Differential Loran for 2005

Benjamin B. Peterson
Kenneth Dykstra
Peterson Integrated Positioning, LLC
30 Pond Edge Drive
Waterford, CT
Tel: 860.442.8669
Email: benjaminpeterson@ieee.org

Kevin M. Carroll
Anthony H. Hawes
U.S. Coast Guard Loran Support Unit
Tel: 609.523.7204
Fax: 609.523.7320
Email: kmcarroll@lsu.uscg.mil
ahawes@lsu.uscg.mil

ABSTRACT

A multimodal group of engineers, scientists, and industry representatives, including the U.S. Coast Guard (USCG) and Federal Aviation Administration (FAA) completed a major effort to define and analyze the performance of a new Enhanced Loran system as a backup for the navigation and timing services provided by the NAVSTAR Global Positioning System (GPS) provided services. Each mode of transportation has defined requirements that the new Enhanced Loran must meet to be acceptable in the radionavigation mix of systems. The group developed a set of requirements for Loran maritime navigation in terms of availability, accuracy, integrity and continuity for the Harbor Entrance and Approach (HEA) requirements defined in the Federal Radionavigation Plan (FRP).

This paper discusses the goals of the Loran Support Unit for Fiscal Year 2005 (FY05), and the program to support these goals. The factors related to achieving the objective of moving Differential Loran from the proof-of-concept stage to an operational status will be discussed. Also covered are the results of an initial survey of the Inner Harbor at Boston, MA, USA

KEYWORDS: Loran, radionavigation, GPS, timing

Note: The views expressed herein are those of the authors and are not to be construed as official or reflecting the views of the Commandant, U.S. Coast Guard, U.S. Federal Aviation Administration or the U.S. Departments of Homeland Security or Transportation.

1. INTRODUCTION

The Loran Integrity Performance Panel (LORIPP) and Loran Accuracy Performance Panel (LORAPP) determined that an improved version of the Loran-C system, called Enhanced Loran, could meet the operational requirements of the HEA for maritime positioning use and the FAA-derived Required Navigation Performance of 0.3 NM (RNP 0.3). The U.S. Department of Transportation (DOT) Volpe Center completed a benefit-cost analysis covering this move, with favorable results. Both reports were completed and delivered to the Office of the U.S. Secretary of Transportation in March of 2004. At the time of this writing, the Loran community awaits a public decision regarding the future of the Loran system.

Although a definitive direction for Loran has not been decided, the USCG Loran Support Unit (LSU) has continued research and development into the Enhanced Loran architecture. Having completed the aforementioned reports, a transition is underway from the proof-of-concept stage to a quasi-operational status, which will promote receiver development and other Loran research.

2. DIFFERENTIAL Loran

The basic concept of Differential Loran is to provide two sets of phase corrections to improve the navigation accuracy from the current 0.25 NM level to approximately 20 meters. One set of corrections is called Additional Secondary Factors (ASFs) which are defined as the phase differences between an all seawater propagation path and the actual propagation path and are functions of the ground conductivity and terrain along the path. These ASFs will be obtained by detailed surveys of the coverage area. In addition, there are temporal changes in the observed phase caused by changes in index of refraction along the propagation path and variations in transmitter bias. These variations will be measured at a fixed local monitor site, and communicated to users via modulation of the Loran signal. For a detailed description this data channel the reader is referred to [1].

3. GOALS

There are two main goals for FY05. The first goal is to establish Differential Loran on a 24/7 real-time basis for selected areas of the Northeastern U.S. Previous tests were done either in post-processing or during limited time periods in which Differential Loran data was broadcast over the air waves from the experimental transmitter at the Loran Support Unit. While these relatively short broadcasts were useful to demonstrate that the technology was feasible, continuous broadcasting of real-time data is needed in order to refine the implementation. This has the added potential benefit of promoting receiver development.

The second goal is to develop the procedures and working knowledge necessary to establish Differential Loran in an area. Knowledge gained from the marine and aviation surveys can be integrated in support of this goal. In addition to scientific concerns, some practical considerations may drive the final shape of the new Loran system.

4. PROGRAM

This section outlines the major milestones for FY05. The first part is to establish a test-bed of monitor sites in the Northeastern U.S.

Differential Loran is a technology that is applied to both timing and navigation applications.

Consequently, two types of monitor sites have been identified: 1) Tier I sites which possess a GPS independent, highly accurate source of absolute time (within 10 ns of UTC(USNO)) facilitated by one or more atomic time standards disciplined using Two-Way Satellite Time Transfer (TWSTT), and Tier II sites which have a less accurate and possibly GPS dependent source of absolute time. Tier I and Tier II sites are nominally called "timing" and "navigation" monitor sites, respectively. The Tier I sites will support both timing and navigation users. If GPS service is lost the Tier II sites will revert to pseudorange vice absolute corrections whereby one correction will be set to zero, all others calculated as relative corrections, and the corrections will be useful to navigation users but not to timing users. The message format includes bits to notify users of the type of base station the corrections come from and whether on not the GPS time reference is available.

The Northeastern U.S is the area of the country with the highest seasonal variation in phase propagation. Planned monitor sites include: U.S. Department of Transportation Volpe National Transportation Systems Center (USDOT Volpe), to support some marine surveys in the Boston, MA area, The USCG Loran Support Unit (LSU), Wildwood, NJ, USCG Loran monitor site at Sandy Hook, NJ, due to its proximity to the metropolitan New York City area, and the United States Naval Observatory (USNO), where official time for the U.S. is maintained.

We look first to Boston Harbor for a marine survey. A navigation monitor site has been established at the Volpe Center to support surveys in the area. Once the Boston survey research is complete and as time permits, we would like to apply our refined procedures to another metropolitan area such as New York.

5. ISSUES

Communications Network: Due to the topography of the areas surveyed, monitor sites may be placed in remote areas and at locations with varied methods of access to the Internet. This requires the establishment of an ad hoc network in which data sources can be added, removed, or moved easily. This capability requires a specialized computer network structure. A next-generation IT network for the Enhanced Loran system is being developed at the USCG Loran Support Unit, however it is not due to become operational until FY 2007. An interim solution that will allow for real-time data broadcast is being developed at the LSU.

Monitor Site Density: The seasonal variation in phase propagation is region-dependent. Differential Loran technology reduces the error due to this variance. However, for a given area and a given location within the area, the achieved accuracy, using the corrections from a monitor site, degrades with distance from the site.

6. SURVEY CONSIDERATIONS

There are several factors to consider when executing a marine survey. Some of the most important ones are discussed here.

