Integrating Loran and GNSS for Safety of Life Applications

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BIOGRAPHY

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INTRODUCTION

Navigators have often used integration of information from multiple sensors to form a more robust and accurate navigation solution. Integrated Loran and global navigation satellite system (GNSS) is one combination that has been examined in the past to improve accuracy and availability. With the recent development of Enhanced Loran (eLoran), the next generation of Loran, the relatively recent idea of combining the two systems for safety of life application becomes a possibility [1]. This is because eLoran is designed to support in safety critical applications such as aircraft and maritime navigation [2]. This ability provides redundancy to GNSS in critical applications if it is disrupted. This goal was given further impetus by recent events.

In February 2008, U.S. Department of Homeland Security (DHS) announced that eLoran will be implemented to provide "an independent national positioning, navigation and timing (PNT) system that complements the Global Positioning System (GPS) in the event of an outage or disruption in service [3]." Additionally, an ongoing effort within Radio Technical Commission for Maritime Services (RTCM) to write minimum performance specifications (MPS) for eLoran sensors for maritime applications is under way. Specifically, the MPS will specify the performance of an eLoran receiver supporting maritime harbor entrance approach (HEA). A parallel RTCA effort for eLoran avionics supporting non precision approach (NPA) is expected to begin. These efforts focus on eLoran as a standalone sensor with the capability of integration with other sensors.

It is likely that these efforts will lead to the development of new Loran and integrated GNSS/Loran receivers and products [5]. For the purposes of the paper, GPS will be used as the proxy for any of several GNSS system since it is the most prevalent. As a complementary system, it is envisioned that Loran will generally be integrated with GPS into a single navigation unit. It is expected that customers will ask for and industry will be driven toward integrated systems.

There are many possibilities for combining the outputs from the GPS and Loran sensor into an integrated navigation solution that uses the strengths of each system. While the integration can be done in many ways, one has to be careful when doing so for safety critical applications. Tightly coupled combinations may inadvertently allow integrity faults in one system to cause integrity faults in the other. Take the example of using GPS to provide propagation delay (i.e., additional secondary factor or ASF) corrections for Loran. The GPS solution can be adversely affected by GPS satellite clock drift for some time prior to detection. With ASF calculation coupled to the GPS solution, the ASF are corrupted by the GPS clock drift. This can result in the loss of integrity for both systems. Hence, it is important to understand and design means of integrating GPS and Loran for integrity in these safety of life application. Additionally, for the RTCM and RTCA efforts, it is important to understand the features of such integration as they need to be incorporated within the standards.

This paper examines issues involved in integrating GPS and Loran for integrity in safety of life application. The integration may benefit safety of life application by: 1) providing of integrity if none is available and 2) maintaining integrity and providing improved performance. An important step in achieving either is the use of Loran/GNSS to generate additional secondary factor (ASF) estimates. These estimates, when generated with integrity, can be used to significantly improve Loran performance (availability or accuracy) for safety of life applications should GPS be limited or unavailable. Additionally, these estimates are needed to improve Loran accuracy so that its measurement can be useful in fault detection in an integrated Loran/GNSS solution. This is accomplished through the use of receiver autonomous integrity monitoring (RAIM) algorithms. Hence this paper will investigate two areas. First it will demonstrate how to generate accurate ASF estimates through the course of normal operations. It will discuss how integrity can be provided to these estimates. Second, the paper examines the use of the estimates and determines when Loran is beneficial in increasing GPS/RAIM availability.

BACKGROUND & OVERVIEW

This section presents background information in several important areas. First, it discusses the reasons for integration. It also examines Loran measurements, system integrity and basic integration techniques. The discussion of Loran measurements will be useful when considering integration. Background on how integrity is achieved on each system is provided as integrity needs to be carried over to the safety of life combination.

REASONS FOR INTEGRATING LORAN/GNSS

Ideas on integrating Loran and GNSS have percolated since the 1980s [4]. The primary reasons then for using the combination resulted from the limitations of the GPS constellation. Limited number of GPS satellites visible lead to the idea of combining GPS and Loran pseudoranges. Details of how this is accomplished can be seen in [6][7]. Another reason for the combining Loran and GPS stemmed from selective availability (S/A). The idea was to use the better short term repeatable accuracy of Loran with the inherently better long term accuracy of GPS [8].

Improvements in the GPS constellation and the elimination of S/A reduced interest in integrated Loran/GPS. Only in certain applications where GPS signals are limited or weak is such a combination effective. Urban canyon environment reduces the visibility of GPS satellites and additional pseudoranges from Loran are can improve navigation performance and availability [9]. Another example is combining the accuracy of Loran timing to aid reception of GPS indoor.

A current area of interest is integrating for safety of life applications. The difficulty in this integration is that separation of hazard is important philosophy in integrity. Inherent in integration is the mixing of information. So the challenge is to combine information in such a way that faults either do not "crossover" or they are bounded.

As such, we can conceive some guiding principles for combining the two systems and preventing cross contamination of integrity faults. Principles include: 1) eliminating cross system feedback, 2) leaving range measurements unadulterated or with known changes whose effects are bounded and 3) determining weighting means that are consistent with relative measurement uncertainty for each sensor.

One limitation on the use of Loran is that it is a horizontal positioning system. Loran ranges, discussed next, are measurements of the distance between the user and transmitter over the surface of the earth. It is not known if the range has any dependency on altitude when near the earth's surface (< 5 km). Fortunately, this range difference is on the order of tens of meters, at most. However, this can be significant for aviation integrity and some care should be taken when combining it with GPS for vertical position. Hence the most natural combination for safety of life GPS/Loran is for land or maritime applications which occur on the earth's surface. In this paper, the example applications will be more directed towards maritime.

