RM2024 or RM202T plug-in modem cards. Back-up communications uses the Racal-Wadco 103-AA Bell 103 type modem-phone at the LSOS.

LSOS Software

As described earlier, the LSOS design employs Hewlett-Packard Series 200 microcomputers (HP-9826) under Hewlett-Packard's PASCAL Operating System. The single LSOS operations program and associated hardware interfacing are completely invariant to transmitter type, master/secondary station configuration, and single/dual rate configuration. Operations flexibility is obtained using a software initialization data file at the LSOS. In this way, a standard software version can be distributed to all ROS stations. LSOS software is supplied to transmitting stations on four 5-1/4 inch flexible disks. These disks contain information as follows:

LSOS1: PASCAL System/Libraries/Configuration files, LSOS Operations program, and station-dependent initialization data

LSOS2: PASCAL System/Libraries/Configuration files, LSOS Initialization program

UTIL1: PASCAL System/Libraries/Configuration files, disc initialization and file cataloging/duplication utilities

UTIL2: PASCAL System/Libraries/Configuration files, disc file cataloging/duplication utility, LSOS off-line Multiprogrammer diagnostic utilities, LSOS modem test utility

The HP9826 under the PASCAL operating system supports seven levels of interrupts, from level one (lowest) to level seven (highest). LSOS supports three external interrupts as follows: keyboard (level one), Multiprogrammer (level three), and serial communications interrupts (level three).

The commented PASCAL source code listing of the LSOS program is on file at the U. S. Coast Guard Electronics Engineering Center, Wildwood, N.J. The commented PASCAL source code listing is approximately 10000 lines in length. The compiled code file which automatically commences execution upon power-up is a 111-K byte native MC68000 code file. A general software flowchart documenting program flow of the LSOS Operations program is found in Figure 4.

LSOS Alarms

As described in the section on LSOS hardware, the LSOS uses Event Sense Cards (Model 69434A) manufactured by Hewlett-Packard for its 6940A
Figure 4. LSOS Software Flow Diagram
Multiprogrammer in order to sense any alarm condition. Event sense cards monitor 12 external data input lines and advise the computer when any change occurs in these external lines. During the LSOS system start up sequence, the LSOS software "programs" each Event Sense card in the Multiprogrammer with a bit mapped octal reference word. This twelve bit reference word (represented by a four digit octal word) is what the Event Sense card uses to determine whether or not an alarm condition is present.

When an alarm occurs, the external data will no longer agree with the programmed reference word for the Event Sense card. The card then generates a bus interrupt (Hewlett-Packard Interface Bus, or HPIB) to the computer via the Multiprogrammer and Multiprogrammer Interface. LSOS program flow is interrupted and execution of the procedure Multi Interrupt commences as depicted in Figure 5. HPIB and serial interrupts are first disabled, and Multi Interrupt calls a procedure called Find_Culprit. This procedure verifies the presence of an interrupt, reads the latched input of each Event Sense card to determine which card(s) were the offenders, writes new octal reference words out to the offending cards, and calls a procedure called Decode_Alarm.

The Decode_Alarm procedure takes the pre-interrupt reference word and compares it to the post-interrupt latched input for each offending Multiprogrammer Event Sense card to determine which bit(s) caused the interrupt. Each alarm is then ordinarily mapped to its distinct ASCII character for incorporation into the alarm queue for each rate. A procedure called Handle_Alarm is called from the Decode_Alarm procedure to update the list of current LSOS alarms, and finally those alarms just detected are added to each First-In-First-Out (FIFO) alarm queue for subsequent transmission to RSOS.

LSOS Alarm List Structure

LSOS maintains a singly-linked list of current LSOS alarms and their times of occurrence as indicated in Figure 5. As new alarms occur, the Alarm_List_End pointer is incremented. The Alarm_List_Start pointer always points to the first (oldest) alarm, while the Alarm_List_End pointer always points to the last (most recent) alarm. Dynamic memory allocation is employed via the "new" and "dispose" mechanisms of PASCAL, so only current alarms require computer memory.

LSOS alarms queues are handled in a similar fashion with individual queues being allotted for each controlling RSOS. The queue arrangement for LSOS is, however, slightly more complex than a simple list structure. This added complexity is required in order to ease the communications burden during times of casualty, where many alarms must be transmitted at the same time.

LSOS Alarm Queue Structure

Referring to Figure 7, one recognizes that LSOS maintains an array (indexed by rate) of queues of singly-linked list structures. Each list represents the set of alarms that occurred during any single interrupt. Each alarm is entered into the appropriate Loran-C rate queue as part of a variant record entry with a tag field of First_Char_This Interrupt. If the entry is in fact the first alarm entry for the interrupt, the variant record will have two additional elements; namely, Next_List and Alarm_Time. Any other alarms discovered during this interrupt need only be recorded in the record.
Figure 6. LSOS Alarm List Structure

ALARM_CODE | TIME OF ALARM | NEXT
---|---|---

NOTES:
1. "ALARM CODE" IS AN ABBREVIATED ORDINAL ALARM INDEX.
   Ex: "TMR1_FAIL-LO" WOULD BE THE "ALARM CODE" FOR LO RATE TIMER NO. 1 FAILURE.
2. "TIME OF ALARM" IS THE TIME OF DAY THAT LSOS DISCOVERED THE ALARM.
3. ALARM_LIST_START, ALARM_LIST_END, and NEXT ARE ALL POINTERS TO ALARM LIST RECORDS.

NOTES:
1. "ALARM CHARACTER" IS A SINGLE ASCII CHARACTER CORRESPONDING TO A GIVEN ALARM. THIS CHARACTER WILL BE TRANSMITTED AS PART OF A TRANSMISSION STRING TO RSOS TO NOTIFY RSOS OF A GIVEN ALARM.
   Ex: ASCII 32 CORRESPONDS TO "STATION CONTACT CLOSURE ALARM NO. 1".
2. "ALARM TIME" IS THE TIME OF DAY THAT LSOS DISCOVERED THE ALARM.
   Ex: 10:26:35.
3. ALARM_Q_STARTPTR, ALARM_Q_ENDPTR, NEXT_LIST, and NEXT ARE ALL POINTERS TO ALARM QUEUE RECORDS.
4. AT DUAL-RATED STATIONS THE LSOS COMPUTER MAINTAINS SEPARATE ALARM QUEUES FOR EACH OF THE TWO CONTROLLING RSOS COMPUTERS.
with the alarm character and a pointer to the next alarm character since Alarm_Time and Next_List are the same as for the initial list entry. By establishing the queue structure in this manner, we are easily able to improve the information transmission rate compared to the alternative of transmitting each alarm separately. All alarms that occur at the same time are transmitted in one transmission string packed from one alarm queue list structure. Using this method, LSOS can reliably decode and transmit as many as sixty alarms in less than two seconds at 1200 baud.

Should communications fail between LSOS and RSOS, the LSOS computer will continue to maintain its alarms queues up to a maximum of 300 list entries (single rate case) or 150 list entries/rate (dual rate case). These maximums were established to avoid memory overflows due to heap/stack collisions under the PASCAL Operating System. Once communications have been re-established either via primary or backup communications facilities, the LSOS will then advise the RSOS of the entire alarm history for the period of lost communications. Alarm queue list entries are transmitted in character string format as shown earlier in Figure 1. One queue list entry is transmitted upon each RSOS poll. The alarm queue for each rate has transmission priority over the data queue for each rate, so no data will be transmitted to a given RSOS if there is an alarm in its queue.

LSOS Data

In order to assist the remote watchstander in his effort to spot potential problems or recover from equipment casualties at the transmitter site, the LSOS computer periodically takes a set of data and transmits this information to RSOS. The LSOS automatic data taking interval may be set at the RSOS to an integer number from one to ten minutes inclusive. LSOS simply decrements a "Time to Next Data" timer and automatically takes data at time "zero". At a dual-rated station LSOS takes data at the minimum of the two data rates set by each controlling RSOS. The default data interval upon LSOS startup is three minutes.

As discussed earlier, LSOS can provide data to RSOS on the following parameters: TINO, Local Amplitude, ECD, SYNC, Austron Amplitude, Master-Local Phase, Cycle Compensation, Equipment Status, Bravo Control receiver TINO, Bravo Control receiver Master-Local Phase, and Bravo Control receiver Amplitude. Data taken is considered to be either "Normal" or "Bravo" type data. A data set may be initiated by command from the LSOS keyboard, the RSOS keyboard, or by internal LSOS command when "Time to Next Data" becomes zero. Regardless of command origin, any data set consists of a complete set of "LO" rate and "HI" rate data (if station is dual-rated) and a set of Bravo data, should the station also be a master transmitting station. At a dual-rated LSOS, both rates' data are provided to each controlling RSOS.

LSOS Data List Structure

LSOS maintains an array (indexed by rate) of singly-linked lists of "Normal data" and their respective times of occurrence. As new data sets are taken on each rate, the data list end pointer for that rate is incremented. The data list start pointer for that rate always points to the first (oldest) data set, while the data list end pointer always points to the last (most recent) data set for that rate. The five most recent data sets are maintained in this list for use at the transmitter site. These may be listed at any time by using the LSOS "Last Data" command.

A similar method is used to maintain recent "Bravo data" at a master transmitting station. LSOS maintains an array (indexed by Austron receiver, Bravo 1, 2, or 3) of singly-linked lists of "Bravo data" and their respective times of occurrence. Likewise start and end pointers are incremented and maintained so that the five most recent data sets are available for listing using the LSOS "Last Data" command.

LSOS Data Queue Structure

LSOS software maintains independent FIFO data queues for each rate at a transmitting site. Each piece of data constitutes a data queue entry. The queue structure is shown in Figure 8.

![Figure 8. LSOS Data Queue Structure.](image)

The Data_Type_Code is a single ASCII character used to indicate data type (e.g. TINO, SYNC, etc.). Next is a pointer to the next queue entry. The Information Morsel is part of a variant record and may actually take three forms as follows:

1. It may be a string, used for indicating end of data set and for tagging time of day to the data round (ex: 10:35:25).

2. It may be a character, used as a bit mapped equipment status character indicating status of PATCO, Timers, Coupling Networks, or Transmitters.
3. It may be a real data value (ex: 39889.6 for TINO).

As each piece of data is taken, LSOS software enters it into the data list structure. Serial interrupts for communications are enabled throughout the majority of the data taking routine, thus allowing continued response to RSOS polling. In this way LSOS can maintain the data set measurement sequence, and still respond to RSOS polling by transmitting each data value immediately after it completes the measurement.

Should communications fall between LSOS and RSOS, the LSOS computer will continue to maintain its data queues, up to a maximum of 100 data sets (single-rate case) or 50 data sets/rate (dual-rate case). As in the case of the alarm queues, these maximums were established to avoid memory overflows due to heap/stack collisions under the PASCAL Operating System. When communications are restored, data is transmitted as before.

**LSOS Commands**

Probably the most important function of LSOS software is its capability of responding to command requests. From an operational standpoint it is clear that alarm and data information is of little value at a remote site if nothing can be done to correct a known casualty at the transmitting site. Commands may be issued from the RSOS computer, the LSOS keyboard, or via internal software command from LSOS. In most cases LSOS immediately executes any requested command. LSOS software is intelligent enough, however, to reject commands in certain circumstances. For example, LSOS will not allow oscillator phase adjustments on the #2 oscillator that supplies 5MHz timing signals to the #2 timer if the Operate timer is timer #2. Command capabilities of LSOS were listed above. A description of command implementation at LSOS follows.

**Commands from RSOS**

LSOS receives characters transmitted from RSOS via the serial communications interrupt facilities within the LSOS software as depicted in Figure 9. A procedure called "Pack N Decode" packs the incoming message characters from each communications channel. When the "EOT" character is received by LSOS, the routine verifies the message format, compares LSOS and RSOS station identification codes, and compares calculated and received checksum strings. If all information is determined to be correct, the procedure "Pack N Decode" maps the command character to a valid LSOS command, and a procedure is called to execute the command and respond to the requesting RSOS computer. If command message format is judged to be suspect by LSOS, the LSOS computer requests a re-transmission from RSOS before initiating any command action. If LSOS recognizes that the RSOS computer has been initialized for a different configuration (e.g. dual vs. single rated station, tube type vs. SSX type transmitter, etc.) due to inconsistencies in the station identification code, no commands of any kind may be executed and all communications from that RSOS are essentially ignored.

**Commands from LSOS Keyboard and Internal Software**

Commands may also be executed from the LSOS computer "softkeys" located on the upper left hand side of the HP9826 keyboard. This capability may be used in troubleshooting, training, and certification at the local site, or may be used simply for convenience by a local watchstander. Each key function has a corresponding descriptive label presented on the LSOS display. Most commands from the LSOS keyboard require that the LSOS be commanded into "Station Maintenance" (local control) for any action to take place. This facilitates better division of control responsibility for the LSOS and RSOS.

Special function key interrupts represent a level one interrupt from the keyboard, and are of lower priority than alarm or communications interrupts. Lower priority keyboard interrupts are latched, so interrupts from the keyboard are rarely "ignored" for more than a few milliseconds. When a keyboard interrupt is detected, an immediate check is performed to ensure that a valid function key was pressed. If the "softkeyhook" procedure determines that no valid function key was pressed then no action is taken whatsoever. If, instead, a valid function key press is decoded, the "softkeyhook" procedure maps the key to a specific request-action, and sets a global requested action variable equal to the decoded command request. All commands are accomplished external to the procedure for decoding softkey interrupts. In fact, the command execution procedure is called directly from the main program loop whenever a valid request is generated via special function keys.

LSOS also may accomplish commands from time to time on its own. Examples of these "internal software" commands are Take Data, Do Diagnostic, and Reset HCG. LSOS maintains an internal timing counter in order to automatically provide data sets to RSOS. LSOS Multiprogrammer diagnostic routines are performed automatically every ten data sets. Likewise, if LSOS detects an HCG fault, the system automatically attempts to reset the fault.

**Command Execution**

Most commands are accomplished under LSOS computer control by closing or opening relays on the relay cards within the Multiprogrammer. Figures 10a through 10c show a programmers' model for the Multiprogrammer depicting each Relay and Event Sense card bit, and each associated function. For instance, LO rate timer secondary station "Blink" is initiated by closing bit zero of the "A" relay card. The Blink line, which is normally held to a TTL high from the RSOS Interface and the RCI, is pulled low when this relay is held closed, thus initiating timer blink. Since the relay must remain closed for the line to remain pulled low, timer blink will stop if the Multiprogrammer is de-energized. An equipment switch is accomplished in a similar manner. For instance, to accomplish an al rate timer switch from timer #1 to timer #2, Multiprogrammer relay card "A" bit 11 relay is closed only momentarily. This action prompts a double-throw multiple contact latching relay in the Timer Control Set to switch positions, thus causing a timer switch. To switch back, we momentarily close Multiprogrammer relay card "A" bit zero.
NOTES:

1. THERE MAY BE UP TO FOUR SEPARATE COMMUNICATIONS INTERRUPT SERVICE ROUTINES AVAILABLE DEPENDING ON INITIALIZATION AND SERIAL INTERFACE CONFIGURATION. (e.g., LO RATE NORMAL, LO RATE BACKUP, HI RATE NORMAL, HI RATE BACKUP COMMUNICATIONS CHANNELS).

2. COMMUNICATIONS INTERRUPTS ARE LEVEL 3 INTERRUPTS (AS CONFIGURED ON THE HP 98626 SERIAL I/F) TO THE HP 9826 COMPUTER.

Figure 9. Communications Interrupt Service Routine
Software Flow Diagram

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### 400 @ RELAY READBACK

<table>
<thead>
<tr>
<th>D11</th>
<th>D10</th>
<th>D9</th>
<th>D8</th>
<th>D7</th>
<th>D6</th>
<th>D5</th>
<th>D4</th>
<th>D3</th>
<th>D2</th>
<th>D1</th>
<th>D0</th>
</tr>
</thead>
<tbody>
<tr>
<td>GROUND</td>
<td>+5 VOLTS</td>
<td>SW</td>
<td>RELAY READBACK</td>
<td>XMTTS</td>
<td>EP Trigger</td>
<td>XMTR EMER</td>
<td>SELECT</td>
<td>RATE DATA</td>
<td>RES</td>
<td>SELECT PATCO 1</td>
<td>MCC</td>
</tr>
</tbody>
</table>

### 401A RELAY READBACK

<table>
<thead>
<tr>
<th>D11</th>
<th>D10</th>
<th>D9</th>
<th>D8</th>
<th>D7</th>
<th>D6</th>
<th>D5</th>
<th>D4</th>
<th>D3</th>
<th>D2</th>
<th>D1</th>
<th>D0</th>
</tr>
</thead>
<tbody>
<tr>
<td>SELECT LO TIMER 2</td>
<td>LO</td>
<td>A U T R O N AMP</td>
<td>(+)</td>
<td>LO</td>
<td>A U T R O N AMP</td>
<td>(-)</td>
<td>LO</td>
<td>M-LO</td>
<td>(+)</td>
<td>LO</td>
<td>M-LO</td>
</tr>
</tbody>
</table>

### 402B RELAY READBACK

<table>
<thead>
<tr>
<th>D11</th>
<th>D10</th>
<th>D9</th>
<th>D8</th>
<th>D7</th>
<th>D6</th>
<th>D5</th>
<th>D4</th>
<th>D3</th>
<th>D2</th>
<th>D1</th>
<th>D0</th>
</tr>
</thead>
<tbody>
<tr>
<td>SELECT HI RATE DATA</td>
<td>RCI</td>
<td>O H S A B L E</td>
<td>HI</td>
<td>LPA</td>
<td>10²</td>
<td>HI</td>
<td>LPA</td>
<td>10³</td>
<td>MASTER BLINK Z</td>
<td>MASTER BLINK W</td>
<td>MASTER BLINK Y</td>
</tr>
</tbody>
</table>

### 403C EVENT SENSE

<table>
<thead>
<tr>
<th>D11</th>
<th>D10</th>
<th>D9</th>
<th>D8</th>
<th>D7</th>
<th>D6</th>
<th>D5</th>
<th>D4</th>
<th>D3</th>
<th>D2</th>
<th>D1</th>
<th>D0</th>
</tr>
</thead>
<tbody>
<tr>
<td>STATION ALARM 12</td>
<td>STATION ALARM 11</td>
<td>STATION ALARM 10</td>
<td>STATION ALARM 9</td>
<td>STATION ALARM 8</td>
<td>STATION ALARM 7</td>
<td>STATION ALARM 6</td>
<td>STATION ALARM 5</td>
<td>STATION ALARM 4</td>
<td>STATION ALARM 3</td>
<td>STATION ALARM 2</td>
<td>STATION ALARM 1</td>
</tr>
<tr>
<td>(CHR 43)</td>
<td>(CHR 42)</td>
<td>(CHR 41)</td>
<td>(CHR 40)</td>
<td>(CHR 39)</td>
<td>(CHR 38)</td>
<td>(CHR 37)</td>
<td>(CHR 36)</td>
<td>(CHR 35)</td>
<td>(CHR 34)</td>
<td>(CHR 33)</td>
<td>(CHR 32)</td>
</tr>
</tbody>
</table>

### 404D EVENT SENSE

<table>
<thead>
<tr>
<th>D11</th>
<th>D10</th>
<th>D9</th>
<th>D8</th>
<th>D7</th>
<th>D6</th>
<th>D5</th>
<th>D4</th>
<th>D3</th>
<th>D2</th>
<th>D1</th>
<th>D0</th>
</tr>
</thead>
<tbody>
<tr>
<td>LO RH PULSE BLINK</td>
<td>OSC 3</td>
<td>ERROR</td>
<td>STBY OSC ERROR</td>
<td>ADV OSC 2</td>
<td>RET OSC 2</td>
<td>ADV OSC 3</td>
<td>RET OSC 3</td>
<td>OPER OSC ERROR</td>
<td>P-GEN</td>
<td>1 FAIL</td>
<td>LO RATE</td>
</tr>
<tr>
<td>(CHR 55)</td>
<td>(CHR 54)</td>
<td>(CHR 53)</td>
<td>(CHR 52)</td>
<td>(CHR 51)</td>
<td>(CHR 50)</td>
<td>(CHR 49)</td>
<td>(CHR 48)</td>
<td>(CHR 47)</td>
<td>(CHR 46)</td>
<td>(CHR 45)</td>
<td>(CHR 44)</td>
</tr>
</tbody>
</table>

Figure 10a. Programmer’s Model of HP 6940 Multi-Programmer

186
### 405E EVENT SENSE

<table>
<thead>
<tr>
<th>D11</th>
<th>D10</th>
<th>D9</th>
<th>D8</th>
<th>D7</th>
<th>D6</th>
<th>D5</th>
<th>D4</th>
<th>D3</th>
<th>D2</th>
<th>D1</th>
<th>D0</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCQ ALARM</td>
<td>OFF</td>
<td>XMTR NOT FAULT</td>
<td>XMTR NOT AUTO</td>
<td>XMTR SYSTEM FAULT</td>
<td>XMTR 1 NOT READY</td>
<td>XMTR 1 NOT READY</td>
<td>XMTR 1 NOT READY</td>
<td>XMTR 1 NOT READY</td>
<td>XMTR 1 NOT READY</td>
<td>XMTR 1 NOT READY</td>
<td>XMTR 1 NOT READY</td>
</tr>
<tr>
<td>(CHR 67)</td>
<td>(CHR 66)</td>
<td>(CHR 65)</td>
<td>(CHR 64)</td>
<td>(CHR 63)</td>
<td>(CHR 62)</td>
<td>(CHR 61)</td>
<td>(CHR 60)</td>
<td>(CHR 59)</td>
<td>(CHR 58)</td>
<td>(CHR 57)</td>
<td>(CHR 56)</td>
</tr>
</tbody>
</table>

### 406F EVENT SENSE

<table>
<thead>
<tr>
<th>D11</th>
<th>D10</th>
<th>D9</th>
<th>D8</th>
<th>D7</th>
<th>D6</th>
<th>D5</th>
<th>D4</th>
<th>D3</th>
<th>D2</th>
<th>D1</th>
<th>D0</th>
</tr>
</thead>
<tbody>
<tr>
<td>LO TIMER 2</td>
<td>LO TIMER 1</td>
<td>HI TIMER 2</td>
<td>HI TIMER 1</td>
<td>MASTER BLINK 2</td>
<td>MASTER BLINK 1</td>
<td>HI COUPLER</td>
<td>TIMER</td>
<td>TIMER</td>
<td>TIMER</td>
<td>TIMER</td>
<td>TIMER</td>
</tr>
<tr>
<td>LOCAL</td>
<td>LOCAL</td>
<td>LOCAL</td>
<td>LOCAL</td>
<td>LOCAL</td>
<td>LOCAL</td>
<td>LOCAL</td>
<td>LOCAL</td>
<td>LOCAL</td>
<td>LOCAL</td>
<td>LOCAL</td>
<td>LOCAL</td>
</tr>
<tr>
<td>(CHR 78)</td>
<td>(CHR 78)</td>
<td>(CHR 77)</td>
<td>(CHR 76)</td>
<td>(CHR 75)</td>
<td>(CHR 74)</td>
<td>(CHR 73)</td>
<td>(CHR 72)</td>
<td>(CHR 71)</td>
<td>(CHR 70)</td>
<td>(CHR 69)</td>
<td>(CHR 68)</td>
</tr>
</tbody>
</table>

### 407G EVENT SENSE

<table>
<thead>
<tr>
<th>D11</th>
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<th>D4</th>
<th>D3</th>
<th>D2</th>
<th>D1</th>
<th>D0</th>
</tr>
</thead>
<tbody>
<tr>
<td>STATION EPA</td>
<td>HI P-GEN</td>
<td>HI P-GEN</td>
<td>HI P-GEN</td>
<td>HI P-GEN</td>
<td>HI P-GEN</td>
<td>HI P-GEN</td>
<td>HI P-GEN</td>
<td>HI P-GEN</td>
<td>HI P-GEN</td>
<td>HI P-GEN</td>
<td>HI P-GEN</td>
</tr>
<tr>
<td>LOCAL</td>
<td>FAIL</td>
<td>FAIL</td>
<td>FAIL</td>
<td>FAIL</td>
<td>FAIL</td>
<td>FAIL</td>
<td>FAIL</td>
<td>FAIL</td>
<td>FAIL</td>
<td>FAIL</td>
<td>FAIL</td>
</tr>
<tr>
<td>(CHR 91)</td>
<td>(CHR 90)</td>
<td>(CHR 89)</td>
<td>(CHR 88)</td>
<td>(CHR 87)</td>
<td>(CHR 86)</td>
<td>(CHR 85)</td>
<td>(CHR 84)</td>
<td>(CHR 83)</td>
<td>(CHR 82)</td>
<td>(CHR 81)</td>
<td>(CHR 80)</td>
</tr>
</tbody>
</table>

### 408H HIGH SPEED A/D CONVERTER

### 409I RELAY READBACK

<table>
<thead>
<tr>
<th>D11</th>
<th>D10</th>
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<th>D5</th>
<th>D4</th>
<th>D3</th>
<th>D2</th>
<th>D1</th>
<th>D0</th>
</tr>
</thead>
<tbody>
<tr>
<td>LO LPA LOAD</td>
<td>LO LPA LOAD</td>
<td>LO LPA LOAD</td>
<td>LO LPA LOAD</td>
<td>LO LPA LOAD</td>
<td>LO LPA LOAD</td>
<td>LO LPA LOAD</td>
<td>LO LPA LOAD</td>
<td>LO LPA LOAD</td>
<td>LO LPA LOAD</td>
<td>LO LPA LOAD</td>
<td>LO LPA LOAD</td>
</tr>
<tr>
<td>1-8</td>
<td>1-4</td>
<td>1-2</td>
<td>1-1</td>
<td>1-6</td>
<td>1-4</td>
<td>1-2</td>
<td>1-1</td>
<td>1-6</td>
<td>1-4</td>
<td>1-2</td>
<td>1-1</td>
</tr>
</tbody>
</table>

*Figure 10b. Programmer's Model of HP 6940 Multi-Programmer*
### 410J RELAY READBACK

<table>
<thead>
<tr>
<th>D11</th>
<th>D10</th>
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<th>D8</th>
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<th>D6</th>
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<th>D4</th>
<th>D3</th>
<th>D2</th>
<th>D1</th>
<th>D0</th>
</tr>
</thead>
<tbody>
<tr>
<td>TC-2</td>
<td>TC-1</td>
<td>RCVR PCI</td>
<td>LO LPA 10^4</td>
<td>LO LPA 10^2</td>
<td>LO LPA 10^4</td>
<td>HI POS LPA</td>
<td>HI NEG LPA</td>
<td>HI LPA EXECUTE</td>
<td>LO POS LPA</td>
<td>LO NEG LPA</td>
<td>LO LPA EXECUTE</td>
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</table>

### 411K RELAY READBACK

<table>
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<tr>
<th>D11</th>
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<th>D5</th>
<th>D4</th>
<th>D3</th>
<th>D2</th>
<th>D1</th>
<th>D0</th>
</tr>
</thead>
<tbody>
<tr>
<td>HI LPA LOAD</td>
<td>HI LPA 1-4</td>
<td>HI LPA 1-2</td>
<td>HI LPA 1-1</td>
<td>HI LPA .1-4</td>
<td>HI LPA .1-2</td>
<td>HI LPA .1-1</td>
<td>HI LPA .01-4</td>
<td>HI LPA .01-2</td>
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<td></td>
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### 412L RELAY READBACK

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<th>D5</th>
<th>D4</th>
<th>D3</th>
<th>D2</th>
<th>D1</th>
<th>D0</th>
</tr>
</thead>
<tbody>
<tr>
<td>BRAVO-3 M-LO (+)</td>
<td>BRAVO-3 M-LO (-)</td>
<td>BRAVO-2 M-LO (+)</td>
<td>BRAVO-2 M-LO (-)</td>
<td>BRAVO-1 M-LO (+)</td>
<td>BRAVO-1 M-LO (-)</td>
<td>BRAVO-3 AUSTRON AMP (+)</td>
<td>BRAVO-3 AUSTRON AMP (-)</td>
<td>BRAVO-2 AUSTRON AMP (+)</td>
<td>BRAVO-2 AUSTRON AMP (-)</td>
<td>BRAVO-1 AUSTRON AMP (+)</td>
<td>BRAVO-1 AUSTRON AMP (-)</td>
</tr>
</tbody>
</table>

### 413M RELAY READBACK

<table>
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<tr>
<th>D11</th>
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<th>D8</th>
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<th>D6</th>
<th>D5</th>
<th>D4</th>
<th>D3</th>
<th>D2</th>
<th>D1</th>
<th>D0</th>
</tr>
</thead>
<tbody>
<tr>
<td>BRAVO-3 RCVR PCI</td>
<td>BRAVO-2 RCVR PCI</td>
<td>BRAVO-1 RCVR PCI</td>
<td>XC2-1</td>
<td>XC1-2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### OCTAL TO BINARY

**CONVERSION CHART FOR MULTI-PROGRAMMER REFERENCE WORDS (EXAMPLE)**

<table>
<thead>
<tr>
<th>D11</th>
<th>D10</th>
<th>D9</th>
<th>D8</th>
<th>D7</th>
<th>D6</th>
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<th>D4</th>
<th>D3</th>
<th>D2</th>
<th>D1</th>
<th>D0</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>1</td>
<td>4</td>
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<td>1</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>4</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 10c. Programmer’s Model of HP 6940 Multi-Programmer

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Oscillator advance/retard commands are the only equipment related commands that are not accomplished via relay closures. These commands are issued to the Multiprogrammer Digital Output Card. The Digital Output Card provides the proper phase adjustment direction, amount, and gating information to the Phase Microsteppers via the RSOS Interface unit.

RSOS Hardware

The original prototype RSOS equipment included an HP9845 as its central computer. This system required an RSOS computer for each LSOS to be controlled. To control a typical chain of four transmitter sites, each with LSOS equipment, would have required four RSOS equipments at the remote site. Using four computers is disadvantageous in the following respects:

1. Increased hardware costs.
2. Degraded operator interface: Operator would have to deal with more than one computer to perform a given task for each of the transmitting stations.
3. Increased space consumption at already crowded control stations.
4. Increased energy consumption.

To eliminate the disadvantages of the original RSOS design, one computer is used in the RSOS to operate up to four LSOS equipments. The improved RSOS provides two visual display formats. The operator normally sees a composite chain display showing only necessary information on the whole chain. The operator may optionally call up a detailed station display when necessary. The computer Special Function Keys (SFKs) will operate equipment only on the selected station. A typical RSOS hardware configuration is shown in Figure 11. A functional block diagram of the RSOS equipment for a single LSOS configuration is shown in Figure 12.

The heart of the improved RSOS equipment is the HP9836 desktop computer. The HP9836 is one of Hewlett-Packard's newest and most powerful desktop computers. The HP9836 is based on the Motorola MC68000 microprocessor with sixteen bit processing and thirty-two bit internal architecture. The computer has a 12.2 inch CRT display (25 lines by 80 characters) with a graphics resolution of 512 dots horizontal by 390 dots vertical. The HP9836 is capable of controlling/monitoring up to four (in one chain) LSOS equipments. The computer receives information from the LSOS equipment through the communications link via the HP98626A interface. The computer program updates all functions and displays, and maintains communications with the transmitter site. The video terminal (CRT) displays the current operational data. Figure 13 shows the full chain display normally seen by the RSOS operator. Figure 14 shows a normal display when in the individual station display mode. The HP9836 contains two internal 256K 5-1/4 inch flexible disk drives, used to load all the RSOS programs. The HP9836 requires two HP98256 256K byte RAM boards to run the RSOS executive program. An HP2671G thermal printer, identical to the LSOS printer, provides a hard copy of the log, alarms, command responses, and data plots. The computer also controls the Visual Alarm Unit (VAU).

The VAU displays the condition color of the ROS. If no alarms are active, it is green. The most severe pending alarm determines the display color. In addition, with the first occurrence of a red alarm, the horn will sound. It can be silenced by the operator. This unit repeats the alarm status of the HP9836 screen and audio beeper. The unit is driven by the outputs of the internal HPIB interface of the HP9836.

An HP9888A bus expander is required for an RSOS controlling more than one LSOS. The bus expander is needed for the additional HP98626A interfaces for each LSOS.

An Eclair UPS-501-1 Uninterruptible Power Source is used to provide all the RSOS equipment with uninterruptible 115 VAC.