1. Geographic Survey Boundaries: The single most basic question to answer in conducting a marine survey is: what are the boundaries of the area to be surveyed? As an example: consider the Chesapeake Bay, VA area, which is large and has many tributaries and other waterways connected to it. A decision needs to be made concerning the areas of a waterway that require Differential Loran.

2. Seasonal Variations: The phase of the signal from a given Loran station and a given observation point varies temporally. When conducting a marine survey, it is necessary these temporal changes be measured at the local monitor site and that these variations in phase be taken into account in processing the survey data. Once a survey has been completed, a table of geographic points and associated nominal ASF values are calculated. Once calculated, this table or "grid" is loaded into a user receiver module. A navigation monitor site sends out the temporal corrections for the area covered by the grid. In the receiver, the temporal corrections are used to increment or decrement the base offset for the grid values as a whole. This method is effective as long as the phase variation is relatively uniform throughout the geographic region that the grid covers. It is assumed that the temporal variations in phase are constant over the coverage area of a particular monitor site. To verify that this is valid for a particular coverage area it is necessary to survey the area at multiple times during the year

3. Grid density: This factor is influenced by the spatial gradient of the ASF for a given area. A spatial gradient develops when there is a significant difference in the land path between a given Loran station (LORSTA) and two points. Assuming that it is desirable to have a uniform level of accuracy for the area that a grid covers, the existence of a gradient is problematic since it means that the grid points must be closer together for the high-gradient regions of the area. Another solution is to divide the area into sub-grids of different point spacing, or simply restrict grids to cover areas where the ASF gradient is below a certain threshold. Finally the grid must be in a format amenable to receiver manufacturers.

4. Source of Ground Truth/Geographic datum: There are two possible sources of ground truth for the ASF surveys: the USCG maritime Differential GPS system and the Wide Area Augmentation System (WAAS) operated by the FAA. DGPS is based on the North American Datum of 1983 (NAD 83) and WAAS is based on the World Geodetic System 1984 (WGS 84). Both systems have comparable accuracy. In the surveys done this far, we have logged both DGPS and WAAS data simultaneously and have compared the two sets of fixes and compared the differences to that predicted by the differences between NAD 83 and WGS 84.

7. 2005 Loran DATA CHANNEL (LDC) TEST

The real-time dissemination of Differential Loran data (i.e.: moving data from multiple monitor sites to a central database and broadcasting the same data from a Loran station) will represent a major move forward for Differential Loran, allowing more effective test of the technology and process, and will support additional research in the field. The success of this endeavor depends on proper integration of specialty software and COTS hardware.

LORSTA Seneca, NY is the planned first broadcast node in this network. Initially, observations from monitor sites at the US DOT Volpe Center at Boston, MA and USNO at Washington, D.C. will be broadcast from this station.

Communications between the monitor sites, a central server and LORSTA Seneca, NY will be crucial to the success of this endeavor. Currently, the operational network for the Loran system is being used for the present Loran data collection efforts. There are three obstacles to using this scheme for real-time corrections. First, the architecture of the current operational network coupled with the protocols employed is not amenable to the type of data requirements for research. Second, the security policy for the operational Loran network does not permit adding users on an ad hoc basis and with varying security assurance levels, and does not allow access from the Internet. Third, the remote possibility that a catastrophic network glitch could be caused by this research makes using the operational network an unattractive option. For these reasons, it was decided that a network other than the operational network would be used. Due to the prohibitive cost of acquiring another research network for this specific purpose, it was decided to use the Internet for communications during this test and research phase.

LSU has undertaken the effort to determine the requirements for the next-generation Loran network, which will support Differential Loran messaging, however the planned operational phase is for FY2007. An interim, Internet-based solution is being developed at LSU to facilitate research and monitoring of the differential messages. This communications scheme will allow dissemination of real-time differential corrections.

8. ARCHITECTURE OF DIFFERENTIAL Loran DATA NETWORK

In general, Differential Loran is being implemented for this experiment in the following way: Monitor sites (navigation or timing) are placed at strategic locations near certain waterways. The sites produce Loran observations at a specific reporting interval which are immediately sent to a central computer at LSU via the Internet. Upon arrival at LSU, the observations are logged and immediately relayed to the applicable LORSTA (initially LORSTA Seneca) for broadcast. So there are three types of nodes in the aforementioned network: monitor, central, and broadcast nodes. Only one central node (the server) exists. The location of the monitor nodes is influenced mainly by available space/real-estate, proximity to desired coverage area (for navigation sites), and proximity to existing sources of high-quality oscillators (e.g.: cesium clocks).

9. REQUIRED EQUIPMENT

The equipment being used for this experiment is mostly commercial off-the-shelf (COTS). The nodes are connected via the Internet.

The central node requires the least amount of equipment, consisting of a fast computer running connected to the Internet and running specialized software to relay the differential messages.

The broadcast node requires a computer to receive the messages from the server and encode them for transmission to the standard equipment at the Loran Station. The computer at this node is also connected to a Loran receiver, and a source of absolute time. Finally, an uninterruptible power supply (UPS) will be used to prevent unnecessary loss of power.

The monitor node requires a computer connected to a source of UTC and a Loran receiver. A very stable oscillator is required for a timing monitor site. A UPS is also used at this type of node.

10. BOSTON HARBOR SURVEY

An initial survey of the Inner Harbor at Boston, MA, USA was conducted on July 17, 2004. Although previous marine surveys have been conducted, this survey helped bring some lingering issues to the fore. ASFs are calculated and organized by cells in a two dimensional grid of latitude and longitude. Cell size is a variable to be determined, and it may vary from port to port or even within a port. Specialized software has been developed to perform some calculations on the raw survey data. The software calculates and plots for each cell:

a. Number of samples
b. Mean
c. Standard deviation
d. Maximum difference to any adjacent cell

Figures 1 through 8 illustrate the analysis for Boston harbor. Figure 1 shows the path of the survey on a nautical chart.

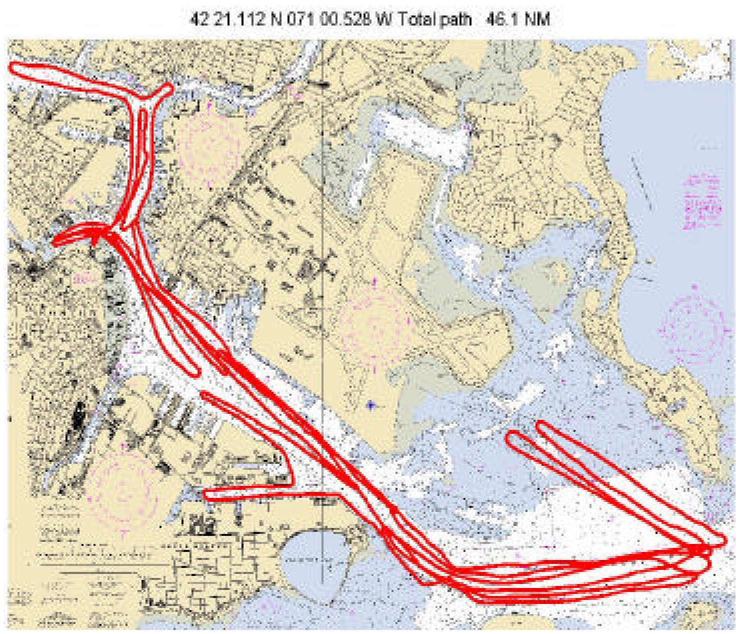

Figure 1. Path of Boston Harbor Survey

Figures 2 and 3 show the number of data points per cell for cell sizes of 0.005 and 0.002 degrees respectively.