LORAN MEASUREMENTS

Traditionally, position determination and navigation using Loran was accomplished using a single chain. When using chains, either time difference (TD) or time of arrival (TOA) measurements can be used. TD measures the difference in propagation time between two signals. Single chain processing facilitates the measurement by enabling signal identification and relative propagation time calculation. The master station can be uniquely identified based on its phase code. The secondaries transmit based on a published nominal emission delay (NED) relative to the master. This delay is created such that each signal has its own exclusive time window within the chain. So, after the master signal has been identified, the identity of each secondary signal can be determined. One TD measurement results in one hyperbolic line of position (LOP) on which the user may reside. Two TD measurements are thus adequate to determine horizontal position. TOA measurements are also straight forward when using a single chain. Pseudoranges akin to GNSS can be determined from TOA of the signal from each station by removing its respective NED. In the absence of propagation delays and transmission errors, each pseudorange is differs from the true range by a common clock offset. The offset can be solved in using the traditional least squares position estimate. When used in chain based solutions, the TD and TOA solutions are essentially the same.

Positioning can be accomplished with signals from multiple chains, though with additional requirements. One requirement is being able to identify the transmitting station of the signals used from each chain. Under Loran-C, the identification of secondaries without other information, such the master, is difficult. However, even with station identification, each chain can only be used individually, as in single chain operations.

Enabling combined use any available Loran signal requires being able to identify the station and determine the chain offset. One method is to solve for the chain time offset by widelaning the signals from the different chains. The pattern of relative time differences between signals of two US (European) chains repeats roughly every 30 to 60 seconds (300 to 600 seconds) with the phase code interval (PCI) being integer multiples of 200 (20) microseconds. If one has station identification and a reasonable estimate of position (~10 km for US, ~ 1 km for Europe), the chain time offset can be determined through widelaning. Having a good time estimate can be used to determine the offset without the need to widelane. Even a reasonable time estimate (within a few seconds) can narrow the scope of the widelane such that a position estimate is not necessary.

Enhanced Loran was designed to facilitate all in view operations. Hence it incorporates messages to identify each station and determine precise time. Additionally, it mandates time of transmission (TOT) control whereby each station is synchronized to UTC and broadcasts at a precisely known time. Under the current Loran-C system area monitor (SAM) control, the secondaries may transmit as much as one microsecond off from the anticipated time based on published NED. The result is that all in view operation with SAM control can suffer very large errors that do not exist under TOT control.

LORAN PHASE VARIATIONS

Like GPS, Loran signals suffer from propagation delays that can greatly affect its accuracy if not corrected. There are three major propagation delay factors in Loran. The primary factor (PF) accounts for the propagation time needed to traverse the atmosphere. The secondary factor (SF) is the increment of time for traversing an all seawater path. Both the PF and SF are calculated based on standard models and are fixed for a given signal at a given location. Additional secondary factor (ASF) represents the remaining delay – that is the extra delay on the Loran signal due to propagation over nonhomogenous land path vice an all seawater path. ASF represents the largest source of variation in the Loran measurements. As a result, ASF estimates are traditionally used in Loran and quoted accuracy usually assumes use of ASF maps. However, even with such static corrections, the residual ASF, essentially its temporal variation from the static nominal ASF estimate, can be significant - 500 meters or more peak to peak. To enable maritime HEA, differential Loran corrections broadcasts specifically treat this temporal variation allowing for sub 10 m accuracy in position. For aviation, such corrections are not employed and so a model bounding these ASF temporal variations is used. Such corrections for aviation will likely be too cost prohibitive for a back up system.

PROVIDING INTEGRITY: ELORAN & GNSS

Safety of life requires assurances that the system is performing nominally. This means that integrity must be present. One method is to have integrity provided by each individual system and then applied to the combination. Another method is to use the combined system to provide integrity.

Enhanced Loran is designed to support aviation and maritime navigation – two safety of life applications. As such, integrity is an inherent part of its design. The design philosophy is that integrity would be provided by both the system and the user. The system would ensure that the transmitters are performing nominally. It also monitors threats such as skywave interference. The user incorporates models for Loran performance under nominal conditions and develops a bound for the range and position error based on these models and receiver measurements.

GPS integrity can be provided through several sources. Augmentation systems (AS) such as spaced based augmentation system (SBAS) or ground based augmentation systems (GBAS). Additionally, cross checking using redundant measurements (i.e., RAIM) is also used to provide integrity.

If integrity is unavailable on at least one of the two systems, then combination can be used to provide it. One means is to use RAIM techniques since the combination of the two systems should provide an increased multiplicity of measurements. As RAIM is based on the use of redundant measurements, the increase in measurements, particularly ranges, could enable or improve RAIM performance.

INTEGRATION TECHNIQUES

Integration techniques can be divided into three general categories: position domain, range domain or tracking domain. Basic architectures for each of these techniques are seen in Figure 1, Figure 2, and Figure 3, respectively. For the purpose of safety of life and redundancy, only the first two techniques have obvious utility. Deep integration, such as at the tracking loop level, inherently involves cross feeding of information in a manner does not allow the effects of each sensor to be easily separated. As a result deep integration is not considered.

Position domain integration techniques for safety of life are limited given the limited information available. Error detection through position solutions comparisons does not provide an easy means of detecting fault as 1) the Loran solution is generally less accurate and 2) if the two solutions disagree, one cannot decide which solution, if any, to trust.

