Analysis of the Effects of ASF Variations for Loran RNP 0.3

Sherman Lo, Per Enge, Stanford University,

As the Loran groundwave propagates, the signal is delayed. Additional Secondary Factor (ASF) is the value of the delay of the signal over the actual terrain relative to an all seawater path. The envelope to cycle difference (ECD) is the delay of the envelope relative to the carrier. Good ASF estimates can significantly increase the accuracy of Loran. Since precise estimates for the current ASF may not be available, the variations could result in large errors. Thus, for Loran to have the integrity and accuracy necessary to meet RNP 0.3, the variation in ASF needs to be well understood and modeled.

The Loran Integrity Performance Panel is examining these groundwave propagation effects. One major area of work is determining a method for providing ASF to the user and bounding the result error. The ASF variation can be separated into spatial and temporal variation components. Furthermore, it can be separated into components that are correlated and uncorrelated between the measurements received by the user at a given instance. This paper will address the models examined for bounding the error. It examines the modeling of temporal ASF variations, spatial ASF variations and the use of position domain bounds. Results of the model on system performance will also be shown.

1.0 Introduction

Historically Loran has served many navigation needs. One notable exception is the use of Loran for landing aircraft. However, the current state of affairs and system improvements has provided greater impetus for examining the ability of Loran to meet the requirements of non-precision approach (NPA) [1,2]. The Loran Integrity Performance Panel (LORIPP) has been chartered by the Federal Aviation Administration (FAA) to evaluate Loran for NPA, targeting Required Navigation Performance 0.3 (RNP 0.3) [3].

If Loran can be demonstrated to provide RNP 0.3 capabilities, this would allow it to perform an integral function of the National Air Space (NAS). The NAS is transitioning to primarily Global Positioning System (GPS) based navigation. By providing RNP 0.3, Loran will be able to provide redundancy GPS for aviation. Redundancy is important due to both concerns about GPS vulnerability and the need for robustness in safety critical applications. Furthermore, this ability, coupled with Loran's potential capabilities in other navigation and timing modes could allow the US to provide for GPS redundancy using only Loran.

1.1 RNP 0.3 Requirements

For Loran to provide redundancy to GPS for aviation, Loran must meet aviation requirements. Three areas of primary concern are meeting required levels of integrity, availability, and continuity. Integrity is the fidelity of the system – the reliability that the information provided is true. For RNP 0.3, the requirement is that the probability of hazardously misleading information (HMI) is less than 10^{-7} per hour. An instance of HMI is defined as when the horizontal protection level (HPL), the bound on horizontal position error (HPE) generated by the system, is exceeded by the true HPE. Availability represents how often the system can be used for the desired application. To use a system for RNP 0.3 approach, HPL must not exceed the horizontal alert limit (HAL) of 556 meters (0.3 nautical miles). Implicit in this statement is that integrity requirements have been met. The requirement for RNP 0.3 is that availability (HPL < HAL) must be at least 99.9%. The requirement must be met at every point in the coverage area and cannot represent a spatial (or temporal) average. Continuity is the ability to use the continue using the system for the desired application if it is initially available. For RNP 0.3, the approach is 150 seconds in length and the requirement is for at least 99.9% continuity. Table 1 summarizes the requirements.

Requirement	**Definition (Metric)**	**Minimum Requirement**
Integrity	HMI is when HPL < HPE	Probability HMI = 10^{-7}/hour
Availability	HPL = HAL (556 m) No HPL means not available	99.9%
Continuity	Given HPL = HAL initially HPL must exist & HPL = HAL for 150 seconds	99.9%

Table 1. Primary Requirements for Aviation (RNP 0.3)

The system integrity is determined by ones ability to accurately estimate and bound the range or timing error. In turn, the size of the bounds is an important factor in determining the HPL which consequently affects availability and continuity. Hence groundwave propagation effects need to be carefully examined since they contribute significantly to range errors experienced by the user thereby affecting Loran’s ability to meet RNP 0.3 requirements.

1.2 Propagation Variations

Propagation affects the Loran signal delay and the envelope to cycle difference (ECD), the relative delay of the Loran carrier relative to the envelope. These two phenomena are of considerable importance when analyzing the ability of Loran to meet aviation requirements. In meeting those requirements, these variations must be understood and bounded to insure that hazardous information is not presented. The LORIPP analysis thus far has focused primarily on the overall delay in propagation and hence the paper will focus in this area. While a reasonable ECD model has been developed, it will not be discussed currently since additional data is being gathered for analysis. Understanding ECD is important for accurate cycle selection. This is vital since incorrect cycle selection results in a range error of 3 km or more.

The true propagation time for Loran is typically divided into three factors. The primary factor (PF) is the propagation time for the signal to traverse the atmosphere. The secondary factor (SF) is the increment of time for traversing an all seawater path. Third is additional secondary factor (ASF), which represents the incremental propagation delay of the Loran signal due to traversing heterogeneous earth vice an all seawater path. PF and SF are solely dependent on distance and thus can be calculated. ASF can vary with time and location and needs to be measured or modeled. The user receiver will only have an estimate for ASF and the difference between the estimate and actual ASF is a ranging error. This difference can represent the largest component of error on the Loran range (time of arrival or TOA) or time difference (TD) measurement and hence it results the largest uncertainty in position error. Relating this back to the RNP 0.3 requirements, to provide integrity to Loran, it is necessary to quantify and bound the difference between the actual ASF and the value used by the receiver. The bound on the ASF difference is a major component in determining coverage, availability and continuity.

$$\text{True Propagation Time} = PF + SF + ASF \qquad (1.1)$$

This paper discusses the analysis and treatment of ASF for the RNP 0.3. It begins with background on the basic model for treating ASF and details how the ASF fits in the calculation of the HPL. The following sections will outline the basic analyses used for determining the value of the temporal and spatial ASF bounds for the HPL. Finally, the effect of these values on preliminary availability, continuity calculations will be shown.

2.0 Background

This section presents background on the factors that effect variations in ASF. An understanding of these factors is used to develop a basic ASF model. It also discusses the HPL or integrity equation and how position errors due to ASF variations are bounded in the calculation of HPL.

2.1 ASF & Modeling ASF

Factors such as local ground properties (conductivity, etc.) and terrain along the path of groundwave propagation affect ASF. Changes in these factors result in changes in ASF. The ground properties, such as conductivities, of a given location are weather dependent. As nearby locations experience similar weather conditions, they should have similar ground properties. Within the local vicinity, the spatial differences in weather are not great. Thus resulting changes are temporal since weather changes with time. The change in ASF due to changing ground properties is denoted as temporal variation. As the receiver moves, the propagation path changes resulting in a change in the terrain encountered. The change in ASF due to the changing terrain is denoted as spatial variation. Hence ASF can be divided into temporal and spatial terms. Experience has shown that both phenomena can be significant and must be considered.