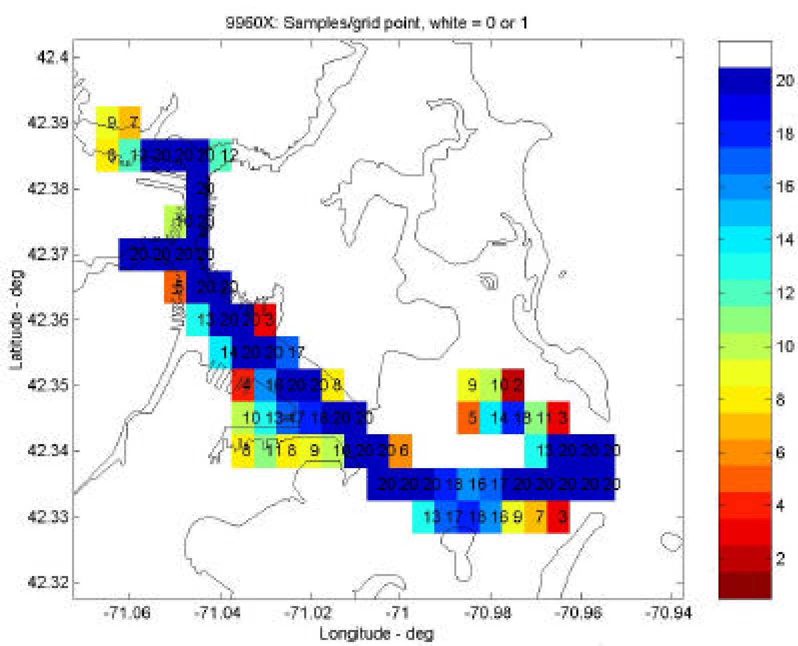

Figure 2. Number of Data Points per Grid Cell (Cell Size 0.005 degrees)

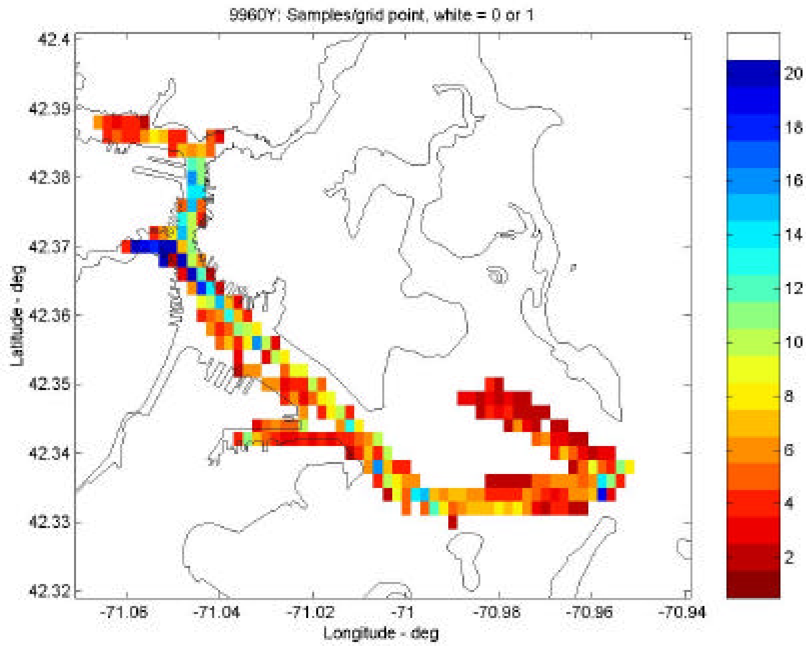

Figure 3. Number of Data Points per Grid Cell (Cell Size 0.002 degrees)

Figure 4 shows the mean ASF for the 9960Y signal.

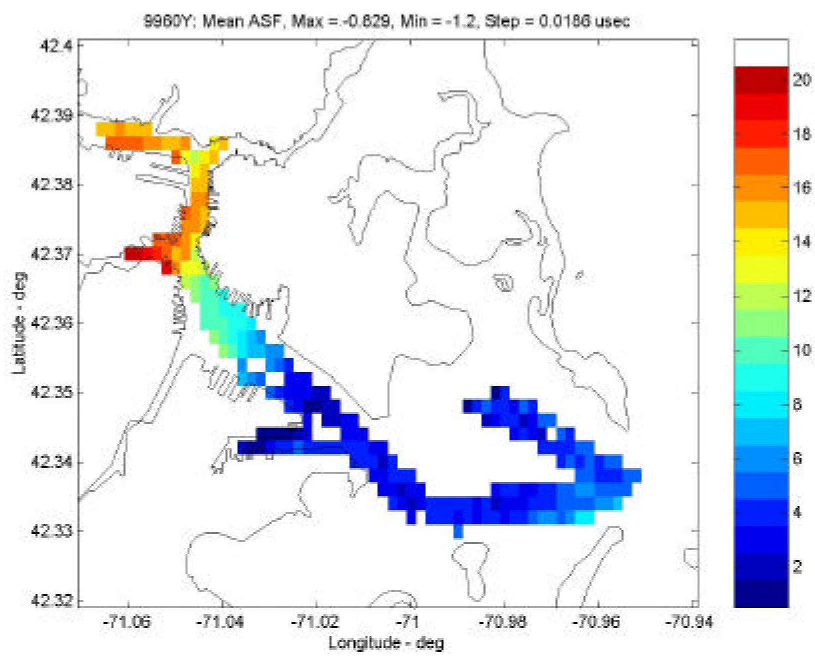

Figure 4. Average ASF for 9960Y (Carolina Beach) Signal

The ASFs are relative or pseudo-ASFs meaning that they are all relative to the 9960M signal which has its ASF set to zero. The values are therefore the difference between the 9960Y (Carolina Beach) ASF and the 9960M (Seneca) ASF and are negative due the larger portion of land in the path from Seneca to Boston. Figures 5 and 6 show the maximum absolute value of the difference in ASF to any of the eight adjacent cells for cell sizes of 0.002 and 0.005

degrees respectively.