RSOS Software

The RSOS software consists of an executive program and an initialization program. Both programs are written in Hewlett-Packard Pascal for the HP9836. The executive program consists of approximately ten thousand lines of code. It takes two floppy disks to store the executive program and the data files required to operate the RSOS equipment. An initialization program provides the flexibility in RSOS to collect data and alarms from a variety of stations and chain configurations. The initialization program creates a large data record, which stores all the pertinent information on the Loran-C chain (chain name, rate, alarm conditions, and allowed commands) and the individual stations (data tolerances, data plot limits, station name, and station configuration). The initialization process stores this data on one of the executive program's flexible disks for later access by the executive program. The primary function of the executive program is to monitor and control the LSOS equipments in the designated chain. The major modules

Figure 11. RSOS Equipment Desk
Figure 12. RSOS Functional Block Diagram

Northeast U. S. Coast Chain, Seneca, N. Y. Rate: 9960

<table>
<thead>
<tr>
<th>LORSTA Caribou (W) ALPHA</th>
<th>LORSTA Nantucket (X) ALPHA</th>
</tr>
</thead>
<tbody>
<tr>
<td>TINO (uS) : 13311.40</td>
<td>TINO (uS) : 26469.90</td>
</tr>
<tr>
<td>ECD (uS) : 0.90</td>
<td>ECD (uS) : 0.20</td>
</tr>
<tr>
<td>AMPL (Amps) : 580.00</td>
<td>AMPL (Amps) : 550.00</td>
</tr>
<tr>
<td>Last Data: 08:14:03 (Int=3)</td>
<td>Last Data: 08:14:43 (Int=3)</td>
</tr>
</tbody>
</table>

(0) Pending Alarms
Condition: GREEN

<table>
<thead>
<tr>
<th>LORSTA Carolina Beach (Y) ALPHA</th>
<th>LORSTA Dana (Z) ALPHA</th>
</tr>
</thead>
<tbody>
<tr>
<td>TINO (uS) : 41820.60</td>
<td>TINO (uS) : 54390.40</td>
</tr>
<tr>
<td>ECD (uS) : 0.50</td>
<td>ECD (uS) : 1.50</td>
</tr>
<tr>
<td>AMPL (Amps) : 652.00</td>
<td>AMPL (Amps) : 672.00</td>
</tr>
<tr>
<td>Last Data: 08:15:24 (Int=3)</td>
<td>Last Data: 08:16:16 (Int=3)</td>
</tr>
</tbody>
</table>

(0) Pending Alarms
Condition: GREEN

Condition: GREEN Current Station: W 12 Apr 1983 08:16:56 Z

Figure 13. RSOS Chain Display
LORSTA Nantucket

Rate: 9960X

<table>
<thead>
<tr>
<th>Transmitter</th>
<th>Coupler</th>
<th>9960 Timer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>REMOTE</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>9960 Data</th>
<th>Actual</th>
<th>Assigned</th>
<th>Tol</th>
</tr>
</thead>
<tbody>
<tr>
<td>TINO (uS)</td>
<td>26469.90</td>
<td>26470.00</td>
<td>0.20</td>
</tr>
<tr>
<td>SYNC (uS)</td>
<td>26930.50</td>
<td>26940.00</td>
<td>0.20</td>
</tr>
<tr>
<td>Cycle Comp (nS)</td>
<td>20.00</td>
<td>20.00</td>
<td>50.00</td>
</tr>
<tr>
<td>Mast - Local (nS)</td>
<td>234.65</td>
<td>234.80</td>
<td>100.00</td>
</tr>
<tr>
<td>Ant Current (AMPS)</td>
<td>541.00</td>
<td>550.00</td>
<td>20.00</td>
</tr>
<tr>
<td>ECD (uS)</td>
<td>0.20</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>Autron Amp (V)</td>
<td>0.70</td>
<td>0.70</td>
<td>0.10</td>
</tr>
<tr>
<td>Last Data Set:</td>
<td>17:57:15</td>
<td>Data Interval:</td>
<td>3 min</td>
</tr>
</tbody>
</table>

Off Air Time: 00:00 [0]
Blink Time: 00:00 [0]
Comms Status: Carrier Detected

Operations Normal

Set Data Int | Reset W/C | Enable Cmd | Shift Control | CHAIN LEVEL
User Functions | Xmtr Commands | OSC/Timer Cmds | LPA/Blink Cmds | Silence

Figure 14. RSOS Normal Display

Figure 15. RSOS Software Structure
Figure 16. RSOS Software Flow Diagram

of the executive program are shown in Figure 15. A flow diagram of the executive program is shown in Figure 16.

The RSOS executive program uses a serial polling method to collect data and alarms from the LSOS equipments. The LSOS equipments do not interrupt the RSOS with data and alarm messages. Instead, on each pass through the main executive loop, RSOS sends a polling command to LSOS and waits a set time for a response. If a reply is received by RSOS, a message checksum is calculated. If the checksum indicates a transmission error, RSOS will poll LSOS again. LSOS sends a negative acknowledgement if there are no new alarms or data. If alarms or data are present, LSOS will send either the data or the alarm message (alarm messages are sent before data messages). Only one message from LSOS is sent in response to a poll. When an alarm is received, the Visual Alarm Unit (VAU) will flash yellow if the alarm is not operational in nature or, red if it is an operational alarm. If a red alarm occurs when in chain display level, the display level will automatically change to the station display which contains the red alarm. An initial red alarm also causes the VAU audio alarm to sound. This alarm can be reset with an HP9836 Special Function Key (SFK) or a switch on the VAU. All other alarms are reset on the HP9836 as they are cleared at the transmitter site. When an alarm occurs, it is logged on the printer log and displayed on the station display with the time of occurrence. When the alarm is cleared, it is also logged with the time. When the operator takes action to try to correct the problem, this action is also logged. Off-Air and Blink time are kept for a twenty-four hour period and then zeroed at the beginning of the next day. The time counter is not incremented during an off air period of less than sixty seconds (momentary). However, a separate counter located next to the off air counter, the momentary counter, is incremented. Also the number of occurrences of blink are shown next to the blink time.
If a data message is received, RSOS will show a "LSOS TAKING DATA" message on the CRT and will maintain the message until RSOS receives an end of data set message from LSOS. RSOS will then display the time of the last data set on the CRT. RSOS copies all the data from the current data set in a data record. The data record contains fields for all the Normal data. In the case of a master station, the data record will maintain Bravo Control receiver data as well. Additionally, the data record contains fields for the "alternate" rate, Normal data if the station is dual-rated. The data record is initially equal to the last data set, so that all data that LSOS did not send will remain the same (LSOS only sends data that has changed). The data record is then added to a singly-linked list which consists of the last five data sets. Dynamic memory allocation is employed, so only the last five data sets require computer memory. The data from the data record is also stored on disk in data files. Each station has a "primary" rate Normal data file and an "alternate" rate normal data file on disk. There is also a Bravo data file for the "primary" rate. Each file will store a maximum of four hours of data.

Data is received at regular intervals (operator controlled) and the CRT display is updated automatically. The RSOS operator has the transmitter data available in three forms: (1) the screen display, (2) the last five data sets, and (3) a graphic plot of the data. The CRT display is automatically updated by data received from the transmitter site. Also, RSOS can plot all the data from each station automatically every four hours on the printer. In addition to the four-hour plots on the printer, the watchstander can plot data on the CRT.

There are two screen display modes on the HP9836. One is graphics, which is where data plots are generated, and the other is the normal alphanumeric screen display. The graphics mode allows a maximum of two plots per station to be updated constantly in the background as data is received, and still maintain the normal "alpha" display. The plots can be viewed by entering the graphics mode at any time. The graphic plots will allow a maximum of a twenty-four-hour plot time, at which time the plot will start to write over itself. Also, the graphic plots may be dumped to the printer via a Dump Graphics command.

The graphics dump is the method by which the four-hour plots are plotted on the printer. This procedure of plotting data on the printer takes several minutes. The RSOS computer will request pending alarms from each station prior to each graphics dump. If a red alarm condition is detected, the RSOS computer will automatically terminate plot operations.

RSOS controls the LSOS equipments by using command messages. When the watchstander enters a command, the RSOS executive program generates the corresponding command message. The command message is then transmitted to the desired LSOS equipment. RSOS then waits a set time for a reply. The possible command replies from LSOS are:

1. LSOS rejected command: The command will have to be repeated since LSOS was busy, or LSOS is disallowing the command for some valid reason.

2. Time-out-command incomplete: The command will have to be repeated since LSOS did not reply.

3. Comms Down-Command not available: Communications line is not operational.


All commands and control actions are accomplished from the keyboard of the HP9836. This keyboard is a standard typewriter keyboard with a keypad and ten Special Function Keys (SFKs). All commands are entered from the SFKs. The lower portion of the screen display is provided to display special function key labels. All commands require the pressing of more than one key. This eliminates the possibility of entering a catastrophic command by inadvertently touching the keyboard. All operator commands are logged on the system printer, along with the time of day, and LSOS response to the command.

A keyboard interrupt is generated each time an SFK is used to enter a command on the HP9836. The executive program contains a keyboard interrupt service routine which maps each SFK to the desired command. The executive program checks for pending commands on each pass through the executive loop. If there is a pending command, the executive program will then execute the command procedure routine. The keyboard interrupt is the only interrupt capability supported in the RSOS executive program.

**SYSTEM PHILOSOPHY**

Under normal operations, there is no need for operator intervention. However, when an alarm occurs or a signal parameter drifts out of tolerance at the transmitter site, the operator uses the ROS commands to remedy the situation. Using all the information available, the operator can correct some alarm conditions and keep the station on-air while a technician travels to the station.

When a casualty occurs at the transmitter site, the remote operator must determine what the problem is and attempt to correct it. The ROS does not add any alarm recovery capability that is not available to a watchstander located at the transmitter site. To successfully recover from the casualty, the remote operator must analyze past and present transmitter site alarms. Additionally, since RSOS is typically located at the control site, the remote operator can use monitor receiver data to assist in his decision making process. If the operator determines an equipment casualty has occurred, the remote operator must be able to switch to independent redundant equipment. This is accomplished by the remote operator from the RSOS keyboard.

**INSTALLATIONS**

Completed installations of the improved ROS are as follows:

- Searchlight, NV (9940Y) (6/83)
- Fallon, NV (9940M) (4/84)
Currently scheduled installations of the improved ROS are as follows:

<table>
<thead>
<tr>
<th>Location</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>George, WA</td>
<td>11/84</td>
</tr>
<tr>
<td>Port Hardy, BC</td>
<td>11/84</td>
</tr>
<tr>
<td>Grangeville, LA</td>
<td>3/85</td>
</tr>
<tr>
<td>Raymondville, TX</td>
<td>3/85</td>
</tr>
<tr>
<td>Tok, AK</td>
<td>6/85</td>
</tr>
<tr>
<td>Baudette, MN</td>
<td>10/85</td>
</tr>
<tr>
<td>Dana, IN</td>
<td>FY-86</td>
</tr>
<tr>
<td>Nantucket, MA</td>
<td>FY-86</td>
</tr>
<tr>
<td>Jupiter, FL</td>
<td>FY-86</td>
</tr>
<tr>
<td>Caribou, ME</td>
<td>FY-86</td>
</tr>
<tr>
<td>Carolina Beach, NC</td>
<td>FY-87</td>
</tr>
<tr>
<td>St. Paul, AK</td>
<td>FY-87</td>
</tr>
<tr>
<td>Tracen, Gov. Is., NY</td>
<td>FY-87</td>
</tr>
</tbody>
</table>

**FUTURE PLANS AND POSSIBLE ENHANCEMENTS**

The improved ROS as designed is very flexible in both its hardware and software configurations, and is highly modular in design. The hardware could be expanded and software enhanced to interface to any number of improved measuring devices in future years. Clearly we have not really tasked the LSOS computer to do much more than provide data information, alarm information, and to relay commands. The LSOS could be easily modified to evaluate conditions and provide closed-loop control of some station equipment. Historically we have stayed away from this type of "smart" control, and have left all decision making to the remote operator. There are currently no plans for implementing this closed-loop control.

A compromise to the closed-loop control concept could be the incorporation of an alarm analysis feature at the RSOS. Such a feature could assist the remote operator in evaluating a transmitter site casualty, and could recommend a course of action. Each type of casualty has a typical set of alarms or data present, and the RSOS software could be modified to evaluate any abnormal situations by analyzing the current alarms and data, and providing recommendations.

Current plans call for an evaluation of interfacing an upgraded version of the Calculator Assisted Loran-C Controller (CALOC) to the ROS. CALOC is typically co-located with ROS at a Loran-C control site, and performs normal chain controlling functions. All equipment commands recommended by CALOC can be performed by the improved ROS. By allowing the ROS to accomplish equipment-related commands requested by CALOC, we would eliminate the need for the Remote Control Interface (RCI) at the transmitter site. Additionally, the CALOC-to-RCI TTY communications link between the control site and the transmitter site could be eliminated.

**CONCLUDING REMARKS**

The need to reduce Loran-C operating costs has spawned the development of a flexible and powerful remote operating system capable of freeing five or more billets from each ROS'd station. Historically, we know that the SSX/ROS station typically costs less to operate than a fully manned FPN-42-type station. We also expect that signal availability will remain unaffected with the advent of the SSX/ROS stations replacing aging FPN-42-type stations. By installing ROS at existing FPN-44 and FPN-45 stations, we will make these stations more cost effective to operate. We expect we will not alter operations and availability at these stations after the installation of ROS. In short, we see ROS as a system that not only serves to trim the operational budget of Loran-C, but also helps to justify the upgrade of our aging FPN-42 transmitters with newer solid-state transmitters, thereby providing improved reliability at a lowered cost for the user community.

**ACKNOWLEDGEMENTS**

The authors would like to express their appreciation to CAPT W. H. Hayes, Jr., CDR R. E. Burke, Jr., LCDR Z. S. Chavez, and ET1 R. Finstad for their comments and support during the preparation of this paper, and subsequent presentation. The authors would also like to recognize LCDR R. J. Weaver, LT D. Alsip, Mr. R. Altiery, ET1 R. Finstad, and Mr. M. Letts for their efforts in the successful design and development of the improved Remote Operating System.

**REFERENCES**


HOW GOOD THE AIRCRAFT ARE DOING WITH
THE SIGNALS FROM FOX HARBOR

BY

WILLIAM A. MCKENZIE, TRANSPORT CANADA

This subject matter was informally presented "hot from the field"
as being very apropos to the attendees interested in Loran C's future inAvionics.

Mr. McKenzie wishes to inform all recipients of these proceedings
that he is now prepared to furnish formal updated material upon request.

MAILING ADDRESS: 38 Berkley Drive
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Canada
FINALLY — A PRACTICAL ECD ESTIMATING TECHNIQUE

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ABSTRACT

The traditional use of Loran-C as the principal marine navigation system in the US and Canada, is accompanied at an increasing rate by airborne and terrestrial applications.

Masquerading as cycle slips, incorrect cycle identification and other such uncomplimentary phrases, the matter of envelope-to-cycle difference (ECD) has been of great interest to the receiver manufacturer and Loran-C user.

Technical papers presented at earlier WIA symposia have reported the predictability of ECD over seawater, and the misbehavior of ECD as the signal passes over land.

This paper presents the results of an analysis of a large quantity of ECD data. A technique for predicting ECD over non-homogeneous signal paths is presented which is useful for chain planning as well as predicting equipment operation in overland applications.

INTRODUCTION

The term envelope-to-cycle difference (ECD) refers to the relationship between the zero cycle crossing of the 100 kHz carrier and the envelope of the Loran-C pulse. A zero ECD condition exists when the thirty microsecond point on the pulse envelope is coincident with the third positive-going zero crossing of the phase.

As the signal propagates from the antenna, the ECD is seen to change. Proper receiver operation depends upon the ECD being within a usable range. The precise manner in which ECD changes with distance from the station would be a valuable tool for system managers, the receiver designer, and ultimately the user.

During the course of implementing a Loran-C system for the Kingdom of Saudi Arabia, it was necessary to locate the two master transmitter stations well inland. The prime service area of this maritime system is the Red Sea, the Arabian Gulf, and the Arabian Sea. Transmitter ECD assignments had to be made such that the ECD in the prime service area would be suitable for the navigation receiver.

The principal governing criterion is the Minimum Performance Specification (MPS) for Marine Loran-C receivers. The MPS provides the following ECD specifications:

- Range from -2.4 to +2.4 usec in normal coverage area
- Range from -3.8 to +1.8 usec in extended coverage area

Earlier reports to the WIA have addressed the matter of ECD variation. This paper builds on this earlier work and presents a practical method of predicting ECD of the Loran-C pulse in the service area.

BACKGROUND

Prior to the advent of the hard limited digital Loran-C receiver, envelope and cycle of the transmitted slave station signals were maintained in synchronization with the master station. Independent servo loops for envelope and cycle were used both in user receivers and the timer-synchronizers at the transmitter stations. A master-slave time difference was provided by both the cycle and envelope loops.

Management of the Loran-C system in those days consisted of controlling these two time differences to assigned time difference values at the system area (SAM) monitor. At the transmitter, the fine adjustments, called Coding Delay Adjustments (CDAs), were made by a resolver to shift the phase of a 100 kHz input to the timer-synchronizer. Similarly, a phase resolver in a 10 kHz circuit was used to insert Envelope Timing Adjustments (ETAs). The disparity between the TD as indicated by the cycle servo readout, and that of the envelope loop was called Envelope-Cycle Discrepancy (ECD). Monitor stations ordered occasional ETAs to maintain the assigned envelope TD. To the navigator, as the ECD approached five microseconds, the usability of the system rapidly deteriorated. Another important parameter to watch was the differential ECD; the difference between the ECD of the master and each slave since the receivers used servo loops to determine envelope TD.

With the advent of the rubidium oscillator, closely followed by the cesium beam frequency standard, Loran-C entered the present mode of free-running operation. The essence of free-running operation is that there is no longer a closed loop as in the former synchronized operating mode. Instead, phase adjustments are made, chiefly to correct for the slight difference in frequency between the on-air frequency standards at the master and secondary transmitter stations. Fine adjustments are now called Local Phase Adjustments (LPAs). LPAs in the modern Loran-C network are executed by keyboard entry at the chain control station.
ECD RE-DEFINED

A number of years ago a standard definition was adopted for the Loran-C pulse shape. The various Loran-C transmitters meet the standard shape to various degrees, and with varying degrees of difficulty.

As part of the Coast Guard's Loran-C improvement program of the mid-1970's, a hardware unit called the Electrical Pulse Analyzer (EPA) was developed. The EPA is installed at all Loran-C transmitter stations. It provides a means of checking the shape of the antenna current pulse. The term ETA is no longer valid since the control of ECD is accomplished by adjustment of transmitter pulse shape.

Part of the Coast Guard's system management consists of monitoring pulse shape as observed at the transmitter, and a value related to pulse shape that is obtained from the monitor receiver.

It is interesting to note that the four types of Loran-C transmitters in use have quite different pulse shape controllability characteristics. The older transmitters (AN/FPN-39 and AN/FPN-42) accomplish shaping of the pulse in the high power amplifier stages and tuned circuits, and therefore require considerable adjustment to maintain the pulse shape within acceptable limits. The AN/FPN-44/44A/45 transmitters after being outfitted by the most recent modifications are quite linear and extremely responsive to adjustments in the transmitter drive waveform. The AN/FPN-64(V) generation of transmitters, by virtue of its method of generating a composite Loran-C pulse, is provided with a set of discrete settings. These settings, entered in the pulse amplitude and timing control (PATCO) unit, establish the operating parameters of loops under microprocessor control. The table of PATCO settings typically provides for excellent pulse shape and transmitter ECD values at about one-half microsecond increments.

In practice, changes in operational assignment that is new monitor "control" ECD values are seldom made. According to the Loran-C Signal Specification, the ECD tolerance for most Loran-C chains is plus minus 1.5 microseconds. The point is that precise control is neither practical nor required by the operations doctrine. Therefore, the burden is on the user (receiver manufacturer) to live with the resultant ECD throughout the service area.

THE PROBLEM

In 1978 at the Seventh Annual WGA proceedings, LCDR Bill Jones' paper on ECD reported a very predictable behavior over seawater. Experimental data collected showed that ECD changes in a negative direction with distance from the transmitter. The rate of change over seawater is approximately 2.5 microseconds per thousand miles. The result of these well-documented test flights was the adoption of the Coast Guard's policy that transmitters would be adjusted to provide a range of zero to plus 2.5 microseconds in the coastal service area. This work also pointed out that the correlation of data on the West Coast was poorer than that observed for flights off the East Coast.

At the following WGA symposium, Walt Dean offered a report on the ECD variations in overland propagation. He observed inexplicably large variations from the expected values of ECD at a number of inland points.

In the case of our work in Saudi Arabia, we did not have the capability for collecting in-flight data, nor did we have monitors along the southern coast of the Arabian peninsula. The problem, therefore, was to predict ECD in those offshore waters to a high degree of confidence. With the preceding reports as background, a technique for making predictions of overland effects was developed.

THE APPROACH

In order to look into the matter of ECD, baseline information was obtained from the Coast Guard chain commanders for all continental US and Canadian chains. This information consisted of the transmitted ECD values for each signal, and the corresponding ECD values from the monitor stations.

The Coast Guard's operational data and published conductivity values along the paths from transmitter to monitor stations were then examined to determine whether there might be a relationship between the two. The difference in ECD at the transmitter and monitor over the more homogeneous paths suggested a definite pattern. The difference was observed to be greater over paths of poorer conductivity. A tabulation of these data was made and further examined. The conclusion is graphically shown in Figure 1. The values of conductivity published by the International Radio Consultative Committee (CCIR) are not continuous. Values of conductivity were limited to those published in CCIR Report No. 717. This plot of ECD change in microseconds per one hundred nautical miles is bounded on the higher conductivity end (sigma = 5) by the value 0.25, as established in LCDR Jones' report (op cit.).

To determine the validity of the curve, data taken on the US West Coast were used. Over a period of several years, considerable effort had been expended in collecting information on field strength and ECD along the entire West Coast. LCDR Kirkman, then at US Coast Guard Pacific Area Loran office, compiled and zealously guarded this large cache of information. never quite finding the rainy day to work on it. A total of 615 data points were selected from data taken from land-based monitor van readings as well as airborne data. The information provided readings over water as well as over land.

The ECD data from all four stations of the 9940 chain was then plotted on a fresh chart. Over this chart a tracing was made of the major features of terrain, essentially the elevation of mountain ranges encountered along the signal paths. Over this tracing, the CCIR conductivity profiles were then applied.
This composite chart was then used to examine the profiles of several dozen ray paths from each Loran-C transmitter station. Each path was divided into segments according to the conductivity "boundaries" crossed from transmitter to observation point. In many of these cross-sections, several observation points were encountered.

THE RESULTS

For each profile, the "new" ECD curve was used to estimate or predict the change in ECD over the path. This predicted value was compared to the observed ECD value and found to agree quite well. On the average, this technique appears to yield a value within one-half microsecond of the observed value.

In his paper, Mr. Dean suggested that there is a relationship between terrain and ECD variation. In addition to the conductivity profiles, I attempted to plot similar profiles of observed ECD values versus elevation above sea level. I found that there was so little correlation of the data that no quantified report can be made. I fully support Mr. Dean's observation that there appears to be a reversal of change in ECD. That is, as the signal passes over a sharp change in terrain, the ECD appears to go positive, and then later "recovers." This phenomenon seems to affect the area within approximately one hundred miles of the sharp discontinuity along the ray path.

APPLICATION

The technique for estimating ECD is quite straightforward. First the transmitted, or incident value of ECD is computed. The incident value is reduced by the contribution of each segment of the propagation path.

The incident value of ECD is the published antenna current ECD plus 2.5 microseconds.

\[ ECD = ECD_i + 2.5 - \sum_{n=1}^{N} [(Dn)(Cn)] \]

where \( ECD \) = resultant ECD value in usec

\( ECD_i = \) transmitted (antenna current) ECD

\( N = \) number of segments

\( Dn = \) segment length in NM

\( Cn = \) ECD lapse rate from Fig 1

AN EXAMPLE

One of the paths used in verifying this technique is used as an example. The path conductivity profile (Sigma Values) is tabulated below.

<table>
<thead>
<tr>
<th>Segment</th>
<th>Distance</th>
<th>Sigma</th>
<th>Measured</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>19</td>
<td>.01</td>
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<td>2</td>
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<td>.01</td>
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</tr>
<tr>
<td>7</td>
<td>26</td>
<td>5.0</td>
<td>1.9</td>
</tr>
</tbody>
</table>

The transmitter is the 9940 Master (Fallon NV) which has a nominal transmitter ECD of +1.0 microsecond. The resultant estimated ECD values at the end points of segments 5, 6 and 7 are 2.5, 2.38 and 2.31 microseconds, respectively. The all-seawater values for these distances would be 2.98, 2.86 and 2.8 microseconds. These comparisons are typical of the results of analyzing a large amount of data taken on the US West Coast.
The degree of disagreement between the measured and estimated values of ECD results from a number of sources. The error budget includes a number of factors which contribute to the uncertainty in the estimating process. These include:

- Accuracy of the transmitter station's "ECD meter"
- Accuracy of ECD readout of the control receivers
- Pulse shape control within the assigned ECD tolerance
- Actual versus predicted path conductivity
- Effects of terrain

Since the conductivity values upon which this technique is based are themselves estimated values, the curve of Figure 1 is intentionally biased on the conservative side. This is shown in the example where the estimated ECD value is bracketed by the "all seawater" and observed ECD values.

The average difference between estimated and observed ECD is approximately 0.4 microseconds. Considering the number of contributing sources, this degree of agreement is quite acceptable.

Figure 2 is extracted from Walt Dean's paper. The scatter of observed ECD data shows the poor correlation when considering only the distance from the transmitter.

**CONCLUSIONS**

This paper has shown that predictions of ECD is possible for overland paths.

The lapse rate of ECD over areas of poor conductivity can be considerably greater than that of an all-seawater path.

ECD goes positive in the vicinity of sharp increases in elevation of terrain. The data is insufficient to further quantize this local anomalous ECD behavior. At distances of fifty to one hundred miles beyond the change, the ECD returns to the expected value.

The plot of ECD as a function of conductivity was developed from actual measurements. It provides a capability of predicting ECD to 0.5 microsecond or better.

The application of the prediction technique can be used to extend the effective usable range of Loran-C signals.
RECOMMENDATIONS

The present technique of controlling ECD at the transmitter through maintenance of the proper pulse shape should be retained.

The tolerance presently allowed for ECD should be reserved for variations in the propagation medium.

 Adopt + 0.5 microsecond tolerance for pulse shape control at the transmitter.

System managers should study total coverage areas of all chains.

Transmitter assignments should be revised to eliminate the present bias in favor of the maritime areas.

REFERENCES

1. International Radio Consultative Committee (CCIR) Report 717, XIVth Plenary Assembly, Kyoto 1978

2. Minimum Performance Standards (MPS), Marine Loran-C Receiving Equipment, RTCM Paper 12-78/00-100


LORAN-C 1984: A HIGH TECHNOLOGY NANOSECOND ACCURACY SYSTEM FOR HHE AND RESTRICTED WATERWAY NAVIGATION.

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Raman Tempo
816 State Street
Santa Barbara, CA 93102

ABSTRACT

This paper describes the achievable accuracy using Loran-C for HHE and restricted waterway navigation. Although this paper focuses on restricted waterway test experience it is also obvious these results substantially impact aviation and overland applications. Highlighted in this paper are "new" technological features that have been added to the system over about the past 10 years. Most important are technological issues including compensation techniques for Loran-C error sources, chain control, and receiver related advancements.

SECTION 1 INTRODUCTION AND SUMMARY

Introduction

The objective of this paper is to define achievable accuracy and resolution using the Loran-C radio-navigation system and describe techniques for achieving this capability.

Over the last several years, the Coast Guard, FAA, and the marine community have been investigating techniques for using Loran-C for precise navigation. These investigations include analytical studies supplemented by field tests in selected ports, inland waterways, and the national airspace to develop performance and operational data. The US Coast Guard Office of Navigation, Short Range Aids to Navigation Division, desires to assimilate the base of knowledge on Loran-C precision navigation and present this information in a form that will encourage and stimulate the Loran-C receiver industry to exploit the full capability of the Loran-C system.

This paper includes a compilation of research information on Loran-C performance and operational capabilities from Government and industry studies, analyses, tests, and experiments to characterize the maximum potential accuracy and resolution achievable with the Loran-C system. Specific attention has been given to:

1. Description of the Loran-C error sources and means to compensate.
2. Description of geographically dependent effects, especially the land/sea interface.
3. Definition of Loran-C coverage contours.
4. Definition of various Differential Loran-C concept alternatives, including: automatic corrections, manual corrections, initiate and go, and on-the-fly correction.
5. Definition of receiver performance specifications and limitations, with particular attention to resolution and accuracy.

Summary

Section 1 provides a definition of the new 1984 Loran-C navigation system. The literature includes numerous Loran-C navigation descriptions; however, Section 1 not only defines the system but highlights significant technological and operational changes and improvements that have occurred in about the past 10 years. These new Loran-C system features are summarized below in Table 1.

Section 3 of this paper defines in quantitative terms the source and magnitude of Loran-C temporal and spatial errors. Transmitter timing fluctuations, propagation (temporal and spatial), noise (atmospheric), and frequency interference are presented in quantitative terms. Section 4 provides a description of the compensation techniques that can be used to minimize Loran-C errors. Compensation techniques for temporal and spatial fluctuations are presented in Section 4. Since noise, frequency interference, receiver error, and cycle selection problems are reduced or eliminated by good receiver design practices mitigation techniques for these are presented in Section 5.

The error sources, causes, and proven compensation techniques that are dealt with herein are summarized in Table 2. A few important observations referring to items listed in Table 2 should be made:

1. (Items 1, 2, 3) Data in Section 3 includes examples of very large errors caused by both temporal and spatial errors. We no longer care how large these errors are since there is a proven compensation technique for each error source as demonstrated in Section 4. Of course, knowing the origin of these errors is a requirement.
2. (Items 4, 5, 6) Limitations may actually be associated with the user equipment. Two differential Loran-C tests have shown 25- to 50-foot accuracy is achievable. When examining the raw test data it is obvious these values

<table>
<thead>
<tr>
<th>Improvement</th>
<th>Technological Operation</th>
<th>Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loran-C Pulse Control</td>
<td>I</td>
<td>Textbook shape pulse</td>
</tr>
<tr>
<td>Solid State Transmitters</td>
<td>I</td>
<td>99.9 percent time availability</td>
</tr>
<tr>
<td>Improved Chain Control</td>
<td>I</td>
<td>Increased chain stability, reliability</td>
</tr>
<tr>
<td>Procedures</td>
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<tr>
<td>Improved Loran-C Methods</td>
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<td>Improved compensation for temporal fluctuations</td>
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<tr>
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<td></td>
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<tr>
<td>Improved Planning (GODP)</td>
<td>I</td>
<td>Improved accuracy</td>
</tr>
<tr>
<td>Considerations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>User Equipment</td>
<td>I</td>
<td>Improved resolution, automation, and reliability</td>
</tr>
</tbody>
</table>
Table 2. Loran-C error sources and compensation techniques.

<table>
<thead>
<tr>
<th>Error Source</th>
<th>Cause</th>
<th>Compensation Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Transmitter timing fluctuations</td>
<td>Cautions, timer, and transmitter variations</td>
<td>Accurate and stable time base frequency, phase adjustments on short- and long-term basis, cycle compensation loop</td>
</tr>
<tr>
<td>2. Temporal fluctuations</td>
<td>Refractive index changes along propagation path</td>
<td>Differential Loran-C and variations of this method</td>
</tr>
<tr>
<td>3. Spatial effects</td>
<td>Bridges (such as Golden Gate)</td>
<td>Differential Loran-C and variations of this method</td>
</tr>
<tr>
<td>4. Noise (atmospheric and mankind)</td>
<td>Electrical discharges in the atmosphere and power generation equipment</td>
<td>Conduct grid survey, reflect warpage in grid. This is a one-time fix. Use position reference system or visual grid survey methods (PLAG)</td>
</tr>
<tr>
<td>5. Frequency interference</td>
<td>In-band 90-110 kHz</td>
<td>Band limiting and switched G in the receiver.</td>
</tr>
<tr>
<td>6. Receiver</td>
<td>Out-of-band 70 kHz and 130 kHz</td>
<td>Linear: Filtering down at 100 kHz ahead of amplifier and clipped linear amplifier. Hard limiters: all linear processing at low-level output has square wave shape. Signal processing filters to minimize effects of interference and noise, shape the envelope, and minimize unwanted distortions. Narrow band switching of the filters is provided to gain SNR. Use band limiting, interference filters (match filters), and switched G in the receiver. Filter the analog signal or change cross-correlation process to eliminate synchronous interference. Linear and hard limiter amplifiers have wide-band amplifier with low internal noise.</td>
</tr>
</tbody>
</table>

3. (Items 2,3) A compendium of test data has been collected over the past 10 to 15 years and presented in Section 4. A clear distinction has been drawn between spatial and temporal effects (terrain elevation, effects of structures, time varying effects such as surface impedance, retractive index changes, etc). This distinction is of great importance when recognizing the limitations of techniques such as PLAD or positionning reference systems (Trisponder, Mini-Ranger, Maxiran, etc) used for Loran-C surveys. These techniques strictly provide a calibration of spatial effects. Differential Loran-C methods or variations thereof are required to compensate for temporal fluctuations.

4. (Items 1,2) A functional flow diagram of all the major subsystems required to design an automated differential Loran-C system is included in Section 4.

5. (Item 2) Automatic differential systems appear more practical than manual due to the frequency update (correction interval) requirements for most harbor and river areas.

6. PLAD type systems are effective. However, caution is a necessity since the presurveyed points only include a measure of spatial error and not real-time corrections for temporal fluctuations. The data in this paper shows the need for real-time corrections (100-second correction interval preference, 15 minutes in certain situations) to compensate for temporal errors.

7. Operation of initialization techniques are presented in Section 4. Additionally, a review of these techniques starting in 1968 to the present is provided.

8. To compensate for spatial changes requires a Loran-C grid survey. Both the visual aid and position reference systems are defined. Issues associated with grid survey standardization are summarized.

The impact on Loran-C receivers resulting from the phenomenal boom in the microprocessor industry and microprocessor developments is described.

Regulatory and legislative issues do play a major role and an urgent need does exist to examine potential legal problems for restricted waterway use as was achieved by the Coast Guard for the CCZ.

Functions and requirements for radionavigation aids vary depending on harbor, river, seaway dimensions (depth and width of the channel), vessel type and size (cargo, pleasure craft, and several other categories), and equipment performance characteristics associated directly with the electronic navigation system being used. The remainder of this paper focuses on the Loran-C electronic navigation system—a proven system for Coastal Confluence Zone and restricted (harbors, rivers, and seaways) waterway navigation.

SECTION 2
LORAN-C NAVIGATION SYSTEM DEFINITION

Loran-C is a low-frequency, radionavigation aid operating in the radio spectrum of 90 to 110 kHz. Although primarily employed for navigation, transmissions are used for time dissemination, frequency reference, and communications. These other applications of Loran-C do not affect the navigation accuracy. The Loran-C system consists of transmitting stations in groups forming chains—a coverage area specific to each chain, receiving equipment, a propagation medium between transmitters and receiver, and methods of application. At least three transmitter stations make up a chain. One station is designated master while others are called secondary. Chain coverage area is determined by the transmitted power from each station, the geometry of the stations, including the distance between them and their orientation. Figure 1 shows subsystem interconnections for a 3-station chain. Within the coverage area propagation of the Loran-C signal is affected by physical conditions of the earth’s surface and atmosphere which must be considered when using the system.