The temporal and spatial change can be treated as a decoupled problem. Temporal ASF variations account for the change in the ASF with time due to changes in ground properties. The temporal variation from a given station is assumed to be the same within a small region, such as the airport terminal area. However, the propagation paths to different parts of the region may have significantly different terrain. This leads to spatial differences in ASF that are not time dependent. Equation 1.2 shows this model for ASF with the true ASF for a user around a location x_o is modeled as the sum of an average value plus a temporal and a spatial term. Since it is not possible to provide the true ASF, the Loran aviation receiver will have an average ASF for a given approach. This average ASF is the average at a specified location, which will be denoted as the calibration point. Therefore insuring the safety of the position solution will require that bounds for errors due the temporal and spatial component be provided. The bound for the temporal component will be discussed in section three while the bound for the spatial component will be discussed in Section 4.

$$ASF_{total}^{tx_i}\left(x_{user}, x_o, t\right) = ASF_{average}^{tx_i}\left(x_o\right) + ASF_{temporal}^{tx_i}\left(x_o, t\right) + ASF_{spatial}^{tx_i}\left(x_{user}, x_o\right) \text{[b1]} \quad (1.2)$$

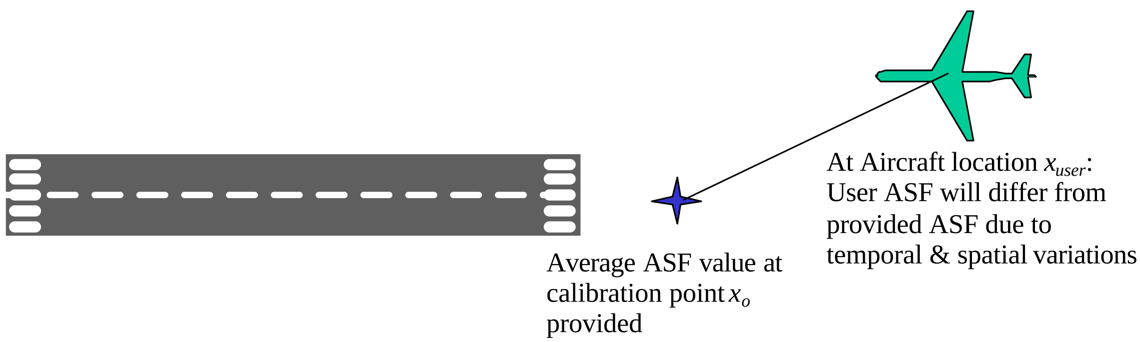


Figure 1. Variation of User ASF

2.2 Assessing ASF in terms of RNP 0.3

The temporal ASF is being studied using data from multiple sources. A data collection network has been set up and in place for the past year [4]. In addition, historical data such as Time Interval Number (TINO) is also being studied. Similarly spatial ASF is being studied using a number of sources. The BALOR algorithm and software developed at the University of Wales, Bangor uses the latest techniques to estimate the affects of terrain on ASF variations [5,6,7]. In addition, ground tests have been conducted to validate the performance of the model [7].

Hence, a reasonable amount of data and research are available for assessing the effect of ASF on aviation requirement. The unifying idea for the assessment is the HPL or integrity equation. The inputs to and construction of the HPL equation should guarantee integrity while the resulting HPL will dictate availability and continuity.

2.3 The Loran HPL or Integrity Equation

The Integrity Equation is the formula by which the confidence bounds on the error sources in a user's range measurement are tallied to form a bound on position error. In Loran, the integrity equation is synonymous with the HPL equation since horizontal position is being protected. It should provide integrity. As stated earlier, the requirement is that the probability of HMI is less than one in ten million (10^{-7}). The HPL equation for Loran contains four terms and is seen in Equation 1.3.

$$HPL = k\sqrt{\sum_i K_i a_i} + \left|\sum_i K_i b_i\right| + \sum_i \left|K_i g_i\right| + PB \qquad (1.3)$$

where

- k : the factor on standard deviations of the overbounding gaussian needed to achieve the desired confidence level. I.e. k =5.33 results in a probability of an error exceeding that value of 0.98×10^{-7}.
- K_i : the weighting factors derived from the pseudoinverse of the geometry matrix
- a_i : the standard deviation of the Gaussian distribution that overbounds the randomly distributed errors
- b_i : an overbound for the correlated bias terms
- g_i : an overbound for the uncorrelated bias terms
- PB : position domain bound

Temporal and spatial ASF variations are treated by three of these four terms. ASF cannot be treated as a random variable since the time constant of ASF is long relative to that of the position solution. Therefore it is generally treated as a bias. The temporal ASF model, discussed in the next section, divides the variation into two components: correlated bias and uncorrelated bias. The spatial ASF can be treated as an uncorrelated bias. The treatment is conservative and the direction of the ASF change is determined from the BALOR model. Hence another method, a position domain (PD) bound, is examined to leverage the known relationship of changes in ASF, particular the direction or sign of the change.

2.4 Commentary

Aviation requires that integrity is shown at a very high level. This means the HPL must bound extremely rare cases resulting in HPL values far above the accuracy (95% level). At the same time, HPL must be less than HAL for availability. The design of Wide Area Augmentation System (WAAS) and Category I Local Area Augmentation System

(LAAS), the systems currently deployed for providing GPS the integrity required for aviation, reflects the HPL inflation. In these systems, the ratio of HAL to system accuracy is roughly 25. If the ratio is applied to Loran, the RNP 0.3 HAL (556 meters) implies that Loran needs an accuracy of 22 meters. This level of accuracy is not reasonable without differential corrections and in order to meet RNP 0.3 requirements, the task facing Loran integrity is indeed difficult. It is important to separate the bounds into various forms and utilize as much known correlation as possible. It is important to also develop good estimates of bounds for ASF that provide integrity without being too conservative.

3.0 Temporal Variations in [b2]ASF

The temporal variation in ASF is due primarily to changes in local properties such as ground conductivity. The amount of variation differs in different parts of the country. It is particularly large in areas such as the Northeast U.S. where the ground can vary from frozen to moisture laden to dry. An illustration of this is seen in the estimate of ASF variations from historical data generated by Robert Wenzel (Figure 2). Hence an area of particular concern is the Northeast US and the data collection was primarily focused on these areas.

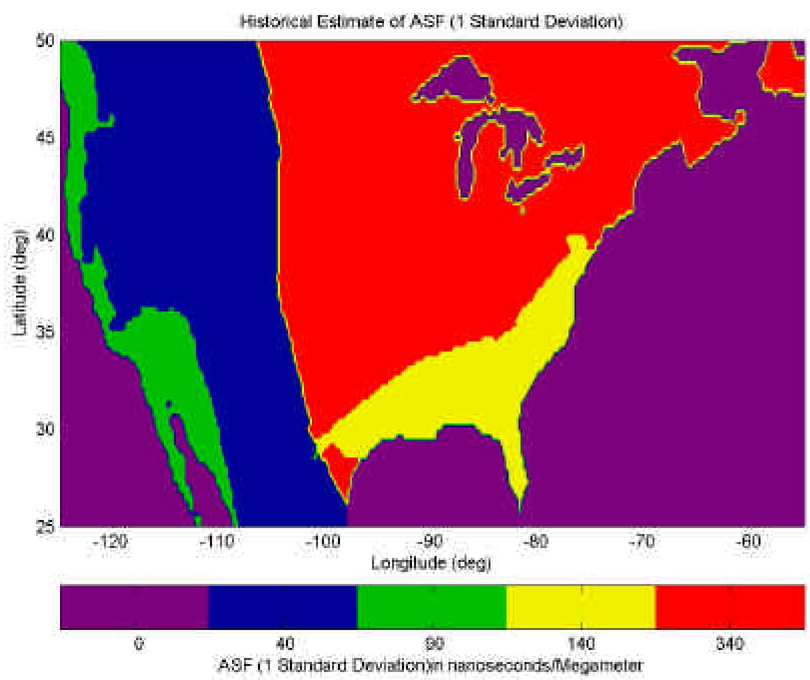


Figure 2. Standard Deviation of Temporal ASF Variations from Historical Data [R. Wenzel]

3.1 Basic Temporal ASF Model

ASF temporal variations are divided into a correlated and uncorrelated component. It is important to separate out the correlated portion since some credit can be taken for the correlation in the calculation of the HPL. Otherwise, error due to the worst-case combination of ASF temporal variations will have to be applied.