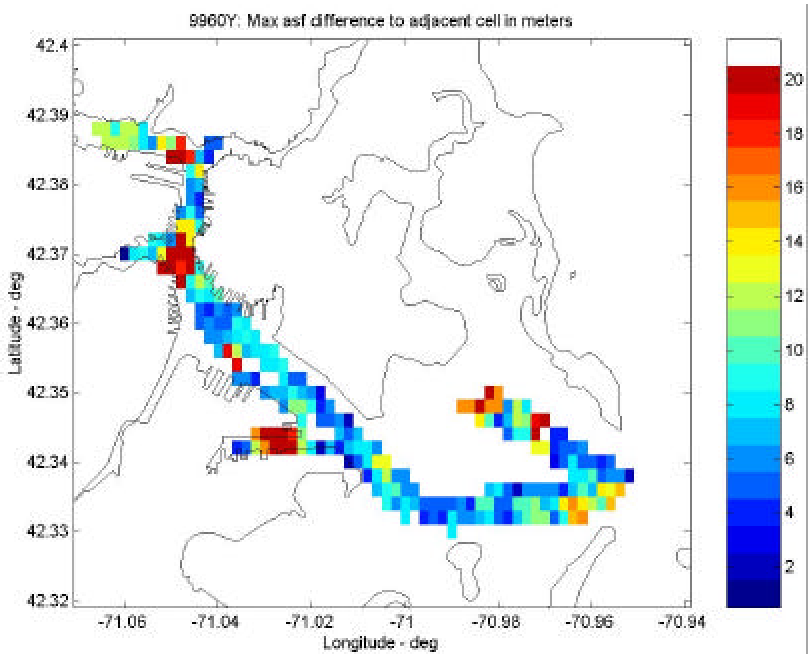

Figure 5. Difference in ASF Between Adjacent Grid Cells (cell size 0.002 degrees)

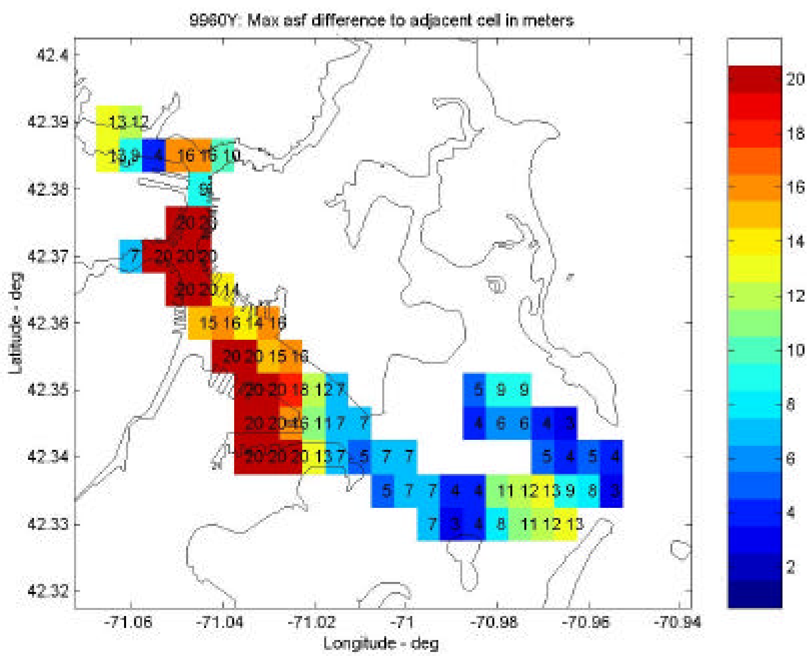

Figure 6. Difference in ASF Between Adjacent Grid Cells (cell size 0.005 degrees)

Figures 7 and 8 show the standard deviation of ASF for cell sizes of 0.002 and 0.005 degrees respectively.

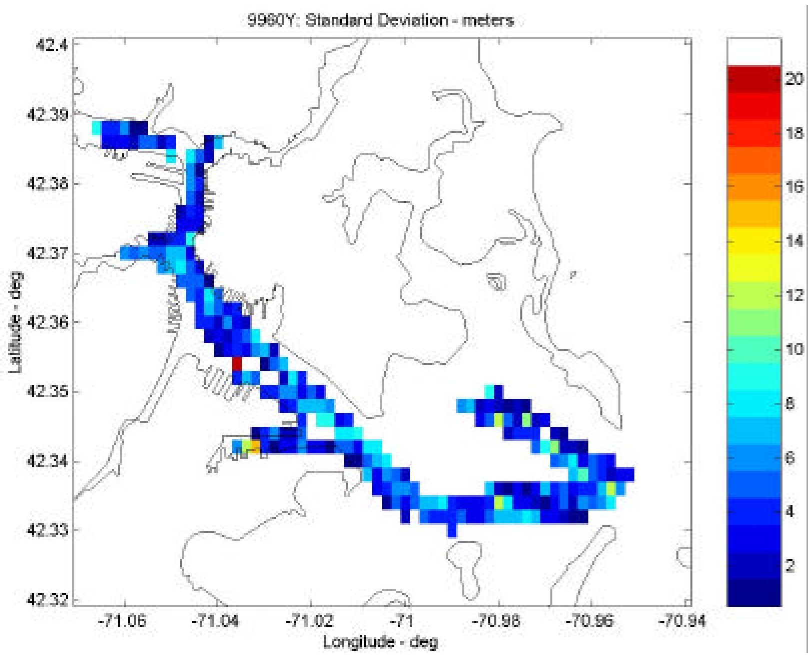

Figure 7. Standard Deviation of ASF By Cell (cell size 0.002 degrees)