One position domain method that may be useful is to use GNSS to provide estimates the effects of ASF on the Loran position output. The estimate can then be used to provide improved Loran accuracy should GNSS be loss. It may also benefit integrity in this event though those benefits may not be significant. Integrity bounds from the GNSS solution, established either through the use of augmented GNSS, RAIM or other integrity techniques, can then bound the initial error on the estimate. ASF spatial and temporal models can be used to grow the error bound on the ASF [10][11]. A basic model, seen in Equation 1, can be expressed as having the position domain ASF bound be the sum of the nominal bound and factors ($k_{ASF,d}$, $k_{ASF,t}$) that account for the growth of ASF in distance and time. The most important and difficult step is validating the bounding growth factors. Additionally, the improved ASF estimate results in improved accuracy which aids the receiver in detecting Loran cycle selection errors. The drawback of the technique is that the estimate only has relevance to the combination of Loran station used when creating the estimate and near the location where the estimate was generated. Estimating ASF in the range domain provides a much more useful solution.

$$ASF_{bound} = ASF_{bound,nom} + k_{ASF,d}d + k_{ASF,t}t \quad (1)$$

Range domain combination is where the most benefits will likely reside. As discussed previous combined GNSS/Loran ranges can improve availability. This combination can provide integrity by providing the redundancy of signals required by RAIM. This requires that Loran has reasonable ASF estimates for each pseudorange used. Otherwise, Loran range errors are far too large to detect GNSS faults. Additionally, the standard weighted square sum error (WSSE) statistic used for RAIM requires understanding of the residual range error distribution for efficient use. Without ASF estimates, the Loran errors would have large, unknown biases, making the application of RAIM overly conservative.

Range domain combination can provide these ASF estimates and thus it provides a solution to its own requirement. Various methods have been used to record these ASF estimates including modeling conductivity [12] and ASF grids [13]. As seen from the discussion, generating ASF estimates using GNSS is an important step. Many implementations for generating ASF grids and maps have been suggested before. However, these designs generally require a rigorous survey. A user will not want to be constrained to perform surveys at unsurveyed locations and so a more user friendly approach is proposed. The next section of the paper will detail how the user can generate these estimates thorough its own nominal operations. These estimates can have integrity provided that the GNSS solution used for making the estimates have integrity. The ASF estimates with integrity can then be used in a variety of manners. If GNSS integrity source (i.e. augmentation system such as SBAS) is loss, then Loran/GNSS RAIM is possible. If GNSS is loss entirely, then Loran with ASF can be used the ASF variations bounded for spatial effects.

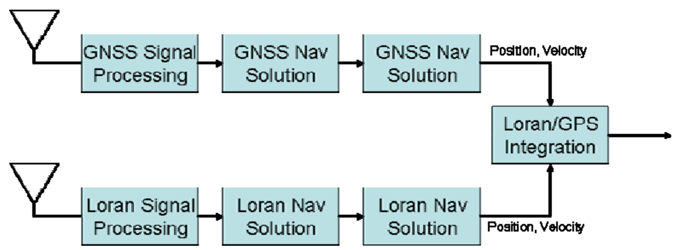

Figure 1. Position Domain Integration

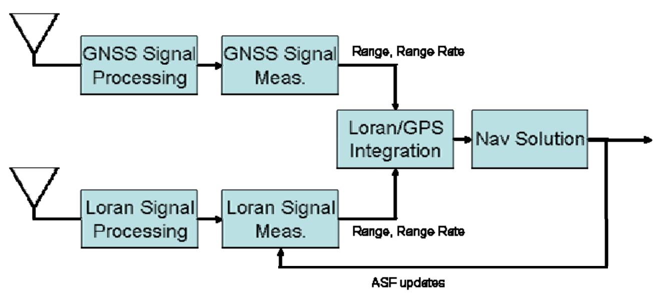

Figure 2. Range Domain Integration

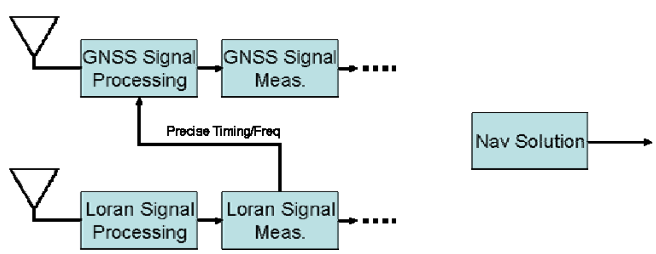

Figure 3. Tracking Loop Integration

SUGGESTED RANGE DOMAIN INTEGRATION

Range domain integration seems to be the most reasonable means of providing safety of life. This paper suggests a possible integration technique whereby the combined system, when operating nominally, uses GPS with integrity (via augmentation system or RAIM) to get position and to generate ASF estimates (i.e. grids). Should GPS integrity be unavailable, then the combination of ASF corrected Loran and GPS can be used to provide integrity and perhaps improve accuracy. These options and fallbacks are illustrated in Figure 4. The next two section discusses how this grid can be generated and analyzes how the resulting ASF corrected Loran can be used with GPS.

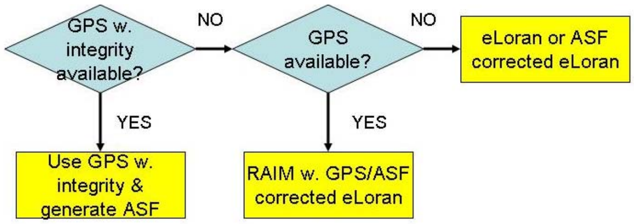

Figure 4. Integrity Options for Integrated System

LORAN ASF USING DEJA VU NAVIGATION

The provision of accurate ASF estimates is the key to enabling useful integration of Loran and GNSS. eLoran is designed to provide accurate ASF for HEA through the use of ASF grids and differential Loran (dLoran) corrections from local monitors to account for spatial and temporal variations of ASF, respectively. However, this method will only cover a limited number of areas – major harbor shipping channels and does not necessarily aid other modes of transportation such as aviation.

This section will detail a method of using an integrated Loran/GPS to provide ASF grids and temporal corrections to achieve a similar level of performance. This technique can be used to supplement mariners in areas where dLoran is not supported or by aviators in some circumstances. It is termed "déjà vu navigation" for the purposes of the paper as it uses prior measurements in the same region will to form and update ASF grids. As the goal is safety of life, we will discuss how to provide integrity to these ASF estimates.