A basic mathematical model for providing this division is seen in Equation 1.4, which shows the ASF for each user-transmitter pair. The assumption is that the correlation in temporal ASF is partly related to land distance since the changes are due to changes in land properties. The ASF from station *i* at time *t* is equaled to the mean ASF from that station plus a land distance related term *dTOA(t)* that is the same for all received transmitters, a common mode term *c(t)*, and a residual error term $e_i(t)$. The total land distance to the user from transmitter *i* is $d_{i,land}$.

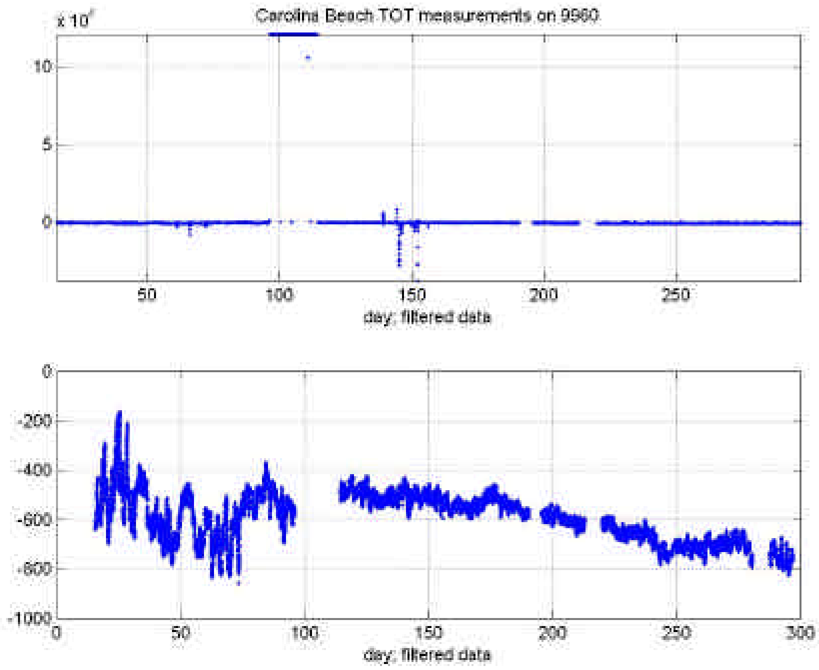
$$ASF_i(t) = ASF_{i,mean} + dTOA(t) * d_{i,land} + c(t) + e_i(t) \quad (1.4)$$

Equation 1.5 represents the residual temporal variation after the average ASF from the calibration point has been applied by the receiver. The residual temporal variation represents the user's error in estimating temporal ASF. There are three terms in this error and the effects of these terms must be bounded to protect integrity. The *dTOA(t)* term is common to all stations and changes in the ASF variation are correlated since the term move in the same direction though with different magnitudes due to different $d_{i,land}$. The common term, *c(t)*, does not affect the position solution since it is common and will be estimated out in the position solution. In practice, this term may also incorporate some of the correlation. The residual error term, $e_i(t)$, varies independently between stations and therefore must be treated as an uncorrelated bias.

$$\Delta ASF_i(t) = dTOA(t) * d_{i,land} + c(t) + e_i(t) \quad (1.5)$$

The model was designed to be simple while capturing the essential correlations in the ASF variations. Hence, the results fold into the HPL equation with $dTOA(t)*d_{i,land}$ being a correlated bias and $e_i(t)$ being an uncorrelated bias for each station *i*. Calculation of the HPL requires determining bounding values for *dTOA* and e_i. The groundwave data collection system fielded by the LORIPP provides data for this calculation. Time of arrival (TOA) monitors are operating in locations such as Sandy Hook (NJ), Cape Elizabeth (ME), Annapolis, and so on [4]. Time of transmission (TOT) monitors are located at some secondary transmitters while it is assumed that master rates are being transmitted synchronized to Universal Time Coordinated (UTC). The limitation on examining ASF is that there must be TOA and TOT data.

Both the TOA and TOT data needs to be filtered to remove faulty data points. The TOA and TOT monitor system depends on both a GPS receiver for UTC synchronization and significant software and hardware linkages. Any faulty output or errors a given part can lead to a faulty data points. Large timing spike, jumps are errors due to the data collection system and not due to ASF. Data points whose validity is questionable should be eliminated. Several metrics are used to decide the data points that are kept in the analysis. An example of raw (top) and filtered (bottom) TOT is shown in Figure 3. Proper filtering is necessary since data errors that are not removed lead to model errors.



[b3]

Figure 3. Raw (top) and Filtered (bottom) Time of Transmission Data

3.2 Estimating Temporal ASF Model Parameters

ASF is calculated from the filtered TOA and TOT data. The ASFs from Sandy Hook are presented as an example. There are five ASFs available at any given time – Nantucket, Carolina Beach, Seneca, Caribou, and Dana. The estimates for the correlated and uncorrelated term in the temporal ASF model are generated using four of the five stations and the result is tested on the station not used to generate the solution.

The Figure 4 - Figure 6 shows a couple of examples. The only times shown are times where all five ASFs are available. Figure 4 shows the model coefficients calculated using all five stations. Figure 5 shows the estimated model coefficients if Caribou is excluded from the set used to make the determination. The bottom plot shows the error on the model when applied to Caribou with the bounds representing the maximum residual error from the applying the model to the stations used to generate the model. Recall the maximum residual error is used as the bound on the uncorrelated temporal error. Ideally, the maximum residual error will bound the residual error for stations not used to generate the model. Unfortunately, that has not always been the case. Figure 6 shows the results if Nantucket is excluded. In this case the error bound generated using the model does not bound the error on Nantucket. Several possible explanations exist: 1) non-groundwave propagation phenomena (early skywave), 2) poor data, and 3) inadequate model. The only cause of concern is an inadequate model. The first two causes are not covered by the model and should not be used for the modeling. Hence, more detailed examination of those cases is necessary.