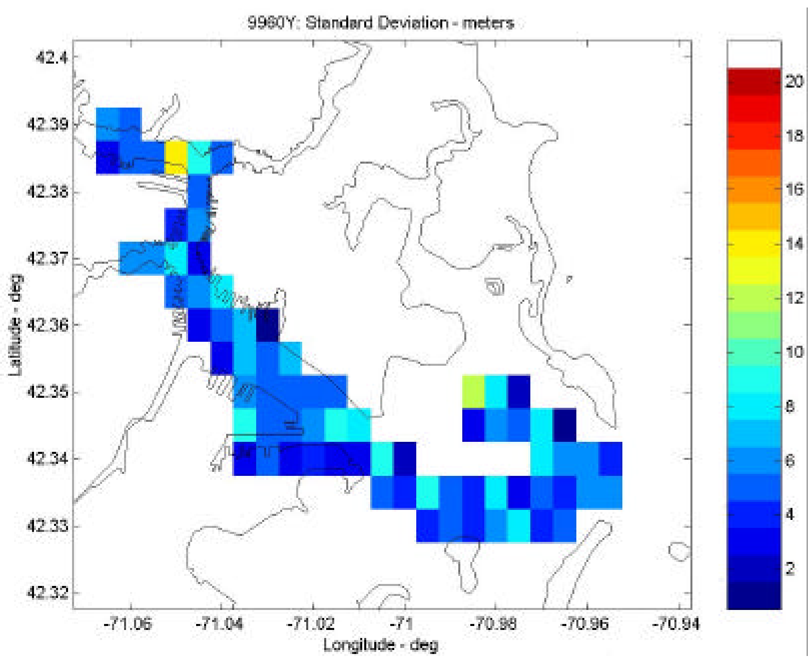

Figure 8. Standard Deviation of ASF By Cell (cell size 0.005 degrees)

The intent is to determine whether enough data was collected, the data collected is valid, and that the cell density is sufficient such that variations within a cell or between adjacent cells are adequately bounded.

11. DGPS VS. WAAS

Figure 9 shows the comparison of DGPS and WAAS positions for the survey. The mean East difference is 0.05 m with a standard deviation 0.24 m and the mean North difference is -1.05

m and with a standard deviation 0.26 m. The values predicted by HTDP.exe from NGS Geodetic Tool Kit (www.ngs.noaa.gov) are 0.18 m East and -1.01 m North.

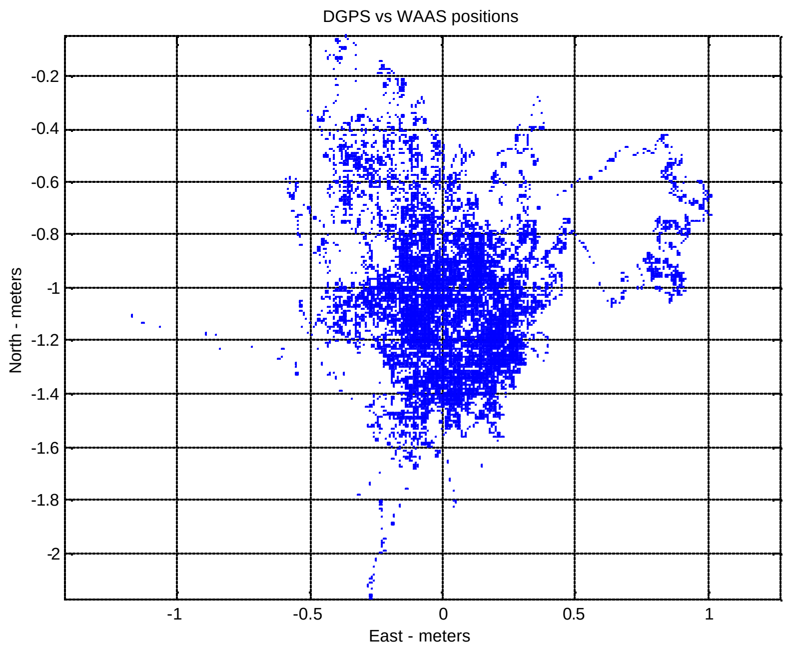

Figure 9. Difference between GPS and WAAS positions for Ground Truth

12. NINTH PULSE POSITION MODULATION (PPM) VERSUS EUROFIX

For a number of years the Northwest Europe Loran System (NELS) has operated Eurofix, which is a method of transmitting Differential GPS data by three-state pulse position modulation (PPM) of the Loran signal [2]. In Eurofix, the last six pulses of the eight in a Group Repetition Interval (GRI) are modulated by either advancing or retarding some of these pulses by one microsecond. 128 balanced (equal number of advanced and retarded pulses) patterns are used to transmit one seven bit word per GRI. Ten data and twenty Reed Solomon parity words comprise a thirty word, thirty GRI message. Of the ten data words, 14 of the 70 bits are for CRC leaving 56 data bits.

In the proposed Loran modulation scheme for the United States [1], a ninth data only pulse is added and modulated using 32-state PPM resulting in one five bit word per GRI. Nine data and fifteen Reed Solomon parity words comprise a 24 word, 24 GRI message.

Since Eurofix has existed for years, has proven itself to be a reliable data link, and has been recognized as an International standard by the International Telecommunications Union (ITU), a logical question could be asked as to why the need for a new modulation method for Loran. Both systems have comparable data rates and message lengths, Eurofix could easily transmit data we are proposing for differential Loran. In addition, it has been suggested that since both modulation schemes could be used simultaneously on the same Loran signal, that the United States should consider using ninth pulse PPM for differential Loran and use Eurofix for transmitting other data. The main difference between the two schemes is the ability to cancel eight of nine of cross rate pulses per GRI in 32-state PPM vice two of eight in Eurofix to improve navigation solutions. It was earlier felt that due to long time constants, maritime and timing receivers can merely blank cross rate and that the main issue was aviation where short time constants preclude cross rate blanking. However, it may be issue for maritime receivers as well due to more stringent accuracy requirements.

The reasons we chose to adopt 32-state PPM vice Eurofix are related to the ability of receivers to navigate with modulated signals and not the ability to communicate data. The concept of using both systems simultaneously is also eliminated because of the receiver's ability to navigate with modulated signals.

In the analysis to show that an enhanced Loran could meet both aviation RNP 0.3 and maritime Harbor Entrance and Approach (HEA) requirements in [4], it was assumed that all navigation receivers would cancel vice blank the majority of cross rate interference (CRI). A simple scheme to cancel CRI was presented in [3], and other proprietary and presumably more complicated schemes exist in current user equipment. Since the arguments that follow are based on the difficulty of canceling CRI in Eurofix, a natural question to ask is: Is it feasible to cancel cross rate with Eurofix? In general we see two possible methods of attempting to cancel cross rate with Eurofix.

1. In a block processing mode, a receiver could demodulate all received signals, first, wipe off the data, use the demodulated data to recreate the received waveform and then cancel CRI. If demodulation errors occur, then the canceling is not effective. Using this approach, only the demodulation error rate of only those pulses subject to CRI is a relevant statistic as those that do not overlap pulses from another rate need not be canceled. In Eurofix, if one successfully demodulates five of the six modulated pulses within a GRI, it is possible to know the data on the sixth and cancel it as well because of the balanced nature of the code. However, because both the tracked signal and the CRI consist of pulses at one millisecond intervals, if one pulse is interfered with, the probability that two or more pulses are interfered with is very high.

