Loran Coverage Availability Simulation Tool

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BIOGRAPHY

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ABSTRACT

The Loran coverage availability simulation tool (LCAST) was initially created for the 2004 Federal Aviation Administration (FAA) Loran technical evaluation report. The tool incorporated the then current models, algorithms and figures of merit being developed for the evaluation report. Models for noise, noise mitigation, signal strength, additional secondary factor (ASF), and envelope to cycle difference (ECD) were important inputs into LCAST. Algorithms include the integrity equation and cycle determination. Other figures of merit include station availability and continuity derived from historical data. These features allowed the tool to make our best estimate of the NPA availability and continuity coverage as well as HEA performance.

Since the report, the tool has evolved to incorporate the ability to test new models being developed by the evaluation. Newer noise processing, cycle determination algorithm and ASF variation models have been added. The tool has been modified to test performance changes for different infrastructure scenarios, station selection algorithms and many more.

This paper describes the LCAST. It details the design of the tool. It covers the models, algorithms and assumptions that are incorporated into the tool. It also presents some recent scenarios analyzed using LCAST.

INTRODUCTION

In February 2008, the US Department of Homeland Security (DHS) announced that enhanced Loran (*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 [1]." This announcement came after many years of research and development by the Federal Aviation Administration (FAA) Loran technical evaluation team. This team was charged with creating an enhanced Loran design, based on current modernization of the Loran-C system, that can support aircraft non-precision approach (NPA), maritime harbor entrance approach (HEA) and precise frequency (Stratum I) and time. The design was developed using thorough analyses of the hazards affecting Loran and mitigation techniques for those hazards. As a result of the complexity of the multiple factors that would affect the various requirements of HEA and NPA, it was necessary to create a tool that could quickly determine the anticipated performance of the new, unrealized system.

As such, the FAA Loran technical evaluation team developed a tool which came to be known as the Loran Coverage Analysis Simulation Tool (LCAST). The tool could test out different design options, scenarios, and error models to determine their effect on Loran performance for NPA, HEA and other applications. Additionally, it is capable of quickly analyzing the system performance under different scenarios. The goal is to develop a tool similar to the Matlab Algorithm Availability Simulation Tool (MAAST) used for Wide Area Augmentation System (WAAS) [2]. LCAST was essential for developing many results presented in the 2004 FAA Loran technical evaluation report [3].

OUTLINE

This paper will detail the components and design of the LCAST. The first part discusses the components of the tool such as the models and algorithms incorporated. It covers the methodology by which the tool uses such inputs and determines the resulting coverage.

The second part of the paper focuses on the use of LCAST for analyzing the aviation use of Loran. Four examples will be presented. First, the NPA and HEA assessments from the 2004 Loran technical evaluation are presented. Second, the performance of Loran for enroute flight is given. This was studied to determine if Loran can support enroute and automatic dependent surveillance-broadcast (ADS-B) operations by meeting required navigation performance (RNP) 1.0 standards [3]. The infrastructure for enroute will provide less accurate additional secondary factor (ASF) values, however the error bounds are larger than for NPA. Third, the performance with updated models is examined. As mentioned before, newer ASF, noise processing, and cycle determination models have been developed. LCAST is used to assess the performance with the newer models. Finally, the performance with additional stations is presented.

BACKGROUND

Enhanced Loran is the next generation of Loran-C designed to support various PNT applications, particularly safety critical operation such as landing aircraft and maneuvering ships through a harbor channel. To support these applications, an *eLoran* user needs to incorporate many features and hazard model to ensure safety. LCAST incorporates these features and models to properly analyze the resulting performance against the requirements of the target applications of NPA and HEA. Meeting these requirements means understanding and mitigating hazards affecting *eLoran* performance