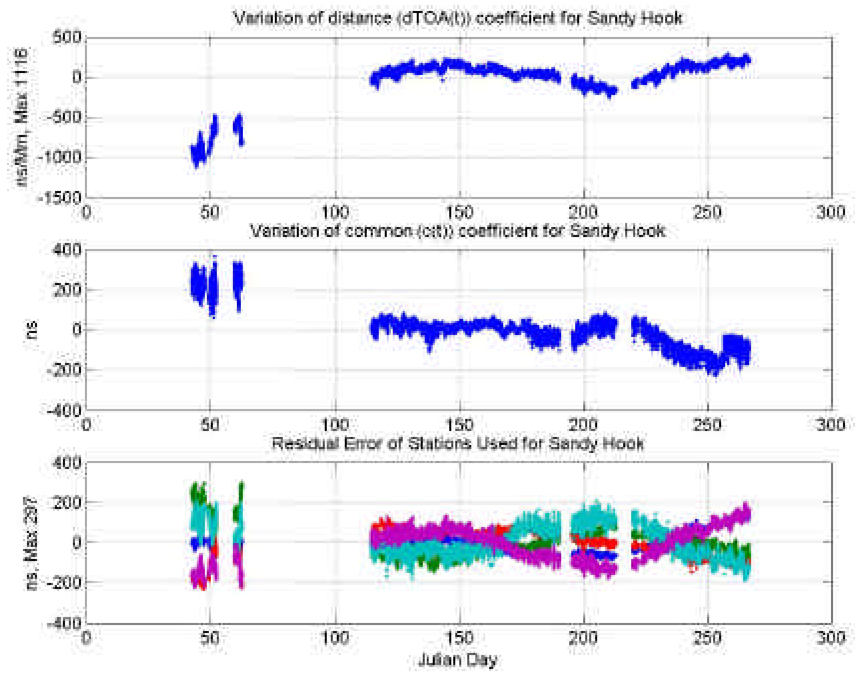


Figure 4. Estimate of Temporal ASF Model Values, All Stations Used: Correlated (top), Common (middle), Residual Error (bottom)

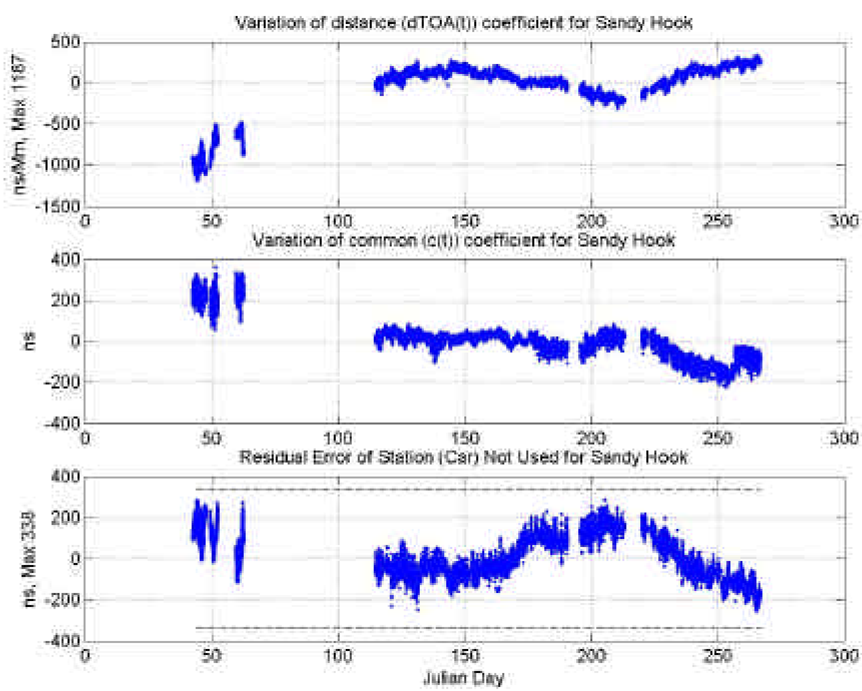


Figure 5. Estimate of Temporal ASF Model Values, Caribou Not Used: Correlated (top), Common (middle), Residual Error (bottom)

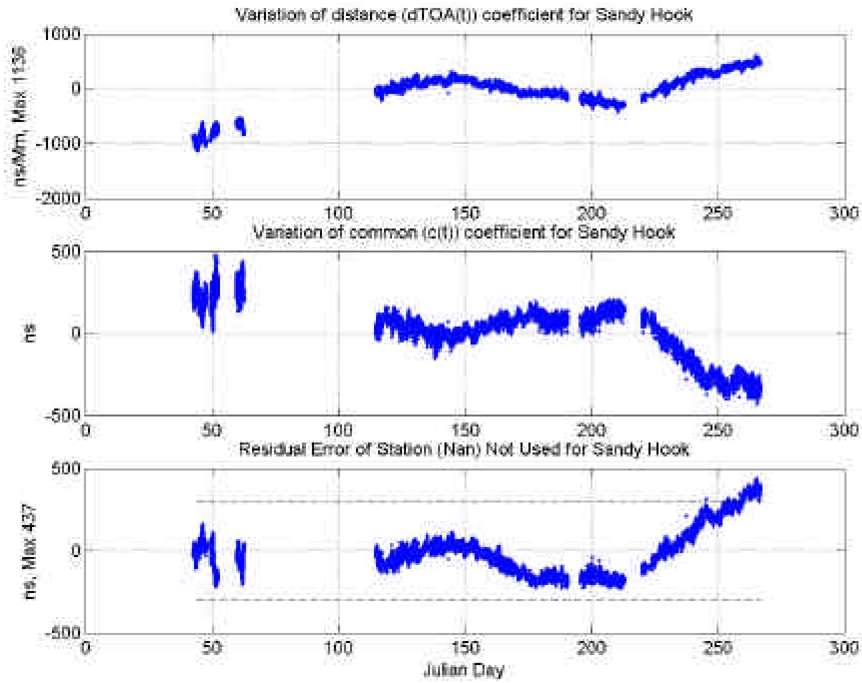


Figure 6. Estimate of Temporal ASF Model Values, Nantucket Not Used: Correlated (top), Common (middle), Residual Error (bottom)

Table 2 summarizes the results from the other TOA monitors. It presents estimates of the maximum correlated coefficient (*dTOA*) and the maximum uncorrelated error ($\max e_i$) from applying the model using the estimated coefficients on all available ASF. The last column indicates the number of times where the bound on residual error (uncorrelated error) was exceeded by the error of the station not used to generate the model.

Monitor	Num Stations	dTOA (All Sta)	Residual Err (All Sta)	Num Excess Sol'n
Cape Elizabeth	5	1089	307	3
Sandy Hook	5	1116	297	4
Annapolis*	7	299	390	2

Table 2. Estimates of Correlated (dTOA) and Uncorrelated (Residual Err) Components of Temporal ASF Variations using Land Distance Model (*No Winter Data)

3.3 Other Variations and Models

The model presented represents one means of bounding the variation. Modifications or other models could be used. For example, since correlation should fall off for locations further and further away from the user, land distance further away should thus be weighed less. A model that uses a correlation related to the square root of distance or some other power relationship could more fully express the relationship. This can weigh longer distances less since large distances usually implies that there is more land distance further away. Another technique to incorporate correlation is to go to use a bound in the position domain (PD).

A position domain bound is a bound on the error in the position domain. In essence, the errors are calculated in the position domain from which a bound on the worst case is determined. Using a PD bound may prove useful since it may more fully incorporate temporal ASF correlations. One hurdle is to determine a method by which this bound can be generated. Generating the temporal ASF PD bound may require monitors at each approach. If this were required, PD bound for temporal ASF would not be cost effective. Currently, PD bound for temporal ASF variation is only being used as an evaluation tool.

The position domain analysis shows that the bounds at least seem conservative and it is rare that the error even approaches the resulting bound in the position domain. Figure 7 shows a comparison of range domain bound (using the values derived from Sandy Hook) and position domain errors. The RD bound always bounds the error. However this value is always greater than the position error by at least 100 meters. This difference implies that a PD bound may result in a significant reduction in HPL while meeting integrity requirements. PD bounds will be discussed more in the section on spatial ASF.