This approach could be done sequentially starting by demodulating the strongest signal, wiping off its data and canceling its interference to other rates, then demodulating the next strongest signal, etc. It should be noted however, that cross rate as low as -10.2dB relative to the tracked signal can cause demodulation errors without even considering the affects of noise. This approach would require running 30 to 40 Eurofix demodulators in parallel but would not require decoding the Reed Solomon forward error correction on more than one.

2. After demodulation and decoding and data wipeoff. In this case the receiver can use the power of the Reed Solomon forward error correction to help recover and wipe the data off of the CRI pulses and presumably eliminate many of the demodulation errors. However, in this approach, delays of up to 2.997 seconds (for GRI 9990) for completion of a message are incurred before the RF data can be used for navigation purposes and these delays exceed the time bounds for aviation receivers in particular. As above it would also mean running 30 to 40 Eurofix receivers in parallel and in this case it would include decoding the Reed Solomon forward error correction on each channel. It should be noted that this approach is what was envisioned in WAAS messaging scheme evaluated in 2001 [5]. However, in that case all stations transmitted the same complete message within a UTC second. The receiver needed only to demodulate and decode the message from the strongest station in order to be able to recreate and cancel the CRI from all signals, and the maximum delay before using RF data to navigate was one second.

If CRI canceling is not feasible, an alternative approach is cross rate blanking. In this case the receiver tracks the cross rate and when a cross rate pulse lies within a specified time window of a tracked pulse, the data is discarded. In the analysis that follows, we develop a model for calculating what fraction of tracked pulses are interfered with by modulated cross rate pulses and what this means in terms of loss of processing gain and navigation performance. This is illustrated in figure 10.

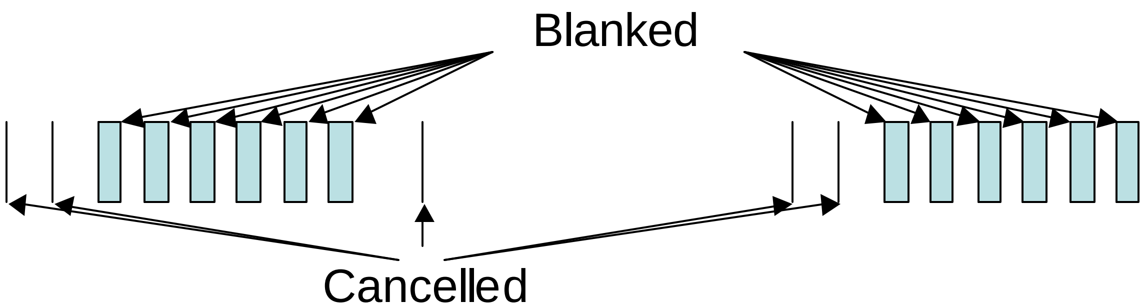

Figure 10. Model for CRI blanking in Eurofix

For each cross rate GRI, the fraction of time blanked is given by the number of signals multiplied by six pulses per GRI multiplied by the blanking interval per pulse divided by the length of the GRI. In our analysis we are assuming a blanking interval of 0.5 milliseconds per pulse, the first two not modulated pulses in a GRI are canceled, and that only the last six pulses in the GRI are blanked The overall fraction not blanked is then the product of (1 - fraction of time blanked for each GRI) for all cross rate GRI's. Due to cross rate blanking at transmitters, this model will not accurately predict the probability of multiple cross rate hits, but will accurately predict probability of at least one cross rate hit.

Figure 12 shows the predicted signal strengths for a 400 kW Loran transmitter for various land conductivities and for first and second hop skywaves. In our analysis we are interested in the maximum range that a cross rate Loran signal (groundwave or skywave) can interfere and require either canceling or blanking. The most severe CRI problem exists at night due to numerous strong skywaves. The second hop nighttime skywave curve in figure 12 predicts approximately 54 and 46 dB relative to one microvolt per meter for ranges of 2000 and 2500 NM respectively and we will use these two candidate ranges in the analysis that follows.

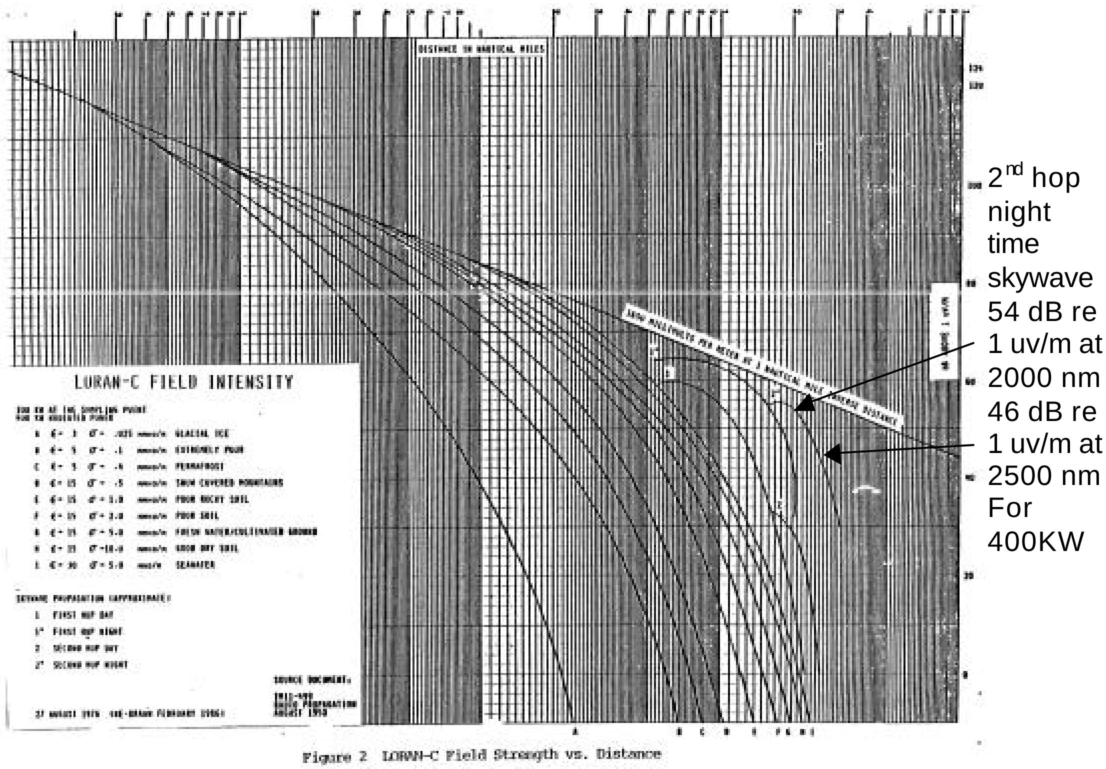

Figure 12. Predicted Loran signal strength versus distance.