Natural and manmade noise is added to the signal and must be taken into account. These physical conditions and noise effects can be troublesome and impact Loran-C signals. However, as will be
Figure 1. Loran-C subsystem interconnection for 3-station chain.

demonstrated later, all known error sources can be minimized by using existing error compensation techniques and good receiver design practices. Receivers determine the applied coverage area by their signal processing techniques and can derive position velocity and time information from the transmission. Methods of application provide for conversion of basic signal time of arrival to geographic coordinates, bearing and distance, along track distance and cross error, velocity vectors, and time and frequency reference.

All transmitters in the Loran-C system share the same radio frequency spectrum by sending out a burst of short pulses and then remaining silent for a predetermined period. Each chain within the system has a characteristic repetition interval between the pulse bursts that enables receiving equipment to be uniquely synchronized thereby identifying the chain and stations within the chain being employed.

The U.S. Coast Guard has introduced present day technology into the Loran-C system as follows:
1. Use of solid-state transmitters.
2. Better chain control procedures.
   a. Improved algorithms to provide corrections
   b. Automated unmanned control monitors
   c. Increased number of monitors, and, strategically locating the control monitors.
   d. Use of microcomputers.
3. Using present day grid calibration techniques (position reference* systems and PLAD* type systems) for Loran-C surveys. Charts are now reflecting real-world data rather than pure predictions.
4. Increased redundancy and back-up procedures to provide continuous service.
5. Good chain planning is now resulting in shorter baselines and higher signal-to-noise ratios.
6. Transmitting antenna improvements.
7. Improved communications control between stations.

Results of the above can be stated quantitatively in terms of the traditional gauge of performance (ie, the percentage of usable time the service is available each month). The availability and reliability of Loran-C systems throughout the world continues to improve (Reference 2).

The worldwide Loran-C chains have provided 99.9-percent service (less scheduled outages). Periods of scheduled off-air are linked to the same deficiencies which have plagued Loran-C chains for years (ie, maintenance of the towers, transmitters, and couplers which are part of third- and fourth-generation equipment). The new chains are displaying a significant decrease in off air time due to; the installation of solid state transmitters and dual antenna couplers.

Coverage Area

The coverage area of a chain is usually defined in terms of signal strength and geometry of the transmitting stations with respect to each other, as they will support a specified position accuracy from a Loran-C receiver having certain minimum performance characteristics. Coverage area as defined herein is the term applied on charts prepared by the US National Ocean Survey and the US Defense Mapping Agency and in the Loran-C implementation plan by the Coast Guard.

Loran-C coverage now encompasses over 20-million square miles around the US (including Hawaii and Alaska), Japan, Canada, Pacific Ocean, Atlantic Ocean, Mediterranean Sea, and the Norwegian Sea.

- Red Sea
- Gulf of Aden
- Arabian Sea
- Persian Gulf
- Gulf of Aden
- Jordan
- UAR
- Saudi Arabia
- Portions of Indian Ocean
- Iran
- Egypt
- Sudan
- Ethiopia
- Pakistan
- India
- Mexico
- Europe

Figure 2. Potential areas of expansion.

These new chains are being designed to provide high accuracy (well below 500 feet). Privately-owned Loran-C chains are being considered in the Arctic (northern frontiers of Canada) and other areas. The applications are requiring accuracies better than advertised for the CCS.
...and radio navigation, offshore applications, etc. Techniques such as differential Loran-C and Loran-C mini-chains have been demonstrated and proven.

SECTION 3
LORAN-C ERROR SOURCES

The US Coast Guard has conducted numerous efforts to determine the source, magnitude, and statistics of Loran-C error sources. These error sources are significant in terms of magnitude and frequency of occurrence; however, in each case there is a compensation technique. Fortunately, the Loran-C system has matured over the years and proven compensation techniques have been developed. Additionally, Loran-C today includes the use of high technology and good design practices developed from many years of experience for both Loran-C transmission and user equipment. Estimates for each category of error source will be provided based on a review of tests conducted over the past 10 to 15 years. Then this section will be followed by a description of compensation techniques and good receiver design practices.

Sources of Fluctuations in Transmitted Signals

Predicted transmitted error in terms of timing synchronization, pulse shape control, phase control, and parameter drift will now be estimated.

Timing Synchronization. The time when each pulse is transmitted is controlled by a cesium beam frequency standard that provides stable and accurate time base frequency of 5 MHz and 1 MHz which are used as inputs to the Loran-C timer set. Together these two equipments form a "Loran-C clock." Synchronization of the clocks at all the stations in a chain is accomplished by LPAs (Local Phase Adjustments) on a shortterm basis and frequency and phase adjustments on a long-term basis.

The frequency standard used at Loran-C stations is a Hewlett-Packard Model 5061A cesium beam atomic frequency standard. The setability of these standards is ±10 ppm. In other words the fractional frequency offset between two 5061A standards cannot be reliably reduced below this level. A fractional frequency offset of 7 x 10⁻¹⁴ corresponds to 40-nanosecond gain or loss of time per day between the two clocks. If the frequency of the two clocks remained constant after being set then three 20-nanosecond LPAs per day would correct for this drift and the maximum error during one day would be ±10 ns. However, the frequency of cesium beam oscillators changes with time in an unpredictable manner. In addition there is phase noise and the timer certainly adds some additional phase noise or jitter and the information used to derive wave is corrupted by all the other temporal fluctuations.

In Reference 3 a model of cesium beam standards was developed. The state space equations of this model are given by

\[
\begin{align*}
X_{k+1} &= 1 \Delta t X_k + 0 1 1 0 1 a_k \\
Y_{k+1} &= 0 1 Y_k + 0 1 -8 x_{k} b_k
\end{align*}
\]

where

\[
\{a_k\} = \text{zero mean sequence of uncorrelated random variables on constant variance }
\]

\[
\{b_k\} = \text{corrupting the phase offset }
\]

Based on 3 to 4 years of clock data at the Naval Observatory, values for \(s_0\) of 5 ns and \(s_0^2\) of 8.9 x 10⁻¹⁴ have been determined.

We assume that the noise sequence that drives the frequency offset is actually a series of small jumps occurring once every GRI. Then the value of \(s_0\) would be given by

\[
o_0 = 8.9 \times 10^{-14}/(86400/GRI)^{1/2} = (8.9 \times 10^{-14}/(8.64 \times 10^4/0.0994)^{1/2} = 1 \times 10^{-17}
\]

Thus in the short term most of the fluctuations due to frequency standard instability are due to phase noise since the longer term frequency effects are removed by LPAs. Thus we estimate that the short-term variations are about 5-ns rms. Due to the fact that the timer has a quantization level of 6 ns, we roughly estimate an rms error of about 10 ns due to the Loran-C timer set.

Not all of the fluctuations in the transmitted signal are due to cesium standard instability. The transmitter itself is also a source of signal fluctuation. However, the transmitter is maintained in phase lock with the 5-MHz output of the cesium standard to within ±20 ns by the cycle compensation loop. Plots produced at Loran-C transmitting station Middletown, California (the X-secondary on the West Coast USA Loran-C chain), have been examined that show these slight adjustments (Reference 4). The cycle compensation loop function is recorded continuously and the records are saved. This loop compensates for changing bias levels within the transmitter and changing delay times. It is estimated that because of the fact that the cycle compensation loop only makes 20-ns corrections, fluctuations in the signal due to the transmitter are roughly estimated to be 6 ns.

The rms of the cesium variations, the timer variations, and the transmitter variations yield an equipment error of

\[(10)^2 + (5)^2 + (10)^2\]² = 15 ns

Loran-C Temporal Timing Fluctuations

There are three categories of important error sources that can cause TD Loran-C timing fluctuations. These are: receiver-induced, transmitting equipment, and propagation fluctuations. To determine the magnitude and source of Loran-C transmitting induced timing fluctuations it would be necessary to locate receivers near (50 to 70 km) two or more transmitters in a service area. Through simple addition and subtraction of the significant propagation and equipment fluctuations could be separated as long as the fluctuations are larger than receiver error (typically 25 ns). Specifically this measurement configuration requires the following assumptions:
1. The propagation fluctuations in a signal traveling in one direction over a given baseline are equal to the propagation fluctuations in a signal traveling in the opposite direction.

2. Propagation fluctuations over the short paths are small compared to other timing fluctuations.

3. Receiver-induced fluctuations are small compared to chain and propagation fluctuations.

4. Chain fluctuations are the same for all receivers in the service area of interest (ie, chain fluctuations are not spatially dependent).

We have been able to separate equipment and propagation induced fluctuations.

TD and TOA measurements have been conducted over a large area in the Southern Triad of the West Coast, USA (Reference 5). One of the West Coast experiments was aimed at determining the stability of Loran-C signals. No Loran-C timing fluctuations could be attributed to large atmospheric changes even though numerous cold and warm weather fronts (parallel and perpendicular to the propagation paths) passed over the various propagation paths. The timing fluctuations were typically below 35 ns (rms, standard deviation) each week for 12 weeks. Propagation fluctuations (rms, standard deviations) were below 20 ns and masked by receiver noise. Additionally, two receivers (LC204 and BRM-5 linear) were colocated at Ft. Cronkhite (near San Francisco) monitoring TD and TOA for ten continuous months. The propagation paths ranged between 50 nmi and about 475 nmi. The mean values over the entire 10 months (which included winter—the most severe fronts cross the paths) did not change more than 60 ns and standard deviations were <35 ns. The Ft. Cronkhite measurement site is only 100 miles north of the control monitor (located at Point Pines, CA). This shows good control when the receiver (user) is near the monitor.

The West Coast results show a very stable (Southern Triad) Loran-C system that was not significantly affected by frontal systems passing over the propagation paths. Additionally, the results at Ft. Cronkhite show good control when the user is in the vicinity of the control monitor.

Previous Experiments on the East Coast. The expectations, based on earlier East Coast data collections, that weather phenomena might change the groundwave phase by as much as 0.5 to 1 microsecond or more were not borne out in any of the data collected on the West Coast (USA) and more recently in the Canadian Great Lakes region.

Diurnal fluctuations measured over a propagation path (753 nmi) between Carolina Beach and Dana have revealed 1-microsecond changes in the winter and 0.5-microsecond changes in the summer (Reference 6). The propagation paths in the Great Lakes experiment are as long as the Carolina Beach-Dana path (in both cases typically 550 to 650 nmi). There is a difference in conductivity or about a factor of 2 which should not have a significant impact. These large timing fluctuations have been attributed to the passage of frontal systems. Attempts to explain the above changes in Loran-C TDs based on meteorological (ie, changes in temperature occur the same time as the change in TD) explanations have been attempted by several researchers (References 7, 8, and 9). Even though the Loran-C data compares well with a specific weather parameter (temperature), the fact remains that diurnal TD timing fluctuations are about 4 to 5 times as great as can be explained by simple calculations using expected changes in the index of refraction.

Figures 3 and 4 (taken from Reference 9) show the idealized cold front in terms of H units (variation of the refractive index from unity). In the case of the cold front the change in H would result in a prediction of a rapid change in the primary phase of 100 ns and a change of ~60 ns for secondary phase. This yields a total phase lag increase of 40 ns. From Figure 4 it appears that warm fronts would not produce significant phase changes. It is estimated that shifts in TD's due entirely to atmospheric changes would not exceed 20-ns rms and are probably about 10-ns rms.

Temporal Fluctuations Summary. Tables 3 and 4 show Loran-C temporal timing fluctuations measured over the past 10 to 15 years. Several observations can be made about this tabulation:

1. The largest peak-to-peak temporal fluctuations have occurred in the winter season.

2. These effects in the Northern areas may be related to surface impedance changes (snow, ice, and freezing conditions).

3. These fluctuations are all smaller than reported before approximately 1973 (perhaps improved control, better geometry, shorter baselines, higher SNR, and careful placement of control monitors are impacting these new results).
Table 3. Test results showing temporal fluctuations.

<table>
<thead>
<tr>
<th>Sponsoring Organization</th>
<th>Results</th>
<th>Refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canadian Hydrographic Service</td>
<td>TD fluctuations vary from 0.05 to 0.1 ut peak-to-peak over two to three days</td>
<td>10</td>
</tr>
<tr>
<td>Coos Bay</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crossan/TASC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FM/TSC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Millington and Gamblit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Raven/Nav</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FAM/NSC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>US Coast Guard/Gemini</td>
<td></td>
<td></td>
</tr>
<tr>
<td>US Coast Guard/Seaport</td>
<td></td>
<td></td>
</tr>
<tr>
<td>US Navy/Surry</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Systems Management</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FAM/NSC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>US Coast Guard/Seaport</td>
<td></td>
<td></td>
</tr>
<tr>
<td>US Coast Guard/Institute</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4. Reports produced by the sponsoring/performing organizations have explained these computations reasonably well and have demonstrated the means to compensate for temporal errors.

Spatial Error

The time-of-arrival of a Loran pulse depends on the electrical properties of the earth's surface over which these signals propagate. These electrical properties include the impedance or conductivity of the ground, the roughness or terrain variations of the surface, the refractive index of the atmosphere at the surface, and the lapse rate or rate of change of refractive index with altitude above the surface. Spatial variations of the transmitted Loran signal are primarily influenced by the inhomogeneous surface impedance and by variations in terrain elevation.

Temporal Effects

Temporal effects may be produced by time changes on these spatial features but are more easily influenced by the surface refractive index and the lapse rate of the refractive index of the earth's atmosphere, which are known to change diurnally and with changing weather conditions as discussed earlier.

Spatial Effects Testing. One of the objectives of the Loran-C Signal Analysis Harbor Navigation project conducted by the US Coast Guard was to improve the accuracy and control of Loran-C through a better understanding of Loran-C signal characteristics. An important step in achieving this objective was to better define the predictability of the Loran-C signal phase and amplitude characteristics and to explain differences between observed time differences (TDO) and predicted TDOs using current prediction and calibration techniques with emphasis on terrain and surface impedance behavior.

Four groundwave propagation prediction models or techniques have been reviewed and tested against each other and against a carefully controlled experimental data base by Gambill and Schwartz (Reference 11). This work has been instrumental in understanding the behavior of spatial effects on Loran-C. Therefore, the prediction models used to explain the experimental results will be discussed. The four techniques are:

1. Homogeneous Spherical Earth—A well-researched technique which includes comprehensive published literature.
2. Millington's—A semi-empirical technique currently used for system calibration.
3. Watt's Multisegment Spherical Earth—A theoretical model to account for inhomogeneous earth.
4. Integral Equation Solution—A computer program to calculate signals over irregular inhomogeneous terrain.

Paragraphs below include comparisons between Millington and Integral Equation predictions, and the measured data base to better explain the significance of spatial and surface impedance effects on Loran-C signals. Comparisons have also been conducted using the flat-earth homogeneous spherical earth, and Watt's multiple segment techniques by Gambill and Schwartz in Reference 11 will not be shown here.

Experimental Configuration. Measurements of phase time difference (TDO) and signal arrival times (TOA) were taken at eight sites over a period of 60 days, as nearly as possible along the Yankee to San Francisco Harbor path, between Searchlight, NV, and Ft. Cronkhite, CA. The main reason for these measurements was to complete a comprehensive experimental data base for comparison with predicted results from prediction techniques previously mentioned. Analysis and interpretation of the differences between measured and predicted data were to lend to a better understanding of Loran-C signal characteristics.

The Searchlight/Ft. Cronkhite path was selected for the experiment because of its extremely variable terrain and demonstrable history of short-term weather fluctuations. The assumption was that irregular terrain and variable surface impedance along the path would produce experimental results that differed significantly from simple model predictions and therefore would provide a data base for thoroughly testing models that account for irregular terrain and impedance.

It was also expected that weather variations typical of the time of year might occur during data collection periods along the path. If large variations in measured data occurred concurrently with significant weather phenomena, then the data could provide additional guidance to improve models of weather produced variations in the prediction codes.

Figure 5 identifies the nearest town where data collection sites were established to take TDO measurements. The figure is not drawn to scale, but is intended to show the approximate, relative off-set distance of these locations from the geodesic. The precise (receiver) antenna locations were used to compute predictions. The latitude and longitude in WGS-72 coordinates and the distance from each site to the Searchlight transmitter can be found in Reference 13.

Before proceeding with the experimental results a discussion of modeling techniques used to analyze the test data is in order.

Model Intercomparison.

Classical Techniques. This idealized technique will not produce phase delay estimates with useful accuracy for irregular paths (such as defined in Reference 11). However, because
The classical technique is embedded in other techniques, the numerical procedures should be considered. The general classical theory solution results in an infinite series representation for the complex groundwave loss function. The series converges rapidly for long paths but requires many terms for paths less than 100 km in length. Two short-path approximations are available, one for high surface impedance and the other for low surface impedance.

The evaluation of the classical theory determined the required number of terms in the series for a specified path length and level-of-accuracy, and also defined approximate distances to switch from the accurate series solution to the short-distance approximations (Reference 11).

Millington's Technique Compared to Wait's Multiple Segment Techniques (HULSEG). Both these techniques account for inhomogeneous impedance along the path. The results produced by these two techniques have been compared for several hypothetical cases. One example is shown in Figure 6 for a five-segment path. The results are typical of results obtained for a number of other cases (Reference 11). As a result of this comparison, we concluded that the prediction differences were small compared to errors caused by the neglect of terrain variations.

<table>
<thead>
<tr>
<th>Sponsoring/Performing Organizations</th>
<th>Completion Date</th>
<th>Loran-C Chain</th>
<th>Number of Sites</th>
<th>Test Duration</th>
<th>Measurements</th>
<th>Location</th>
<th>Data Sampling Interval</th>
<th>Data Sample Size (Approx.)</th>
<th>Application</th>
<th>Data Quality (used)</th>
<th>Motivation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canadian Hydrographic Service/Kanem Tempo</td>
<td>1978</td>
<td>Northeast US</td>
<td>3</td>
<td>3 wk</td>
<td>TDM, TDX</td>
<td>Great Lakes Region</td>
<td>Oct 80 to Nov 80</td>
<td>Great Lakes Navigation</td>
<td>0.02</td>
<td>Temporal effects and relation to chain control</td>
<td></td>
</tr>
<tr>
<td>US Coast Guard/Kanem Tempo</td>
<td>1978</td>
<td>US West Coast</td>
<td>10</td>
<td>10 mo</td>
<td>TDX, TDY</td>
<td>West Coast (Southern Tried)</td>
<td>Apr 77 to May 78</td>
<td>Harbor Navigation</td>
<td>0.02</td>
<td>Temporal fluctuation evaluation and means to compensate</td>
<td></td>
</tr>
<tr>
<td>US Coast Guard/Magnavox</td>
<td>1977</td>
<td>US East Coast</td>
<td>3</td>
<td>3 mo</td>
<td>TOAM</td>
<td>Fort Wayne, IN</td>
<td>Apr 77 to May 78</td>
<td>Loran-C System Support</td>
<td>0.02</td>
<td>Cause of Nautical TD variations</td>
<td></td>
</tr>
<tr>
<td>US Coast Guard/Internevi</td>
<td>1973</td>
<td>US East Coast</td>
<td>8</td>
<td>2 yr</td>
<td>TDX, TDX</td>
<td>Delaware River</td>
<td>Jul 70 to Aug 73</td>
<td>Harbor Navigation</td>
<td>0.02</td>
<td>Differential Loran-C evaluation</td>
<td></td>
</tr>
<tr>
<td>US Navy/Sperry Systems Management</td>
<td>1971</td>
<td>US East Coast</td>
<td>3</td>
<td>1 yr</td>
<td>TDX, TDX</td>
<td>Nantucket, MA</td>
<td>Oct 67 to Jan 68</td>
<td>Strategic Submarine Navigation</td>
<td>0.01</td>
<td>Potential improvement afforded by Propagation Corrections</td>
<td></td>
</tr>
<tr>
<td>FAA/TSO</td>
<td>1980</td>
<td>Northeast US</td>
<td>3</td>
<td>14 mo</td>
<td>TDM, TDX, TDX</td>
<td>Burlington, Newport, &amp; Rutland, VT</td>
<td>Oct 70 to Jan 71</td>
<td>Civil A/C Navigation</td>
<td>0.1</td>
<td>Seasonal, Diurnal variations in TD grid size</td>
<td></td>
</tr>
<tr>
<td>US Coast Guard/TASC</td>
<td>1980</td>
<td>St Marys River</td>
<td>3</td>
<td>1 yr</td>
<td>TDX, TDX, TDX</td>
<td>St Marys</td>
<td>May 70 to May 80</td>
<td>Ore Carrier Navigation of St Marys</td>
<td>0.02</td>
<td>Month-to-Month TD variations</td>
<td></td>
</tr>
</tbody>
</table>

Figure 5. Propagation path data collection sites relative to the geodetic.

Figure 6. Comparison of HULSEG and Millington for a five-segment path (sea to land).

Millington's Technique Compared to the Integral Equation Solution. Results from Millington's technique and the integral equation technique have been compared for two cases: one where terrain effects are important, and one where terrain effects are suppressed. These comparisons were made during the process of comparing experimental and predicted results and are discussed later.

Data Preparation. All methods considered require an accurate definition of geodetic path length as input. Also, all methods currently
use a single value for the effective earth radius along the path. The classical approach requires a single value or surface impedance for the entire path. Millington's technique and MULSEG require surface impedance data for as many segments as are required to account for inhomogeneity along the path. The integral equation requires inhomogeneous impedance data for segments along the path and terrain variations relative to a smooth spherical reference.

Path Length. For accurate prediction, path length needs to be determined within a few tens of meters. Phase prediction errors resulting from path length error are approximately 3.3 ns per meter. Accurate site position surveys and geodetic distance calculations using Sodano's technique provided path length accuracy that should limit the phase error to less than 10 ns in this experiment.

Effective Earth Radius. An effective earth radius, $a$, usually larger than the earth's actual radius, $a_0$, is used to approximately account for the refractive effects of the lower atmosphere. Approximate relationships defining the effective radius in terms of surface refractive index are provided in Reference 19 and elsewhere. A ratio of $a$ to $a_0$ of 0.85 was used in the calculations reported here.

Surface Impedance. Crude estimates of surface impedance can be obtained from existing surface conductivity maps or from maps providing general surface and topographic features. These estimates are usually adequate for Millington's technique, where the typical application is to adjust original estimates of surface impedance to match selected experimental data before using these surface impedance values to make predictions.

To make more accurate predictions, surface impedance is estimated using best available data defining geophysical and electrical properties of surface and subsurface layers. The availability and detail of these data depend strongly on location.

Figure 7 shows (thin lines) the best estimate of the surface impedance along the propagation path, using geophysical data from the US Geological Survey and the California and Nevada Bureau of Mines. Data were obtained at various locations for one, two, three, or four layers and processed using a multilayer surface impedance model. The details of the data and processing are provided in Reference 19. Figure 7 shows amplitude data only. The surface impedance phase in all cases was very close to 45 degrees.

Also shown on Figure 7 (heavy lines) is a twelve-segment approximation that was used later in comparing Millington's technique calculations to the integral equation results.

Terrain Data. Terrain data are required only for the integral equation approach. For many areas of the world, digitized data are available that provide more detailed definition of terrain variation than can be used in the computations. Proper automation of data search and smoothing routines can reduce this data preparation task to a reasonable computer effort.

In the experiment described here, digitized data were not available over the entire path and terrain variations were obtained from the most detailed topographic maps available. Digitizing the data from the maps and subsequent verification of the data took 2 to 3 manweeks. Data preparation for the integral equation technique can be a formidable task unless a digitized data base and associated software to scan and select appropriate data are available.

Figure 7. Approximation to the surface impedance for a Millington calculation.

The original data defining terrain along the propagation path are plotted in Figure 8. The detail shown in the figure is more than is required in the integral equation and some data smoothing was applied. Phase predictions shown later used terrain data that were smoothed by averaging data over a 3-km interval.

Comparison Between Predictions and Experimental Data. One primary goal of this effort was to compare pure predictions (i.e., no tuning of input data using measured phase or amplitude data) with measured data. Figure 8 shows the predicted secondary phase (signal phase lag in excess of the free space phase lag) for the integral equation results and Millington's technique results. The integral equation results were obtained using the detailed impedance estimates shown in Figure 7 and the terrain variations shown in Figure 8 (after smoothing). The Millington results were obtained using the twelve-segment approximation to the detailed impedance estimates shown on Figure 7.

Figure 8. Original worst case path terrain data.
The experimental results are shown on Figure 9 by the bars above the measurement sites. The length of the bar indicates approximate bounds on experimental error as defined earlier. Since only relative (not absolute) secondary measurements were obtained, a reference point for the data must be selected. In this comparison we chose to equate predicted and measured secondary phase at Tecopa, the site nearest the searchlight. The origin could also be selected to minimize mean rms difference between measured and predicted values. However, it can be observed from Figure 9 that no origin selection can be made that will remove all large prediction and measurement differences. The maximum difference as shown on the figure between integral equation predictions and measurements is about 6.5 microsecond.

It can also be noted from Figure 9 that the integral equation results produce better agreement with the measured data than Hillington's results (i.e., inclusion of the terrain effects provides an apparent improvement).

To verify that the differences between the Hillington and integral equation predictions are due to terrain effects, a second calculation was performed with the integral equation, but with terrain effects suppressed. These results, with Hillington's technique results repeated, are shown in Figure 10. The agreement between predictions is very good and provides confidence in the computational models. The results provide further verification that Hillington's technique is useful when terrain effects are minimal.

Additional Comparison. Two additional sets of calculations were performed to provide a crude measure of sensitivity of predicted versus measurement difference to input parameters. We believe that terrain data is adequately defined and input value errors would most likely be the surface impedance definition. Figure 11 shows the original integral equation predictions, the measurements, and a new integral equation prediction made with the conductivity of all segments along the path decreased by a factor of 2 (this increases the surface impedance by approximately a factor of 4). Note that the two predictions now almost bracket the measured data. It is clear that selective adjustment of the conductivity of different segments by a factor of approximately 2 could produce good agreement between measured and predicted values. These adjustments were not performed because of the computer costs for repetitive calculations with the integral equation program.

Also shown on Figure 11 by the circle-in-circles are results obtained with Millington's technique with the impedance of the twelve-segment approximation adjusted to approximately minimize the rms difference between Millington's predictions and measurements. Impedance values had to be generally increased to compensate for terrain effects and/or errors in the original impedance values. The results obtained by varying the impedance values indicate that the impedance values need to be known much better than a factor of 2 for accurate (100 ns) predictions over long overland paths.

Clearly it has been demonstrated that deterministic prediction techniques alone are not adequate for precise navigation. However, a careful balance between predictions and measured data (empirical models) may have some merit.

Predicted Weather Effects. Except for one isolated incident, no significant weather-produced illusions were observed during the West Coast experiments. As a result, little emphasis was placed on prediction of weather effects. One
example of predicted weather-produced fluctuations was produced using surface weather data from near Reno (Nev., NV) near the master transmitter. The atmospheric pressure in millibars, the temperature, and dew point temperature were taken at Reno. These values were used to compute the surface refractive index and a corresponding value of effective earth radius. Phase fluctuations, which are the sum of the primary and secondary phase fluctuations, were computed for path lengths of 100, 300, 500, and 700 km. The predicted phase fluctuations were small, showing a maximum value of 15 ns. These values agree in order of magnitude with the experimental observations during the Loran-C Signal Analysis West Coast Experiment with one exception, where it is postulated that a larger change was produced as a result of precipitation-induced surface impedance changes. A discussion of this exceptional case was provided in Reference 11.

Conclusions. Detailed conclusions and recommendations are provided in Reference 11. A summary of the discussion in Reference 11 is provided below.

1. For a smooth, inhomogeneous earth, Hillington's technique andWAIT's multiple segment technique produce nearly identical results. Therefore, Hillington's technique should be used in preference to WAIT's because of its greater simplicity and shorter running time.

2. Hillington's technique and the integral equation technique give nearly identical results for a path with highly inhomogeneous impedance when the terrain variations are suppressed for the integral equation calculations.

3. The integral equation calculations show that both terrain and surface impedance variations are important in predicting secondary phase. Our numerical computations indicated that the terrain can be defined with sufficient accuracy with data points spaced at approximately an integration step size of 1 km. Our experimental observations and predictions indicate that to obtain prediction accuracy on the order of 100 ns or better, the surface impedance uncertainty must be much less than a factor of 4 for overland paths.

4. The effect of terrain variations (in this case elevations greater than one wavelength above the mean geoid) was to increase the secondary phase. Thus, matching calibration data with impedance variations alone requires higher than actual impedance values to compensate for the terrain effects.

5. Data preparation for the integral equation method is a formidable task. The hand preparation of the data for the worst-case path required an effort of about 1 man-month. Digital terrain data tapes for the path were not available. Hand preparation of data for a coverage area would not be practical.

6. The highly variable terrain and surface impedance along the worst-case path and the differences between predicted and measured values indicate the need for more closely spaced measurement points to adequately calibrate the changes along the overland portion of the path from an experimental standpoint. On the other hand, measurements made beyond the region of major terrain variations can be used to compensate for the integrated effects of a data of terrain-induced fluctuations. A good example is the match between measurements and predictions at Ft. Cronkhite shown in Figure 9. Ft. Cronkhite is the last measurement point along the path and is located in San Francisco Harbor.

Spatial Effects Measured from Previous Experiments. Tables 5 and 6 provide a summary of spatial test data collected over the past 10 to 15 years. Several interesting points can be made about Tables 5 and 6. First the propagation path experiment previously discussed.

1. Present conductivity maps are not adequate for chart preparation using predictions alone.

2. Caution must be exercised by the user when purchasing Loran-C receiver systems that claim to include propagation corrections if these corrections are prepared using conductivity values from outdated or inaccurate maps.

3. Effects of terrain elevation are pronounced.

4. Surface impedance is time varying (i.e., significant TD variations occur with extremes of dry-to-freezing conditions, precipitation, etc). Loran-C surveys do not account for these seasonal changes. Such surveys only include terrain elevation and surface impedance is reflected in the measurement for an instantaneous period of time.

Compensation techniques do exist to account for all of the above.

Atmospheric and Manmade Noise. There are a number of types of noise that may influence Loran-C signal reception, although, usually only one type will predominate. Broadly, the noise can be divided into two categories depending on whether it originates in the receiving system or externally to the antenna. The internal noise is due to antenna and transmission line losses, or is generated in the receiver itself. It has the characteristics of thermal noise and, in many cases, its effects on signal reception can be determined mathematically with a high degree of precision. External noise can be divided into several types each having its own characteristics. The most usual types are of atmospheric, galactic, and manmade origin.

In the low frequency 100 kHz part of the spectrum noise is developed almost entirely from electrical discharges in the atmosphere and manmade sources, such as power generation equipment. The strength of the Loran-C signal is stable, so it is this electrical background interference that varies with weather.

Atmospheric noise is generally characterized by short pulses with random recurrence superimposed upon a background of random noise. Averaging these short pulses of noise power over several minutes yields average values that are nearly constant during a given hour.

The noise can be better understood by examining the model shown in Figure 12. The model consists of the impulsive disturbances, \( I(t) \); Gaussian noise, \( W(t) \); and the desired signal, \( S(t) \). The impulsive-noise atmospheric noise model is characterized by a randomly occurring impulse of the form

\[ I(t) = \sum_{n} I_{n} \delta(t) \]

where \( I \) is the area under the signal curve \( t \). \( \delta(t) \) is the impulse of the noise, \( I_{n} \) is a random variable with equal likelihood of being \( I \), and \( n \) is a normal
Table 5. Spatial test information.

<table>
<thead>
<tr>
<th>Sponsoring/Performing Organization</th>
<th>Completion Date</th>
<th>Loran-C Region</th>
<th>Number of Sites</th>
<th>Coverage (km)</th>
<th>Spacing (km)</th>
<th>Application</th>
<th>Data Quality (ms)</th>
<th>Motivation</th>
</tr>
</thead>
<tbody>
<tr>
<td>US Coast Guard/TASC</td>
<td>1979</td>
<td>US West Coast</td>
<td>27</td>
<td>2500</td>
<td>20-100</td>
<td>SSC Navigation</td>
<td>0.1 - 0.2</td>
<td>Loran-C chart errors</td>
</tr>
<tr>
<td>US Air Force/MITRE</td>
<td>1979</td>
<td>Southeast US</td>
<td>125</td>
<td>80 x 140</td>
<td>10</td>
<td>A/C navigation using ANN-101 RCVR</td>
<td>0.1 - 0.2</td>
<td>Grid warpage caused by land paths</td>
</tr>
<tr>
<td>US Coast Guard/TASC</td>
<td>1978</td>
<td>St. Marys River</td>
<td>25</td>
<td>120</td>
<td>4</td>
<td>Acoustic navigation of St Marys River</td>
<td>0.2</td>
<td>Chain calibration</td>
</tr>
<tr>
<td>Canadian Hydrographic Service/Kaman Tempoe</td>
<td>1978</td>
<td>Northeast US</td>
<td>10</td>
<td>1000</td>
<td>200</td>
<td>Great Lakes Navigation</td>
<td>0.1 - 0.2</td>
<td>Conductivity map improvement</td>
</tr>
<tr>
<td>US Coast Guard/Kaman Tempoe</td>
<td>1978</td>
<td>US West Coast</td>
<td>8 on radial</td>
<td>800</td>
<td>100-1000</td>
<td>4 km in harbor</td>
<td>0.07 - 0.2</td>
<td>Grid Prediction evaluation</td>
</tr>
<tr>
<td>Canadian Hydrographic Service/Kaman Tempoe</td>
<td>1977</td>
<td>Canadian West Coast</td>
<td>200</td>
<td>3000</td>
<td>30-1000</td>
<td>4 km in harbor</td>
<td>0.5 offshore</td>
<td>Local grid warpage</td>
</tr>
<tr>
<td>US Army/Same</td>
<td>1975</td>
<td>US East Coast</td>
<td>61</td>
<td>1000</td>
<td>10</td>
<td>Terrestrial navigation using man-pack RCVR</td>
<td>0.2</td>
<td>Coordinate conversion model verification</td>
</tr>
<tr>
<td>US Army/Same</td>
<td>1973</td>
<td>US East Coast</td>
<td>54</td>
<td>3x8</td>
<td>0.5</td>
<td>Terrestrial navigation using man-pack RCVR</td>
<td>0.1</td>
<td>Coastal-induced anomalies</td>
</tr>
<tr>
<td>Commerce Dept./Same</td>
<td>1972</td>
<td>US East Coast</td>
<td>74</td>
<td>1000</td>
<td>5</td>
<td>Basic propagation research</td>
<td>0.1</td>
<td>Local grid warpage</td>
</tr>
</tbody>
</table>

*Measured site-to-site change in TOA.