In this paper, the term calculated and estimated ASF will be used to represent the ASF calculated from measurements and ASF estimated from the grid, respectively. The updating and overall ASF grids refers to the ASF grid generated from the current set of calculated ASF and the final ASF grid from all surveys. The steps in déjà vu navigation are as follows:

1) Determine calculated ASF and generate updating grid and weighting
2) Calculate temporal offset
3) Update overall ASF grid map and grid weight.

The first two steps can be accomplished with each new calculated ASF or once a set of calculated ASF (i.e., all ASF from a trip) is available. The later reduces computational costs while the former allows for the use of the latest information should GPS be suddenly unavailable.

CALCULATION OF UPDATING GRID

The calculation of ASF grid can be achieved in many ways. These techniques generally employ precise surveys to yield the desired grid. This process is expensive and unrealizable for a large area. The déjà vu navigation technique generates a full grid based solely on measurements taken in the course of normal operations. As more measurements and trips over the region are taken, the grid is refined and updated to improve its performance.

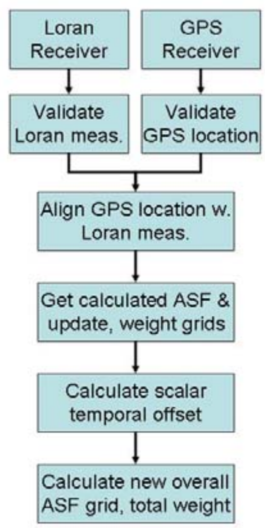

Figure 5. Generation of each calculated ASF

The first step is to collect calculated ASF and generate an updating ASF grid. The basic concept is seen in Figure 5. It starts with collecting measurements from a Loran and GPS receiver. If integrity is required, both the Loran measurements and GPS location should be validated. The Loran measurement should be free of cycle slips and non-nominal errors. The GPS location should have integrity. Next, align the outputs of the GPS and Loran such that they are referencing the same time/location. ASF estimates can then be calculated using GPS position and Loran range measurements. The GPS position is used to get the true range which is then converted to an "ASF-free" Loran propagation time by accounting for the PF and SF. This ASF free propagation time is differenced from the measured propagation time to get the calculated ASF (in units of time). This is done for each Loran signal used and is seen in Equation 2.

Calculated ASF = measured propagation time – "ASF-free" propagation time (2)

Each calculated ASF is used to generate the entire grid – an updating ASF grid. This is achieved by having each calculated ASF contribute to the estimate of ASF at each grid point. The contribution or weight should, of course, depend on the relevance of the ASF estimate. In the technique that was tested, an exponential weighting based on distance was used. This is seen in Equation 2 where w_i represents the weight on grid point i, d_i is the distance from the measurement point to the grid point and k is a constant. A series of calculated ASF can be used to generate a combined weighted ASF estimate by combining the updating ASF grid and weighting associated with each of them. Calculation of the temporal offset, especially if the measurements are taken apart in time, may be necessary for the combination.

$$w_i = k \exp\left(\frac{-d_i}{gridsize}\right) \quad (3)$$

CALCULATION OF TEMPORAL OFFSET

A second necessary component for having an accurate ASF is to have a term accounting for the temporal variation. This is necessary under nominal conditions of generating and updating the grid. It is also required to use the grid should GPS be lost.

Under nominal conditions, the calculation of temporal term can be achieved in many ways. One method is to compare the calculated ASF at the current point with the estimated ASF from the overall ASF map at the closest grid points. In the proposed technique, a more sophisticated technique is used. The calculated ASF, as discussed in the previous section, is used to generate an ASF grid, represented in Equation 4 in matrix form as $A_{ASF,curr}$. Associated with the grid is a weighting matrix, $W_{ASF,curr}$, with weights corresponding to each point. The base ASF grid and weight matrix is given as $A_{ASF,map}$ and $W_{ASF,map}$, respectively. The temporal offset is then derived from the difference of two ASF maps multiplied entrywise (Hadamard product) by the normalized weighting matrices.

$$offset_{temporal} = \sum_{termbyterm} \left(A_{ASF,curr} - A_{ASF,map}\right) \times \frac{\left(W_{ASF,curr} \bullet W_{ASF,map}\right)}{\left|\left(W_{ASF,curr} \bullet W_{ASF,map}\right)\right|} \quad (4)$$

The process above discusses how to get the temporal offset given GPS. However, the benefit of integration through the use of the ASF estimates requires that we can calculate the temporal offset during a GPS outage. We propose some methods that can be used. If the GPS outage occurs in the course of navigation, then the last calculated offset is used. If the outage occurs prior to travel, a known location (i.e. dock or airport hangar, etc.) can be used as a position reference instead of GPS to generate the offset. The approach of using known position references can be applied in another way. If the travel should transit over known locations such as an area supported by eLoran HEA, this can be used for determining the offset. However, there are some caveats to the approaches. First, the offset will degrade obviously decorrelate temporally. Second, the location used to generate the offset must be part of the ASF grid previously generated.

UPDATE ASF GRID MAP

The final step is to incorporate the updating grid into the full grid map to generate a new grid map and weighting. The combination used is based on weighting. The calculation for the overall ASF map and weighting are seen in Equations 5 and 6. The ASF estimate is generated by interpolating from the overall ASF map using the weights.

$$A^{new}_{ASF,map} = \frac{\left(A_{ASF,curr} \bullet W_{ASF,cur} + A_{ASF,map} \bullet W_{ASF,map}\right)}{W^{new}_{ASF,map}} \quad (5)$$

$$W^{new}_{ASF,map} = W_{ASF,curr} + W_{ASF,map} \quad (6)$$

ASF WITH INTEGRITY

The technique described also needs to address integrity of the ASF generated. Assurance of integrity must come from three sources: 1) integrity on the GPS position, 2) bounding the growth of the residual ASF as point moves further from the locations used to generate the grid and 3) the temporal degradation of the temporal offset. A means of assuring integrity is to develop a bound matrix associated with the ASF and weighting matrix above that accounts residual ASF beyond the grid value.