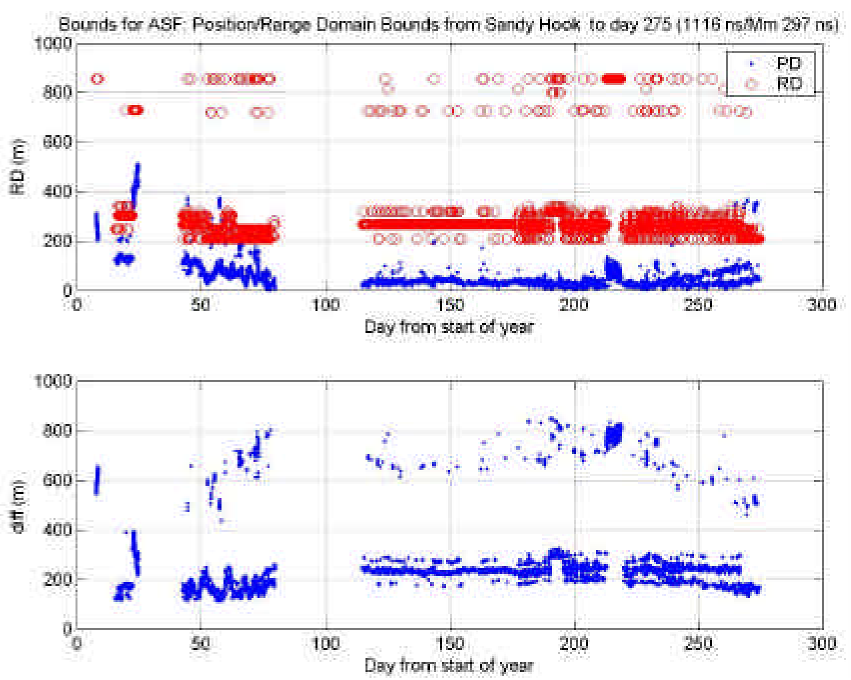


Figure 7. Comparison of Position Error and Range Domain Bound (Bound and Error comparison top, Difference between Bound and Error bottom)

3.4 Conclusions

It is important to separate the temporal ASF variations into correlated and uncorrelated components. The division is important for improving availability while meeting the integrity requirements. Different models will still be examined to better account for and use the correlation in temporal ASF measurements between stations. Other data sources such as TINO will be examined.

From the analysis, a value of 1000 ns/Mm and 300 ns as bounds for the correlated and uncorrelated temporal ASF terms seems representative of the variations in Northeast US (NEUS) over one year. While these values may change based with more study, it provides preliminary estimates for the correlated and uncorrelated values to begin the requirements analysis. This amount of variation can exist during the winter, while, as seen with the Annapolis data, summer variations are less extreme. The temporal ASF variations in the NEUS should represent the worst-case variations. The western US, with a drier and more temperate climate, should exhibit less variation.

4.0 Spatial ASF

Spatial ASF analysis begins by using a model for the variations due to terrain path. In particular, irregular terrain can cause variations in signal properties beyond that predicted from path conductivities. Spatial variation is modeled using the BALOR software that uses the algorithms discussed in [5,6,7]. The model utilizes coastline information, conductivity maps, and accurate terrain databases to determine the propagation delays and attenuation of a signal. A sample map of the ASF variations at Cape Elizabeth from the Nantucket signal produced using this model is seen in Figure 8. Experience and modeling has shown that the worst spatial ASF conditions occur in mountainous terrain and coastal regions. The coastal regions can have high spatial ASF variation because the propagation path of some signals changes from a mostly seawater path to a mostly terrestrial path as the user moves. This is particularly bad in places like Point Pinos, California where the terrestrial path is mountainous near the user. As seen later by the bounds generated, variations are much lower in the interior US with the exception of mountainous regions.

In contrast to temporal ASF variation, data collections serves primarily to valid the model rather than to be the basis for estimate model parameters. It would be next very difficult and timing consuming to gather an amount of data adequate to generate a plot similar to Figure 8.

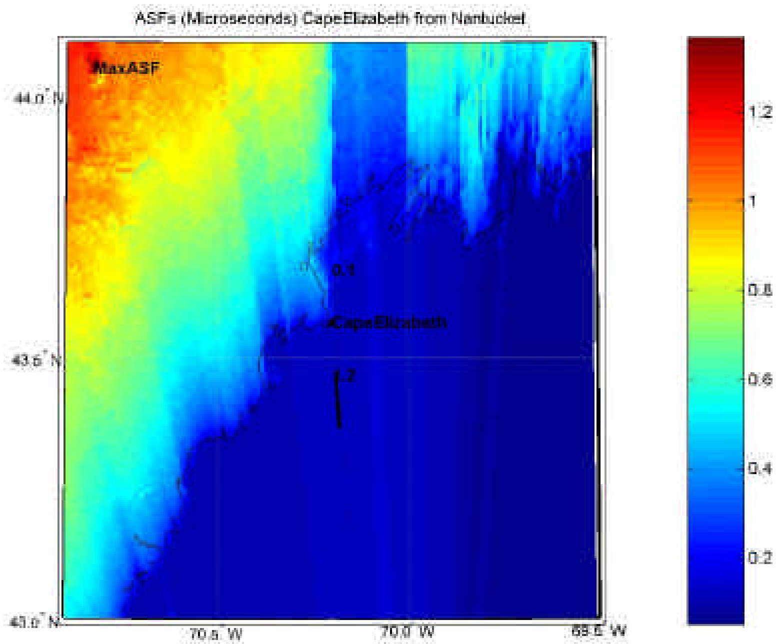


Figure 8. Spatial Variation of Nantucket ASF Around Cape Elizabeth (0.1 microsec, largest deviation 1.2 microsec) [BALOR model]

4.1 Comparing Model & Data

Data has been collected at Grand Junction (Colorado), Little Rock (Arkansas), Pensacola (Florida), and Point Pinos [8]. Since the user is provided an average ASF value for the airport (calibration site), the variation of concern is the differential ASF between the calibration site and the actual user location[b4]. A sample result is shown in Figure 9.

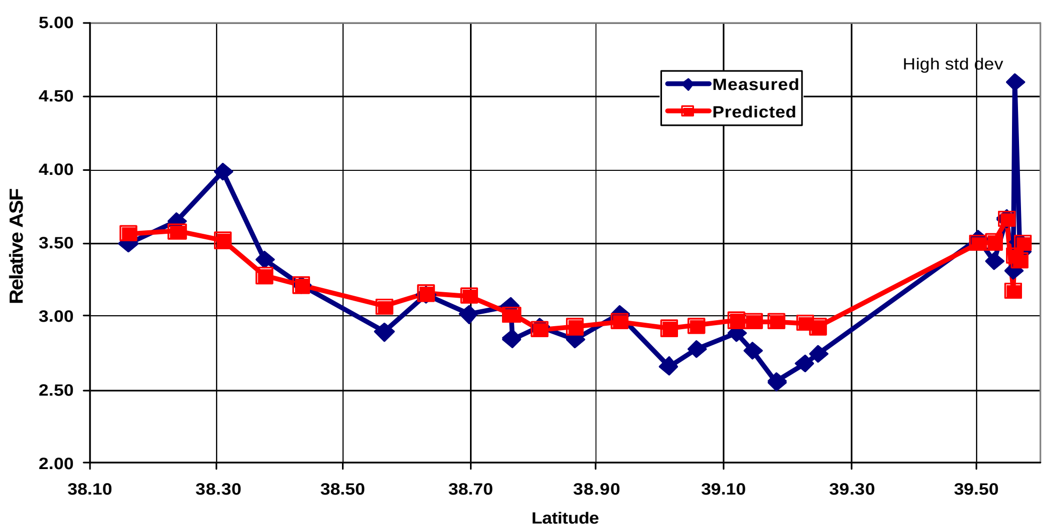


Figure 9. Comparison of Measured Differential ASF versus Model (ASF around Grand Junction for the Boise City Signal) [G. Johnson]

Comparison of the model with collect data is encouraging with the values and trends are in reasonable agreement. However, this small amount of data is not adequate for definitive validation of the model. It is not clear whether the BALOR model will serve as a basis for determining spatial ASF for an operational system. However it represents the current state of the art and is the only tool available to conduct an analysis of spatial ASF variations. It is adequate for LORIPP and provides a good idea of the effect of spatial ASF. The data validation leads to the belief that the actual effect of spatial ASF will be similar to the values derived from the model. Hence the bounds determined using BALOR should be reasonable.