Table 6. Spatial test results.

<table>
<thead>
<tr>
<th>Sponsoring/Performing Organization</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>US Coast Guard/TASC</td>
<td>Cz partly reduces Cn 1 to 2 in TOA anomaly.</td>
</tr>
<tr>
<td>US Air Force/MITRE</td>
<td>Marine wavemage, waveage independent of altitude below 100 ft.</td>
</tr>
<tr>
<td>US Coast Guard/TASC</td>
<td>Conductivity is nonuniform in 70 km x 130 km coverage area.</td>
</tr>
<tr>
<td>Canadian Hydrographic Service/Kaman Tempoe</td>
<td>Conductivity map is incorrect by factor of 2 to 10 in certain regions.</td>
</tr>
<tr>
<td>US Coast Guard/Kaman Tempoe</td>
<td>Accurate prediction requires terrain and conductivity data. TO residuals changes rapidly at land-sea interface.</td>
</tr>
<tr>
<td>Canadian Hydrographic Service/Same</td>
<td>Effects of land-sea interface and mountains are pronounced.</td>
</tr>
<tr>
<td>US Army/Same</td>
<td>TO residuals after large-area calibration of linear model are 0.3 on average.</td>
</tr>
<tr>
<td>US Army/Same</td>
<td>TO anomaly is observed at sea/land interface.</td>
</tr>
</tbody>
</table>

Figure 12. Model of signal and noise at the input to Loran-C receiver.

random variable with mean $\mu$ and variance $\sigma^2$. The subscript $k$ refers to a particular cycle being examined (given that the impulse occurred in that cycle). The impulse occurrence rate $\lambda$ is the range 30 to 2000 impulses per second, and the occurrences are assumed governed by a Poisson distribution.

For the Loran-C model carrier, the quantity $V_{\text{cm}}$ (median value of the voltage deviation as tabulated in Reference 27) can be related to the noise model by

$$V_{\text{cm}} = 20 \log_{10} \left( \exp \left( \frac{\sigma_k^2}{2} \right) \right),$$

where $V_{\text{cm}}$ is given in dB. It can be shown that

$$E_n = 20 \log_{10} \left( \frac{\nu}{0.0033} \right) \exp \left( \nu_k + \sigma_k^2 \right),$$

or

$$E_n = F \cdot 95.5 + 20 \log_{10} \left( \frac{\nu}{B} \right) + \log_{10} B (\mu V / m),$$

where $E_n$ is the rms noise field strength, $F$ is called the noise parameter (effective noise factor that results from the external noise power available from a loss-free antenna where $F = 10^{-1}$), $\nu$ is the frequency of the measurement in Hz ($\nu < 10^3$), and $B$ is the bandwidth (20 kHz). In the noise model, values of $\sigma_k$ are obtained for $\nu$ and $\sigma_k$, Table 7 summarizes the results obtained from the model for the San Francisco harbor area. The model can be executed for any desired location worldwide. The table indicates that the median noise values, $\nu$, differ the greatest between summer and winter and expected (the difference is approximately 7 to 17 dB) depending on the time block. Table 7 shows a substantial change for time of day for the three time blocks shown for each season.

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Table 7. Noise results for San Francisco harbor (carrier frequency 100 kHz and bandwidth of 20 kHz).

<table>
<thead>
<tr>
<th>Season</th>
<th>Time</th>
<th>Fm (kHz)</th>
<th>Flm (kHz)</th>
<th>Lm (dB)</th>
<th>Ln (dB)</th>
<th>Aver. Lower</th>
<th>Upper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>0800-1200</td>
<td>10.5</td>
<td>7.5</td>
<td>1.58</td>
<td>1.65</td>
<td>12.38</td>
<td>12.61</td>
</tr>
<tr>
<td></td>
<td>1500-1530</td>
<td>10.5</td>
<td>7.5</td>
<td>1.58</td>
<td>1.65</td>
<td>12.38</td>
<td>12.61</td>
</tr>
<tr>
<td></td>
<td>1600-1630</td>
<td>10.5</td>
<td>7.5</td>
<td>1.58</td>
<td>1.65</td>
<td>12.38</td>
<td>12.61</td>
</tr>
<tr>
<td>Spring</td>
<td>0800-1200</td>
<td>10.5</td>
<td>7.5</td>
<td>1.58</td>
<td>1.65</td>
<td>12.38</td>
<td>12.61</td>
</tr>
<tr>
<td></td>
<td>1500-1530</td>
<td>10.5</td>
<td>7.5</td>
<td>1.58</td>
<td>1.65</td>
<td>12.38</td>
<td>12.61</td>
</tr>
<tr>
<td></td>
<td>1600-1630</td>
<td>10.5</td>
<td>7.5</td>
<td>1.58</td>
<td>1.65</td>
<td>12.38</td>
<td>12.61</td>
</tr>
<tr>
<td>Summer</td>
<td>0800-1200</td>
<td>10.5</td>
<td>7.5</td>
<td>1.58</td>
<td>1.65</td>
<td>12.38</td>
<td>12.61</td>
</tr>
<tr>
<td></td>
<td>1500-1530</td>
<td>10.5</td>
<td>7.5</td>
<td>1.58</td>
<td>1.65</td>
<td>12.38</td>
<td>12.61</td>
</tr>
<tr>
<td></td>
<td>1600-1630</td>
<td>10.5</td>
<td>7.5</td>
<td>1.58</td>
<td>1.65</td>
<td>12.38</td>
<td>12.61</td>
</tr>
<tr>
<td>Fall</td>
<td>0800-1200</td>
<td>10.5</td>
<td>7.5</td>
<td>1.58</td>
<td>1.65</td>
<td>12.38</td>
<td>12.61</td>
</tr>
<tr>
<td></td>
<td>1500-1530</td>
<td>10.5</td>
<td>7.5</td>
<td>1.58</td>
<td>1.65</td>
<td>12.38</td>
<td>12.61</td>
</tr>
<tr>
<td></td>
<td>1600-1630</td>
<td>10.5</td>
<td>7.5</td>
<td>1.58</td>
<td>1.65</td>
<td>12.38</td>
<td>12.61</td>
</tr>
</tbody>
</table>

Atmospheric noise, manmade noise, and spectral interference can be most troublesome sources of degradation when using Loran-C. Section 4 details good design practices that can minimize noise.

Spectral interference

In the frequency bands 60 to 90 kHz and 100 to 130 kHz there are broadcast stations that operate with keyed CW, AM, PSK, and FSK modulation schemes. Several of these stations are located near coastlines and also in the vicinity of the Great Lakes region and are used for long-range communications. These transmitters have radiated powers in excess of 100 kW. Users of Loran-C in the vicinity of one or more of these sources must be able to cope effectively with the interference. Not all spectral interference is from outside the 90- to 110-KHz band. Both skywave interference and cross rate interference sources also adversely affect receiver performance.

Data Summary. It is customary to further classify spectral interference by frequency band location of the interference relative to the 90- to 110-KHz band. The classifications are as follows:

1. In-Band Interference: Interference whose carrier frequency lies in the band 90 to 110 kHz.
2. Near-Band Interference: Interference whose carrier frequency lies in the frequency bands 70 to 90 kHz and 110 to 130 kHz.
3. Out-of-band Interference: Interference whose carrier frequency lies in the frequency bands below 70 kHz or above 130 kHz.

Special tests were conducted in the field (Reference 4) to observe interfering signals, to determine the signal acquisition time of a typical user receiver throughout the Great Lakes region, and to monitor receiver operation. Figure 12 illustrates sites along each radial where measurements occurred. The site code from this figure is used in Table 8 to identify locations. Paragraphs that follow include results of each of the above.

During the field experiment several interfering frequencies were detected using a spectrum analyzer and are summarized in Table 8. The input to the analyzer was from an LC104 receiver (RF output jack). The notchers were not used on the receiver during the tests that resulted in the data displayed in Table 8. Table 8 shows all the frequencies that were scaled from spectrum analyzer photographs. Some general comments regarding Table 8.

Table 8. Frequencies scaled from polaroid photographs.

<table>
<thead>
<tr>
<th>Date</th>
<th>Measurement Site</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Flite (40)</td>
<td>100 kHz</td>
</tr>
<tr>
<td>B</td>
<td>Wallencott (42)</td>
<td>100 kHz</td>
</tr>
<tr>
<td>C</td>
<td>Port Hope (31)</td>
<td>100 kHz</td>
</tr>
<tr>
<td>D</td>
<td>Pesho Lake (32)</td>
<td>100 kHz</td>
</tr>
<tr>
<td>E</td>
<td>Ft. Frances (51)</td>
<td>100 kHz</td>
</tr>
<tr>
<td>F</td>
<td>Ash Lake (59)</td>
<td>100 kHz</td>
</tr>
</tbody>
</table>

1. The Eastern portion of the Great Lakes is affected by frequencies of 71.2, 122, and 60 kHz.
2. The Northwestern portion of the Great Lakes region is affected by several frequencies but when examining the photographs the effects are not nearly as severe as the Eastern Great Lakes region.
3. Ash Lake had an unusual amount of interference as compared to other sites. Again, this may be due to the randomness of broadcast times from these interfering transmitters rather than anything unique about the Ash Lake site location.

Interference from out-of-band signals was also examined in the Chesapeake Bay. One source (an 88-kHz, high-power, narrow-band transmitter located in Annapolis, MD) reduced the receiver's sensitivity by several dBs. When properly adjusted, successful operation occurred in the presence of this interfering signal as long as the vessel was greater than approximately a few hundred meters away from the transmitter.

Bench tests indicated that the narrow-band notch filters (that are manually controlled) did not adversely affect the receiver's accuracy or ECD characteristics if they were adjusted outside the Loran-C band (below 90 or above 110 kHz).
SECTION 4

AUGMENTATION TECHNIQUES TO

COMPENSATE FOR ERRORS

The previous section has defined and provided quantitative information for the following Loran-C error sources:

a. Transmitter
b. Temporal (including refractive index and surface impedance)
c. Noise
d. Frequency interference
e. Spatial.

Some of the above error sources vary with geographical location and time; while others are dependent on equipment design or geometry. The approach in this section is to define compensation techniques that are presently available to minimize these error sources.

Differential Loran-C to Compensate for Temporal Errors

Loran-C signals are monitored at a fixed site, and the TD (Time Difference) can be compared with a reference TD for the monitor site. A correction can then be computed and transmitted to users. This technique, called Differential Loran-C, whereby realtime corrections are applied to Loran-C TD readings has been shown to provide improved accuracy (Reference 13), and this technique shows promise for marine navigation in the harbor and harbor entrance (HHI) areas (Reference 13).

A general differential Loran-C system is shown in Figure 13. The important features of this system are:

- Multiple monitors.
- Use of loran-C control monitor information.
- Use of an estimator/predictor.
- Improved correction algorithm.
- Multiple communication links.

![Figure 13. Differential Loran-C System](image)

These features all represent departures from the traditional differential concept and are expected to improve system performance.

The central idea of differential concept is to estimate the errors in user time differences and then transmit the error estimates to the user so that he may correct his TD readings and hence obtain improved accuracy.

Before installing a differential Loran-C there are several factors that must be considered during the design phase. These are summarized below. Standard covariance analysis (Reference 28) should be used to investigate the performance sensitivity to correction update, estimator complexity, SEA, modeling errors, and estimator/predictor design parameters such as weighting factors. Simulation using existing Loran-C system models should be used to determine performance versus the following:

- Number of monitors
- Orientation and spacing of monitors
- Characteristics of user and monitor receivers
- Location of control monitor
- Availability or control monitor data
- Length of sample time for computing monitor reference TD means.

The impact of the communication channels should be analyzed separately using standard techniques for communication systems. The more important parameters are

- Size of differential coverage area
- Frequency of correction
- Magnitude and precision of correction
- Site and frequency choice
- Modulation and error correction
- Number of monitors.

Communication channel requirements should be defined and communication channels postulated. Bit error rates should be determined and input to the system simulation and their impact on system performance evaluated. Validation tests to verify the above should be conducted prior to installation and operation.

Review of Past Work and Performance Expected

The concept of using a monitor receiver to correct a user receiver was originally proposed by the Naval Electronics Laboratory (NEL) for the Omega radio navigation system and was called differential Omega (Reference 29). The purpose of the original concept was to estimate the average phase velocity to a monitor receiver and then determine a phase velocity correction factor that would be used to correct published charts and tables. These correction factors would then be broadcast to the Omega users in the vicinity of the monitor receiver. Experiments were performed where the difference between the charted reading of the monitor location and the monitor receiver reading was used as a correction factor.

One very significant observation was made concerning the experiments. Three stations, Aldra, Haiku, and Trinidad, were tracked. The station at Aldra had only been in service a very short time and was not properly synchronized. As might be expected, the error in user position from the use of charts for the Aldra-Trinidad pair was very large. However, the error in user position after the differential correction factor was applied was quite small. In other words, differential Omega was not affected by improper system synchronization.

In the summer of 1973 an experiment was conducted in the Delaware Bay area to collect data...
for analyzing the potential of Loran-C for high-accuracy, all-weather navigation in river, harbor, and harbor entrance environments (Reference 1). The differential Loran-C correction factor used in this study was somewhat different than the differential Omega correction factor described above. Instead of taking the difference between the actual monitor TD reading and the charted value of the TD, the correction factor was computed by differencing the actual TD from its long-term sample mean. Thus the differential concept was being applied to the repeatable mode instead of to the normal mode of system operation. Using this concept one does not need to know the monitor location at all. All that is required is that the monitor receiver be in operation long enough to compute a long-term sample mean.

The experiment specifically examined the improvement versus distance and improvement versus monitor TD averaging (correction update rate). The long-term sample means were computed using 1 week of data. The significant results of this experiment were as follows:

- Maximum improvement was obtained for a 100-second update interval (the data sampling interval) with little or no improvement for update intervals longer than 15 minutes. The corrections for the longer intervals were based on TD averages over the interval preceding the correction.
- Signals with high SNR showed the most improvement.
- There was no apparent tendency for differential errors to increase with increasing distance from the monitor (maximum separation was 69 miles).
- Errors attributed to differential changes in path transmission times were insignificant.

A second differential Loran-C study (Reference 3) was commissioned by the Coast Guard as part of the Loran-C Signal Analysis project. Its purpose was to provide necessary data for the evaluation of the potential use of Loran-C for high accuracy, all-weather navigation in a harbor, harbor entrance (HHE) environment. Four modes of system operation were considered.

1. Absolute location
2. Relative location
3. Differentially augmented absolute location
4. Differentially augmented relative location.

To provide an assessment of the absolute mode, a means of converting TDs to absolute geodetic position is necessary. The mariner normally performs this conversion with the aid of nautical charts which have Loran-C grid lines drawn on them. However, there are no such published charts for the San Francisco harbor, and an intermediate step to provide a calibrated grid for the harbor is necessary.

The specific objectives of this experiment were thus to provide a calibrated grid of the San Francisco harbor and estimates of the spatial distortion, and obtain the data required to assess the performance of Loran-C in the above mentioned modes.

To accomplish these objectives, a series of experimental deployments were planned which included both land site and vessel measurements. The measurements began 8 April and were terminated 9 May 1978.

The harbor experiment was divided into three phases: (1) a planning phase; (2) a land site measurement phase at sites around the periphery of the harbor and on Treasure, Angel, and Alcatraz Islands; and (3) a vessel measurement phase conducted aboard the USCG research vessel Polaris. Figure 14 shows the location of the 13 land sites and an outline of the areas covered by the

Figure 14. San Francisco Harbor test area.
L = latitude of user position
\lambda = longitude of user position
E_x = emission delay for X-ray (\mu s)
E_y = emission delay for Yankee (\mu s)
V_{MX} = average phase velocity from Master for TDX (km/\mu s)
V_{M Y} = average phase velocity from Master for TUY* (km/\mu s)
V_{X} = average phase velocity from X-ray (km/\mu s)
V_{Y} = average phase velocity from Yankee (km/\mu s)
\Delta_d(L, \lambda) = geodetic distance to Master (km)
\Delta_d(L, \lambda) = geodetic distance to X-ray (km)
\Delta_d(L, \lambda) = geodetic distance to Yankee (km).

Note that TUY measurements at three positions (3 TDX, 3 TUY) are sufficient to determine all of the parameters in the idealized model. When less than three measurements are available, parameters must be estimated by predictions or obtained from other sources. To obtain the necessary parameters for the initial idealized grid from available data, Fort Cronkhite data and USCG chain calibration data were used. From the chain calibration data the values of the emission delays were determined by averaging TDX data taken on the baseline extensions. The values obtained were:

\[ E_x = 28094.467 \mu s \]
\[ E_y = 41967.620 \mu s \]

The phase velocity \( V_Y \) was estimated using the phase predicted from the integral equation program for the Yankee path to Fort Cronkhite. Then values were assigned to \( V_Y, V_{M Y} \), and \( V_{MX} \), which, when adjusted for the land-to-sea interface effects, matched the Fort Cronkhite data for TDS and TUY reasonably well. The phase velocities determined were:

\[ V_{MX} = V_{M Y} = 0.299061 \text{ km/\mu s} \]
\[ V_X = 0.2983804 \text{ km/\mu s} \]
\[ V_Y = 0.299150 \text{ km/\mu s} \]

As a first approximation, we assumed that spatial grid distortions were primarily the result of phase recovery at land-sea interfaces and the scattering of signals from large metallic bridges. At land-sea interfaces, the secondary phase of the Loran-C signal undergoes a rapid decrease (see Figure 15, which is typical for all lower to higher conductivity changes). When the interface is far from the transmitter, the phase recovery is primarily determined by the overwater distance after the transition, as illustrated in Figure 16. This effect was employed to calculate first-order grid distortions relative to the idealized grid. A typical example of the distortion is shown in Figure 17.

Obviously, in the real world, \( V_{MX} \) and \( V_{MY} \) must be equal, and they are treated as in this subsection. However, Equation 1 can be used as a numerical fit to data, as it is in later sections. A better fit can be obtained by allowing \( V_{MX} \neq V_{MY} \).
phase fluctuation versus distance from the bridge. In the pulsed mode of operation, the fluctuations damped out more quickly than in the cw mode. Based on this analysis, it was predicted that the largest distortion would occur on the harbor side of the Golden Gate Bridge. This results because the X-ray signal is parallel to the bridge, producing little interfering reflection and the Master signal arrives perpendicular to the bridge, producing maximum reflection. For the Bay Bridge the distortion was predicted to be less severe than for the Golden Gate Bridge, with TDY being most affected. No significant distortion was expected near the Richmond Bridge since its height is only a small fraction of a wavelength at 100 kHz.

The land harbor sites and the vessel tracks were selected on the basis of the analysis described above. For details of the selection process, see Reference 12. As an example, a closely spaced series of parallel vessel tracks in the vicinity of the Golden Gate Bridge was selected to map the scattering effects predicted.

**Fixed Land Site Phase.** The purpose of the land site measurements was to provide data necessary to obtain: (1) a calibrated, accurate harbor grid; (2) an evaluation of grid accuracy and anomalies; (3) an evaluation of repeatable (reproducible) mode Loran-C; and (4) an evaluation of differentially augmented relative mode Loran-C. The land harbor site measurements were made using five receivers in three deployments of approximately 1 week each. Since two sites were visited twice, data were collected at a total of 13 sites. Figure 14 shows the location of the sites. The crosses represent deployment 1 sites, the circles represent deployment 2 sites, the squares represent deployment 3 sites, and the triangles represent deployment 4 sites, which were common to deployments 2 and 3.

**Data Collection and Analysis.** The data collected are summarized in Table 9. The values in Table 9 were computed using 7 to 9 days of data (data sample interval of 100 seconds) for each site (the actual number of days of data for each site is indicated in the data sample column of Table 9). All standard deviations are small (i.e., below 30 nanoseconds). Table 9 also shows the largest standard deviations. As already mentioned in Section 4, this is attributed to problems at the Point Pinos SAM. Note the shift in mean TDY and mean TOY at Fort Point and Fort Mason between weeks 2 and 3. Fort Cronkhite data also exhibited similar behavior.

![Figure 18. Phase error produced by reflection from Golden Gate Bridge.](image)

To evaluate the accuracy of the idealized grid and calibration techniques, a series of grids were prepared based on the data from selected land sites. The accuracy of the results was assessed by comparing predicted TUs for the measurement sites with the actual measured values. A thorough discussion of these procedures can be found in Reference 11. The idealized grids were derived from the following data: (1) the original grid parameters estimated in the planning phase; (2) fixed sites with all over-land paths (Fort Cronkhite, Sears Point, Bacteria Bay, and Berkeley Marina); (3) fixed site data with both on-shore and mid-harbor locations (Sears Point, Alcatraz, and Fort Bakery); and (4) data from all sites using a least squares fit. The accuracy of the grids fits to the data progressively improved from (1) to (4). This comparison is summarized in Table 10.

**Table 10. Harbor experiment data summary (values in microseconds).**

<table>
<thead>
<tr>
<th>Deployment</th>
<th>Measurement Site</th>
<th>Data Sample (Days)</th>
<th>Mean TDY</th>
<th>Mean TOY</th>
<th>Std. Dev. TDY</th>
<th>Std. Dev. TOY</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1. Sears Point</td>
<td>7</td>
<td>27129.3622</td>
<td>42306.6406</td>
<td>0.0180</td>
<td>0.1919</td>
</tr>
<tr>
<td>2</td>
<td>2. Point Pinos</td>
<td>7</td>
<td>27862.9723</td>
<td>42561.7578</td>
<td>0.0201</td>
<td>0.1916</td>
</tr>
<tr>
<td>3</td>
<td>3. Angel Island</td>
<td>7</td>
<td>27863.2447</td>
<td>42562.2817</td>
<td>0.0202</td>
<td>0.1917</td>
</tr>
<tr>
<td>4</td>
<td>4. Point Pinos</td>
<td>7</td>
<td>27726.0820</td>
<td>42417.2894</td>
<td>0.0270</td>
<td>0.1673</td>
</tr>
<tr>
<td>5</td>
<td>5. Point Pinos</td>
<td>7</td>
<td>27288.0800</td>
<td>42031.9482</td>
<td>0.0293</td>
<td>0.0033</td>
</tr>
<tr>
<td>6</td>
<td>6. Binary Bay</td>
<td>7</td>
<td>27272.6992</td>
<td>42364.9556</td>
<td>0.0419</td>
<td>0.0550</td>
</tr>
<tr>
<td>7</td>
<td>7. Point Pinos</td>
<td>7</td>
<td>27928.5600</td>
<td>42350.8047</td>
<td>0.0781</td>
<td>0.0572</td>
</tr>
<tr>
<td>8</td>
<td>8. Point Pinos</td>
<td>7</td>
<td>27127.9627</td>
<td>42317.5537</td>
<td>0.0520</td>
<td>0.0236</td>
</tr>
<tr>
<td>9</td>
<td>9. Point Pinos</td>
<td>7</td>
<td>27125.8922</td>
<td>42304.1811</td>
<td>0.0590</td>
<td>0.0276</td>
</tr>
<tr>
<td>10</td>
<td>10. Point Pinos</td>
<td>7</td>
<td>27126.4922</td>
<td>42304.3511</td>
<td>0.0532</td>
<td>0.0276</td>
</tr>
<tr>
<td>11</td>
<td>11. Alcatraz</td>
<td>7</td>
<td>27756.0491</td>
<td>42310.1647</td>
<td>0.0671</td>
<td>0.0333</td>
</tr>
<tr>
<td>12</td>
<td>12. Point Pinos</td>
<td>7</td>
<td>27121.7395</td>
<td>42301.2305</td>
<td>0.0227</td>
<td>0.0277</td>
</tr>
<tr>
<td>13</td>
<td>13. Point Pinos</td>
<td>7</td>
<td>27758.3700</td>
<td>42303.1967</td>
<td>0.0185</td>
<td>0.0193</td>
</tr>
<tr>
<td>14</td>
<td>14. Alcatraz</td>
<td>7</td>
<td>27759.4256</td>
<td>42302.5667</td>
<td>0.0374</td>
<td>0.0393</td>
</tr>
<tr>
<td>15</td>
<td>15. Berkeley Marina</td>
<td>7</td>
<td>27764.7800</td>
<td>42311.9375</td>
<td>0.0518</td>
<td>0.0276</td>
</tr>
</tbody>
</table>

Conclusions from Fixed Site Data. The error contours from the planning phase did not explain the difference between measured values and the initial idealized grid. It was discovered that an additional major error source was due to the nonlinear phase distance relationship (i.e., phase is not really a linear function of distance even for a short homogeneous path segment as assumed in Equation 1). Additionally, it was determined by the n-sea measurements that the required model parameters were estimated from data taken at a carefully selected set of calibration sites. The effects of the nonlinear phase-distance effect were felt at moderately close distances to the transmitter, where the phase versus distance function has significant curvature. Thus, grid fits may have larger errors for short baseline systems than for long baseline systems (given equal accuracy in the calibration data). The sensitivity to conductivity changes is greater, thus temporal changes in the ground conductivity due to precipitation or freezing can cause significant grid instabilities.

The use of grids based upon phase velocity as a polynomial function of range and bearing from such transmitter was not considered. It was reasoned that the additional complexity of these grid models would only yield slight accuracy improvement, since the required smoothness in the spatial derivatives of the phase is clearly not obtained in the complex signal path impedance structure found in harbors.

The analysis of grid calibration techniques found in Reference 11 provides an upper bound for grid fit error of 200 microsec for the area covered by the calibration sites. This error analysis also predicted larger grid errors for TDY.
Table 10. Summary of harbor fixed site data reduction and grid preparation.

<table>
<thead>
<tr>
<th>Site</th>
<th>Distances to Harbor</th>
<th>Estimated Parameters Used in Experiment Plan</th>
<th>Overland Path Data</th>
<th>On Shore and Mid-Harbor Data</th>
<th>Least Square Fit to 13 Sites</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Distance (m)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$D_1$ ($D_2$)</td>
<td></td>
<td>$TD_1$ ($TD_2$)</td>
<td>$TD_1$ ($TD_2$)</td>
<td>$TD_1$ ($TD_2$)</td>
</tr>
<tr>
<td>Fort Cromwell</td>
<td>374.506 (140.539)</td>
<td>746.67 (212.73)</td>
<td>212.271</td>
<td>211.742</td>
<td>211.033</td>
</tr>
<tr>
<td>Fort Riley</td>
<td>375.406 (140.737)</td>
<td>745.34 (212.30)</td>
<td>212.151</td>
<td>211.742</td>
<td>211.033</td>
</tr>
<tr>
<td>Point Point</td>
<td>376.254 (140.955)</td>
<td>744.65 (212.45)</td>
<td>212.052</td>
<td>211.742</td>
<td>211.033</td>
</tr>
<tr>
<td>Point Point</td>
<td>377.406 (141.156)</td>
<td>743.93 (212.55)</td>
<td>211.951</td>
<td>211.742</td>
<td>211.033</td>
</tr>
<tr>
<td>Point Point</td>
<td>378.506 (141.357)</td>
<td>743.21 (212.63)</td>
<td>211.851</td>
<td>211.742</td>
<td>211.033</td>
</tr>
<tr>
<td>Point Point</td>
<td>379.606 (141.558)</td>
<td>742.49 (212.70)</td>
<td>211.751</td>
<td>211.742</td>
<td>211.033</td>
</tr>
</tbody>
</table>

than TDV, which was confirmed by the measurements. The final idealized grid had about 100% accuracy for the harbor area best sampled by the calibration sites. An obvious means of improving grid accuracy would be to use multiple grids. The number of grids and their boundaries could be selected based on an error analysis which bounds the error of each subgrid.

An alternative grid parametrization considered was the linear grid, which is a linearization of equation (4) about some fixed location. Obviously a linear grid is less accurate over a large area, but errors near the linearization point may be quite small. Thus, one might consider the use of multiple linear grids to achieve the same accuracy as the idealized grid. This essentially trades increased parameter storage needed for the simpler coordinate conversion algorithms (i.e., one only needs to solve a set of linear instead of nonlinear equations).

The linear grid is of interest from the standpoint that it is simple, easily implemented, and need not provide absolute position (see Reference 31). Both the idealized grid and the linear grid have the very desirable property that the grid calibration can be completely automated and performed in real time. This has been implemented for the linear grid by the USCOC.

Evaluation of Differentially Augmented Relative Mode (Differential Loran-C). The fixed site data from the first deployment were processed to simulate a differential Loran-C system. The concept of differential Loran-C was tested in the differential Loran-C Time Stability study (Reference 18) as earlier stated, in this study conducted in 1973, it was shown that the differential mode of operation resulted in improvement factors of 1.5 to 3 over the repeatable mode. In the differential mode, a monitor receiver at a known, fixed location is used to compute a correction that is provided to users in the area. The user then adds this correction to his receivers TDs to obtain more accurate TDs. The basic formula for computing the correction for X-ray from data at site G is

$$ DC(t_1) = TD_{GX} - TD_{GX}(t_1), \quad (2) $$

where $DC(t_1)$ denotes the differential correction at time $t_1$, TD_{GX} is the average monitor or control TD, and TD_{GX}(t_1) is the monitor TD at $t_1$. The error in the differential correction, or the differential error DE, is the sum of the signal variation at the mobile location and the DC, namely

$$ DE(t_1) = (TD_{SX}(t_1) - TD_{GX}) + (TD_{GX}(t_1) - TD_{GX}), \quad (3) $$

where $S$ is the mobile user site. If the time differences are highly correlated and the two receivers measure without error, then the DE would be quite small.

Consider the problem of finding the optimal estimate of the user TD given the TD at the monitor. It is well known that the linear minimum variance unbiased estimate is given by

$$ TD(t_1) = K(TD_{GX}(t_1) - TD_{GX}) + TD_{SX} \quad (4) $$
where \( \overbrace{TDSX(t_i)} \) denotes the minimum variance estimate of \( TDSX(t_i) \) and the gain \( K \) is given by

\[
K = \frac{E \{ TDSX(t_i) - TDSX \} (TUGX(t_i) - TDGX)}{E \{ TUGX(t_i) - TDGX \}^2}
\]

(5)

where \( E \{ \cdot \} \) is the expectation operator. If we multiply Equation 4 by \(-1\) and add \( TDSX(t_i) \) to both sides we get

\[
(TDSX(t_i) - TDSX) - K(TDGX(t_i) - TDGX) = TDSX(t_i) - TDSX(t_i)
\]

(6)

We see that this represents a general expression for the differential error. Since \( TDSX(t_i) \) minimizes the variance of Equation 6, we conclude that

\[
OC^*(t_i) = -K(TDGX(t_i) - TDGX)
\]

(7)

is the optimum differential correction. It is clear that Equation 2 is a special case of Equation 7 where \( K = 1 \).

If \( K = 1 \) as computed by Equation 5, then we conclude that

\[
COV(TDSX, TDGX) = COV(TDGX, TDGX)
\]

(8)

or \( TUGX \) and \( TDGX \) are perfectly correlated. It is obvious that using Equation 7 as a correction rather than Equation 2 should reduce the variance of the differential error. The form of Equation 7 has a nice intuitive explanation. Since we are dividing up the variance of the monitor TD, we see that as the variance goes up, the gain goes down. However, since the numerator of Equation 5 is the covariance of the mobile and monitor TDs, we see that for highly correlated TDs the gain will approach unity no matter how large the variance of the monitor becomes. This is a very satisfying logical result.

The terms in Equation 5 can be estimated from experimental data. To do this we can estimate the covariance and variance by computing the sample covariance and the sample variance. The formulas are given by

\[
COV(TDSX, TDGX) = \frac{1}{2} \sum_{i=1}^{N} [TDSX(t_i) - TDSX][TDGX(t_i) - TDGX]
\]

(9)

and

\[
COV(TDGX, TDGX) = \frac{1}{N} \sum_{i=1}^{N} [TDGX(t_i) - TDGX]^2
\]

(10)

where \( N \) is the number of data samples. Thus Equation 5 becomes

\[
K = \frac{\sum_{i=1}^{N} [TDSX(t_i) - TDSX][TDGX(t_i) - TDGX]}{\sum_{i=1}^{N} [TDGX(t_i) - TDGX]^2}
\]

(11)

Equation 11 is fine for investigating the differential concept. However, it is not very useful for real-world use. There are several immediate reasons for this. Among them is the fact that although the sample variance can be computed for the monitor receiver, it may be difficult to compute for the covariance of the mobile receiver against the monitor unless a large sample of data is available from the mobile receiver. For the real-world use of differential Loran-C, we need an expression for \( COV(TDSX, TDGX) \) which can be precomputed without the need of experimental data from the mobile receiver.

We can use the fluctuations model described in Reference 13 to compute the desired covariance, if we make the following assumptions: (1) that chain, propagation, and receiver variations are mutually independent; (2) the monitor and mobile receiver are close enough so that the propagation fluctuations are identical at both receivers for each signal; (3) the signals from each transmitter are mutually independent; and (4) the receiver fluctuations at each receiver are independent.

If these assumptions are satisfied, then

\[
E(TDX x TDGx) = E(x_0(t_i)^2) + E(m_0(t_i)^2)
\]

\[
+ E(x_i(t_i) - m_i(t_i))^2
\]

(12)

Using data from the stability experiment (Reference 13), we can estimate the value of \( K \) for TDX to be 0.98 and for TDU to be 0.99.