The integrity of the GPS position can be obtained through the use of an augmentation system (SBAS, GBAS) or RAIM techniques. Care should be taken that there are no faults in the GPS position solution and that its errors are bounded. For example, in using an augmentation based solution, the equipment should wait past the time to alert (TTA) of the augmentation system to utilize the ASF estimate associated with that position solution.

If it is desired to develop bounds on the ASF estimate, the position error bound, such as the horizontal protection level (HPL), derived from augmentation system or RAIM can be used. It can be incorporated into the ASF estimate and ASF grid. The result is to generate a bound matrix on ASF estimation error corresponding to the overall ASF grid matrix. At each grid point, bound(s) on the position is used as the nominal bound values for the matrix. The nominal value can be modified by other factors when applied (temporal changes, weight of the estimate, etc.)

The spatial change in ASF needs to be accounted, particularly for locations that are more distant for measurement points. One issue with the methodology discussed above is that it slightly biases the ASF grid values towards those of the locations that are visited the most. A model for spatial change can be used to "project" the nominal bound matrix value from the location it was developed to each grid point based on distance between the locations.

As Loran temporal variations are generally slow, the temporal offset generally degrades slowly. However, this degradation can, in some instances, result in several meters of error over a few hours. Fortunately, the variation is correlated between signals and some of the effect will be estimated by the Loran clock offset.

Clearly integrity, particularly for aviation, is not a simple matter. The discussion here is really meant to stimulated deeper examination and refinement of the approaches outlined rather than promulgating a definitive solution.

EXPERIMENTAL SET UP

An evaluation of the ASF grid generation technique was made using data collected over the last couple years in the Thames River in New London, Connecticut. The same set up using a Locus Satmate 1030 Loran receiver and a Trimble DGPS receiver was used for all trials. These instruments were carried aboard a 27 foot Island Packet sailboat. Most of the data collected was taken under sail. In all 37 trips over 2006, 2007 and 2008 are used to study the performance of the déjà vu ASF grid technique. The Thames River channel and surrounding waters are seen in Figure 6 and Figure 7.

Since an accurate time base was unavailable aboard the ship and because eLoran has not been implemented, Loran TD measurements were used. The TD measurement was aligned with DGPS position. The processing also included removing DGPS outliers based on the location. While quality measures and flags on the DGPS output was available, they were not used for the preliminary analysis. As a result, a few faulty DGPS position outputs remain.

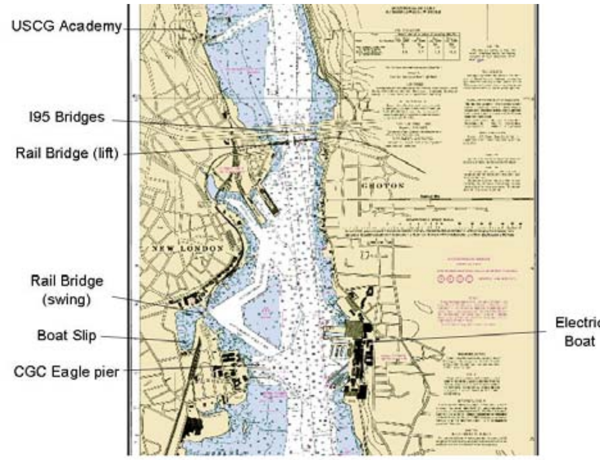

Figure 6. Thames River Harbor Approach

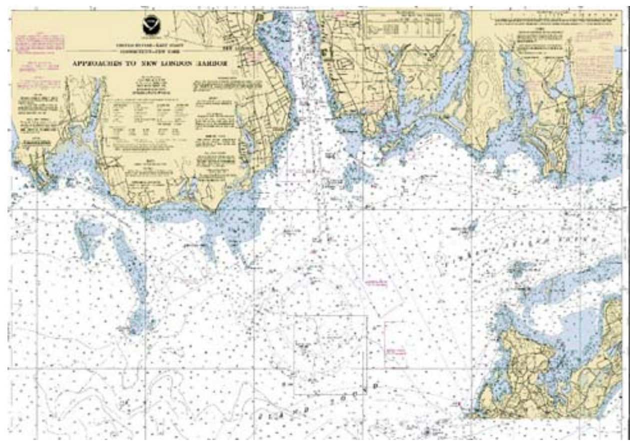

Figure 7. New London Harbor Approaches & Surroundings

PERFORMANCE

First, examine the basic grid generation process. The basic steps of the algorithm can be seen in Figure 8. The top two plots of the figure shows the updating ASF grid (left) and its associated weighting (right) generated during one trip. This grid and weighting is used to update the overall ASF grid and weighting maps seen in the bottom two plots.

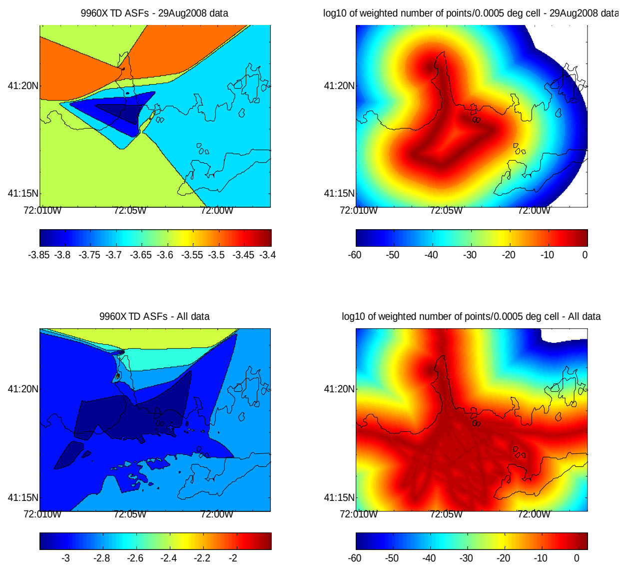

Figure 8. Updating ASF grid and weight (Upper left/right) & overall ASF grid and weight (Lower right/left)

Now examine the performance of the grid as it is generated and updated. Figure 9 shows the route of the second data collection run (left) and the cumulative distribution function (CDF) (right) of the run using the current overall ASF map. The color code used for the map indicates different levels of performance. Line segments in green indicate errors less than 20 m, yellow is between 20 and 50, and red is greater than 50 m. As seen in both the map and the CDF, the performance is pretty poor with 95% accuracy greater than 150 m. That is not surprising as only one previous run was available to generate the underlying ASF correction grid.