4.2 Bounding Spatial ASF

Spatial ASFs can be treated in two ways. The first method is as an uncorrelated error in the range domain (RD) with one bound on spatial differential ASF for each station. For each signal, the RD bound is generated using the maximum difference in spatial ASF between the coverage area and the calibration point. The value depends on the area over which the bound is valid. The maximum extent of the terminal area is typically 10 nm. The range domain bound must be treated as an uncorrelated error between stations and the bound contribution from each station is added in the worst possible way to determine its contribution on HPL. The result for Cape Elizabeth is shown in Figure 10. The bounds determined are very large along the coast and in the mountains. Better values can be achieved if correlation can be incorporated. Hence another method must be used if acceptable availability is to be achieved.

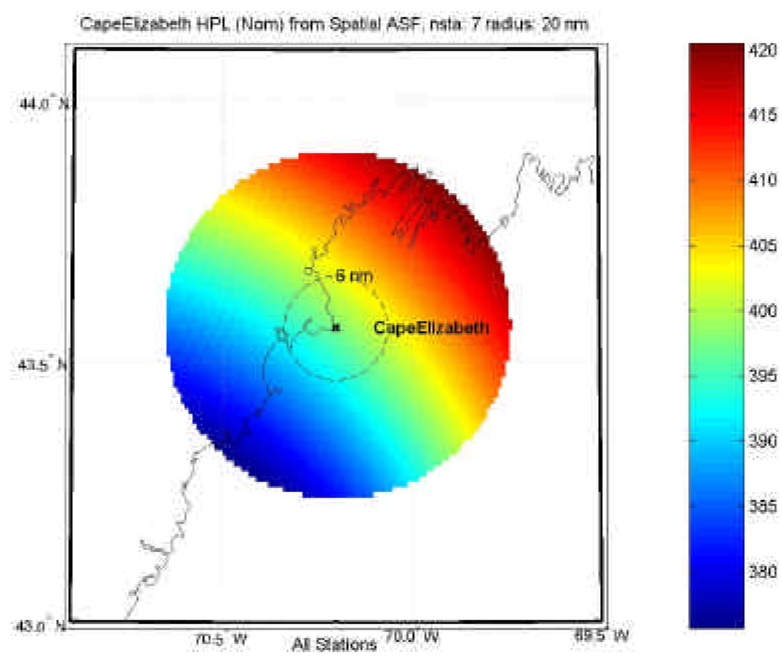


Figure 10. Calculated Nominal HPL Contribution Using Range Domain Bound on Spatial ASF (No Stations Lost)

The second method is to use a position domain bound. The advantage of this method is that it incorporates the known relationship in the direction of spatial ASF variation whereas the first method must assume the worst-case direction. The direction of the ASF change is known from the model though this information is difficult to provide in the range domain due to the volume of data that needs to be provided. The PD bound provides a method of providing the information in a compact form. Since the geometry and the spatial variations are temporally invariant, the PD bound only needs to be determined once for a given location.

Generating the PD bound is relatively straightforward. For a given location, a bound on position error can be calculated using both the magnitude and direction of all ASF changes at that location. The PD bound provided to the user is the maximum value of the position error over the coverage area. This simplifies the information the receiver needs to incorporate the direction correlation. Only one bound is necessary instead of a bound for each range plus spatial correlations. However, the drawback of the PD bound is that it is only valid when the receiver uses the station sets used to generate the bound. This is not an overbearing restriction since one can select the sets used to generate the bound. This is done first by generating PD bounds for the desired sets of stations. The PD bound provided is the maximum value over all sets. However, increasing the sets prescribed by the PD bound increases its value thus reducing its benefits. Figure 11 shows an example with the bounds being valid for any solutions containing at least six of seven stations provided that Nantucket is always used. For Cape Elizabeth, the Nantucket signal has the most significant influence to the HPL. Some stations may always be required to achieve a desired bound level.

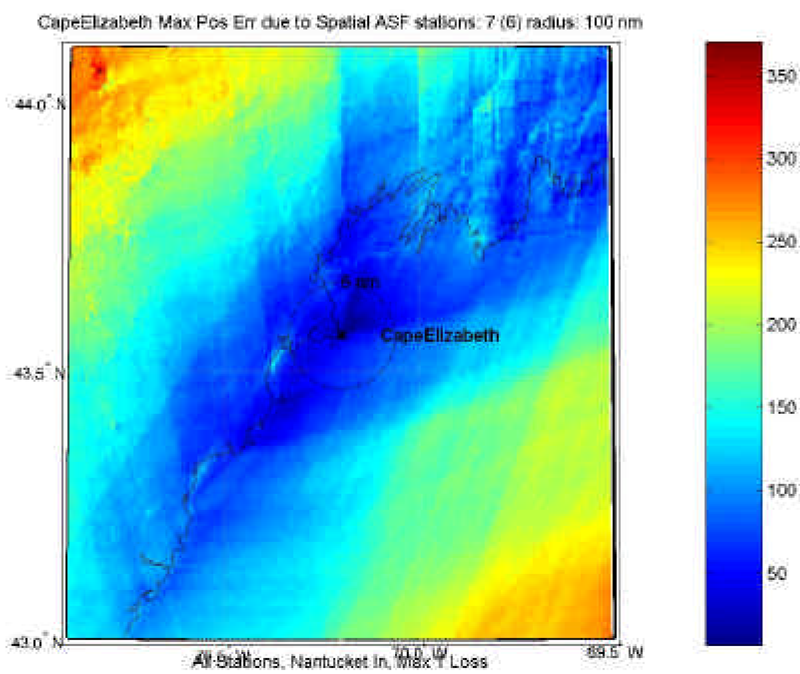


Figure 11. Calculated Worst Case HPL Contribution Due to Spatial ASF Using Position Domain Bound (Up to One Station Lost, Nantucket Always Present)

A comparison of the RD and PD methods demonstrates the advantage of the PD. Table 3 compares the HPL contribution due to PD and RD bounds for Cape Elizabeth for a few scenarios. The PD bound lowers the HPL by 50% or more vice the range domain bound. The PD is necessary to achieve availability in coastal and mountainous locations. This can be seen in Table 4 which shows the PD bound for various locations. Since a 10 nm mile radius should represent the extent of the terminal area, it is the critical value to examine. Larger radii are examined to see trends in the growth of the bound. If the bound does not increase too quickly, one bound value may be used to serve multiple airports