Figure 13 illustrates what ranges of 2000 and 2500 NM mean to a user in the Upper Midwest portion of the United States. A 2500 NM circle includes all North American Loran station except Attu and a 2000 NM circle includes all except Attu, Port Clarence and St. Paul.

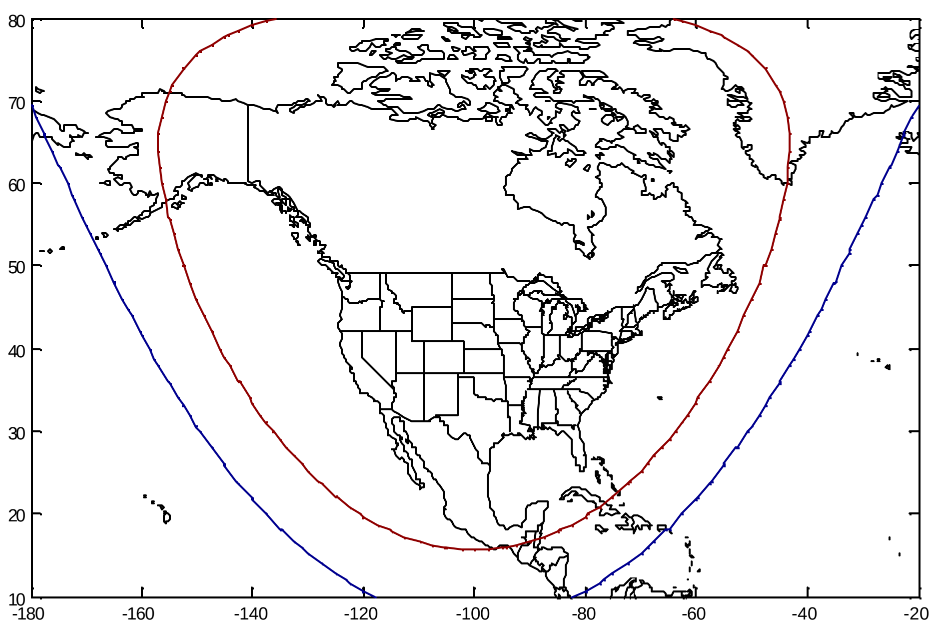

Figure 13. 2500 and 2000 NM circles from a point in North Dakota.

GRI	N stations	Probability not blanked	
9960	5	0.849	1 - (5*6*0.5/99.6)
8970	5	0.833	
7980	5	0.812	
9610	6	0.813	
5930	4	0.798	
9940	4	0.879	
5990	4	0.800	
7960	3	0.887	Not Port Clarence
7270	3	0.876	
9990	1	0.970	Only Kodiak
Overall		0.197	7.05 dB loss

Table 1. Example calculation for Upper Midwest for tracking 8290 and blanking all cross rate from stations within 2000 NM

Table 1 is an example calculation of the fraction of pulses not blanked and shows a 7.05 dB loss in processing gain for a receiver at night in the Upper Midwest blanking all cross rate signals from stations within 2000 NM. For comparison, for the same location and range, range, the fractions of pulses not blanked are 0.778 and 0.099 for 32-state PPM and all pulse blanking respectively.

Figures 14 and 15 show the results of repeating these calculations over a grid spanning North America and Western Europe for ranges of 2000 and 2500 NM respectively. What they show is the substantial difference between the two regions regarding the extent of nighttime cross rate interference. Because there are not nearly as many Loran signals in Europe, a receiver can blank cross rate interference and still have enough unblanked pulses for acceptable performance.

The certification of Loran for aviation use currently has a bigger push in the US than Europe and is a major aspect of the US's Loran evaluation. The aviation receiver requires significantly less averaging time constants than present day European receivers. This means is that European receivers, with longer time constants, can average over more pulses if blanking CRI. In addition, if using Reed Solomon forward error correction to recreate the transmitted signal and cancel cross rate as described above, becomes more feasible because the 30 GRI delay between receiving the RF signal and processing it for navigation is more acceptable and the number of Eurofix receivers that need to be implemented in parallel is much smaller.