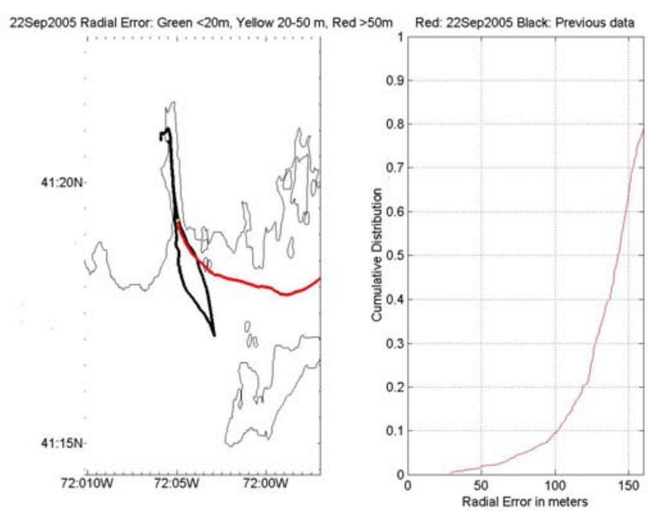

Figure 9. ASF corrected Loran performance and CDF of second run

Figure 10 shows the same type of plot for the fifth data run. In this case, the four previous trials have been used to generate the ASF grid. As a result, the grid is better as is the performance of the ASF estimates. As seen in the figure, most of the run is in yellow or better and the 95% accuracy level is around 40 meters.

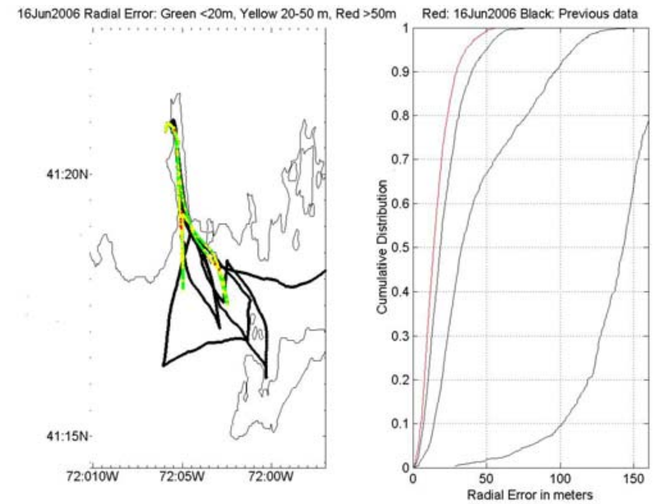

Figure 10. ASF corrected Loran performance and CDF of fifth run

Figure 11 shows the result from the 37th (most recent) data run. Note that not all of the runs were used as some were filtered out due to outliers and bad temporal offsets. As seen in the CDF, the 95% accuracy level on some of the runs approaches 20 meters. In general, the 95% accuracy level seems to be about 25-30 meters. Some performance improvements could be achieved with better elimination of GPS outlier.

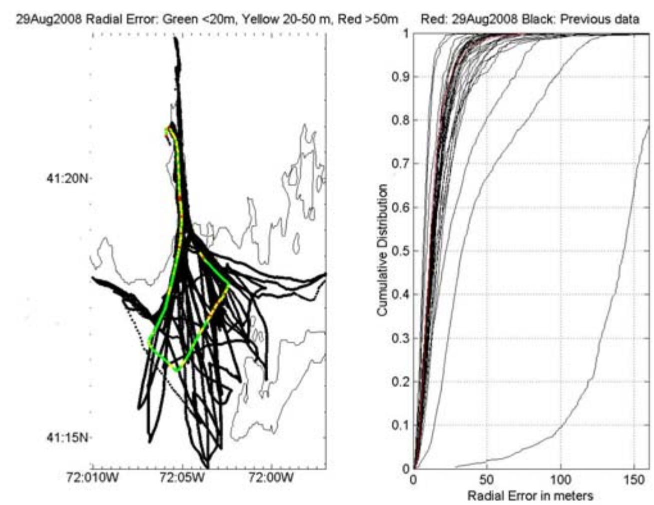

Figure 11. ASF corrected Loran performance and CDF of 37th run

OVERALL ASF MAP

The overall ASF map of TD from Nantucket, MA generated using all runs is seen in Figure 12. Since TD measurements are used the result is a difference of the

ASF from Nantucket and that of the 9960 master station (Seneca, NY). This can be seen in the increasingly negative ASF on the map as one moves from north to south. Some outliers can be seen – these are caused by hard metal objects that are known to re-radiate Loran signals.

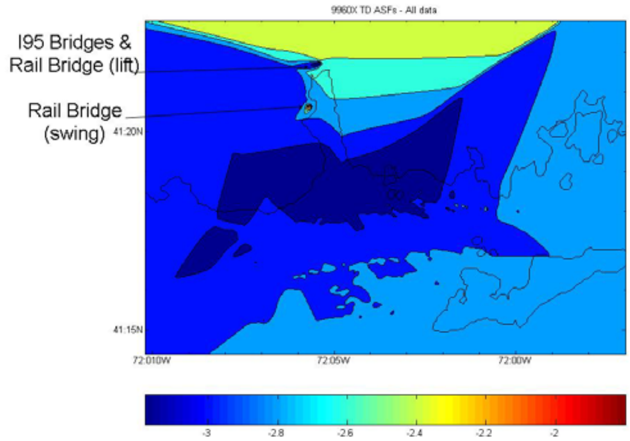

Figure 12. Overall ASF map from all runs

TEMPORAL OFFSET

The calculation of the temporal offset is a necessity. This can be seen in the temporal offsets calculated in these data runs. Examples of the calculated temporal offset are seen in Figure 13. Within the data record during a given year, there can be variations of several hundred nanoseconds – equivalent to several tens of meters. Much of the variation is known to occur during the winter. However, data collection on the Thames during this period is not possible. Additionally, changes in transmission methodology such as going from SAM control to TOT clearly affected the offset.