Situation	Radius (nm)	Bound from PD (m)	Bound from RD (m)
Cape Elizabeth nominal	10	87.30	276.96
Cape Elizabeth 1 loss	10	220.94	501.17
Cape Elizabeth 1 loss inc Nantucket	10	131.51	306.08
Cape Elizabeth 2 loss	10	344.02	602.65
Cape Elizabeth 2 loss inc Nantucket	10	252.2	542.72

Table 3. Comparison of Position Domain and Range Domain Bound for Cape Elizabeth

Location	Terrain	Num Sta	Nominal		1 Loss		2 Loss	
			10 nm	20 nm	10 nm	20 nm	10 nm	20 nm
Cape Elizabeth, ME	Coast	7	87	166	221	374	344	546
Destin, FL	Coast	7	319	439	395	545	537	720
Plumbrook, OH	Interior	9	22	39	28	63	99	190
Bismarck, ND	Interior	7	36	55	64	67	87	132
Grand Junction, CO	Mountain	9	205	266	259	291	289	388
Point Pinos, CA	Coast, Mountain	7	181	371	540	846	632	1306
Spokane, WA	Mountain	11	60	103	80	138	98	170
Little Rock, AR	Interior	9	36	48	51	65	68	76

Table 4. Position Domain Bound for Various Locations

4.3 Conclusions

The resulting PD bounds depend on many factors such as number of stations available, geometry, number of lost stations acceptable, region, and so on. The base case to examine a range of 10 nautical miles since this generally represents the maximum extent of the terminal area. In fact, the terminal approach paths only covers a fraction of the 10 nm radius circle and a lower bound may be derived if the search is restricted to only the paths. However, the first cut analysis will use a 10 nm radius circle.

First, examine the non-coastal and non-mountainous region. Under this case, a value of 100-120 meters seems to a reasonably conservative estimate for a bound for PD errors with up to two stations loss. This may be even lower if more "geometry critical" stations are required to be in the solution. Mountainous regions and coastal regions will be higher and the degree of increase depends on local terrain and geometry.

5.0 Integrity for ASF

Demonstrating integrity means demonstrating, for any given instance and location, the probability of hazardously misleading information (HMI), HPE > HPL, is less than 10^{-7}. A HMI can come from a variety of sources such as an undetected cycle slip and as a result, the allocation of the HMI probability due to any given sources is less than 10^{-7}. Conservatively, this means having the probability that each bound is exceeded less than or equal to the allocation.

Integrity requirements generally cannot be demonstrated using data alone due to the volume of data necessary to prove a 10^{-7} probability. Since highly accurate models for ASF variations do not exist, integrity cannot be proven using modeling. A combination of model and data will be used. Since maximum bounds are used to account for ASF in the HPL equation, a conservative measure of integrity would require that these bounds are always true. Otherwise, if these bounds can be exceeded, there will exist times where the bound is exceeded. These instances, the probability of HMI is easily be higher than 10^{-7}. Note that no credit is taken for the conditional probability that one is in such a condition. While this approach is conservative, it makes sense because a user must have integrity regardless of when (and where) the user is operating.

"Proving" integrity for temporal ASF is not a straightforward task. One approach is to first look at the overall bound – the combination of the correlated and uncorrelated bound. This overall bound must exceed all possible temporal ASF variations. This question is complicated by the common term that is taken out. An affirmative answer to the sufficiency of the overall bound is a necessary but not sufficient condition. Second, one has to examine the uncorrelated bound and determine if these bound effectively bounds all uncorrelated errors. If it does not then some of the uncorrelated error is treated by the user as a correlated error.

The first question is easier to answer but is complicated by the common term that is included. The current values seem adequate and the values used are about five times larger than the historically derived one standard deviation value (for stations less than roughly 800 km away). Answering the second question is more difficult however inferences can be made from examining data. One way is to examine the correlation coefficient of measurements at a given location. The LORIPP will have to use data from multiple sources, physics and experience to guide the analysis.

The integrity question for spatial ASF is equally difficult. The solution to this issue is to select an inflation factor on the ASF variation such that it bounds potential discrepancy between model and data. Similarly, the overbound factor will be determined based on data, physics and experience.

6.0 Availability & Continuity

Availability and continuity can be determined once the HPL can be calculated. The HPL can be calculated once the bounds meeting the desired integrity requirement are determined provided for all hazards affecting the range measurements. These hazards include noise, transmitter jitter, and ASF and the bounds for these hazards factor into HPL equation (Section 2.3). Geometry also factors into the calculation of HPL. Consequently, the HPL is also location dependent since the transmitters available, signal strengths, and their geometry changes with location. A coverage map is used to visualize the results.

6.1 Availability

Availability is the probability that, at a given time period, a Loran solution can be used for RNP 0.3 approach. Basically, this means that the HPL must not exceed the approach horizontal alert limit (HAL) of 556 meters. Under a given set of conditions, the value of HPL can be calculated and based on this value the system is either available or unavailable for RNP 0.3. Several factors make availability at a given location probabilistic. Station availability, noise, and interference are all probabilistic phenomena that affect the value of the HPL calculated and therefore, change the HPL from the nominal value.

Availability tools have been developed and various situations have been tested. An example scenario is shown in Figure 12. The figure shows the availability based on HPL only (without cycle resolution testing). It uses a 99% noise value and 15 dB of non-linear processing gain for impulsive noise. Range domain bounds of 1000 ns/Mm and 300 ns are used for the correlated and uncorrelated temporal ASF, respectively. A position domain bound of 120 m is used for the spatial ASF bound.

6.2 Continuity

Continuity is the probability that there is availability throughout an approach (150 seconds) given that availability existed at the start of the approach. This value can be computed by determining for all combination of stations that results available solution, the probability that availability persists for the next 150 second period. The calculation also depends on probabilistic events such as transmitter outage, changes in interference and noise over the period. The scenario used to generate the availability diagram is used to generate the continuity plot in Figure 13.

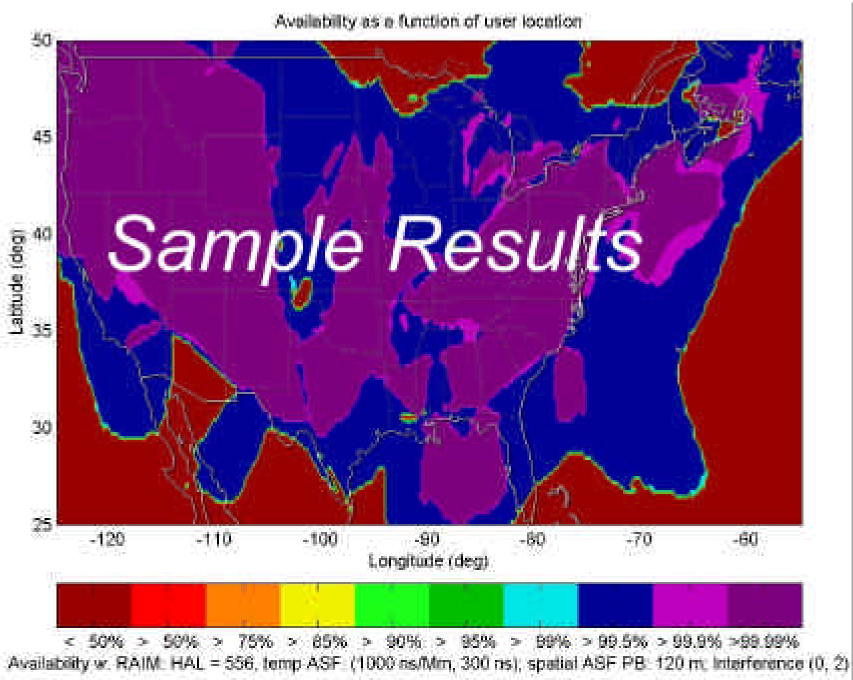


Figure 12. Availability Using Nominal Conditions at 99% Noise Level, Temporal ASF (corr, uncorr): 1000 ns/Mm, 300 ns Spatial ASF PB: 120 m