Data Collection and Analysis. One week of data collected at Sears Point, Point Molate, Angel Island, Treasure Island, and Hunters Point was used to simulate differential Loran-C. Sears Point was arbitrarily designated as the monitor receiver to correct Point Molate, Angel Island, and Hunters Point, while Angel Island was designated monitor to correct Treasure Island. The differential error was computed for five different averaging intervals: 100 s, 15 min, 2 hours, 6 hours, and 24 hours. For each averaging interval, the differential error was computed for two differential gains, 1.0 and the value computed by Equation 11. Histograms of each of these differential error sequences, sample standard deviations, and improvement ratios were produced. The improvement ratio is defined as the ratio of the standard deviations of the uncorrected mobile TD to the corrected mobile TD.

Figures 19 and 20 show the improvement ratio versus correction averaging interval for TDX and TDU, respectively. Each plot has two curves, one for the standard differential gain (ie, \( K = 1 \)) and the other for the optimal differential gain as computed using Equation 11. For TDX the curve...
exhibits the expected behavior of an exponentially decaying improvement ratio with a maximum for no averaging. Of course the curve for the optimal gain remains above the curve for standard gain, but the improvement is not dramatic. Figure 20 for TDX is much more interesting. Notice that the improvement ratio is a maximum for 15-minute averaging of the correction. Since the Yankee signal has a lower signal-to-noise ratio than X ray, the variation in TDX at the two sites has a larger independent component, which is reduced by averaging. However, averaging the correction also reduces the components that are correlated with the user TD. Apparently there is sufficient time correlation in TDX to yield improved results even though the correction is averaged longer.

While the standard gain yields degraded performance for 24-hour averaging of the correction on TDX, it yields improvement for this long averaging interval on TDX. This is further proof that TDX has significant long-term correlation. In general, though, the improvement ratios for TDX are higher than those for TDY, as one would expect due to the higher signal-to-noise ratio on the X-ray signal.

In Figures 21 and 22 the improvement ratio versus distance from the monitor is plotted. There does not appear to be any consistent pattern. In fact, for TDX this curve peaks at 33 km, with the general trend of increasing improvement with distance. TDY, however, behaves more as one might expect with improvement decreasing with distance. A strong negative correlation between distance from the monitor and improvement ratio implies that propagation fluctuations are dominant in the differential error. However, the verification and stability experiments have clearly shown that propagation fluctuations are much smaller than chain fluctuations and are on the order of receiver fluctuations. Since the Yankee signal path is the longest, one would expect propagation fluctuations to be more pronounced. Examination of the stability data also reveals that Yankee chain and equipment fluctuations are somewhat smaller than for X-ray. This seems to explain both the decrease in improvement ratio with distance and the larger low-frequency spectral components observed for TDX.

Sears Point correcting Angel Island showed the best performance of the five pairs. The standard deviation of the corrected time differences was 0.3 ns for TDX, and 12.6 ns for TDY. A careful examination of the data reveals the following points: (1) the data sample for this pair was by far the largest; (2) portions of days 102 and/or 106 were missing at Point Molate; Hunters Point, and Treasure Island due to receiver simulator tests or receiver problems; and (3) these particular days showed significant chain fluctuations that were highly correlated at both Sears Point and Angel Island. These facts tend to make the improvement for Sears Point correcting Angel Island look much better than for the other pairs. Results from the Differential Loran-C Time Stability study show that 7-ns rms was the smallest DE standard deviation obtained (based on 1 week of data). Simulator tests performed on the receivers for comparable signal-to-noise ratios suggest that no further improvement is possible beyond this level.

The TDX data for most site pairs were highly correlated \( p > 0.85 \). Thus, the improvement gained by using the optimal differential gain was only slight. The exception was Sears Point and Point Molate. The correlation between TDX at these locations was \( p = 0.75 \). The standard deviation of TDX was 18 ns at Point Molate and 21 ns at Sears Point. The standard deviation of the differential error for \( K = 1 \) was 14 ns and 12 ns for \( K = 0.66 \), about a 15-percent improvement. The improvement gained by using the optimal \( K \) was generally larger for TDX than TDY as expected, due to the lower signal-to-noise ratio on Yankee. The improvements due to the use of the optimal \( K \) are encouraging enough to warrant further investigation.

The optimal \( K \) derived here is based only on instantaneous signal fluctuations. We have already seen that there is significant time correlation in TDX. This suggests that the differential correction should be based on the output of a Kalman (or Weiner) filter that could exploit this time correlation in an optimal manner. Other extensions naturally handled by the Kalman filter structure would include multiple monitors.

Figure 20. Improvement ratio versus correction interval for TDX.

Figure 21. TDX improvement ratio versus distance from monitor.

Figure 22. TDY improvement ratio versus distance from monitor.
Differential Loran-C Recommendations. Since there is little or no correlation between differential improvement and distance from the monitor, we conclude that differential propagation fluctuations are not as significant as receiver and chain fluctuation fluctuations. Furthermore, it appears that chain fluctuations are a significant error source in TDs measured in the San Francisco Bay area even though the Control Monitor is nearby at Point Pinos.

Automatic initialization and update would be far superior over manual initialization because of the frequency update (100 sec) requirements to obtain maximum accuracy (25 to 50 feet) as defined in the preceding paragraphs. This maximum accuracy is required in large portions of most rivers, harbors, and other narrow waterways. The limiting factors for achieving higher accuracies than presently available using differential Loran-C are equipment related (i.e., further reduction in receiver error is required). Automation of differential Loran-C implies carefully designed software, communication links, and devices to avoid errors in processing and transmitting corrections.

Initialization Techniques Using Loran-C (Initialize and Go/Initialize on the Fly)

The ability to initialize and go and initialize on the fly has been under development by the US Air Force and US Coast Guard since 1968. This is not a new technology to the military sector. In 1968 a Loran Assist Device (LAD) was developed for a unique military aircraft requirement and was followed by several other military versions. In 1970 a Coast Guard Loran Assist Device (COGLAD) was developed to evaluate Loran as an aid to laying buoys. With the development microprocessors in 1973, a small, simple processor (CLAD) was developed and tested by the Coast Guard. The original COGLAD was upgraded and tested on the Great Lakes in 1976. PILOT (Precision Intracoastal Loran Translocation) was developed in 1979 and tested aboard ore carriers on the Great Lakes in late 1980. PILOT is a preproduction microprocessor-controlled graphics terminal using Loran and prerecorded charts to aid ships piloting rivers and harbors. Each new system used increasingly sophisticated data processing techniques, required less operator training and attention, and represented a lower potential production cost. These improvements were largely the result of the phenomenal developments in the integrated circuit and microprocessor industry in the last decade.

The design objective of the PLAD system was to demonstrate that Loran repeatability (i.e., return to presurveyed way points) could be successfully used to pilot harbors and rivers, and that the system be sufficiently portable for professional pilots to carry aboard commercial vessels. PLAD can be used in any harbor or river that has good Loran-C coverage (geometry and SKR) and has been surveyed. To change the PLAD operational area requires that one memory data chip in PLAD be replaced but no hardware or software modifications are required. PLAD and this interchangeable chip are both identified in Figure 23.

There are numerous variations in applying initialization. One such procedure is summarized below using the PLAD system:

1. Approximately one hour before boarding a vessel, PLAD should be taken to a calibration point, set up, allowed to lock on, and commanded to execute an automatic calibration run.

With sufficient data collection, initialization can also occur at the departure point and previously surveyed way points can be used for navigation. Specifically at each waypoint the nominal Loran time differences are obtained from a survey and known to the navigator. In the neighborhood of a waypoint the difference between the TD measured by the navigator and the surveyed TD of the nearby waypoint is a differenced TD. The TUs obtained from the two secondary transmitters are unique to the position (x, y) at which they are measured, where x and y denote horizontal displacements relative to the waypoint.

The relationship between the two TUs and x and y is nonlinear. For given TUs the solution for x and y is obtained by an iterative procedure. Once the navigation algorithm has converged to final values of x and y, the ship's horizontal velocity components are also readily calculated as linear.

Most Loran-C receiver manufacturers provide sound guidance for optimum antenna locations and information on how to avoid shipboard noise.

2. After the calibration samples are taken, the TD bias values from the auto calibration run are loaded into the TD bias section of PLAD and the unit is shut down in order to carry it aboard the vessel.

3. The unit is taken aboard the vessel and set up at a convenient point for the navigator or user taking into account proper location to avoid shipboard noise and antenna problems.

4. When the receiver indicates lock on (approximately 5 to 15 minutes), the user can select a course and be sure that the PLAD display settles on the proper range.

5. Select appropriate displays (along track distance, cross track distance, along track speed, cross track speed, etc) with which to navigate.

Figure 23. PLAD system block diagram.
combinations of the time derivatives of the measured TDs. The TD time derivatives are available from the TD filters.

The St. Marys River minichain used the above technique in 1979 successfully. The St. Marys Loran-C minichain features short propagation paths, and good geometry. Therefore it was possible to reduce the geometry to a single plane tangent to the earth at the origin. No account was taken of the earth's curvature in computing the theoretical transmission path lengths. Reference 34 extended this technique used in the St. Marys to allow the computation to be used with the most general configurations of Loran transmitter and waypoint geometry.

The previously surveyed TDs do fluctuate with time, as demonstrated earlier in this report. Depending on the accuracy requirements (harbor or river dimensions) differential Loran-C may also be required when using systems such as PLAD. There is a clear tradeoff when employing the above augmentation techniques individually or combined that must be made for each individual harbor, river, and waterway (accuracy requirements, harbar, river dimensions, and geometry must be considered). These considerations have been discussed earlier. See References 32 through 34 for further detail.

Grid Calibration

There are two techniques (and variations thereof) that are used for grid calibration:

1. Position Reference System — This technique requires the simultaneous (time synchronized) recording of both Loran-C TDs and range values or phase differences from a position reference system. These signal values are all converted to latitude and longitude for comparison of Loran-C with the positioning reference or "truth" system. The positioning system is calibrated to a known accuracy.

2. Visual Grid Survey — This method was developed to determine TD coordinates of the physical features of an HHE area. The process consists of selecting route waypoints; computing estimates of TDs; estimating position of surrounding navigation features; surveying (measuring) TDs along visual ranges, channel edges, and at sides to navigation in the vicinity of the waypoints; statistically defining the TDs for the waypoints. This technique is used to determine the evaluate navigation parameters for repeatability and accuracy.

These grid survey techniques only account for spatial change in a harbor or river environment. After a successful survey the spatial features (bridges, terrain elevation, large structures, islands, etc) are built into the grid (i.e., the grid is warped). To control Loran-C temporal timing fluctuations still requires the use of differential Loran-C with correction intervals less than 15 minutes for high accuracy. Based on data evaluated to date daily broadcasts may not be sufficient to represent changes in the time varying components of the Loran-C grid for locations utilizing narrow waterways. In open bay areas (such as the Chesapeake) daily broadcasts may be sufficient (i.e., less accuracy required).

Each of the grid calibration techniques will now be described.

Position Reference System. Kalman Tempo (Reference 13) collected data on a research vessel in San Francisco harbor for the US Coast Guard.

This was the first intensive harbor calibration ever sponsored by the Coast Guard.

While measurements were being made at fixed land sites, data were also being collected aboard the research vessel Polaris in the harbor and harbor entrance. Figure 15 shows an outline of the area covered by the vessel, both Loran-C and TD data. The vessel position was measured quite accurately using the Trisponder radar system. The vessel position measurement should be an order of magnitude better than expected Loran-C errors to reasonably measure any errors in the Loran data. Summer data collected at Fort Cronkite had suggested a 30-meter (2D) Loran-C error, which dictates a requirement for a 3-meter (2D) error in locating the vessel. The Trisponder radar system (a master unit and track plotted on the vessel and four transponders on the shore) provided this accuracy. This accuracy was proven based on calibrating the Trisponder position between two known points at distances that were similar to those used during the Loran-C harbor calibration. Vessel position was recorded every second. A total of 11 days of data were taken, 9 with 100-second averaging and sampling of the Loran-C data.

The object of this phase of the experiment was to provide data for an assessment of absolute mode Loran-C in a typical harbor environment and to study grid anomalies produced by bridges. To assess the absolute mode, idealized grid parameters which were obtained by least squares fit of land site data were used for conversion of time differences to latitude and longitude and vice versa.

Before comparison between the Trisponder position data and Loran-C data could be accomplished, a number of technical problems had to be addressed. These included: (1) correction of the Loran-C data to compensate for dynamic errors due to vessel motion and the long averaging times of the receivers; (2) the editing and filtering of the Trisponder data; and (3) proper handling of large data gaps in the Trisponder data. These are briefly discussed below.

To correct the Loran-C data for averaging errors, the Trisponder data were used to estimate vessel heading and speed. The receiver averaging was modeled and an expression was obtained for the error as a function of heading and speed. This expression was used along with the heading and speed data to estimate the error due to averaging for each TD. Finally, this estimate was subtracted from the Loran-C data.

The Trisponder data were found to have some bad data points and outliers. Much of this bad data was caused by signal scattering from large vessels that passes near the Polaris. A Kalman filter was used to reject those bad data. The Trisponder data were filtered in cartesian coordinates, and data editing was performed by comparing the data with its prediction from the filter. If the difference was too large, the data point was rejected and replaced by the prediction.

At other times the line-of-sight to the transponders was interrupted by large vessels. In this case data gaps up to 60 seconds occurred. To fill these gaps the predictions from the Kalman filter were used. However, if the filter covariance became too large, no comparison was made for that Loran-C sample and the Kalman filter was reinitialized.

To test the validity of the dynamic error removal algorithm, simulator tests were performed.
by Kaman Tempo at ECELR (US Coast Guard Electronic Engineering Center). The LRRC-12 (Loran-C Receiver Test Complex) simulator was programmed to produce a series of TDs which simulated a vessel steaming at 6 knots. It was found that the dynamic error was corrected to within 10 ns.

Data Collection and Analysis. A block diagram of the processing system used to compare the Loran data to the Trisponder data is shown in Figure 24. An example vessel track is shown in Figure 25 along with the corresponding vessel position obtained from Loran-C. Figure 26 compares latitude and longitude as computed by the Trisponder (truth system) represented by the small dots and the Loran-C system as represented by the "rat" dots. Figure 27 shows time difference errors as arrows emanating from the "true" vessel position and pointing in the direction of time difference gradient. For TDX the arrows are at angles from the vertical of approximately 120 degrees for positive errors and -30 degrees for negative errors. TDY errors are represented by arrow points up (0°) for positive errors and down (180°) for negative errors.

![Figure 24. Block diagram of vessel data processing system.](image)

![Figure 25. Vessel track from Trisponder and Loran-C data.](image)

The difference between true and measured position was generally low in the inner harbor, which follows from the fact that the placement of the land harbor sites used in the grid fitting is such that the grid is optimized for this area. Two areas exhibited systematic charting errors. They were near Angel Island and Alcatraz for both the X-ray and Yankee time differences. Pre-experiment analysis based on the land-sea interface phase recovery indicated that only X-ray would show large errors in those areas.

In an attempt to explain the systematic TD errors around Angel Island in both TDX and TOY, we considered prediction errors at Point Blunt and Alcatraz. For Point Blunt grid fit errors were 138 ns for TDX and -9 ns for TOY, while at Alcatraz we have -42.3 ns for TOY and 15 ns for TDX. The large error for TDX at Point Blunt seems to correlate well, and the errors in TOY for Alcatraz are in agreement for the area east of Alcatraz but not to the west. Furthermore, if we attempt to use the error contours from the planning phase, we again find good agreement for TOY. However, the large TOY errors around and to the west of Angel Island are predicted to be zero. Further analysis is needed to explain the behavior of TOY by considering other error sources. However, one cannot rule out the possibility that the error rate is really in the "truth" system and not Loran-C.

The errors around the three bridges follow the general pattern predicted by analysis in Reference 12. It was predicted that errors in TOY would be worst around the Golden Gate Bridge while errors in TDX would be worst around the Bay Bridge. The Richmond Bridge was not expected to produce severe errors in either TDX or TOY. The reasons for these predictions are as follows: (1) the Golden Gate has the largest cross section; (2) the X-ray signal passes almost parallel to the bridge while Master is almost perpendicular; (3) the reflection of Yankou from the Golden Gate would approximately cancel the effect of Master; and (4) the Richmond Bridge is too small to cause significant scattering. The TOY errors around the Golden Gate Bridge are somewhat larger than around the Bay Bridge but are smaller than the TDX errors around the Golden Gate. TOY errors around the Bay Bridge were larger than TDX errors as expected.

One day of Loran-C data with 10-sec averaging was collected in the Golden Gate Bridge area. The closer spaced samples gave a good picture of what happens as a vessel approaches the Golden Gate Bridge. An error buildup in TOY began about 1000 to 1200 meters from the bridge. This compares quite well with the start of the major lobe in Figure 19. The signal then became totally useless when the vessel approached within 400 to 600 m of the bridge, in that the received signal became so unstable that it could not be used for navigation. The signal was again usable about 400 to 600 m from the bridge on the seaward side.

Errors in position were higher in the San Pablo Bay area and seaward from Golden Gate Bridge. These areas were not effectively sampled by the calibration sites, and thus the grid fit should be poor in these areas.
The means and standard deviations of the differences between grid predictions and measured data for the inner harbor (excluding the areas near the Golden Gate and Bay Bridges) are:

\[
\begin{align*}
\text{TX} & = 34.1 \text{ ns} \quad \sigma_{\text{TX}} = 65.1 \text{ ns} \\
\text{TY} & = -0.6 \text{ ns} \quad \sigma_{\text{TY}} = 64.7 \text{ ns}
\end{align*}
\]

Note the mean offset in TX could be corrected by changing the X-ray emission delay. In general the performance is quite good. If one considers that the standard deviations of the received signals are about 20-ns rms, then we see that approximately 60-ns rms is due to charting errors.

Conclusions. The results of this experiment show that Loran-C can provide reliable and accurate navigation for use in piloting San Francisco Bay and other harbors and restricted waterways provided proper precautions are exercised near bridges and the proper equipment is used. The quality of the results is encouraging and shows that the software and techniques developed to process the vessel data form a solid basis for user equipment design and automated harbor calibration techniques.

Some general conclusions are also possible concerning the distortion caused by large bridges. Bridge height must be a significant fraction of a wavelength to produce significant signal distortion. This conclusion is based on a simplified analysis and the fact that the Richmond Bridge produces little or no distortion compared to the large Golden Gate and Bay Bridges. The simple scattering theory predicts fairly well the general behavior and spatial pattern of measured signal distortion.

Visual Grid Survey/Waypoint Navigation. The Visual Grid Survey Technique was developed to determine the TU coordinates of the physical features of an HMI area. The process consists of:

- Choosing route waypoints
- Computing estimate of TUs
- Estimating position of surrounding navigation features
- Surveying (measuring TUs along visual ranges, channel edges, and at aids to navigation in the vicinity of the waypoint

There are two basis ways of visually determining waypoint TUs. In the ideal case, the ends of all channel segments are marked by the intersection of two ranges. The survey vessel proceeds back and forth through the waypoint along each range. Linear regression techniques are employed to fit a straight line to the TD data. The intersection of the TD lines marks the waypoint.

In the case where ranges are not available, the channel features near a desired waypoint are surveyed, including if available, any fixed aids in the vicinity. An estimate of the waypoint is made and the location of the channel features predicted. The waypoint TUs are adjusted as necessary until the resultant graphical representation of the channel features matches the real world.

In those cases where distance to land or a fixed aid precludes an accurate visual check on the waypoints derived from floating aids, a short-range, transponder system is set up to act as the reference for waypoint determination. This is necessary in areas such as lower Delaware Bay and Chesapeake Bay. Use of a positioning system in the CGZ is of paramount importance for chain calibration because of the lack of visual aids several miles offshore.

Recommendations. The federal government must establish standards of Loran-C surveying. This includes setting standards on specific survey techniques (positioning systems and visual), type of equipment (and calibration procedures for equipment being used), positioning, coordinate conversion algorithms, and variables, use of Kalman filters, and standard techniques to account for vessel motion and dynamics during survey.

Commercial surveying of Loran-C grids minimize government involvement and facilitate transference of costs directly to the user, it is quite likely Department of Transportation will endorse commercial navigation survey to account for spatial error. However, the need for differential Loran-C to compensate for temporal fluctuations will most likely require DOT involvement.

SECTION 5

RECEIVER PERFORMANCE SPECIFICATIONS

The Loran-C Receiver. Loran-C receivers are complex and their use requires other elements of the system (proper geometry, and means to compensate for temporal and spatial effects) discussed previously to be matched properly for successful performance.

A typical installation consists of 4 basic elements. These include: antenna system, analog signal processing, digital signal processing, and control and display. References 4 and 35 have defined the operation of these four receiver functions. This section will concentrate on a review of past test data and the compensation techniques that can be used to reject noise, frequency interference, and reduce errors. Reference 36 provides a summary of data collected for 28 receivers.

One, the antenna, consists of a 1- to 3-meter steel whip mounted in such a location as to minimize its capacitive reactance. Since any short (compared to a wavelength) antenna exhibits low resistance and high capacitive reactance, a coupling is employed to provide noise attenuation, passband filtering, and impedance matching to a 50 Ohm coaxial cable.

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within the receiver, individual manufacturers use different signal processing techniques, time constants, etc. to process Loran-C signals as demonstrated in the receiver survey updated for this effort. A typical Loran-C receiver employs a hard limited, microprocessor controlled digital design. It operates in a differential envelope mode to determine proper cycle selection.

A good Loran-C receiver must include the following performance characteristics:

- Sensitivity/selectivity (measure of receiver's ability to lock on to desired signals, eliminating those which are out-of-band).
- Dynamic range (range of signals that can be processed in the receiver).
- ECD range (range of ECD values for which the receiver will initially achieve lock and stay in lock).
- Lock-on time (time taken for the receiver to initiate proper tracking of the Loran signals).
- Dead reckoning time (time after a receiver has lost signal before it starts the acquisition, settle, and track process over again).

The sensitivity of a Loran-C system is controlled by the combined characteristics of the receiver and antenna coupler, including front-end bandwidth, noise and gain characteristic, and receiver signal processing and averaging technique. Typical marine Loran-C receiver specifications state a -10-dB SNR performance at 5- to 7-minute lock-on time as shown in the survey. Based upon laboratory tests the 3-dB coupler/receiver bandwidth of typical Loran-C receivers are set to about 20 to 25 kHz. New design such as the Ilco includes wider bandwidths. At this bandwidth, the lock-on sensitivity is measured to be about -2-dB SNR over a range of 31 us ECD offset. Once the typical receiver is locked-on, its tracking sensitivity (minimum SNR at which it continues to maintain proper track) was measured to be -7 dB. When tracking below this value, receivers have been observed to lose lock. The receiver must then reacquire if the "lost signal" time was greater than the dead reckoning time.

Typically, signal dynamic range of 20 to 30 was observed in the tests. This dynamic range capability of the typical Loran receiver exceeded signal variations encountered in various tests. Thus, dynamic range is not considered to be a very critical receiver characteristic unless a receiver is operated in close proximity to one of the several continental Loran-C transmitters or the source of a strong interfering signal.

To prevent cycle slip, a Loran-C receiver must tolerate a wide range of ECD. In addition, it is essential that no skywave signals be introduced at the sampling point. Trade-offs have been studied between sampling the pulse at the third cycle (no skywave contamination) versus sampling the pulse at a later cycle yielding a higher SNR reading at the expense of skywave contamination and envelope distortion. It was found that skywave contamination increases the range of ECD observed on incoming signals, which already possess local phase variations and initial ECD offset. This added ECD range often exceeded the receiver's ECD limits and results in loss of lock or cycle slip.

Time for Search, Time to Correct Cycle, and Envelope Times

The typical Loran-C user is also concerned with other important receiver performance characteristics. These include:

1. Time for search.
2. Time to correct cycle (sometimes referred to as settling time).
3. Envelope times (time to return to third cycle from adjacent cycle).

An Intermap LC204 receiver (very typical of hard-limiter type receivers) was chosen to assess typical user receiver performance based on the above three criteria. Several times at each site throughout the Great Lakes region the LC204 was turned off and then on again to test the reacquisition times of a typical user receiver.

All of the results are presented in tabular form in Reference 4. As an example we have chosen Table II which is representative of the signal acquisition times obtained. Table II shows time for search, time to the correct cycle and envelope times for Loran-C station Bineca (Hustur), Loran-C Station Caribou (W), and Loran-C station Carolina Beach (Y). Under the column entitled "Envelope Times" the U represents up 1 cycle and the D represents down 1 cycle. The time to return up or down to the original cycle is the value indicated in seconds. Key points regarding Table II are listed below:

1. Time for search for M ranges between 2 and 11 seconds and W and Y ranges between 4 and 26 seconds.
2. Average time to correct cycle for M, W, and Y are 196, 801.3, and 267 seconds, respectively.
3. Envelope times for M, W, and Y averages are:

<table>
<thead>
<tr>
<th>Up</th>
<th>Down</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>W</td>
</tr>
<tr>
<td>6</td>
<td>9</td>
</tr>
</tbody>
</table>

   Table II. LC204 acquisition (all times in seconds).

   *Comparing the envelope of the secondaries to the measured slope of the master.
To summarize, the LC204 had no trouble in initially acquiring the Loran pulse throughout the test area. The time required to settle to the correct cycle was generally 3 to 4 minutes on Chet, 6 to 8 minutes on Caribou, and 4 to 7 minutes on Carolina Beach. At Peshu Lake, Caribou or Carolina Beach would reliably cycle select. At Peshu Lake, Caribou would reliably cycle select. Most of the receivers conducted in the survey do not have characteristics much different than the above.

Compensation of Frequency Interference and Noise

To mitigate against these noise and interference effects the Loran-C receiver design should include use of the four design principles delineated below:

1. Band-limiting is required in the Loran-C receiver for noise reduction and elimination of out-of-band signals. In most designs, bandpass limiting is achieved in the antenna coupler, with some final tuned circuits, in some cases with switched Q, in the receiver. The switched y circuit permits narrowband RF for the search mode, and wideband for Pulse Group Time Reference and Coherence. The exact bandwidth (30 kHz) selected depends on the SHK design goal, number of poles in the filter, and trade-offs of the cost of the filter versus costs of processing sampled data.

2. There are two basic design types of the analog signal processing. The types differ by virtue of the two different amplifier types: linear and hard limited. With linear amplifiers, limiting is done at low level ahead of the amplifier. The amplifier has a wide range automatic gain control that adjusts the gain in each interval such that the amplifier output is the same amplitude for all stations' signals. Envelope shape processing is done at high level, so that there are two outputs, an envelope and a cycle channel for sampling. A modification of this amplifier type is the clipped linear amplifier, that operates linearly over the expected signal ranges but limits high amplitude signals such as atmospheric noise bursts or crossing rate Loran-C signals.

   The alternative type of amplification is the hard limiting amplifier. In this case, all linear processing must be done at low level. Two hard limited RF amplifiers are then required to make envelope and cycle signals available for the sampling process. The amplifier then amplifies the signal and limits the amplitude until the output has a square wave shape with the polarity equal to the instantaneous polarity of the input waveform.

   In both types of amplifier, the overriding requirement is that delay through the amplifier not vary with received signal amplitude or AGC setting. In general, this means a very wide-band amplifier (10 to 100 MHz), with very low internal noise.

3. The signal processing circuits are essentially filters that minimize the effects of interference and noise on cycle shape and envelope appropriately, and minimize unwanted distortions. The bandpass limiting circuits are designed so that when their effects are considered with the filter in the antenna coupler, the exact bandpass is achieved which minimizes atmospheric noise, while maintaining the envelope shape unique for good cycle selection and maintaining an overall linear phase shift characteristic over the passband for good timing accuracy. Narrowband switching of the filters is provided to gain SNR during search, at the expense of envelope shape. This envelope distortion is of no consequence during search.

4. Interference filters are narrowband rejection filters for reduction of the effects of near-band signals, which can adversely affect the operation of the receiver. The number of notch filters is a design decision that must be based on interference known to exist in the operating area, the receiver bandpass characteristics, and any sampled signal processed that have interference rejection capabilities. Interference effects can be classed in two general types: high level signals that cause the receiver circuits to act nonlinearly, and signals that are coherent with the spectrum of the sampled data process (cross correlation), called "synchronous interference." High level continuous signals must be reduced by filtering the analog signal, ahead of the active stages. In the case of high level atmospheric noise bursts and crossing rate Loran-C signals, a form of limiting is more effective. Synchronous interference can be handled by either notch filters or changing the cross correlation process to eliminate the synchronism, or both.

Control and Display. In addition to performing signal processing functions, the receiver also provides for control and display functions. In a microprocessor-based receiver, the control display group is simply a keyboard/display peripheral of the microprocessor. This provides for input and storage of initialization conditions, and for output either through a visual display or electronic interface. Several receivers surveyed in Section 6 have this capability.

   Through the use of microprocessors and related signal processing circuits, modern Loran-C receivers provide high quality navigation data at a low cost. As microprocessor techniques continue to grow, it is reasonable to expect receiver prices to be reduced somewhat further; however there is a point at which the price will be controlled by the packaging, installation and servicing costs, and not by the cost of the integrated circuits used to perform the signal processing functions.

   What is actually possible is real-time input from a Loran receiver combined with other variables of vessel movement, permitting rapid calculation of fixes, currents, and courses to steer to reach desired waypoints or destinations. This is just the result of following the trend of more and more logic and memory density.

   The existence of more memory implies storage of more and more secondary-phase factor data that gives the conversion process its accuracy. Probably in the final analysis, it will not be the limitations of calculator memory that determine performance, but the availability of the secondary-phase factor data to fill that memory that will be the pacing element.

ACKNOWLEDGMENTS

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PROPOSED COMMON VIEW LORAN-C TIMING
CONTROL

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Abstract: Recently developed common-view, simultaneous-observation time transfer techniques have potential benefits for Loran-C timing and control.

1. Summary: It will soon be practical to control Loran-C timing and to provide constant emission delay and cross-chain timing to within 10 ns. Recent advances in time transfer techniques allow consideration of alternative control techniques and philosophies which were impractical until now. One such control philosophy is proposed as potentially advantageous and worthy of further discussion within the Loran-C community.

2. Short, simplistic history of Loran-C timing and control:

1. 1950s and early 1960s: When Loran-C was first introduced, it was viewed as an improvement to Loran-A. Loran-A was then operated in "synchronized" mode, with the secondary signals actively echoing (i.e., synchronized in real time to) the received master signals; so too with Loran-C. Service area monitor receivers were used to control signal timing in order to minimize navigation errors in the vicinity of those monitors. "Proper operation" philosophically meant that the "coding delay" or baseline extension time-difference was to be held constant, based on a time-difference measurement made in another location; of course this was logically impossible, but the system worked reasonably well. Both the real-time synchronization and the monitor/control philosophy added significant timing "noise" to the Loran-C signals but, in those "olden days," that was the best that could be done.

2. later 1960s and 1970s: With the advent of atomic standards (first Rubidium and later Caesium standards), it became feasible to end the "synchronized" mode of station operation, in favor of a "free-running" mode. This stabilized Loran-C timing considerably, as the secondary station no longer retransmitted the timing "noise" received on the master signal. Service area monitor receivers were still used to control signal timing but, due to longer averaging times and (later) computer-assisted automation, the timing "noise" introduced by the monitor receivers was further reduced. Fundamental chain "calibration" was defined in terms of a "hot-clock" trip and "emission delay" measurement. Proper operation was redefined to mean that the "correlated numbers" as observed at the monitor were to be held constant, based on time-difference measurements made there; of course this was impossible if two geographically separated sites observed the same signals, but, at that time, that was the best that could be done, and this approach significantly reduced the timing "noise" inserted by the monitor/control system.

3. 1980s: With Caesium standards in GPS satellites, we have now the opportunity to control Loran-C emission delays to a fixed number, in real time, and thus to reduce further the timing "noise" which the control method introduces into the system. I now propose a new operational approach to Loran-C control and timing, examine the potential for that control, and hope that this short note provokes more productive thought and debate than has occurred thus far on this topic.

3. Summary of common-view time transfer:

1. Stanford Telecommunications Inc. has developed Time Transfer Units which provide timing data using the SPS (formerly yclept "C/A channel") of GPS. These have been used and tested at US Naval Observatory (1), (2); they work well.

2. Simultaneous "common view" observation of the same satellite has been shown to allow two fixed users to achieve both precision and accuracy of better than 10 ns in synchronizing their clocks. Non-simultaneity of satellite observation results in significant degradation (20-50 ns). (3)

3. In the past year, publications citing more recent efforts have again shown that the "common-view" technique allows clock synchronization to better than 10 ns, and have shown that "common-view" results agree with those of "hot-clock-trips" to better than 10 ns. (4), (5))

4. Proposed alternative Loran-C system control:

1. Within each chain (i.e., collection of transmitting stations with a common "GRI"), each station has a time transfer unit (TTU); the emission delay of each station is controlled (to 10 ns, nominally) to the published value through the use of common-view time transfer. The Master is similarly controlled to UTC (or alternative reference).

2. Each chain is controlled "on time" (UTC or alternative reference) with respect to each other chain through the same medium and, again, to nominally 10 ns.

3. Where propagation changes (temporal variations in ASF) cause accuracy degradation beyond what is acceptable for that local area, a local area monitor is provided (for differential Loran-C) and propagation
corrections are published and/or broadcast. There is otherwise no Coast Guard need for a "monitor" to effect Loran-C timing control.

5. Advantages and disadvantages of proposed control:

Major advantages:

1. Cost: The Coast Guard could save the cost of maintaining monitor sites for control purposes. The local area monitor stations could be a simpler system than the complex Austron 5000A equipments presently used. Two Caesium standards might eventually suffice at each transmitting site, with the TTU providing "equipment monitor" functions for Caesium status. "Hot clock" trips would be forgotten.

2. Flexibility: Receiver designers could choose to build cross-chain or range-range or pseudo-range equipment. Performance of such equipment would be predictable, while the range, GDOP and signal redundancy improvements might be attractive to users and regulatory agencies.