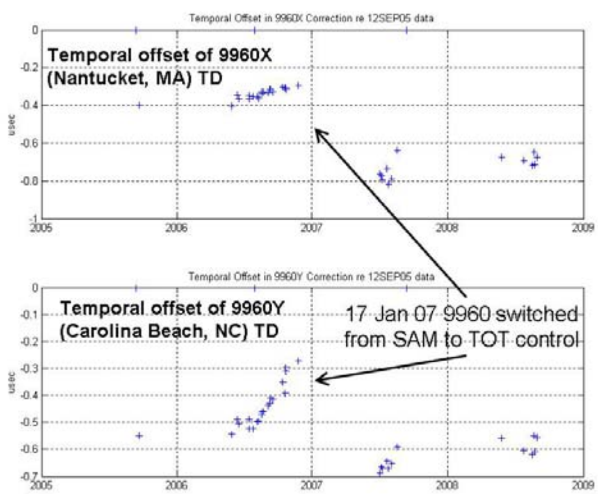

Figure 13. Temporal offset of Nantucket & Carolina Beach TD

UTILIZATION FOR RAIM

With the application of accurate ASF estimates, Loran range measurements may provide benefits when used with GPS ranges for RAIM. In this section, we examine the performance benefits of such a combination. Specifically, the improvement in the availability of integrity is studied. One application of the combination is its use in shipping channels where both GPS and Loran lack the availability to provide the required accuracy and integrity on a stand alone basis. This lack of sole means coverage may stem limited number of GPS satellites visible due to terrain and limited Loran stations in the coverage area. For example, the Alaskan archipelago is an area where this condition may exist for maritime.

This section shows a parametric study on the performance of RAIM using GPS and ASF corrected Loran. The examination determines the situations when such a combination is useful or when it is not. It is meant to be a rough, first cut look at the benefits of the approach.

BASIC ASSUMPTIONS

For the initial analysis, we examine the performance over the conterminous United States (CONUS). We examine the performance of GPS and integrated GPS/Loran given reasonable ASF estimates. The RAIM solution for both cases is produced using a modified multiple hypothesis solution separation (MHSS) algorithm [16]. The MHSS solution results in a HPL based on aviation integrity requirements.

The data collected does not provide enough information to determine an accurate bound for Loran range measurements with ASF estimates. This is because the results from the previous section come from a combination of ASF estimates of varying accuracy. Hence the errors are dependent on how close and how many previous runs were near the location of interest. The results and other ASF grid studies suggest that a reasonable one standard deviation bound is perhaps around than 10 meters or less. However, with integrity, it is often difficult to discern the tails of the distribution (and hence the overbound) from the body of the distribution. The parametric study will examine different assumed levels of the bound to determine what values of bounds are useful.

Assumptions also need to be made on GPS performance without augmentation. One starting point is the Wide Area Augmentation System (WAAS) Minimum Operational Performance Specifications (MOPS) [17]. Section 2.5.9.2 of that document discusses availability calculation for fault detection and exclusion (FDE). The section models the bounding variance of the non ionosphere range error as the sum of four terms, as seen in

Equation 7. The two largest are the range error due to satellite clock and ephemeris ($\sigma_{i,URA}$) and the ionosphere ($\sigma_{i,UIVE}$). The one standard deviation bound on $\sigma_{i,URA}$ is specified by 2.5.9.2 is 5.7 m. The ionosphere error bound, seen in Equation 8, depends on elevation (first term) and geomagnetic latitude (second term). The obliquity factor, F_{pp}, ranges from 1 to about 11 at 90 and 5 degrees elevation, respectively. The ionosphere delay, τ_{vert}, ranges from 4.5 m to 9 m at mid latitudes and equatorial regions, respectively. These values reflect conservative values for GPS performance.

$$\sigma_i^2 = \sigma_{i,URA}^2 + \sigma_{i,UIVE}^2 + \sigma_{i,air}^2 + \sigma_{i,tropo}^2 \quad (7)$$

$$\sigma_{i,UIVE}^2 = \left(F_{pp} \times \tau_{vert}\right)^2 \quad (8)$$

The Matlab Algorithm Availability Simulation Tool (MAAST) was modified to conduct the coverage analysis and performance of the Loran/GPS RAIM combination. MAAST was designed for use for assessing the coverage performance of WAAS under various algorithms [18]. The tool was modified to use of MHSS RAIM algorithm instead of WAAS algorithms. Additional modifications allowed for the inclusion of Loran and the inclusion of a one standard deviation overbound of Loran range error. For simplicity, the overbound was assumed to be the same for all stations and only stations within 1000 km of the user are usable. For GPS, fixed values of the bounds ($\sigma_{i,URA}$, $\sigma_{i,UIVE}$) assumed. Looking towards future performance, using one sigma bounds of 5 meters is rather conservative. Given that and that system performance has already improved since the development of these bounds, the study utilizes bound values of 1.8 meters each. The base RTCA optimal 24 GPS satellite constellation is used [17]. The WAAS geostationary satellites are included but with a very high bound value so that it is effectively not used.

RESULTS

Figure 14 shows the HPL of the GPS/RAIM system without Loran at the 95% availability level. The HPL is the high integrity bound on the horizontal position error (HPE). The result represents a baseline performance. Overall the HPL is between 60-80 m with some locations being less than 60 m.