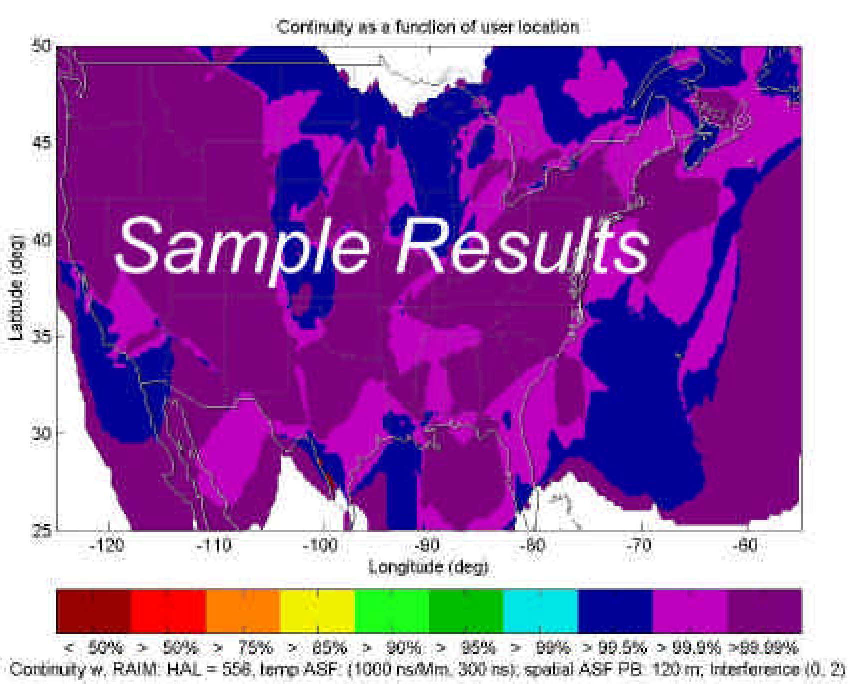


Figure 13 Continuity Using Nominal Conditions at 99% Noise Level, Temporal ASF (corr, uncorr): 1000 ns/Mm, 300 ns Spatial ASF PB: 120 m

6.3 Comments

The plots only represent only one scenario under certain assumptions. It assumes that noise and interference conditions do not change during the approach. This is not always the case and various scenarios will have to be tested. The list below shows some reasonable scenarios. The overall availability and continuity will be constituted from an average of these results weighted by the probability of each scenario occurring.

- Different noise level
- Interference at start of approach
- Interference at end of approach when none existed initially
- Precipitation static (P-static)
- Early skywave

It should be noted that the calculations do not examine all possible changes – only the changes that have a reasonable probability of occurring (> .001%). Since the availability and continuity requirements are 99.9 to 99.99%, the calculation only needs to examine events with a reasonable (greater than .001%) probability of occurring.

One final note is that the coverage tool and models used are still in the process of being refined. The goal is to complete a complete version around December 2003.

7.0 Conclusions

In summary, it is important to properly analyze and bound ASF variations since they constitute an error in the estimate of ASF. Achieving RNP 0.3 will require that credit be taken for correlation. ASF variation is divided into temporal and spatial variations. Temporal ASF is divided into correlated and uncorrelated components. Spatial ASF is bounded using a position domain bound that incorporates the correlation in its calculation. Position domain bound may be used to better incorporate temporal ASF correlation.

The current values for temporal ASF seem to be marginally adequate for achieving the desired availability and continuity. Spatial ASF bounds seem reasonable for the interior US though mountainous and coastal regions are still problematic. Integrity still needs to be formally determined though the current bounds seem sufficient. More analysis on both is forthcoming and it is hoped that refinements will provide an increased margin for meeting the availability and continuity requirements.

The tools to test the availability and continuity effects of the ASF bounds and different means of bounding ASF are being finalized. With these tools, the availability and continuity can be quickly determined. They will enable the LORIPP to complete its investigation as soon as the results from various hazard analyses are completed.

8.0 Disclaimer

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.

9.0 Acknowledgments

The author would like to acknowledge Mitch Narins (FAA AND 702) for his support of Loran and the activities of the LORIPP.

The author would also like to acknowledge the help and cooperation of the members of the LORIPP, particularly Dr. Ben Peterson, Robert Wenzel, Prof. David Last, Paul Williams, Greg Johnson, Captain Richard Hartnett, LT Dave Fowler, LT Kirk Montgomery who have all contributed to this work

10.0 Selected Bibliography

[1] “Vulnerability Assessment of the Transportation Infrastructure Relying on the Global Positioning System,” John A. Volpe National Transportation System Center, August 20, 2001.

[2] Weeks, G. K., Jr. and Campbell, M. “Status of the Loran Recapitalization Project (The Four Horsemen and TOC),” Proceedings of the ION Annual Meeting, Albuquerque, NM, June 24-26, 2002.

[3] Sherman Lo, et al., "Loran for Required Navigation Performance 0.3: The Current Work of Loran Integrity Performance Panel (LORIPP)," Proceedings of GNSS 2003 – The European Navigation Conference, Graz, Austria, April 2003.

[4] Peterson, B. et. al., “Technology to Evaluate eLoran Performance”, Proceedings of the ION GPS Meeting, Portland, OR, Sept 9-13, 2003.

[5] Monteath, G. D., “Computation of Groundwave Attenuation Over Irregular and Inhomogeneous Ground at Low and Medium Frequencies”, BBC Report 1978/7, British Broadcasting Corporation, Research and Development, Kingswood Warren, Tadworth, Surrey, UK , March 1978.

[6] Last, J. D., Williams, P., Peterson, B. and Dykstra, K., "Propagation of Loran-C Signals in Irregular Terrain – Modelling and Measurements Part 1: Modelling," 29th Annual Convention and Technical Symposium, International Loran Association, Washington DC, Washington USA, 13-15 November 2000.

[7] Williams, P. & Last, J.D., "Modelling Loran-C Envelope-to-Cycle Differences in Mountainous Terrain," Proceedings of the DGON European Radio Navigation Networks Symposium, Munich, Germany, June 2003.

[8] Hartnett, R., Swaszek, P., and Johnson, G., "Summer Vacation 2003-ASF Spatial Mapping in Colorado, Arkansas, Florida, and California," 29th Annual Convention and Technical Symposium, International Loran Association, Washington DC, Washington USA, 13-15 November 2000.

[b1]The temporal variation also vary spatially. So you make explicit the assumption that both the user and the calibration point are within the same spatial region of your temporal correction
[b2]These still have a spatial component; they are not purely temporal.
[b3]Why does the top plot say day; filtered data if it is raw?
[b4]Since “this” then “what”?