3. Lat/Long prediction stability: The Lat/Long prediction and propagation (ASF) algorithms used by receiver manufacturers could be more stable and reliable, as there would no longer be a need to estimate ASF over the signal paths from the stations to the receiver and from the stations to the monitor site (to negate the "corrections" inserted by the monitor site).

4. Differential reference: Once the principle is established of operating a navigation system with maximum stability, while using differential (local area) monitors for enhanced local accuracy, it is a natural extension to use that same location to provide a local area monitor for other systems, such as Omega and GPS. One communications link could serve to disseminate all correction data for all systems. Navigators transitioning between systems could think in terms of range from one local area monitor.

Disadvantage: With the present system, the monitor/control site inserts "timing noise" due to the effects of propagation changes along the signal paths from the stations. The result is that Loran-C time difference temporal changes are reduced in the vicinity of the monitor/control site, while these changes are potentially increased in other areas. The present mode of operation is an obvious advantage to navigators near the monitor/control site, and a potential disadvantage to navigators elsewhere. The proposed mode of operation would require the use of differential Loran-C in order to achieve best accuracy, just as is required today.

6. The next step: I invite other Loran-C professionals to submit written opinions in preparation for a discussion session at the 1985 WGA Convention. The WGA could provide an ideal forum for recommending to system operators how to examine further the possibilities of this timing control mode.

7. Summary: Recent advances in time transfer techniques allow consideration of practical Loran-C control for constant emission delay and cross-chain timing within nominally 10ns. This paper proposes such a control philosophy as potentially advantageous and worthy of further discussion within the Loran-C community.

References:


Note: This document represents the personal opinions of its author and of no other person or organization.
LORAN-C IN-BAND NOTCH FILTER
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We analyze a simple interference rejection scheme which provides in-band notching without significant envelope shape degradation. Near-band techniques and tuning characteristics are also addressed.

Introduction

Most low-frequency interference to Loran-C is narrow-band and readily suppressed with common single-pole (fixed or tunable L-C) notch filters of nominal 2-3 kHz bandwidth (at -3 dB) and 20-30 dB notch depth. However, some near-band interference signals (and in-band signals) are not adequately suppressed by such filters without also adversely affecting receiver performance.

This note describes a method for protecting receivers from some effects of near-band and in-band interference. By definition, 90-110 kHz signals can cause in-band interference, while near-band interference results from signals within 70-90 kHz or 110-130 kHz. Receivers are commonly equipped with simple notch filters to reject interference, but using these notch filters results in pulse shape distortion, which can cause cycle selection difficulty. Pulse shape distortion increases when:

1) the notch filter is tuned to a near-band frequency near 90 or 110 kHz;

2) the "notch" filter bandwidth is broad; or

3) the notch filter is tuned within 90-110 kHz.

Existing interference to Loran-C includes both near-band and in-band sources. Existing modulation formats for some of these interference sources result in a "Hobson's choice" for Loran-C receiver operation. Some near-band signals can have broad spectra (example: WWV on 88 kHz with nominally 1 kHz bandwidth at -3 dB); simple notch filters on such signals can require relatively broad bandwidths which are practically unattainable without degrading the receiver's cycle selection capabilities. Some interference sources have frequency assignments in-band (e.g., Prague), while other in-band interference can result from equipment operated by other agencies; although in-band interference is typically (though not always) narrow-band, in-band simple notch filter use typically degrades the receiver's cycle selection capabilities.

This note describes an interference protection ("notch filter") method with the following desirable attributes.

1. The use of this "notch filter" does not cause distortion of the Loran-C pulse leading edge.

2. The "notch filter" has a broad bandwidth (more than 0.6 kHz at ~20 dB).

3. The "notch filter" may be used to reject either "near-band" or "in-band" signals.

4. The "notch filter" frequency is readily controllable by software, and requires no high-Q components.

5. Notch nadir rejection depths well below ~20 dB are obtainable.

Description of the "notch filter"

Consider a linear receiver which uses a specific sampling strobe pattern for a particular function. (Examples of such functions: phase tracking near the "sampling point", velocity aiding near the peak of the pulse; envelope-cycle time-difference measurement near the "sampling point" for cycle selection; early guard strobe measurement for protection against slant range tracking; etc.) For that particular function, then, consider another receiver (otherwise identical, but) which duplicates that specific strobe pattern for the specific function; the duplicate strobe pattern precedes the sampling strobe pattern by a time interval T (see figure 1). The sampled data of the two strobes are then algebraically added. The result of adding this duplicate strobe pattern and sampled data is then to multiply the overall receiver spectral response by \( H_1(f) \).

\[ H_1(f) = 2 \left( \exp(i\pi f T) \right) \cos \left( \pi f T \right) \]  \hspace{1cm} (1)

\[ H_1(f) = 0 \text{ when } f = \left( 2n+1 \right)/\left( 2T \right) = f_n \]  \hspace{1cm} (2)

By placing the advance time "T" under software control, the notch frequency becomes digitally controllable by software. The accuracy and stability of notch frequency control are governed by the receiver's ability to control "T"; the stability and accuracy of receiver control of advance time "T" are limited primarily by the receiver's internal clock resolution and accuracy, and this clock is locked to the Loran-C signals which ultimately derive time-interval stability and accuracy from Caesium atomic standards.

By choosing the advance time "T" sufficiently large that the duplicate strobe pattern samples occur prior to the start of the Loran-C pulse, we are assured that the addition of the sampled data from the duplicate strobes should not distort any measurement of any Loran-C pulse parameter. In many Loran-C receivers, a minimum limit on "T" of 30 microseconds will suffice, while some receivers will...
require a minimum limit on "i" of 70 microseconds or more. A higher minimum limit on advance time "T" will slightly restrict the "notch filter" bandwidth available (as shown below), but will apparently not adversely affect other "notch filter" performance parameters.

The "notch filter" depth and bandwidth are computed as follows. The frequencies for -20 dB "notch depth" (relative to the response to the Loran-C pulse) are computed from equation (3).

\[ f(-20 \text{ dB}) = f(\text{notch}) \pm \frac{(1)}{2} f(\pi T) \]  

(3)

The -20 dB "notch filter" bandwidth is then computed from equation (4) and is tabulated in table 1.

\[ BW (-20 \text{ dB}) = \frac{1}{10} f(\pi T) \]  

(4)

Table 1

<table>
<thead>
<tr>
<th>Advance time &quot;T&quot; (microseconds)</th>
<th>BW (-20 dB)</th>
<th>BW (-12 dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>0.6 kHz</td>
<td>1.6 kHz</td>
</tr>
<tr>
<td>70</td>
<td>0.3 kHz</td>
<td>1.2 kHz</td>
</tr>
</tbody>
</table>

Tuning the "notch filter"

The "notch filter" is tuned by controlling the advance time "T"; for example, suppose that the receiver designer were to choose to adopt a "T" range of 50-70 microseconds. From Table 2, we see that this single "T" range allows the receiver to tune the "notch filter" over three "bands": for interference sources in the range 93-130 kHz, the receiver would tune using the seventh zero of the cosine \((2\pi+13)\); for interference sources in the range 79-110 kHz, the receiver would tune using the sixteenth zero of the cosine \((2\pi+11)\); for interference sources in the range 65-90 kHz, the receiver would tune using the fifth zero of the cosine \((2\pi+9)\). Note the considerable frequency overlap among these tuning ranges.

Table 2

<table>
<thead>
<tr>
<th>Advance time &quot;T&quot; (microseconds)</th>
<th>(2\pi n+1)</th>
<th>(f_0=(2\pi n+1)/(2T))</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>9</td>
<td>90.00 kHz</td>
</tr>
<tr>
<td>70</td>
<td>9</td>
<td>64.29 kHz</td>
</tr>
<tr>
<td>50</td>
<td>11</td>
<td>110.00 kHz</td>
</tr>
<tr>
<td>70</td>
<td>11</td>
<td>78.57 kHz</td>
</tr>
<tr>
<td>50</td>
<td>13</td>
<td>130.00 kHz</td>
</tr>
<tr>
<td>70</td>
<td>13</td>
<td>92.86 kHz</td>
</tr>
</tbody>
</table>

Extensions

For a receiver which is not linear (e.g., sampled/digitized or hard-limited), the strobe duplication and algebraic or electronic summation will be performed prior to such non-linear operations. The relation between the strobe duplication method of "notch filter" implementation and a non-linear receiver depends upon the specific class of receiver in use and is omitted from this short note.

While the use of the strobe duplication method discussed above does not result in Loran-C pulse shape distortion, this method does result in moderately increased (less than 3 dB) noise input to each signal parameter measurement loop. Typically, when adverse in-band or near-band interference is a significant problem, a 3 dB reduction in effective signal-to-noise ratio is tolerable in order to achieve the indicated results. Other filter characteristics (e.g., multiple notches) may also readily be synthesized; the basic principles are: the use of samples prior to the Loran-C pulse can shape the filter response while not affecting the Loran-C pulse envelope shape "seen" by the Loran-C receiver; strobe timing is economically controlled with high precision, accuracy and stability. Note that multiple use of the "advance duplicate strobe" method trivially provides multiple notches; one notch typically suffices operationally, for there is rarely more than one significant in-band interference source.

Other applications of this simple approach to "notch filter" implementation, including simple methods of allowing receiver detection of adverse interference (presence and frequency), multiple notch filter implementations, etc. will be readily apparent. Details will be offered at the 1985 WGA convention.
ABSTRACT

The LORAN-C story, spanning the last quarter century, reflects the efforts and imagination of the men who were dedicated to its achievement. Their growth and development is interwoven in the very fabric of LORAN-C.

This paper recalls the highlights of LORAN-C developments over the last 25 years, stressing the roles played by key personnel in advancing LORAN-C to its present worldwide status.

INTRODUCTION

Many historical reviews have been written about LORAN-C, espousing its beginnings, expansion, and, through the different generations of equipments, evolution from vacuum tubes to the present state of the art. However, none have adequately pointed out the key personnel and the roles they played, and after writing this paper I can understand why. Many, possibly thousands, have had some part in making LORAN-C the system that it is today. Unfortunately, only a few can be mentioned.

THE LATE 1950'S

1957

In 1957, we find Captain Loren E. (Zeke) Brunner had relieved Captain Colmar as chief of EEE with Bill Rohmer and Lt. W.O. Pete Henry also at Coast Guard Headquarters. Previously in 1956, the Air Force had decided they had no use for the Long Range Tactical Bombing System called Cytac. The Cytac chain consisted of three stations on the East Coast. The stations were manned by Sperry Engineers and Coast Guard personnel. Meanwhile, the Navy was looking for a precise navigation system to support the Polaris submarines. Captain Zeke Brunner saw the potential of LORAN-C for satisfying the Navy's needs, and brought it to their attention. This is the reason Captain Brunner is given credit as the Father of LORAN-C within the Coast Guard - because he planted the seed that started LORAN-C. The Cytac system was modified, and 2 of the 3 transmitting stations were relocated to provide the first LORAN-C chain for Navy testing. The stations were located at Martha's Vineyard, Carolina Beach, and Jupiter Florida.

Figure 1 shows the Cytac transmitter. The Cytac timers looked very similar to the FPN-30 LORAN-A Timers. A close look at Figure 1 and you can see the similarity to the FPN-39/42 transmitters.
1958

The LORAN-C testing for the Navy was going well and, around June or July 1958, the Sperry Engineers were removed from the Stations and Coast Guard personnel were to continue the operation. Within 24 hours, the chain was out of synchronization and (as luck would have it) while an important Navy operation was in process. The CNO contacted Captain Brunner to correct the situation. The results were that Sperry Engineers were recalled and LCDR Bill Fern was assigned the task of getting the system back in sync and ensuring that the Coast Guard personnel were trained to take over at a later date. Bill Fern became the 1st CO at LORSTA Carolina Beach. Bill Fern, in effect, became the first Chain Commander.

At some point late in 1957 or early 1958, the Navy was sold on LORAN-C. The idea for a LORAN-C Mediterranean (MED) chain had germinated. Sperry Corp. was contracted to build the First Generation Loran-C Equipment, i.e. the AN/FPN-38 Timer, FPN-39 Transmitter, and the AN/SPN-28 Receiver that utilized common printed circuit boards with the AN/FPN-38 Timer. Naturally, the MED chain was a top priority DoD requirement - which meant Sperry had to come up with equipment in less than a year. Coast Guard personnel started getting orders (February-March) to strange places like "TACK-1" with no location mentioned.

Some of the key Coast Guard (EE types) personnel were Lt. Al. Manning, Lt. Marty Groff, Lt. Court Pohle, Lt. Elmer Lipsey, Lt. Chuck Sanders, Lt. Bob Binler, CWO Archi Yano, CWO Cliff Brunner, and CDR. Dick Pasciutti to name a few.

Key Civil Engineering (ECV types) were Billy Ryan, Byron Jordan, Hugh Wyatt and ECV types on each station.

Lt. Al Manning was assigned as CO of TACK-1, the Master Station at Semeri Crichi Italy, Cliff Brunner to Mattraten Libya, CDR Dick Pasciuti (QA inspection at Brooklyn) was given the job of Equipment Acceptance Testing and later became the
1958 CONT'D

Exec. and Systems Engineer at Naples Italy. Court Pohle became the LORAN-C Projects Engineer at EECEN Wildwood and was responsible for getting the equipment installed and a training course started at EECEN. Elmer Lipsey was assigned the task of shaking the chain down - doing the calibration and declaring the chain operational. Of course, it wouldn't be proper not to mention the infamous LCDR Vic Sutton - the pilot who supplied the various stations from Naples.

The key personnel at Sperry during the beginning LORAN-C years were Walt Dean, Bob Frank, Will Frantz, Winslow Palmer, Al Phillips, Dalton Szelle, and Bill Rice, to name a few. If there were an official LORAN-C Who's-Who (and there probably is) both Walt Dean and Bob Frank would be at the top of the list. Both of these gentlemen have been with the system since the Cytac days and both have numerous patents pertaining to LORAN-C and, I might add, both are still going strong in the LORAN business.

The MED chain was underway. The Enginemen, DC and ECV types were constructing the buildings and getting power set up. Meanwhile, the ET types were going between Sperry and EECEN Wildwood, learning and testing the (1st Article) First Generation LORAN-C Equipment.

FIRST GENERATION LORAN-C EQUIPMENT

Between Christmas and December 31st of 1958, the First Generation LORAN-C equipment was shipped to Floyd Bennett Field for further transport to the MED Stations.

1959

On the morning of 3 January 1959, the rows of Aircraft (C-124s) were packed with MED Station equipments. The front loading ramps were open and waiting for the station COs and electronic types to climb on-board for the long flight across the Atlantic to their respective MED Stations.

On 11 February 1959, the MED chain was on the air. Quite a feat- to procure, design, produce equipment and get it running and on air in less than a year.

Meanwhile, the LORAN-C school at EECEN Wildwood was busy training replacement crews for the MED Chain and new personnel for the Norwegian chain. Some of the Norwegian chain personnel were with the MED chain crew getting hands-on training.

The AN/FPN-38 first generation timer was composed almost entirely of germanium transistors. A multitude of maintenance problems were incurred because of germanium's sensitivities to temperature and static discharges from probes. Captain Zeke Brunner decided the next generation of equipment would be wholly vacuum tubes.

During the fall of 1959, the Norwegian chain was installed using first generation (Sperry) equipment. Some training was conducted at Sperry and EECEN. Planning for the Alaskan and Hawaiian chains was in progress.
1959 CONT'D

The AN/SPN-29 (ITT) shipboard receiver was the prominent Coast Guard monitor receiver during 1959-62 and as late as the 70's on French Frigate Shoals. The SPN-29 receiver was also used by the Navy on its surface ships and some submarines. The SPN-29 receiver had vacuum tubes in the receiver IF, an electromechanical servo package that had a mechanical gearing system that only a watchmaker could love, and about 300 each 2N337 NPN silicon transistors. This receiver had a 60db dynamic range and could actually operate, as advertised, in a minus 20db signal-to-noise ratio. It required a good technician with a light touch, but was also one of the few receivers whose TD readings were reliable.

The gentlemen behind the design of the SPN-29 was Mr. Robert A. Reilly of ITT. Bob Reilly assisted in the development of the AN/SPN-29 receiver, the AN/WPN-2, AN/ARN-40, LORAN-B NAV. REC., Project Manager for the ARN-78 and responsible for the engineering of the AN/FPN-46 timer-synchronizer, just to name a few.

THE 1960'S

March 1960 - Al Manning returned to EECEN to lead the LORAN-C section which provided training to station personnel and also engineered the design of Field Changes to the equipments. CWO Cliff Brunner also returned to EECEN to assist in the equipment engineering functions.

1960 - Second Generation (Sperry) LORAN-C Equipment

In April of 1960, the Sperry-designed AN/FPN-41 timer and FPN-42 transmitter were delivered to EECEN. The AN/FPN-41 timer was almost wholly vacuum tubes, as Zeke Brunner had promised. The Hawaiian chain personnel were being trained on this new second generation equipment.

In late 1960, personnel for the Northern Pacific (Alaskan) chain were being trained on second generation equipment.

1961

In 1959/61, LORAN-B was installed and working (somewhat) in the North Carolina/Virginia areas. Pete Henry was the LORAN-B project officer. LORAN-B used LORAN-A frequencies and the phase-lock techniques of LORAN-C. In 1961, the LORAN-B chain was closed because of insurmountable technical problems. Many proponents of LORAN-B feel that with today's technology the system could work.

Pete Henry has been associated with LORAN-C for many years - first at headquarters, EECEN Wildwood and later retired as a civilian at CG Headquarters. Pete is well-known for his expertise in antenna design - both Pete and Ray Bateson did major design work on the Carolina Beach Tiptop Tower design and later Pete's design efforts on the SLT antenna.

In 1961, LCDR Jim Stewart came thru EECEN as a student enroute to his assignment as Chief EEE 17 District. LCDR Stewart, being very meticulous, learned every facet of the system, and the AN/FPN-41/42 equipments. LCDR Stewart personally ensured that all stations in the Northern Pacific chain were properly aligned and the personnel trained. LCDR Stewart developed much better alignment procedures than were originally available from the manufacturer. His dedication to duty on all assignments would eventually lead him to the rank of Admiral.

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Late 1961 A New Training Facility

With the number of chains installed and planned for the future, the number of students became overwhelming - space and time were at a premium at EECEN. On many occasions, engineering duties were performed at the end of the day or on weekends. You could teach all week and be told Friday afternoon that three SPN-29 receivers had to be repaired and aligned and ready for a plane pickup Monday afternoon.

The decision was made to separate the training and engineering functions; LORAN-C School would move into a new building at Groton, Conn. Lt Court Pohle became the Commanding Officer of LORAN-C School.

Lt Court Pohle, the Engineer, the Mathematician, the Instructor extraordinaire became known as Mr. Loran-C, a title bestowed upon him by the hundreds of students he taught over the next few years.

1962

Port Clarence Alaska Goes On-air: Additional coverage of the Northern Pacific and Bering Sea was needed. Port Clarence was selected as the site. From concept to output pulses took eleven months. Construction started on 21 June 1961. The station was commissioned on 29 January 1962. Lt. M.J. (Ned) Fontaine is in charge of the installation and becomes their first CO. This is the Coast Guard's first 1350-ft antenna, and has stayed up and is driven by a 42 transmitter. This combination develops approximately one megawatt peak power. Ned Fontaine finds constructing LORAN-C Stations to his liking.

The New Third Generation (ITT) LORAN-C Station Equipment. An entire CG advanced electronics school class, two EECEN personnel and a couple of LORAN-C instructors from Groton Conn. attend a training class at ITT taught by the Design Engineers, on the new Third Generation LORAN-C ground station equipment (FPN-44/45 transmitter and FPN-46 timer). The new generation equipment designed by ITT was a radical departure from the previous generations. The FPN-46 Timer was a hybrid affair (vacuum tubes/transistors) with electromechanical (servo) plugin packages for envelope and cycle readouts. The timers proved reliable.

The Transmitters AN/FPN-44 (400Kwatts peak) and the AN/FPN-45 (3 Megawatts peak) were walk-in transmitters 24' long x 12' wide and 48' x 12' respectively. The transmitters used combination air and water-cooling for the power tubes.

The ITT team, under the direction of James Van Etten deserves a "Well Done" for their extraordinary efforts in developing the third generation equipment in the limited time allowed by DoD. Some of the key personnel involved were: James Van Etten, Vern Johnson, Milton Dishal, Bob Rielly, Bud Ellis, Bill Garmany, Bill Rohmer, Claude Pasquier to name a few.

The Coast Guard Resident Inspector Lou Snell also helped in making the equipment a great success.

NWPAC Chain Construction Starts. Lt. Ned Fontaine goes to FESEC (1962-64) to oversee the NWPAC chain installation. Ned is also FESEC's Electronics Officer and COCO for the NWPAC chain. LCDR Ted Wojnar (ECV) is assigned (1962-64) as the NWPAC LORAN-C Project Officer and works out of Yokosuka Japan.
1962 CONT'D

LORSTA Sylt Goes On-Air. LCDR Manning and Lt. Flanders design and get the first DECCA Blanker working. Bill Flanders takes it to Sylt for installation and is assigned as first CO of Sylt, Germany. After getting the station constructed, they go on air for limited periods during the day. Bill remained CO for the next three years. Joe Walsh was the on-site Sperry Representative.

The SPN-30 LORAN-C Receiver. Early in 1962, the Coast Guard procured the SPN-30 LORAN-C receiver from Collins Radio Corp. TX. The SPN-30 was completely solid state and modularized. The ease of maintainability was a major design criteria. The man behind the design was Norm Dickerson. Norm would later spearhead the low-cost receiver group at LITCOM. Arnie Goldman from Sperry also became a part of the LITCOM receiver group. Norm Dickerson is presently VP of Engineering at AMECOM.

1963

The Submarine Thresher Incident. In April of 1963, the first FPN-44/45 and 46 class at Groton, Conn., and their instructor went to EECEN Wildwood to assist in around-the-clock acceptance testing of the equipment. Each man was assigned to various NWPAC stations. W.O. (Pete) Henry was CO of EECEN, and LCDR Manning the Engineering Officer. The acceptance test didn't go as planned. The new transmitter didn't normally stay on the line very long before multiple failures occurred. When the AN/FPN-44/45 failed it was like a Fourth of July event. Resistors would blow up, and capacitors would overheat and expand beyond their original containers. The Litz wire output tank coil would literally blow the end connectors off like an exploding cigar and start burning. In this time frame, it wasn't enough to be a technician/plumber, you also had to be a fireman. Re-engineering went hand-in-hand with the acceptance tests. After such a dramatic account, it should be explained that this is what happens when a new generation of equipment gets pushed out the doors too soon, because of a priority DoD commitment.

The acceptance tests were cut short when the Navy submarine Thresher went down with all hands off the east coast. The ships trying to locate the Thresher needed an accurate positioning system for repeatability. LORAN-C was the best choice, however, they couldn't read Jupiter Florida's signals. This is when EECEN Wildwood came on the air. The LORAN-C instructor was retained to help keep the various equipment working and six students were also retained for watchstanding duties. CDR Edwards became Chain Commander at Carolina Beach. Lt. Jim Culbertson ran the show at Wildwood and a show it was. Just imagine a LORAN-C station with no standby equipment of the same type, i.e., only one each 46 TMR, 41 TMR, 39 XMTR, 42 XMTR and a new unproven 44 XMTR. You start off with a 46/44 combination and soon a 41/42 would be needed - the watchstanders would have to switch timer rooms and insert the proper ETA correction for the time difference between equipments in different rooms. The 46 TMR (with difficulty) would drive the 42 XMTR, the 42/39 XMTRs were used interchangeably with the 41 TMR. CWO Bob Imler, previously the first EMO at Rhodes GK and now at EECEN, is a major factor in keeping the equipment running during the marathon. Bob Imler later retires and becomes a much-needed stabilizing influence at EECEN.

About a month later, the remaining members of the first FPN-44/46 class went to FESEC. These men were unequivocally the best trained watchstanders ever produced.
In July 63, Lt. Bill Roland, a newcomer to LORAN-C, was assigned to EECEN from Monterey and stayed at EECEN LORAN-C Branch until June 1966 when he departed for the new SEASEC LORAN-C chain.

NWPAC Chain - In 1963, the NWPAC chain went on the air. Late in 1963, a typhoon struck and the tower at Iwo Jima was twisted at about the 650 ft. level and a guyline snapped. The guylines were retensioned to straighten the tower. The tower would wait for contracted repair in 1964. The Yap tower also had a problem at about the 700 ft level where the tower contractors had used the wrong bolts but continued to build the tower upward.

1964

In 1964, the Yap tower was forceably lowered and fell - the equipment having been previously removed from the transmitter building. The Yap tower fell in a circle around the building causing no damage. The tower at Angissoq Greenland also circled the transmitter building when it fell.

In July 1964, the Iwo Jima tower fell without warning at 10 AM, with three commercial tower crewmen working at about the 650 ft level. Lt. Ned Fontaine (FESEC Electronics Officer) was going to climb the tower that morning but had decided to check on something else first. Two Coast Guardsmen and an ITT person were changing the transmitter Nr. 1 output tank from Litz wire to welding cable. The Senior LORAN-C Coast Guardsmen told them to take a coffee break.

While they were at coffee break, their modification was checked over. Not 10 minutes later, disaster struck - the tower fell, killing the three tower crewmen and a Coast Guardsman trapped in the battered transmitter building. It was a devastating accident. Transmitter Nr. 1 (under modification) was 60% demolished. LCDR Wojnar was part of the team that investigated the cause of failure. The tower crew had used the wrong procedures for removing the crossbraces. Figures 2 and 3 illustrate the remains of the tower.

Figure 2 Figure 3
1964 CONT'D

LORSTA Marcus took over as master, with Iwo Jima as system monitor. Both Yap and Iwo Jima were back on the air in January 1965.

In 1964, CDR Al Manning departed EECEN and was assigned to Acteur from 64-67.

MIDSIXTIES - During the midsixties, another prominent milestone occurred that should be recognized. Mr. Ed Bregstone joined the Loran-C family as Technical Assistant to Chief of G-EEE4. Ed Bregstone - Super Engineer and Mathematician lent his genius to solving the complex problems of the day.

LORAN-D

In 1963, CDR Elmer Lipsey developed the LORAN-D concept and convinced the Air Force that it would be an ideal Navigation System for tactical purposes. In 1964, Elmer retired from the Coast Guard and went to work for Sperry to help make his concept a reality.

In the fall of 1964, a small group of six Coast Guardsmen were hand-picked by LCDR Court Pohle and LCDR Guy Mizel for the three future LORAN-D Stations. Those men selected were Lt. Paul Pakos, Lt. Gary Bush, Lt. Jim Booth, CWO Bo Branch, CWO Larry Brown and CWO L. Sartin. These six men plus about fifty (50) Air Force, Army and Coast Guard officers and enlisted were taught LORAN-C/D systems at Groton, Connecticut by a Coast Guardsman. After the systems training, Sperry engineers taught the LORAN-D (TRN-21) timing equipment. Most of the Coast Guardsmen returned to their original duty stations until the equipment was developed and available.

1965 The principal people in LORAN-D at this time were LCDR Court Pohle, (CGHQ) LCDR Guy Mizell (CGHQ) Lloyd Higginbotham (ESD) and Dan Redding (AF, Wright Patterson) and Dick Jones (RADC). These men were the driving force behind LORAN-D.

At Sperry, the principals were Elmer Lipsey (CDR, Ret), Walt Dean, Bob Frank with the Avionics package and Bob Butt, Sam Claypoole and John Walsh with the ground station equipment. In 1965, one Coast Guardsman was assigned temporary duty at Sperry to inspect and test the Avionics AN/ARN-85 and ground station equipment (TRN-21 T/S and TRN-39 XMTR) to ensure the equipment met the design specifications. Bob Frank ran the Avionics program with Al Phillips and an aspiring young engineer by the name of John Currie.

Garland King, Major US Army, was also assigned to Sperry. Maj. King, a LORAN-C experienced pilot with two (2) tours in Vietnam was assigned the task of test flying the various aircraft on which LORAN-C was installed. Major King also suggested many improvements that were incorporated into the equipment. Major King recounted many stories of using LORAN-C over the jungles of Vietnam. On more than one occasion, he recounted trying to use DECCA signals (at night) to find his way back to camp in a helicopter. He was elated when LORAN-C replaced DECCA in Southeast Asia. Upon leaving Sperry, LCOL King went to Vietnam on his third and last tour. LCOL King was testing a LORAN-C backpack receiver on one of the Swift Boats and was killed that day. LCOL Garland King was a staunch supporter of LORAN-C. He won't be forgotten.
The Avionics package and the TRN-21 timers at Sperry passed with flying colors, but the Westinghouse Solid State (SCR) transmitters had problems and were about a year late. The original LORAN-D group members were reassigned and later a new group was reorganized - this new group partially consisted of LCDR Guy Mizell, Wayne Williams, Tom Lloyd and Larry Brown, to mention a few.

1966

LCDR Ned Fontaine continued to build LORAN-C stations and, in January 1966, he was at SEASEC starting the construction of the SEASEC chain. CWO Bo Branch also played an important part in the installations. In June 1966, LCDR W. Roland was assigned to Bangkok as Electronics Officer and Chain Commander for the SEASEC chain. The chain was on the air in September of 1966.

Ned Fontaine left SEASEC in the fall of 1966 and started the construction of the Dana Indiana station. Bo Branch and Jim Booth, the first CO, assisted Ned Fontaine.

ACTEUR was also busy with CDR Manning and LCDR Bruce Baren (ECV) adding Cape Race, St. Anthony and Shetland Islands to the North Atlantic Chains. The engineering innovations and techniques used by CDR Manning to upgrade the equipment and chain operations led CDR Manning back to the LORAN-C driver's seat at EEE-4 HQ, the Systems Development branch. CDR Manning relieved CDR Matthews in 1967.

A major addition to the LORAN-C family occurred. Lt. Don Feldman arrived at EECEN from MIT. There's not enough time or space to list all the major improvements that Lt. Feldman made to LORAN-C. Don is best known for his COLAC Timers and later LRE. Don indicates that the MSI chips from the 9600 family by Fairchild made COLAC/LRE possible. A subsequent test of solid state P-Gen at Nantucket by he and Bill Mooney was the start of LRE. Don is also known for his atmospheric noise model-which, for all practical purposes ended the debate about how you process signals. Don went back to MIT to get his Doctorate - Doc. Feldman's genius was felt in most of the forthcoming endeavors with LORAN-C.

1967

During 1963-67, CDR Carl Matthews was Branch Chief of the Systems Development Branch (EEE-4). In 1967, CDR Matthews assigned Lt. Paul Pacos and L. Sartin under LCDR Bill Kohl to write the initial TRANSLOC specifications. In May 1967, the initial version of the TRANSLOC specs was finished and a group of experienced LORAN-C types was brought in from the field to Headquarters to review and comment on these initial specifications. This group of LORAN-C experts found the initial specs not to their liking. A new branch was formed under the supervision of W.O. (Pete) Henry (then a civilian) with CDR Bill Kohl as Branch Chief. Lt. Bill Flanders and Jim Alexander, among others, were assigned to this new branch. This new branch was assigned the task of developing a new set of specifications for a competitive contract.

Meanwhile, DoD realized that TRANSLOC would be a long-term program (little did they know) and they needed something right away to fill an immediate need, thus the Air Transportable LORAN-C System (ATLS) was born to meet the quick reaction capabilities required by DoD.

During April 1967, CDR Matthews set the ATLS requirements for the FPN-44/46 to be repackaged - modified for air transportability and installed in 18-foot shelters, two (2) shelters per C-130 aircraft. CDR Matthews assigned L. Sartin to design the system and write the specification.
During this time frame, Capt. Flemming was Chief of EEE and CDR Jim Stewart was Assistant Chief EEE. CDR J. Stewart became Chief of EEE during 1968 and CDR Al Manning became chief of System Development Branch (GEEE-4). If one person had to be picked who epitomized the title of Mr. Loran-C, and had done more to effect the continuous growth of Loran-C to the system it is today, that person would be Admiral A.P. Manning - ADM. Manning's tireless dedication has been a source of inspiration for those who have followed.

The ATLS System package was designed and the specification was written. A competitive contract was awarded to LITCOM for four station sets. Two of the primary LITCOM engineers were Adek Winger and Milton Pomerantz. The transmitters required numerous modifications for increased reliability.

1968

In 1968, LORAN-C took another leap forward when the foresight of LCDR Roland suggested that the only way for LORAN-C to become acceptable to the civilian populace would be if low-cost receivers were available. In the summer of 1968, LCDR Roland was assigned to Headquarters to head the Low-Cost LORAN-C Receiver program.

1969

In September 1969, the first ATLS station was installed at Tan My Vietnam, which was located approximately 25 miles south of the DMZ and 15 miles east of Hue. LCDR Bruce Baren was the on-site Civil Engineer who got the station constructed, LCDR Geoff Potter was the HQs ECV project manager, and Bill Roland was in charge of the electronics installation. LCDR, Tom Noland was the SEASEC Electronics Officer. Figure 4 illustrates the Tan My ATLS site from the antenna.

![Figure 4](image)

1970

The LORAN 70's plan was generated - which gave new direction and meaning to the LORAN-C system.

The LRE was installed in all the chains and the transmitters were automated. This meant much greater reliability and eventually less manpower - a giant step in reducing the station's complement. Ray Alteri (ECECN) and CDR Jim Blake (EEE-4) install the first LRE in the MED chain.
1970 CONT'D

May 1970, Megapulse demonstrated the SST 1/2 Generation concept to the Coast Guard.

1971, The Low Cost LORAN-C Receiver program made a giant stride when two contracts were awarded to Teledyne (TD-601) and LITCOM (LCR-301).

1972, The Wild Goose Association (WGA) (a name suggested by Vern Johnson of ITT) was formed, with Lloyd Higginbotham elected as the first WGA President.