The performance of a GPS/Loran RAIM is seen in Figure 15. This case assumes that the overbounding standard deviation of Loran range error is 40 meters. This is analogous to a case of Loran without good ASF estimates. Loran without ASF estimates would be even worse. As seen from the plot, the performance is little changed from the GPS only case. This demonstrates that Loran/GPS does not have significant benefits for RAIM unless good ASF estimates are available.

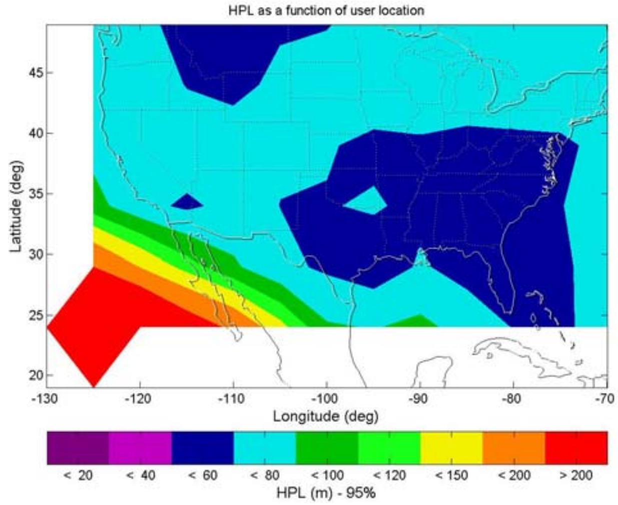

Figure 14. HPL at 95% Availability - No Loran

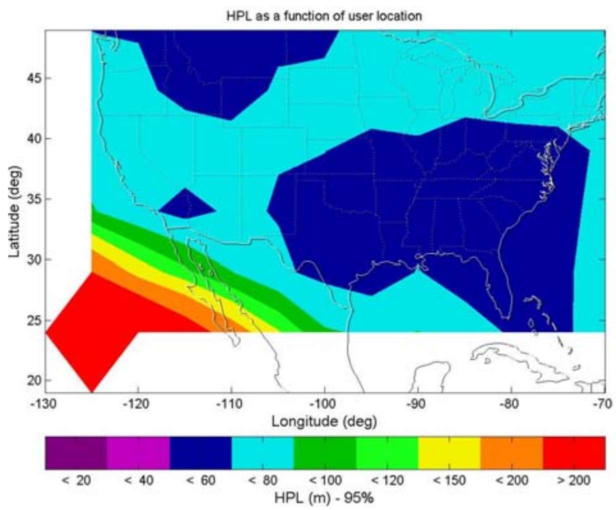

Figure 15. HPL at 95% Availability – Loran (σ_{bound} = 40 m).

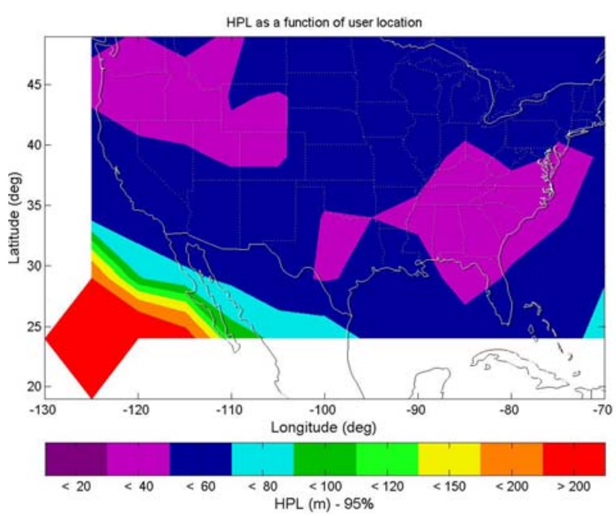

Figure 16. HPL at 95% Availability – Loran (σ_{bound} = 10 m).

Figure 16 show the case where the overbounding standard deviation of Loran range error is 10 m. In this case, the HPL available at 95% improves by roughly 20 meters across CONUS. The HPL is below 60 meters and in some parts less than 40 m. Loran thus can aid and improve GPS RAIM performance if its range errors can be bounded at a 10 meter level (1 sigma). While this is solely a first cut analysis, it illustrates the limits and benefits of Loran for RAIM.

CONCLUSIONS

The integration of GNSS and Loran can be accomplished with some utility for safety of life applications. One potential benefit of the integration is to provide a similar level of integrity while improving availability of an operation above that of the individual sensors. Another benefit is to provide integrity with improved performance should one sensor be unavailable. The key to providing this benefit in integrated Loran/GNSS is having accurate ASF estimates. This reduces the error on Loran range measurements to a degree where it can be used to complement the capability of GNSS.

This paper presents a method of providing accurate ASF estimates through the nominal operations of the integrated system. The estimate is derived from the ASF grid and temporal offset generated by the method. Integrity of estimates can be provided through several means. With the estimates, Loran can be used to complement GNSS in two scenarios. If GNSS augmentation system is unavailable, RAIM using GPS and Loran ranges can be effectively used. If GNSS is lost, the ASF estimates allow Loran to be a more accurate system while maintaining integrity. This enables Loran to back up additional operations or allow it to serve in more places. The methods discussed, particularly the application of the grid, are more suitable to maritime than aviation for a number of reasons. Maritime, due to its ability to integrate Loran signals longer, will have more accurate ASF estimates. Additionally, mariners will have more means of getting the required temporal offset. However, aviation may benefit in some scenarios.

Providing integrity is a difficult process and this discussion in the paper represents only a starting point. Care must be taken in the integration so that integrity is maintained. The difficulty lies in the details of the specific algorithms used.

DISCLAIMERS

The views expressed herein are those of the primary author and are not to be construed as official or reflecting the views of the U.S. Coast Guard, Federal Aviation Administration, Department of Transportation or Department of Homeland Security.

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