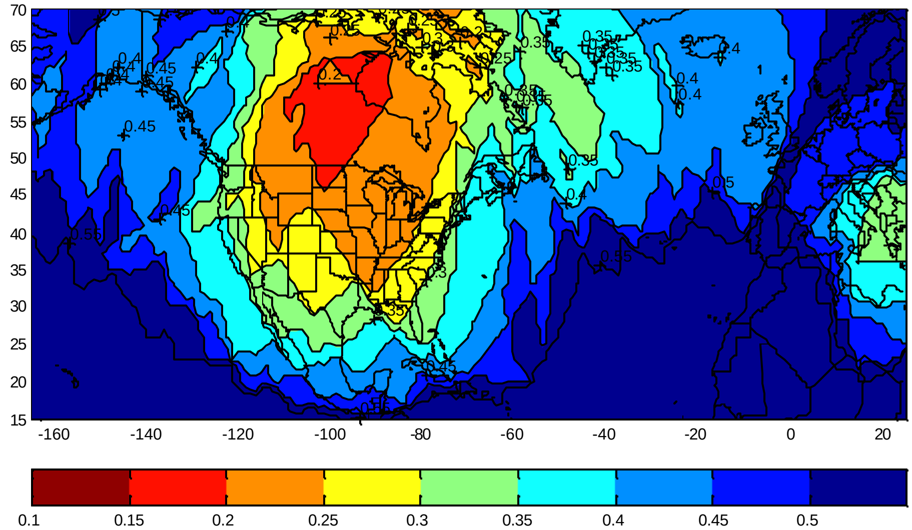

Figure 14. Fraction of pulses not blanked due to CRI: 2000 NM range

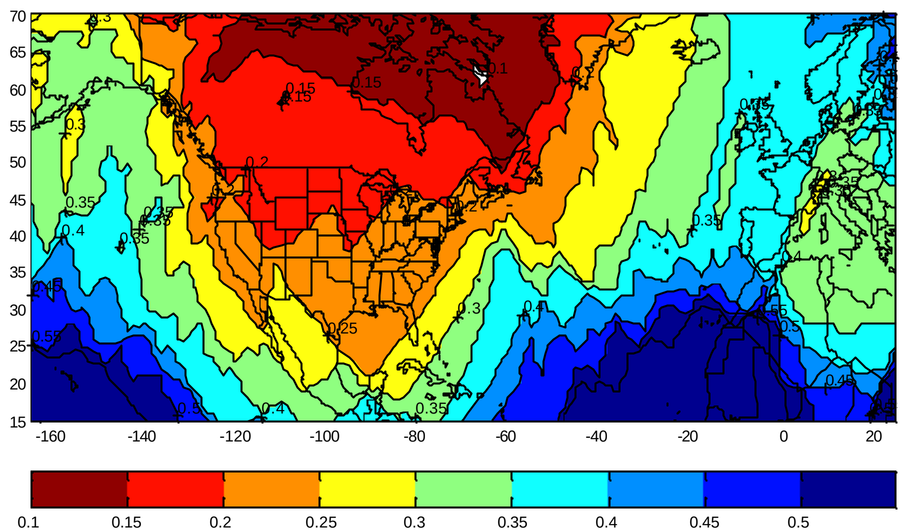

Figure 15. Fraction of pulses not blanked due to CRI: 2500 NM range

Another difference between Loran interference environment in North America and Europe is shown in Figure 16. Since the predicted noise levels are much higher in North America, a Loran receiver needs many more Loran pulses to average over in order to obtain the same performance and cannot afford the loss in processing gain due to cross rate blanking.

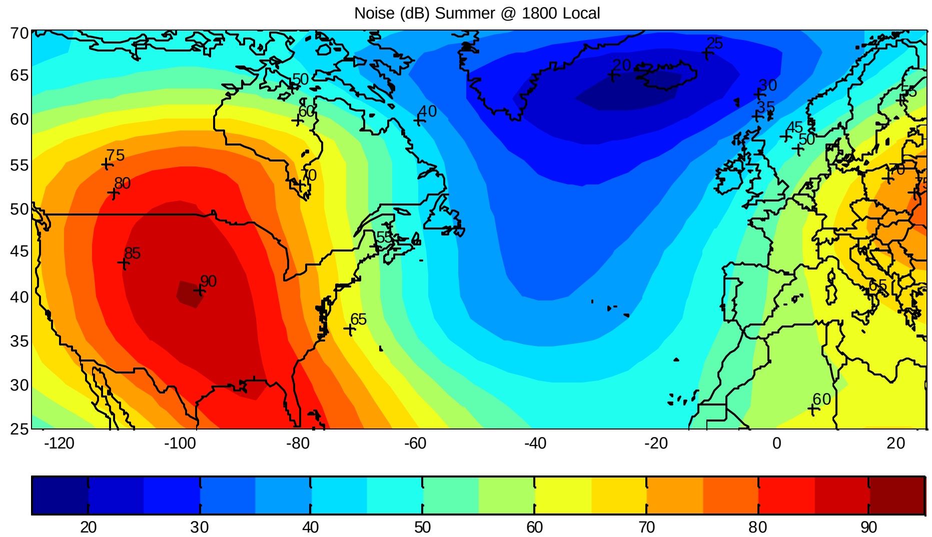

Figure 16. Comparison of ITU Noise predictions for North America and Western Europe.

Initially it was felt, that the main reason for the adoption of 32-state PPM vice Eurofix was to enable CRI canceling in short time constant aviation receivers and that blanking might be acceptable in longer time constant receivers for other applications. Figure 17 illustrates conceptually the functional relationship between averaging time and ranging error for aviation and maritime Loran receivers. For short time constants the error is dominated by noise and is inversely proportional to the square root of the number of pulses averaged or a slope of -0.5 on the log plot in figure 17. This part of the curve is the same for both types of receivers. Eventually the error is dominated by other terms that are independent of averaging time and more averaging does not improve accuracy. These bias terms include the errors in Additional Secondary Factor (ASF) due to spatial variation between the measured grid point and user location, errors in the measurement of the grid and temporal changes in phase. Because the more stringent accuracy requirements of the maritime harbor entrance and approach application, the combination of detailed ASF surveys and the transmission of real time temporal corrections needs to and will reduce these bias terms to a value much lower than the value for aviation. This means that while a marine receiver can average over a longer time due to more modest platform dynamics, it needs to average much longer in order to reduce the noise term down to acceptable levels and may not be able to blank vice cancel CRI either.

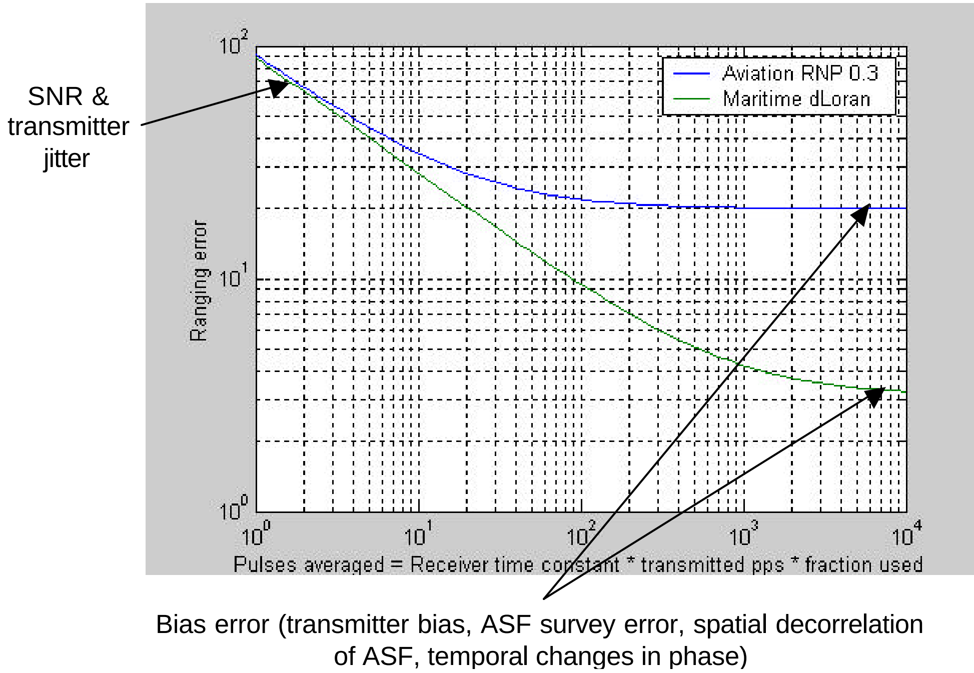

Figure 17. Conceptual functional relationship between averaging time and ranging error for aviation and maritime Loran receivers.

12. CONCLUSIONS

We have presented an outline of the effort to take differential Loran from the proof of concept stage to an operational system. The main issues discussed include the communications network necessary to broadcast real time differential data and the methodology of conducting and analysing ASF surveys. In addition we presented details on the analysis used to reach the decision to use 32-state PPM vice Eurofix for the transmission of differential Loran data.

ACKNOWLEDGEMENTS

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