1972, An ATLS station is installed at Lampadusa. Lt. CDR. Geoff Potter (ECV) oversees the installation. Lt. Bob Bhend (G-EEE-4) supervises the electronic installation.

In 1972, The Air Force LORAN-D chain is relocated from Southeast United States to Germany under the program name of "Mystic Mission". CDR Tom Noland, USCG, is the Liaison Officer to the Air Force. A paper by Mr. Rockwell on the LORAN-D complex can be found in the WGA 1978 proceedings.

1972, The MED chain calibration occurs using SPN-30 receivers, satellite receivers and manpack receivers worn by those infamous scientists of propagation fame - Robert Doherty and Ralph Johler. The time difference predictions for the various monitor points developed by Bob and Ralph were found to be very accurate and helped with the initial lock-on of the SPN-30 receivers.

In 1974, LORAN-C was selected as the primary civilian NAV system in connection with the newly-accepted Coastal Conference Zone around the U.S..

In 1975, one of the first automatic remote control links for LORAN-C was installed between Kamaeya on the Mainland of Honsau Japan and Gesashi Okinawa. The data link was composed of Microwave, VHF Troposcatter and hardwire communications between the various islands, between Okinawa and Japan. With a model 28 Teletype at each end, CD/LPA were automatically inserted in the Gesashi Equipment. The only thing keeping it from working continuously (besides communication outages) was each end telling the other that he had control.

In 1977, The U.S. West Coast Chain, Canadian West Coast Chain and Gulf Coast Chains, and Seneca, N.Y., were added to get coverage required by the Coast Confluence Zone. A well-written paper by Lt. Richard Harvey on the West Coast LORAN-C can be found in the 1978 WGA proceedings.

The work accomplished by Jack Lagon, Dave Olsen and Andy Sedlock with the St. Mary's River project gave new meaning to the methods used in calibration.

THE EARLY 80'S

1980 - Baudet MN. goes on the air to complete the Great Lakes chain.

Thus far the early 80's have seen a slowdown in U.S. Military interest in LORAN-C - everyone seems to be waiting for the advent of GPS. However, not everyone's putting all their eggs in one basket - the international LORAN-C market seems to be growing—they understand the need for an accurate backup system even in the event of a GPS system. The following chains are either in operation or contemplated.
The Suez Canal  
Saudi Arabian Chain  
French Stations  
Possible Norwegian Expansion  
Possible Chinese Stations  
Additional Canadian Stations  
Possible MID-Continent Expansion for Civil Aviation

Conclusion:

I talked a lot about the past and mentioned some of those key individuals who played a leading role in making LORAN-C what it is today — this is not to say those of you out there (the younger generation) won't and aren't making it better — however, you do have one hell of a challenge "from the past".

I apologize for not being able to list the many more people who helped and are helping to make LORAN-C the NAV system of the 80's. However, there is one group of individuals that are never mentioned and they are the thousands of Coast Guardsmen who stood 24 hours a day vigil (mostly on isolated duty) maintaining the signals in synchronization to meet the accuracy requirements. Most non-military types (industry and users) can't comprehend the dedication and emotion involved with the Coast Guard LORAN-C Station personnel in maintaining their station on-air, and in-sync. You have to be there and hear an alarm for "jump sync" or generator output power reduction and watch the people pour out of the buildings at full speed — some times half-dressed at 2 AM — running to the timer or generator room to get their signal back on-air or in-sync. The LORAN-C System has become what it is today because of their dedication to duty.

Acknowledgements: Much appreciation is given to Admiral Manning, Captain Bill Roland, Elmer Lipsy and Bill Flanders (to mention a few) for helping out with the early history.

BIOGRAPHICAL SKETCH

Mr. Sartin joined the LORAN-C group at EECEN Wildwood in 1960. Since 1960, until he retired from the Coast Guard in 1979, he was associated with LORAN-C in one capacity or another. Mr. Sartin, who taught LORAN-C Systems and Equipment Theory for several years, was the Calibration Officer for Phase I of the East Coast Chain in 1966 and the MED Chain in 1972. He was assigned to the Air Force LORAN-D Program in 1964. He was principal designer of the ATLS system, and assisted with the ATLS installation at Tan My, Vietnam. He helped develop the initial TRANSLOC Specs, ATLS Specs and the SST Specs. He and his students helped in the construction and installation of the Northwest Pacific (NWPAC) Chain (1963) and later (1975) the installation of LRE and Transmitter Auto-Switching for all NWPAC stations. He was also the Electronics Officer and COCO for the NWPAC Chain. He is a charter member of the WGA and was convention chairman in 1984.

Mr. Sartin has worked for ASE (Analytical Systems Engineering Corporation) since 1979.
SESSION V
PANEL DISCUSSION

SUBJECT: POSSIBLE CHANGES TO
THE LORAN-C SYSTEM TO IMPROVE
ITS VALUE TO THE AVIATION COMMUNITY
SESSION V
POSSIBLE CHANGES TO THE LORAN-C SYSTEM TO IMPROVE ITS VALUE TO THE AVIATION COMMUNITY

William Polhemus, Moderator

PANEL MEMBERS

Bill Polhemus  Neil Blake  Arnold Stymest  Ken Foret  CDR Bill Schorr
George H. Quinn

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Mr. Polhemus: Welcome to our panel discussion. Our topic this afternoon is "Possible Changes to the Loran-C System to Improve Its Value to the Aviation Community". To start with I'll tell you who each of the panel members is - then I'll go through a formal introduction of Mr. Neil Blake, Deputy Associate Administrator for Engineering for FAA. I'll ask him then to present his remarks - I'll then follow that with some more very brief words to set the scene for the panel to begin interacting with you on the issues that may be of interest and concern either to our FAA friends or to you in the audience. I would like to set the tone of this get-together in the following way:

We have observed a very marvelous and growing sense of enthusiasm at FAA about the potential of Loran-C. As you participate today I want you to think of these gentlemen as having joined us at WGA believing in what Loran can do; well aware of its performance and capabilities from the maritime world; but on the basis of many, many year's of hard knocks and hard study and expensive implementation, knowing full-well what the risks are in bringing a new system into the aviation world. There are different types of people; the risks are very high; when things don't work, you can't heave-to and decide what's wrong when you are in an aircraft. It is a very dynamic world up there and the solutions you reach for those problems you may observe have to be solved enroute, on time, and without confusion.

The gentleman on my immediate left is Neil Blake, most of you know of him - some of you know him as a professional friend. He is Associate Administrator for Engineering and in that capacity leads us in what we do in this country in the process of bringing Loran-C on-line. Next to Neil is Arnold Stymest, he is the Director of Aeronautics for the state of Massachusetts and today he will be filling in as representative of the user. He has with him a copy of the resolution that was passed the week of the 15th of October by the National Association of State Aviation Officials and I think you will find that resolution of great interest. To his left is Ken Foret from Off-Shore
Mr. Blake: I want to thank you very much for inviting us here today. I've had the opportunity to also fly in the mountains of Vermont, somewhat earlier in the game, and also to use Loran as a marine navigation aid and at all times it has performed extremely well. Loran-C as you may know is currently approved as a supplemental navigation aid for enroute and terminal flight operations covering approximately two-thirds of the contiguous United States and parts of Hawaii and Alaska. The supplementary approval, which is described in FAA's Advisory Circular 20-120, requires that pilots using Loran-C for navigation must also have an approved alternate means of navigation aboard the aircraft. This requirement was imposed at least in part because Loran chains, while they are extremely reliable, do not have redundant ground station locations to provide backup coverage everywhere should there be momentary or long-term station outages. Now use of Loran-C in the United States has grown extremely rapidly, particularly in the last several years, and the Aircraft Electronics
Association estimates that approximately 15,000 aircraft and 700 helicopters are now equipped with Loran-C avionics. Certainly the availability of low-cost avionics has greatly spurred the use of Loran-C, particularly within the general aviation community. And this increasing use has also lead to requests by aviation organizations and state transportation officials for closure of the "mid-continent gap" and approval of Loran-C for non-precision approach use. State requests have been received from New Mexico, Oregon, Washington, North Carolina, Ohio, Vermont, North Dakota and from the National Association of State Aviation Officials. We have also received expressions of interest and cooperation from our Canadian friends who have asked us to assist in flight checking and determining the signal quality of the Loran signals throughout Canada and northern territories. Also, members of the United States Congress have indicated an interest in our FAA Loran-C program. So there is extremely widespread interest in the program and, of course, within the user community itself; particularly the helicopter operators. As a result of this rather substantial interest in expanding the use of Loran-C systems, the FAA administrator, Admiral Engen, has stated publicly and I quote:

"In the past, the Federal Aviation Administration has taken a rather passive approach to Loran-C. I recently directed that we advocate its use and work to expand Loran-C coverage and utility for aviation. I've designated Loran-C as an interim supplemental radio navigation system for aviation and assure you that Loran-C will receive more attention."

Now the FAA has taken a number of actions since the Administrator's designation of Loran-C as a supplemental system. I think a significant one is the announcement of a FAA Loran-C policy, and this policy states that Loran-C is an interim supplemental radionavigation system for national aviation use. The FAA advocates completion of Loran-C coverage for the contiguous United
States. The FAA will request the U. S. Coast Guard to provide single coverage Loran-C service over the contiguous United States suitable for safe aviation use. The FAA will establish criteria for Loran-C non-precision approaches and implement these approaches at locations meeting the criteria when this policy is in agreement with the DOD and DOT radionavigation policy as it is stated in the Federal Radionavigation Plan and is to be pursued within that general context. Our status on that policy statement: It's pretty much finished with the coordination within the Office of Secretary of DOT and they have expressed general support. We don't have the final concurrence back, but we expect it shortly. The FAA is currently engaged in activities in support of this policy statement. These activities could result in implementation of additional Loran-C stations. (If you would show the first viewgraph) to close the "mid-continent gap" and also in the definition of procedures, equipment standards and criteria that could lead to the establishment of non-precision approaches at airports where Loran-C signal strength and station geometry could support such operations. This viewgraph, one we showed yesterday, shows not current coverage but the way the coverage will be after some proposed Coast Guard improvements, largely increases in power at a number of stations, are made to the existing network of stations. A study is currently underway at the Transportation Systems Center here in Cambridge to determine the number of Loran-C stations required and where to locate them. And this, of course, would be to provide single level coverage for enroute and terminal IFR use over the contiguous United States and the Gulf of Mexico. You heard about some results of the study yesterday from Janis Vilcans. This is a slightly different one which (on the next viewgraph) shows the coverage as it would exist at the one-to-three signal to noise level with the implementation of five new stations; these are in Montana; Grosse Creek, Utah; Cheyenne, Wyoming;
1986 PROPOSED LORAN-C COVERAGE

COVERAGE WITH 5 NEW 400KW STATIONS
Chandler, Oklahoma; and Meadow Vista, New Mexico. The study only addresses the use of Loran-C for enroute and terminal navigation. Preliminary results, I think, pretty much indicate that five stations will fill the majority of the "mid-continent gap." While completion of Loran-C coverage in the enroute airspace of the 48 states requires primarily government actions to procure, install and operate five new stations, achievement of the non-precision approach capability in all the domestic airspace would require modification of a number of existing stations and possibly require installation of additional ones. Such a program, however, would involve a substantial upgrading of the current system, so our approach has been somewhat different and has been to establish requirements for ground signal coverage and avionics capabilities that would be needed to support use of Loran-C for non-precision approach, then to examine the existing Loran-C coverage as modified by the new stations to determine the areas where signal characteristics would meet the requirements for approaches. And generally, the results of this activity indicate that non-precision approaches could be conducted throughout much of the Eastern United States and some of the West Coast using signals from the currently available stations. Such approaches should be possible throughout the contiguous 48 states when coverage is supplemented by five additional stations in mid-continent. Now the results of the studies and tests that have been conducted to date have established the following requirements for non-precision approaches:

- Signal strength must be at least one-to-one compared to the one-to-three level that has been judged satisfactory for enroute and terminal applications.
- Station geometry must provide good crossing angles for the time difference lines — fairly obvious one.
Seasonal corrections must be applied to the basic time difference computations. These corrections would be provided on the approach plate and would require the pilot to enter them before the start of a non-precision approach unless they came pre-stored within the Loran-C equipment.

A network of monitor stations would be needed to provide the information database to determine the time difference corrections. These same stations could also warn of station outages or signal anomalies. As currently envisioned, the monitor network would consist of approximately 160 stations for the contiguous 48 states located such that one or two would be within a hundred miles of any airport. And, of course, the monitoring network is not looking only for total failures but for signal out of tolerance conditions.

Approach procedures must be prepared for a substantial number of airports. Now FAA currently lacks the inhouse staff to perform this function and is evaluating, for the first time really, the use of contractual services to do at least a portion of the task associated with the establishment of Loran-C approach procedures.

Avionic standards must be developed. Many of the currently existing sets we do not believe are adequate for use on non-precision approaches. The RCTA Special Committee 137 is specifically addressing this area.

Now in addition to these activities some other improvements are needed in the current Loran-C stations and this, of course, includes things like reduction of momentary outages. This, of course, is particularly important when Loran-C signals are going to be used for non-precision approach service. An adjustment of the time delay for initiating a blink condition is also need to be certain that pilots are warned of out-of-tolerance signal conditions within hopefully 10 but no more than 15 seconds of their occurrence. And ten seconds represents the time between the occurrence of the anomaly and the pilot warning that is being used in our current VOR/DME system. In establishing the criteria for non-precision approach use of Loran-C, FAA has identified as one of the requirements the need for one-to-one signal to noise ratio. This requirement, after the additional five stations have been implemented, would permit
non-precision approach capability generally as shown in the white areas on this viewgraph. And as you can see, even with the new stations installed, there are still significant areas within the United States, particularly in the Southern part - some in the Rocky Mountain areas, where the signal to noise ratios are still below the desired one-to-one level. While this level appears adequate for enroute operations, that is the one-to-three level, it creates concerns about cycle slips and other problems on approach applications, particularly in areas where frequency interference problems may exist. Now I have to say that the selection of the one-to-one signal to noise level was based in part on sensitivity and processing capabilities existing in the avionics and marine receivers which were designed several years ago, when this activity was undertaken. And as I noted a moment ago, the RTCA committee has initiated work on developing a minimum operational performance standard for Loran-C receivers that will include standards for enroute, terminal and non-precision approach use. The receivers built to the new standard will, we hope, provide improved sensitivity and special processing features that will minimize the probability of problems occurring and hence, it may be feasible to operate safely at lower signal to noise ratios. And the benefits (and we can show the last viewgraph) - the benefit that will accrue, of course, is in terms of greatly increased areas where non-precision approaches can be conducted. And I think you can see that from this viewgraph which is the one-to-two signal to noise ratio that we could essentially - if we can achieve the desired receiver capability -- cover the contiguous United States. So the benefits of expanding Loran-C coverage and certification of its use for enroute, terminal and non-precision approach we believe are many. State governments certainly see the possibility of having non-precision approach capabilities at a substantially increased number of airports that currently do
not qualify for any type of non-precision approach aid. The availability of instrument approach capability is seen as a positive boon to development of industry within many states. State interest has been at a high level for a very long time with some states even investing some of their own funds supporting our Loran-C evaluation programs. Of course, we appreciate that aid very much. Expansion of the use of Loran-C is seen as a needed improvement by commuter air taxi and business aircraft operators, using many of the smaller general aviation airports not currently equipped for instrument approaches. Helicopter operators, that certainly includes our own Coast Guard, are making extensive use of Loran-C for both low altitude and off-shore operations. The demand for increasing IFR service is increasing all the time. So much so, in fact, that we have been examining the possible use of dependent surveillance techniques in the Gulf of Mexico area. The system that we have had under test for some time uses VHF links to relay Loran-C position information sensed onboard the helicopters to the Houston Air Traffic Control Center. The tests to date have been conducted on an experimental basis and we were delayed somewhat in completing them due to the controller walkout, but the staffing is getting up to the point now that we can begin an operational test soon.

So in summary, the FAA is proceeding with plans, at least, to expand the Loran-C coverage in use. And as I mentioned earlier, these plans are currently entering the coordination process and I think we are getting toward the end of the internal one. If approved there, and we expect it will be, we have other hurdles to get over - one being the Office of Management and Budget and the Congress; and of the two, I think the Office of Management and Budget is always the more difficult one. Nevertheless though, the support of the user community, particularly general aviation and the helicopter segment has been
extremely strong...also the state government support. We believe that interim use of Loran-C as a supplemental navigation aid will fill the need for navigation and approach services that could not be met economically with any other system. But I have to say in closing, in the longer term, we are talking the late 90's or early 2000's. We do see the possibility that aviation use of Loran and Omega may be ultimately phased out when an expanding GPS system is available and, of course, when the cost of the user equipment gets down so that it is competitive with current receivers of all types.

Mr. Polhemus:

I feel a little bit awkward here at the moment trying to fit what should now be the question period for Neil Blake and the need to introduce our other panel members, so if you will bear with me, if it does seem a little awkward to you, don't tell me about it. I'd like to take just a moment to tell you a little more about your panel members. Each has spent a long time in aviation and deserves to be known to you.

Arnie Stymest, Director of Aeronautics for Massachusetts, has been very active in the aviation world here in New England for more than 20 years beginning as an instructor, airport manager, and working at successively more responsible jobs here in New England. He knows intimately the problems of the fixed-base operator, making an airport successful and profitable, stimulating aviation and the like, and ultimately arriving at his present job as Director of Aeronautics, which he undertook beginning in March 1980. Of considerable significance to us today here at the meeting is the fact that Arnie is regional vice president of the National Association of State Aviation
Officials and also a member of the Executive Committee of NASAO and I am hopeful that he will tell us a little bit about a resolution that was passed, as I mentioned earlier, just two weeks ago.

Commander Bill Schorr has given me a marvelous resume — it goes on for at least three lines — and he threatened me with dire consequences if I tried to expand on it, but I think he deserves the plaudits of all of us here for the manner in which he handles the coordination of information and the support I am sure he has given to many of you out there — he certainly has to me — each time I have run aground on some little technical problem or some little administrative problem. He is located, as you know, at Governors Island and as far as I can understand, he is the one that carves up the lines of position every morning and makes sure we have fresh LOPs to use. I am sure we will all benefit considerably from Bill's comments, particularly in regard to the problems of supplying an adequate warning signal in the event that on a rare occasion a transmitter does experience a momentary reduction in performance or outage.

Ken Foret has a very interesting flying background — flew as a chief petty officer in the United States Coast Guard as an AT, and then later left service, graduated from college in the New Orleans area, joined Off-Shore Navigation, Inc. in the late 60's and has been with them since then pioneering many of the procedures that are today common practice in that area. He has flown with us up in the Vermont area and is an experienced crew member in so far as making sure his equipment and the Loran community sees the best side of RNAV systems.
George Quinn has been with the FAA since 1961 - eight of those years located at the Technical Center in Atlantic City, NJ - the place we used to call NAFEC. So he has a very strong background in the problems of installing, integrating and making systems work. He understands from the operational side as well as the staff side the difficulties of bringing new systems on-line. Since the mid 60's, he has been closely associated with all activities at FAA concerned with Loran-C; and as I mentioned earlier, he has been active in risking his life and limb in many of the expeditions into the northern United States.

So with that I have introduced my panel - I'd like to take one brief moment to tell you from the user side what we see as the economic benefits deriving from full implementation of Loran-C.

I mentioned to you yesterday in introducing some of the papers from authors around the country - one of them Dr. Bob Lilly of Ohio - that the state of Ohio had been very aggressive at bringing along airports that would stimulate communities in each of Ohio's counties; and in the process over an extended period of time, like 10 years I guess, some 82 airports were brought on-line as jet qualified airports - that's Lear jet class aircraft. After about five years of this activity, the Department of Transportation conducted two independent studies to determine what economic benefit to the state and or counties might accrue from this rather expensive enterprise. I give you here the numbers from their reports based on comparing progress (these are relative numbers now) in 13 counties that had participated in the project versus a similar number in the state that had done nothing special in the way of upgrading or implementing airports. You can see the economic impact is very substantial. Now a good part of the problem or the success of the project
depends upon the availability of aids that will allow use of the airport under its instrument conditions. In Oregon, the state has been very helpful in taking a look at its own problems, own operational needs, and determining the priorities that might be established if it were to be given assistance in developing non-precision approaches using Loran-C and they summarized the situation for FAA with this table I have given you up here. I might point out that the difference between public use airports and private use is the fact that under private use, as you would imagine, the state theoretically and/or the federal government, has no responsibility for implementation or payment of aid, but there is a subtlety to this that is worth considering. Within the set called private use you have many, many heliports and as I have indicated, 25 in Oregon, presently associated with hospitals. So there is a social benefit side to this activity that one can't turn away from. If we want the full benefit of emergency medical services, helicopter borne emergency medical services, and that's a very fast growing service in the country, we are going to have to make sure that these people can get into and out of the airport. From the standpoint of users as Neil pointed out, we think at the moment there may be 15,000 to 16,000 receivers airborne. Oregon took a look at its own situation - sent out 4,880 questionnaires, received a response ratio of 59% which is a very, very good sample. As you can see from this, out of that set, 1,435 respondents indicated that they either had Loran-C on board or intended that they will have Loran-C equipment before the end of the twelve months of the querie - that's like July or August of this year. By July/August 1985, then, the expectation is that there might be as many as 1,435 aircraft operating out of Oregon or within the borders of Oregon equipped with Loran-C RNAV. Another aspect of this might be of interest both to FAA and you gentlemen out there. Among those who presently are equipped, more than
OREGON:

111 PUBLIC-USE AIRPORTS
5 PUBLIC-USE HELIPORTS
5 PUBLIC-USE SEAPLANE

206 PRIVATE-USE AIRPORTS
83 HELIPORTS
(25 HOSPITALS)
1 SEAPLANE

11 PRECISION APPCHS
14 NON-P APPCHS

LORAN-C EQUIPPED AIRCRAFT (OREGON)

4880 OWNERS/REG ACFT
328 ACFT NOW EQUIP'D
327 TO EQUIP < 6 MOS
780 EQUIP 6-12 MOS
1435 POTENTIAL INSTALL

29%
one-third indicated that they are already using Loran-C for non-precision approaches. So this is an area where despite the fact that the total system isn't ready to publish procedures and work out the formal aspects of it, there is a reality that we can't ignore. I'll present one more graph and then we will jump to our panel. Here is a summary of what we think the economic benefits might be from full implementation of Loran-C RNAV and it can be RNAV in general, it doesn't have to be Loran-C, but RNAV capability that we are allowed to use from ground to ground anywhere we may wish to go. The results come from two studies; one done by a commuter airline in Canada (Norontair) and a second from a study completed for the National Research Council but using the same database that we use for our own studies here. You will notice that if we talk about enroute, I call it direct routing, the level of benefit that is anticipated is a function of the class of user; local service carrier, air taxi charter, business-use general aviation; and there are then the phases of flight recognized - enroute or direct routing to terminal area where we make a pattern of non-conflicting or non-competitive approaches, departures and holding patterns. Finally, the precision approach or non-precision approach capability. Lastly, once we have the capability to measure very accurately speed and position, we can begin to look at flight management on a much less costly basis than many of the systems which are currently going into the more expensive business jet. The bottom line being that there is good reason to believe that the overall benefit to the aviation community can be something between 8-20%. Yet we are laying it on at about the 8% region so that, to us, is the message that needs to be taken to OMB. That, if you wish, converts to 8% of the fuel and the time dependent element of operating cost. And we run these numbers through in terms of U.S. population of aircraft and when fully implemented it could mean as much as 260-270
# POTENTIAL BENEFITS — OPERATING COSTS

<table>
<thead>
<tr>
<th>RNAV PROCEDURE</th>
<th>LOCAL SERVICE CARRIER</th>
<th>AIR TAXI CHARTER</th>
<th>BUSINESS USE GA</th>
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<tr>
<td>Direct Routing</td>
<td>1 - 2%</td>
<td>3 - 6%</td>
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<td>Terminal Area</td>
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<td>SID, STAR, HOLD</td>
<td>1 - 6%</td>
<td>1 - 4%</td>
<td>1 - 4%</td>
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<tr>
<td>Non-Precision Appch.</td>
<td>2 - 3%</td>
<td>2 - 6%</td>
<td>2 - 6%</td>
</tr>
<tr>
<td>Speed/Thrust/Alt.</td>
<td>4 - 8%</td>
<td>2 - 3%</td>
<td>2 - 4%</td>
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<td>time control</td>
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<tr>
<td><strong>RANGE OF BENEFITS</strong></td>
<td><strong>8 - 19%</strong></td>
<td><strong>8 - 19%</strong></td>
<td><strong>8 - 20%</strong></td>
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million dollars per year reduction in operating cost. That's the offset that we claim to the cost of implementing full coverage.

I would like to invite questions from the audience now. Let's start perhaps with questions addressed to Neil. I do have a number here that were submitted to me earlier by some of you in the audience and I will resort to those if you all feel very shy, but as I remember yesterday, we had fire and brimstone, flashing eyes, a whole bunch of things. So I would expect we could fill the time very comfortably with ad hoc questions from the floor.

**Question from the audience:** How soon do you think you'll have the criteria published in TERPS. As you know, we in Canada have adopted TERPS as our criteria. How soon will the Loran-C criteria be published - or do you know?

**Mr. Quinn:** I don't know at the moment - we have programs to collect the data both at the Tech Center (Bob Ericson's collecting the data and analyzing it) and TSC is supporting us in that sort of work. I don't have a specific date at the moment.

**Further question from the floor:** ....

**Mr. Quinn:** It is sort of going in several directions at the moment amongst the operational people and the technical people and we have to tie it all together. I think once we have a firm direction from this policy statement (once it is signed) that we will get much more enthusiastic cooperation from everyone, which is what we need.
Mr. Blake: As a part of that policy statement, there are about three pages of things to do, with organization names after them, and that process I would estimate would take several years.

Mr. Polhemus: Yesterday, Ed Bregstone, who is a very, very ardent and active general aviation pilot and also, as many of you know, very fairly well informed on the Loran game, raised a number of questions which he presented to me again this morning, but I would like to see if I can synthesize them to his satisfaction the following way.

We recognize the need for a_______ project that makes certain we've accomplished milestones that relate to safety and comfort of the inner man in FAA land. But on the other hand, we also know that we are making approaches today on NDB's in locations where there are no backup aids if the NDB goes off or the ADF in your aircraft is inoperative. We do not have redundancy yet we are locked into an approach in areas where there are mountains nearby and the like. On a more rational level, there are many, many airports where there is a single aid available (a single VOR/DME, an NDB or even an ILS servicing one runway but there may be four to six runways at that airport. What we would like to know, Mr. FAA, is there not a way that we could proceed immediately at those locations where there are aids (there are non-precision published approaches). Could we not couple Loran right now with many of these aids and invent a new class, an NDB-L and a VOR-L, and so on, and gain the benefits of the information that we get from Loran-C but retain the protection from a signal integrity point of view using the other aid at the airport.
Mr. Blake: Actually I don't believe you need the backup aid. Our only worry, of course, on any of these systems is that the pilot know within 10, maybe 15, seconds that the signal being presented to him is no longer usable and I think if we have a good monitoring system that we could use with the Loran-C, that will give us warning, that we really don't need any backup aid sitting there. Now to be sure if we lose a Loran station and we lose coverage over a wide area, we want to have that airplane equipped with the normal navigation system - VOR/DME onboard - and procedures in place that will allow that aircraft to climb to coverage if that's required. And, of course, part of the activity going on in this whole certification process, is to be sure that we also have pilot procedures which will cover all the bodies of questions the same as we do with NDB's or any other kind of approach: The only difference is normally NDB doesn't fail softly, if it fails - it fails, and everybody knows it. Loran may have some subtle failures; GPS certainly has the potential for some subtle plot failures that may not be immediately apparent to the pilot if the course is moving slightly from where it should.

Mr. Polhemus: I understand what you said - but I think it somewhat misses the point. We think that in order to arrive at the point where you at FAA would consider that you have your procedures worked out, you have the monitor unit in place and the like, is going to take a given amount of time - a year, two years, whatever. Whereas in the interim, we could, by combining aids, perhaps get started on an approved non-precision approach much, much sooner. I give you as a case in point, Burlington, Vermont -- we have a stack of data, we have FAA designed approaches, but what really is needed right now is to agree upon those caveats which might be imposed that would limit the manner in which the system would be used.
Mr. Blake: Well, I understand your point. I think the conservative FAA approach is going to be to set down the requirements of minimum operational performance standards for the receivers and do our usual good job hopefully developing safe procedures based just on the Loran system itself. Certainly, we may call on other aids to mark the start of the approach fix, but I don't think I could in good conscience say go ahead and certify some of the receivers that are flying today for non-precision approach use. We are setting really several basic criteria: one is the signal strength, one is signal geometry so far as the ground environment is concerned and minimum performance standards for the receiver which will give us the confidence that you don't get into cycle slips or other undetected things that would lead the pilot astray - mislead him so he still thinks he is getting the signal. I don't see that adding some other aid to the Loran signal addresses these basic concerns at all.

Mr. Polhemus: Arnie, would you please tell us a little bit about this resolution that was passed recently at NASAO.

Mr. Stymest: Before I start I would like to say I am a firm advocate of Loran-C and I see a multitude of possibilities with it; not just IFR but VFR too. With the number of airplanes we have in the air today that are not really IFR airplanes using Loran-C, when it does come down the line you are going to see many more - I say 100% saturation with Loran-C in aircraft. This is my first association with the Wild Goose people and I would like to say that my observation is that as far as I can see the quality of the system matches the quality of your association. And really I hadn't heard about the Wild Goose
Association until about a month ago - if somebody had asked me what the Wild
Goose was before that I probably would have thought it was something involving
the Boston subway system.

I tell you one thing, I say probably 40% of our airplanes today in this state,
on the coast especially, have Loran-C in them. Let me get on to this
resolution. We had our National Association of State Aviation Officials'
annual meeting in Wichita last month and on October 17th, the board of
directors voted to pass a resolution on Loran-C to be sent to FAA and DOT.
I'll read you what we arrived at:

"Whereas the National Association of State Aviation Officials
feels a system of Long Range Electronic Navigation signals
presently exist over a portion of the continental United States
and is being successfully utilized by a large segment of the
aviation community, and

Whereas the FAA has currently announced its recognition of the
Loran-C as an interim supplemental air navigation system to be
included in the national airport system plan for both enroute
and non-precision approaches, and

Whereas the capabilities of the Loran-C low frequency signals
provide a unique capability to support low altitude operations
particular with respect to the development of efficient
non-conflicting instrument departures and airway routes and
holding patterns for virtually every airport, and

Whereas these capabilities also strongly favor the development
of helicopter instrument navigational procedures which could
greatly enhance civil emergency support and medical services
operations thus greatly enhancing the value of the Loran-C
system in providing expanded access to the system of airports
and aviation facilities in the United States."

This was sent to the FAA and the DOT. I see all kinds of possibilities with
Loran-C. I see an entirely new low altitude airway structure - I could go on
and name a bunch of things, but basically this is what we sent to the FAA on
October 17th.
Mr. Polhemus: Neil, would you care to add to those remarks in any way?

Mr. Blake: I would just like to say that it is very helpful to have these expressions of user support. We are going to have our trouble getting through the money people at OMB and the more expressions of interest and the more definition of benefits that you could provide us with, I think the easier that job will become.

Mr. Polhemus: Can I ask you to indicate what specifically might an organization like this do and yet not seem to be self-serving?

Mr. Blake: Well I think the questions we always have to answer to these people are really two here; 1) show us a positive cost-benefit ratio and 2) how does this fit in with OMB's policy of non-proliferation of navigational aid systems. I feel more comfortable answering the second part because it will be some time off in the future before there will be 15,000 GPS receivers flying in general aviation aircraft, so I think there is a substantial period of time when we will be having, I think, a very large demand for Loran-C service. But I need to know who the users are and what they see the benefits of such use are to help us and help our contractors, Martin Marietta and TSC in developing a good cost-benefit case to present to the Office of Management and Budget.

Mr. Polhemus: Carl Andren, is it reasonable to try to create an ad hoc committee to address that issue.
Mr. Andren: - It's reasonable. If we can identify the people who are working for Martin Marietta -- we would like to know their names so we can have inputs.

Mr. Blake: We appreciate that very much.

Question from LCDR Perry Campbell: My question to you is regarding this particular resolution sent to DOT and FAA - are they the only ones you sent it to, and if they are, why?

Mr. Stymest: We felt that it was bogged down at FAA and that was the place to send it. We would gladly send it to anyone we thought would help it. We know there is some money bogged down in FAA that is supposed to go to the Coast Guard to put Loran-C stations in and we do not intend to stop there. We are going to do everything we can to get this thing from being bogged down and push it on.

Mr. Polhemus: Perry, did you have in mind some particular organization to whom this could be sent?

LCDR Campbell: Not a particular organization - but you said yourself many times that there is a political side to this as well as the bureaucratic side. Perhaps a better or more distribution....
Mr. Polhemus: Perry has asked, "what was the distribution of the resolution, what could be done more widely to distribute this with a view toward gaining more support and we heard the answer.

Mr. Polhemus: Excuse me, I think Dave Underwood was next...

Mr. Underwood: We were told that the FAA had figures which were similar to yours, perhaps not as optimistic, showing the improvements in operating cost operation time. A reduction in operating time is a reduction in the demand on the FAA system which must in itself have a real cost-benefit to the FAA.

Mr. Polhemus: -Ok - Dave is saying there is an intangible benefit that comes from reducing time in the air which can be translated to dollars not only in terms of the operators cost of operation but in terms of FAA controller time and controller support or system support.

Mr. Underwood: It's not intangible. It's very tangible.

Mr. Polhemus: Tough to measure.

Mr. Blake: Well we appreciate any input of this type - you've got to put on your green eye shade and look at anything and we do too - anything that we submit in the areas of benefits to be sure it will stand the scrutiny of people who are paid to be critical.
Mr. McKenzie: You wanted this special support from Canada - probably the user or group of users would end up writing ............... put on political pressure from the other side, that's what the users would like to do. Second comment I have concerns your 8-19% - we did a study on one particular aircraft, ....................., we used 8% about two years ago, direct point to point savings. You would save an excess of $50,000 a year on one aircraft and it is interesting that 8% is the bottom of your line.

Mr. Polhemus: Well, we could go off-line and talk about why it's that particular number - that was just to provoke comments like your own. In fact, there is a very strong reason for going ahead with RNAV procedures which include, they must include, the terminal area as well.

CDR Dick Burke: I just want to ask Mr. Blake if anyone from Martin Marietta is represented here at the Wild Goose Association.

Mr. Polhemus: Well, the sub-contractor I believe is Systems Control Technology and we did have a paper yesterday from Venezia if you remember describing some work that was done for FAA in crossing the continental United States.

CDR Burke: Are those people doing a good job on that study.

Mr. Blake: Well some of that's being done at TSC - so we really have two efforts going.

CDR Burke: TSC is well represented.
Mr. Stymest: Bill, I have something else I would like to say. There was a remark made, I believe by FAA yesterday, that one requirement of a Loran-C approach was going to be weather observations. I would like to point out that weather observations are only required for part 135 and part 121 operations where you have air taxi or airline operations. But you do have a way of getting around that - AWOS (Automatic Weather Observations Systems) have gone through their trial period now. I think very shortly they will be coming out with certified AWOS systems for all airports. We intend to incorporate the AWOS with a NDB to give continuous weather at any airport that has part 135 operations on a continuing basis and that's how we are going to address that weather observation that FAA pointed out yesterday.

Mr. Polhemus: Leo, before I come back to you, if I may, Bill I would like your thoughts concerning the problem of monitoring, at least from the transmitter side and then maybe we can get a manufacturer to say if that's the way you want to go - hear what the implications might be for the receiver.

Commander Schorr: As I understand it you want me to say something about our monitoring control system.

Mr. Polhemus: Well, we've talked before and others have talked with you about the problem of, for example, modulating the pulse so that we can be told in 10 to 15 seconds in the airborne equipment that we have a signal that may be marginal, failing or whatever. I gather that has some ramifications for other users, perhaps maritime users. You and I have also talked about other ways that we might be able to come back or come out with some protection and I am just trying to stimulate you to tell the folks what you think about it.
Commander Schorr: I understand, --- I heard from Mr. Blake that somewhere on the order of 15 seconds - 10 to 15 seconds after an anomaly of some sort, the user would have to be notified. For some of our happenings in the Loran-C system right now that's a tall order, indeed. If that's to come to pass, and there are a whole plethora of ways it could be made to come to pass, it will involve not just hardware changes but also software changes and cost. I would submit that there are some other receiver tradeoffs that could be made as well - receiver design innovations are on the table so to speak right now, and have been used in various receivers over the last ten to fifteen years, that are not being used by general run-of-the-mill Loran-C receivers. So perhaps, some combination of receiver design changes and transmitter monitor control changes could fit the bill and serve that purpose.

Mr. Polhemus: This morning, I am embarrassed I don't recall who it was that said this, this morning someone reminded us of the fact that many of the marine receivers have a mode called anchor-watch or anchor-warning or drag-anchor or whatever you do in a boat and that if one were to have an active monitor with that mode of operation, that it would sense the fact that its facility is drifting, which of course it would not be doing, and that evidence of drift could be interpreted as a movement away from an acceptable signal level and it would mean that we are not touching the transmitter side of the situation at all. George, would something of that nature be acceptable?

Mr. Quinn: In our last meeting with Coast Guard, we've had two now, we are having another next week, in regard to this whole Loran-C question, we asked them to respond in terms, among other things, in terms of an aviation blink
which would be some modification of the signal that could be recognized by an airborne receiver but would not be the conventional blink of the two pulses. In informal discussions apparently there are a number of ways to do that, so we have left it to Coast Guard at the moment to suggest what they think might be best. One suggestion was to blink one of the other eight pulses automatically and get away from that watchstander. I think in any case for aviation you have to get away from the watchstander initiation of blink. Having that guy flip the switch is just too long. And from the marine point of view, they don't want to see all those blinks I would think because if there are quite a few of them it may degrade their confidence in the system and we don't want to do that either. So to protect both communities, you may want a separate aviation blink and this has an impact on the avionics manufacturers because they will have to modify, hopefully through software, their receivers to recognize this blink and drop a flag for the pilot within 15 seconds.

Mr. Fehlner: (Question from the floor) ...........

Mr. Polhemus: Leo Fehlner is asking us at the panel to help find a way to notify OMB of any information we have that may be of a constructive nature. Shall I leave that with you Neil?

Mr. Blake: We don't have any politician here.

(Question from the floor): ...................
Mr. Blake: Well I think we have to go through the normal beauracratic process of getting the program approved. The question is; if the users request and react favorably to implementation of Loran-C capability, what does it take to get it in the "brown book".

We have to go through a beauracratic process, if you will, to show the cost-benefit of such a program. And then to get the proposed amendment approved within our own Department of Transportation and then by the Office of Management and Budget before we could add it to the mass plan or "brown book" as its called. We have initiated that process and have started the coordination cycle and certainly will utilize any expression of interest in use from the user community in putting together that cost-benefit study.

Mr. Polhemus: Excuse me. Pete, may I ask you a question and you can come back. Could we ask AOPA to feed to Wild Goose the document you are referring to and then it can be circulated within our group which will reach another level and maybe we can somehow coordinate some comments which might achieve what you're after.

From the floor: Yes sir, I'd be more than happy to ..... Unfortunately, the FAA didn't give us a longer comment period ....

Mr. Polhemus: Well, I think that Peter is bringing out something that has been a burr in the saddle or under the saddle for many people in the user community for a long time and that is that while outwardly it would appear that there are adequate means for the needs and desires of the user community to express
itself, in fact it is so difficult to form a consensus, particularly when you're talking about a difficult technical subject, where it almost requires a study to determine what it is that you really need to do to achieve the end that you want. There is not a methodology for doing that. Even in AOPA you do it largely by canvassing or from your own resources guessing at what your group may want. There is a weakness all the way around and I think it would be just great if you (this is a girl scout suggestion, but what the heck) get as much to us as you can and there are some of us that maybe can scratch furiously and get it back to you to edit and back into FAA in time to do at least a little bit of good.

Yes, Jim.

Mr. McCullough: We navigate more or less continuously at sea and find periods kind of like a brown-out of Loran caused by lightning and it goes anywhere from a minor nuisance to no ability to navigate at all. And so it would seem the monitor system may almost be mandatory for summertime operation due to lightning. I haven't heard lightning talked about very much.

Mr. Polhemus: George, would you care to comment, particularly keeping in mind that the ADF is equally vulnerable too.

Mr. Quinn: What's an ADF??? laugh, laugh, laugh

Mr. Polhemus: We have here the champion of modernization of NDB's.
Mr. Quinn: Lightning, in talking with the Coast Guard, is one of the major problems with these momentary outages which concern us. One of the functions of any monitor system we deploy will be for immediate real-time connection to the air traffic personnel, so that they will know whether they should or should not grant clearances for approaches. If there is a loss of signal for a long period because of lightning, then they will know the station is off the air. If it is just a very few seconds, then the minimum operating specs out of RTCA will require that the receiver detect the loss of signal and drop a flag and then the pilot would do a missed approach. So in any case, he will know himself or if he hasn't yet arrived in the area, ATC will not grant a clearance if the signal is not there.

Mr. Dean: I would like to just address the whole monitor situation and a number of these things.

Mr. Polhemus: Walt, excuse me, I think that's important enough for you to address us from the podium.

Mr. Dean: I have a different opinion on the monitor situation than has been expressed mostly here. It's my feeling that the monitor is really secondary, that the real function of detecting signal outages, of detecting blink, belongs with the receiver because that is the direct link from the transmitter and that's where it should go. (Applause) With all of the restrictions that the various people have been putting on saying you have to have one-to-one signal-to-noise and things like that: in a one-to-one signal-to-noise any receiver worth its salt is going to detect all of those things well within the 10 to 15 seconds everybody is talking about. To add another link into the
chain to make the pilot aware that something is wrong I think is the wrong approach to things. That's my opinion - that's based on not just opinions but several year's of experience with receivers. The other thing about blink and this is the thing that always bothered me.... Blink is initiated when the errors in the transmitter are so small that the ordinary airborne receiver hardly knows what's going on. So it is a condition which generally is not something that we worry about. The other thing is the bug-a-boo of cycle slip - in most of these areas practically everywhere that I know of and any decent receiver on board will not have a cycle slip because it does not turn off its envelope circuitry and anybody that does just isn't doing things right and if he isn't doing things right, he shouldn't be flying. I have several other questions on the overall business of how we implement this - I was wondering for example whether it had been given any thought to expansion of the coverage in Alaska? Has anybody thought about that - there is a large area.

Mr. Quinn: We've thought about it but there is no plan to do anything.

Mr. Dean: The other thing I was wondering was what the time schedule might be for actual hardware delivery, installation, etc. for the mid-continent stations.

Mr. Quinn: Let me tell you the normal delays. If we are talking 86 money, which we are hoping for now - Mr. Blake discussed the OMB approach would be for 86 money. The procurement process within any government agency that I am aware of takes eighteen months from the time to initiate the process of procurement until you award a contract, so with 86 money that would put us into mid-87 and then delivery of the transmitters - say you allow a year for
that - to get the transmitters, the land, the antenna... You figure out the timeframe is in the 88 period until you're operational at the new station. Of course, the approach is a different question because you already have two thirds of the country where you could begin the approach business long before the mid-continent is covered. I don't think the two should be linked rigidly that way. And I am glad that Walt agrees with us in all facets about the major link between the ground and the airborne receiver is the signal itself. There is no plan for the FAA to have a direct link from monitors to the aircraft at all.

Mr. Polhemus: I am going to throw in a little bit of Walt Dean kind of thinking I believe. From my own experience with the non-precision approach game and flying nine different manufacturer's systems, I would urge most strongly that we should very quickly come to agreement on a standardized ASF standardized coordinate conversion routine so that if I've got eight aircraft flying side-by-side all using different manufacturer's boxes, that the report to air traffic control correctly states the relative location of those eight aircraft. We cannot tolerate, in my estimation, I have no official platform, but in my estimation it is wrong for us to be proceeding along different paths in that regard. Lastly, and I am probably the only guy in the place that believes this, I think you manufacturers have got to include an honest dead reckoning loop. I saw Mike hide his head, but damnit, the basis of navigation is dead reckoning. You have to have dead reckoning as the protection for that guy in the airplane if and when you have difficulty with the Loran system. And I know the modern digital world wants to avoid it - almost all the radio nav systems avoid it, and I am telling you, you're on the wrong path.
Mr. Dean: I have just one question on your dead reckoning loop and that is you then have to define the accuracy of your dead reckoning loop or you have to say yes dead reckoning but don't use it.

Mr. Polhemus: I am willing to go all the way with you on that.

Mr. Elias: Why did you mention the transformation to lat and long? That is particularly for the approach - why does the approach have to be formulated in lat and long rather than directly with TD's?

Mr. Dean: TD's are not linear - the whole world is operating in latitude and longitude.

Mr. Elias: I am a pilot and every time I've flown an approach I've ignored lat and long completely and want to know my lateral deviation and my time or distance to the precision point. I don't know what lat and long is. I just want to know range and bearing if you wish. Why do I have to know the intermediate step of lat and long?

Mr. Polhemus: I am going to suggest that topic is worthy of a discussion within Wild Goose but not a part of this panel discussion and that leads to another thing. I think we are approaching the day when we may want to have a workshop such as Coast Guard put on at Gettysbury some years ago trying to bring together the various energies which exist in this thing and come to some agreement about how we are going to proceed from here. I don't know if you would perceive that as useful, George.
Mr. Quinn: There has been extensive study work in various grid systems other than lat and long that could be used that lend themselves to much easier use by aviation. The five character designator for waypoints and a different overlaying grid system. That's about where it lies. It was done a number of years ago following the RNAV committee that resulted in the 90-45A advisory but it has never been implemented, but the work has been done.

Mr. Polhemus: Would it be useful to FAA to participate in a workshop?

Mr. Quinn: I suppose. There is more and more interest as this area of navigation is increasing, and in use of some other grid system by some of the operational folks - I was surprised to hear their interest in something other than lat and long because they have been using rho/theta for so long and the lat/long numbers that Henry the Navigator used are a little cumbersome for aviation.

Mr. Polhemus: Ken, two things, go ahead with that particular issue but then I would like you to tell us a little bit about flight following.

Mr. Foret: I would like to just give an opinion on the TD versus the lat/long. Being a pilot and a navigator and having used Loran-A with the whirly knobs and grid charts, I certainly don't think it's the intent of this group to go back to that and have to publish a separate grid system just to utilize Loran-C for a non-precision approach. Most of the points that have been established, initial approach points, final approach fixes, so on and so forth, outer markers and everything that we deal with in aviation right now
have roots back to some coordinate system, whether as expressed yesterday NAD-27 or WGS-72, that can be normalized. The throwback to time differences allows for getting back to the grid charts and ambiguities between two LOPs which in fact lie at different positions and there is certainly room enough for confusion in an all ready busy area of cockpit and pilot interface to Loran-C navigation systems of any type. So I would just like to express the opinion that I don't feel that that would be a positive step in the use of and acceptance of Loran-C for non-precision approaches in a national airspace system.

Mr. Polhemus: This is a topic that can go on a good deal -- Bill, go ahead

Mr. Bill Walker: I am with Navigation Sciences and most of you know that Mort Rogoff, who is president of the company that I represent, has done extensive work on the subject of coordinate conversion and the RTCM special committee concluded that it's a buyer-beware situation the way it is currently being handled and there is nothing in the middle to change the way coordinate converters are going to be implemented by a wide variety of people who are doing it. Therefore, to imply that you should transmit the truth of position of two objects such as aircraft or vessels or vehicles on the street in any system other than the system of which they are commonly measured is fallacious. The coordinate conversion process will have inherent errors in it and you will never be able to get around it unless everyone is calibrated in exactly the same coordinate system. And there is no burden on the pilot anymore than there is a burden on a police vehicle or on the tug boat. The computers which measures time differences simply modulates the radio system and transmits the time difference that is absorbed by a computer and now there is no ambiguity.
Mr. Polhemus: I would not want to navigate in TD's but ... 

Mr. Walker: I am not saying you are navigating in TD's, Bill, what I am saying is the issue of coordinate converters, if we are to attempt to resolve that, in our lifetime, we will never see the situation result to the point where anything could possibly be proved. Whereas, the TD system in which the signals are controlled are non-ambiguous. I don't know how statements could be implied that there is an ambiguity in the system. The managers of the Loran system might want to speak to that a little bit more. But we don't need to navigate a TD system - I am just talking about communicating through a position from one machine to another.

Mr. Polhemus. Good point. Carl, I would suggest a table to end this particular point and that it is an area where some kind of seminar could be very productive.

Mr. Fehlner: I want to talk about lightning. There exists right now a receiver which has five years of Navy experience, immune to lightning, and this is because lightning which reverberates around the world all the time (it's more severe when it's local) is sporadic - it's not Gaussian. Now the signal to noise ratio criteria, as has always shown on the coverage diagrams, is not only meaningless but misleading. I tried to stress for years that what we really want to know is what is the product that the Coast Guard produces - and the product is signal strength and I would like to see these diagrams in terms of signal strength contours for when the transmitter is doing what it is supposed to be doing. Then a person who is a receiver designer has the liberty
of showing that he can behave at some level of signal strength versus another level of signal strength. It just so happens that the receiver I am talking about that's immune to lightning has a 40db advantage over everyone that I know of and so the problem is the receivers. I submit that our good friend Bill Schorr can produce signals and not signal-to-noise ratios. The receiver designers for avionics should take advantage of modern up-to-date, in place signal processes. There is one other aspect of lightning - once in a while it knocks out the whole darn transmitter and the receiver definitely knows that.

**CDR Schorr:** I would have to say that lightning, either primarily or secondarily, causes most of our unusable time - authorized usable time excepted now. It causes receiver problems in reduction of signal-to-noise ratio and certainly I would have to say that in a lightning storm, or somewhere around a lightning storm for most receivers, they will be practically unusable. Loran-C is highly touted as an all-weather navigation system, but in some cases we know the receiver is atmospheric noise limited and there is only so much you can do about Mother Nature. There is a limit. Where that limit is specifically depends upon whose receiver you are using. As Leo says, his receiver (or that receiver you are referring to) has a huge advantage over others. I know of some receivers that are six to seven dB better than others in lock-on performance and in being able to track Loran-C signals through extremely poor signal-to-noise ratios. Let me get back to the lightning bit - lightning causes our signals problems also from the standpoint of momentaries - either momentaries induced because of near hits that cause problems because of induced electricity into the transmitter and, typically, the couplers. But more indirectly, more momentaries are caused by power line fluctuations which in many cases are caused by lightning, not necessarily very
near by - they can be quite a ways away - it depends upon the power distribution grid. Lightning causes us problems from another more subtle standpoint as well - electronic equipment in general does not like transient power and its a tertiary effect, of course, perhaps on a long term, but we have equipment failures that are caused by lightning. One way to isolate the station, or those transmitted signals, from the effects of lightning is to provide integrity to your power supply and most of our stations do this when they can. They have a station policy, normally, that when they see a lightning storm coming, and all of our stations are on commercial power (I am talking about the Eastern U.S.), they will go onto their own station's generators. They do that for self protection as well because they know that there is a high correlation between bad time and lightning storms. So they go on their own stations's generators and solve a lot of those problems. Because we don't have windows in most of our buildings its sometimes a problem detecting it.

Mr. Polhemus: Can I ask you to flip over now, and keep in mind that this is to be a very positive, optimistic feeling, this little group that we have here - that we are going to go, go, go with Loran-C for all aspects of aviation. At the moment I am ready to take my collar off and bow down to the east. There is a frequency of occurrence that goes along with this too. We have been flying a lot of Loran sets around and I can't use all of the fingers of one hand to count the number of occasions that I was getting any kind of a problem. In other words, the frequency of that happening in the aviation world, at least in my experience, has been very, very low. Now, if I were operating on the Equatorial belt maybe I would see quite a different situation, but it is not the case from our standpoint as aviators. What you described is an accurate description but the frequency is low.
**Mr. Dean:** I spent a fair amount of time flying around and travelling around in all kinds of weather with receivers of various kinds and what Bill Polhemus says is absolutely true. Lightning storms don't cause trouble to the receivers - hardly at all - because when you are close to a lightning storm and that storm is producing a stroke now and then, its clipped right off and that's all there is to it. There is one thing that you can get from a lightning storm and you can get it whether you are flying in a plane or sitting on the ground. That is, if you get close to a charged cloud, it will charge up your antenna and all of a sudden the signals will go bye, bye - they'll just disappear and you won't find them again until all of a sudden there is a stroke of lightning and everything clears up - it's beautiful. That's the kind of affect you get when you are near a lightning storm. Granted that in the southern, down in the tropics where there are lots of lightning storms and particularly at night, the noise level can get high, but that's not really the thing we are talking about. The other thing is static, precipitation static, and there you are up against not lightning storms but you are up against things like ice, sleet and maybe dust that's impinging on your aircraft and possibly on your antenna, but mostly on your aircraft. There, the big thing is static wicks, discharges, and bonding of all your metal elements. We went through that little exercise with the aircraft that we had and it made an amazing difference in the ability to ride right through conditions which previously had knocked us out. So, it's not the magical
receiver. Everybody has a hard-limiting receiver and a hard-limiting receiver is really almost immune to impulse type noise of this nature as long as the average level doesn't get up too high, but the other things that it runs into can be problems. So I don't really think the lightning storm situation is anything that we really have to worry about.

**CDR Schorr:** Because of a whole heck of a lot of complaints from Canadian fishermen using Loran-C systems on the George's Banks, the Canadian Coast Guard launched into a very well done and thorough examination of the problems out there. Among other things they found that the loss of usage of the Loran-C system was absolutely correlated with storms - stormfronts coming through, and they found further that the reasons for these problems was the dropping (severe dropping) of the signal-to-noise ratio. What I am saying is that maybe for some receivers that they can float through these periods.

**Mr. Dean:** No. I think that the point is that what causes the very high increase of noise is not the individual lightning strokes of a lightning storm, it's the precipitation static. As a matter of fact, I was sitting in the monitor station in Sardinia and we had a very light rain storm come down (a very gentle rain) and we were looking at the SPN-30's and all of a sudden the noise level came right up as if the signals had just disappeared - it's the precipitation static that does it, it's not the electrical storm, it's not the lightning - it's the charges that build up in the precipitation and in the clouds that actually causes the problem.
CDR Schorr: I was there in Sardina in 1972, Walt, and using a SPN-29 receiver and saw the same thing and I agree with you - I can remember looking, listening to the thunderhead and seeing the scope grass up and when a stroke came, cleared out. I don't think we are talking about the same thing.

Mr. Dean: I guess we can't follow it too far, but the thing is that it's a local condition which is associated with charges and precipitation static, the charges in the clouds rather than the lightning itself - I think that is the distinction I am trying to make.

CDR Schorr: - In this case, with those receivers on the George's Bank, by in large the solution was to follow the operator's manual and that is, the section of the operators manual that explained what to do, was in an obscure place, but what they did was essentially locked their envelope servos down, if you will. They went to the manual mode so that the the cycle selection, the automatic cycle selection process, was disabled. Receivers continued to calculate the ECD, if you will, and blink the lights occasionally, but simply locking or going to manual mode solved most of the problems out there with those receivers.

Mr. Polhmeus: Well, were getting away from our topic which was aviation concerns and those things that might be done to bring along Loran for aviation a little faster. I do sense, John Illgen, that you've got grit for a session out there in Santa Barbara - one more good topic here. Arnie, can you suggest an area of concern to you either from the standpoint of how do we implement more rapidly - how do we get a non-precision approach approved somewhere or some other aspect that is of great concern to you?
Mr. Stymest: I think it is necessary that we do get it and as soon as possible. We've got a lot of airports out there that don't meet the criteria for any other kind of instrument approach whatsoever and Loran-C is the only answer. I intend to keep working on it and we are going to try to do something in this state. I will not accept GPS because Loran-C is here and GPS isn't. So we are going to forge ahead to see what we can do to get FAA to approve non-precision approaches for Loran-C... that's my concern, Loran-C approaches.

Mr. Polhemus: Well, Bob Frank is suggesting that it may be useful for each of us who lives in a state where the interest is high to make contact with an individual and I would recommend that it be the Director of Aeronautics because they have all been sensitized now through a series of meetings where Arnie is a member of the technical committee. That would be useful, I think, for them to know somebody that each can call upon.

Mr. Stymest: I keep in close touch with all the directors in my region and we all touch base on a periodic basis - we are all shooting for the same thing and we realize the importance of Loran-C.

Mr. Polhemus: Neil, in your remarks you acknowledged flight following in the Gulf - what can you say to us about FA willingness to look at it from the standpoint of operation here in the mountains - mountains of New England for example?
Mr. Blake: I think it is strictly a matter of need. Is there enough traffic which would require something other than procedural separation in a particular area. Certainly we are willing to look at it. I think what we will really learn out of the Houston experiment is; do we have the right interface with your traffic controller and can we overlay position reports from Loran with radar so that as the aircraft comes in or out of radar coverage we have correlation with the other traffic in the area. We have just been held up on this one waiting for sufficient controller staffing to be available to run the test.

Mr. Polhemus: Is this something that could be proposed on an unsolicited basis, let's say to TSC, Mike Maroni's shop, and try to get some kind of demonstration program going? Maybe taking advantage of what Teledyne and ONI have done in this particular area.

Mr. Blake: Well, I would suggest that watching what goes on in the Gulf in the next year or so should be a pretty good indication of the problems that we can run into, if any.

Mr. Polhemus: My personal concern right now is that so many of the things that we're anxious to do and think can be done are being pushed out in time because FAA wants the time to come up to speed and be conversed in these things. And one of the areas that I know the states are interested in is somehow speeding up this process - perhaps by joining with FAA in taking on some of the load.
Mr. Blake: Well I think there are other areas where you can help - certainly the special committee I mentioned has not, to my mind, totally come to grips with the requirements that should be placed on the receiver for non-precision approaches. The sooner we can get the MOPs out, particularly looking at not just the one-to-one case, but the one-to-two case. They may not like the way of quantifying the signal-to-noise requirement, but certainly that is kind of a key to getting on with anything. We have to have a receiver specification and we have to have manufacturers building to that specification. And I think there is something you folks can do in that area to hustle that process up. And we will, with your help, hustle in these areas as fast as we can.

Mr. Polhemus: Manufacturers want to comment on that?

Mr. Foret: I would like to make one comment. Some of the remarks at the opening with respect to the FAA's doubting whether or not any of the receivers that are presently on the market today meet non-precision approach requirements seem a little bit out of place. I am not sure that the FAA has done sufficient testing on all of the possibilities and configurations of equipment that's available. To make a statement that none of them probably meet the requirements seems a little bit out of step at this point in time. I am quite sure that most of the receivers worth their weight in salt, as Walt Dean would say, probably do meet the requirements at this particular point in time. Along with that I want to make a brief statement with respect to some of the graphs that we were shown earlier in regards to the one-to-one, one-to-two. I think we missed some of the point here - receiver technology is always advancing. For the benefit of anybody who doesn't realize this, there are presently systems certified and flying with continuous ...........
throughout the "mid-continent gap" at this particular point in time. I only think that it is a matter of time before other manufacturers spool up their technology to catch up with some of these advanced receivers. The FAA's viewgraphs on this subject don't seem to relate to some of the certifications which already have been approved and are in actual aircraft flying, certified for enroute and terminal use over most of the area which we keep referring to as the "mid-continent gap". It doesn't show on any of the maps that I see so I just throw that out. Technology has the capability of bridging most of that gap as we talk today.

Mr. Blake: I think we agree with that - that technology is here. We just have to set the standards that a particular receiver would have to meet for us to allow it to be used for certain types of service. I think a lot of the newer receivers will meet those requirements, but George perhaps you might want to comment.

Mr. Quinn: We have to deal also with the minimum receiver - the criteria we set for signal and that sort of thing are not for the more advanced receivers, they are for the minimum receivers. So the more advanced units should have no trouble meeting it if the criteria we set can be met by the minimum unit. I see there is no bias against the technology, it's just that we have to stick with the minimum as we always have, with VOR/DME or anything else.

Mr. Polhemus: Could there not be a case where we have equipment that will not be certified for IFR use and a subset of that particularly for approach use. I can see where somebody has made the investment to produce a technology which is capable of doing the whole job, that that investment should be honored.
the other hand, somebody who has designed for the VFR market - fine - he understands when he does that, that he is not going to get certified for the whole load.

Mr. Blake: I have to say a word to that - that we got into some difficulty back when we put VOR in - there were VFR sets that were good to 10 degrees and they were being used widely for IFR. So I have a concern - many times a user, even though you tell them, will use a VFR set for IFR service and I have a real concern with that even though I know there are marine sets flying and some very old airborne sets flying. I would at least like to try to discourage that suggestion.

Mr. Foret: I would like to say one other thing on that - the longer that it takes the policies to be formulated so that we can get the equipment approved is only going to prolong the aspect of people using less than the minimum requirements for IFR under actual IFR non-precision approaches. I can attest to the fact that it no doubt goes on daily and by the time the policies are in place, you'll have a larger number than the 15,000 estimated receivers that are out there, by your own words, some of which may in fact not meet the requirements. So expeditiousness in the promulgation of these requirements is no doubt indicated by the large number of units which we see going out on a daily basis.

Mr. Polhemus: Well, we are coming to the end of our day and I suppose we can take a couple more questions if someone has a burning desire. I do know that Carl Andren is going to give us a closing address, so David --- I'll take David's question and one more. I will do this - I have a number of questions
up here - I'll cause them to be typed up and they will become a part of your newsletter -- I understand it will be out in December and I will also see that those get forwarded to George Quinn so he -- Alright David ...

Mr. Underwood: George Quinn mentioned an 18 month period for procurement using FY86 funds. This means that the process you must go through then ought to be completed in 1985. Mr. Blake also mentioned there are hurdles to overcome, both Congress and OMB, and that OMB was the major hurdle. Do you feel, Mr. Blake, that one year is a reasonable time to do all the work you have to do to get your approval in place before the first of January 1986?

Mr. Blake: Well, of course, we are working on the 86 budget right now so the discussions with the OMB folks will take place very soon. Of course, we will be talking with the Congress right after the first of the year until about May of next year. In fact, if they don't vote on it until several days after the fiscal year, this is not anything we can control.---- We can have all the paperwork ready and that can be done this year. Get all our internal approvals and be ready to go out when the monies are available. ---- It is always a major hurdle, we've got to sell them that this new program should be added to the mass plan. The process will be undertaken shortly.

Mr. Polhemus: I think that I am going to ask Jim to give us his question but to feedback at you Dave, I think the burden is also upon us to make sure the ammunition is in the gun belt so that FAA has the ability to go ahead and make a strong case. I think a number of us would be happy to help do that.
Mr. McCullough: We are all trying to think of Loran as a hyperbolic navigation system. Mathematically you can equivalently think of it as three unknowns: time, latitude and longitude - x,y space. Now the signals are there - I don't hear much discussion about treating the signals that are all available whether they are a different grade or they come from a different transmitter, but we talk about three, four, five or eight signals that are available for the navigation of the aircraft. Together with some of these redundancy problems and to give a little higher probability of detecting blunders of the sort of cycle slipping. Maybe we are just coming too recently from plotting LOPs, as curved lines that look like a flat piece of paper. GPS thinks in terms of three unknowns and three equations.

Mr. Polhemus: I have no disagreement with what you are saying but I can sense that that's the kind of evolutionary thing that will emerge as Loran gets accepted and one tries to convince the market that his receiver is better and that's, of course, what ONI has done. I don't see it fitting in today with the concerns of FAA and ourselves into moving ahead very rapidly in the aviation use of the system. I see it as a benefit but not a necessity.

At any rate gentlemen, particularly Mr. Blake, I thank you so much for coming to us up here and giving us what you have. George, I have a C-130 standing by for you.

Thank You panelists....
SPECIAL GUEST SPEAKERS
SPECIAL GUEST SPEAKERS

FOR THE 13TH ANNUAL WGA LORAN-C TECHNICAL SYMPOSIUM
IN BOSTON (31 OCTOBER - 2 NOVEMBER 1984)

Mr. Walter Cronkite, CBS News Special Correspondent and Notable Loran-C User

RADM Theodore J. Wojnar, USCG, Chief of the Office of Navigation

RADM Alfred P. Manning, Jr., USCG, Chief of the Office of Command, Control and Communications

Mr. Neal Blake, Deputy Associate Administrator for Engineering, Federal Aviation Administration (FAA)
1984 WGA CONVENTION
AWARDS
THE FOLLOWING AWARDS WERE PRESENTED AT THE ANNUAL CONVENTION HELD IN BOSTON, MASSACHUSETTS IN 1984

**MEDAL OF MERIT**

THE MEDAL OF MERIT IS AWARDED TO A PERSON OR PERSONS FOR A PARTICULAR CONTRIBUTION OF OUTSTANDING VALUE TO THE DEVELOPMENT OR FOSTERING OF LORAN. THIS AWARD IS NORMALLY GIVEN ONLY AFTER THE EXCEPTIONAL NATURE OF THE CONTRIBUTION IS CLEARLY RECOGNIZED.

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**HONORARY MEMBERSHIP**

AN HONORARY MEMBERSHIP IS AWARDED BY THE BOARD OF DIRECTORS TO AN INDIVIDUAL WHO HAS MADE AN OUTSTANDING CONTRIBUTION TO LORAN.

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<td>Walter Cronkite</td>
<td>FOR HIS LONG-TIME INTEREST IN, AND USE OF, LORAN-C</td>
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John M. Beukers Receiving the Medal of Merit from the Awards Chairman, Mr. Robert Frank
The Medal of Merit of the Wild Goose Association is awarded to John M. Beukers in recognition of his extensive contributions to the development and fostering of Loran, including pioneering work on location of objects by retransmission and remote reception of Loran signals.

As the president of Beukers Laboratories, Inc., he has become the recognized authority on the location of meteorological radiosonde by use of vlf and lf signals and similar object location systems. As a member and past president of the WGA, he has participated to an an exceptional degree in the improved and increased use of Loran-C as chairman of the Committee on Loran-C System Characterization, as a Group Leader in the Loran-C Workshop, and as a witness before the Congressional Committee considering the expansion of Loran-C in the coastal confluence. He has used his experience to present and publish a number of technical papers on retransmission and on more general aspects of Loran-C; one paper received the Burka Award of the Institute of Navigation. His work has resulted in several patents. The Wild Goose Association gratefully acknowledges these and other valuable contributions which have been a significant factor in the promotion of Loran to the important state it enjoys today.

Awarded this first day of November, 1984.

Carl S. Andren, President.
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RADM A. L. Sartin  W. Dean  Manning

N. Blake  RADM T. RADM A. Wojnar  Manning

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THE HARDWARE EXHIBIT SCENE (Cont'd)

W. Dean Walter H. Dahl Cronkite

RADM A. Manning

RADM A. Manning
THE HARDWARE EXHIBIT SCENE (Cont'd)

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RADM R. Bauman

Jimmie Toms  RADM A. Manning  Cal Culver
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A special note of thanks goes to Cal Culver of Micrologics and Charlie Malaqueas of Digital Marine for their special assistance in making the 1984 convention a great success.

The Wild Goose Association extends thanks and appreciation to Analytical Systems Engineering Co. (ASEC) and President Jim Henderson for publishing these proceedings.
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RADM Walter Manning and wife

RADM Walter Cronkite and wife

William St. J. White

Paul Johannessen and wife

Walter Cronkite

Marie Walter Satoko Lillian

Cronkite Cronkite Sartin Campbell

Jim Van Ms. Claire Walter

Etten Manning Cronkite
HOSPITALITY (Cont'd)

Marge and Walt Dean

Walter Cronkite

L. Sartin  W. Cronkite  S. Sartin
REGISTERED ATTENDANCE

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