BASIC ELORAN HAZARDS

Mitigating the sources of variation and error on the Loran signal guided the design of *eLoran*. Many of the major sources are seen in Figure 1. The transmitter introduces bias and jitter into signal. Propagation results in an unknown delay in the signal that can vary over time. This unknown delay is termed additional secondary factor or ASF and it varies spatially and temporally. It also results in attenuation of the signal which affects the received signal strength. Interference generally comes from the Loran system itself whether in the form of ionosphere reflections (skywave) or interference from other stations (crossrate). Finally, noise affects the ability to accurately determine range from the Loran signal. Several sources contribute to noise. Atmospheric noise, ambient noise from activities such as lightning, is typically the largest contributor. Other sources include local noise interference, precipitation static (p-static), and receiver noise. This paper will not go into detail on these hazards and faults as they are covered in other text [4]. In order to support aviation and maritime by meeting their requirements, these hazards must be mitigated.

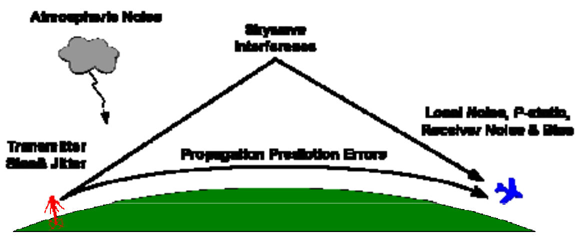

Figure 1. Factors affecting Loran performance

REQUIREMENTS FOR NPA & HEA

The primary requirements of concern for NPA or HEA are the accuracy, integrity, availability, and continuity. These requirements for NPA and HEA are seen in Table 1 and Table 2, respectively.

Performance Requirement	Value
Accuracy (target)	307 meters
Monitor Limit/ Alert Limit (target)	556 meters
Integrity	10^{-7}/hour
Time-to-Alert	10 seconds
Availability	99.9 to 99.99%
Continuity	99.9 to 99.99%

Table 1. Primary NPA requirements (as used for 2004 report)

Performance Requirement	Value
Accuracy (back-up)	20 meters, 2 drms
Monitor/Alert Limit (back-up)	50 meters, 2 drms
Integrity (target)	3 x 10^{-5}/hour
Time-to-alert	10 seconds
Availability (minimum)	99.7%
Continuity (minimum)	99.85% over 3 hours

Table 2. Primary HEA requirements (as used for 2004 report)

Integrity is the ability of the system to inform a user when a signal or solution should not be used. For Loran, under nominal conditions, this is achieved by providing a horizontal protection level (HPL) that bounds the horizontal position error (HPE). Accuracy is the closeness of the solution to the true position. It a statistical measure and specified at the 95% confidence. Availability means that the HPL is at or below specified alert limit for the desired operation. For NPA, this means that the HPL is at or below the horizontal alert limit (HAL) of 556 m. Continuity is the ability to complete an operation once that operation is started. Hence it is the likelihood that the system is available throughout the operation given that the system can initially be used for the operation. An approach is assumed to require 150 seconds and three hours respectively under NPA and HEA. The most challenging NPA requirement for *eLoran* is achieving acceptable availability while providing integrity. The demanding requirement for HEA is accuracy.

DIFFERENCES BETWEEN ELORAN FOR AVIATION & MARITIME

For aviation, providing integrity is paramount. Mitigations were developed to reduce or eliminate the effects of integrity hazards. Mitigation techniques included mandating magnetic loop (H-field) antennas to reduce the effects of p-static and an early skywave warning system. High confidence models for bounding the effects of hazards that are not fully mitigated were developed by the Loran Integrity Performance Panel (LORIPP), part of the FAA technical evaluation team. As ASF is the largest source of variation on Loran measurements, significant effort was spent modeling and bounding it. ASF is treated in three ways. First, a basic nominal ASF estimate is provided for each station at each airport. Second, a bound on the correlated and uncorrelated temporal variation of the ASF from the nominal estimate is provided. This second component is discussed in detail in [5]. Third, a bound on the spatial variation of ASF from the reference point of the nominal estimate is provided.

These models are to be incorporated into the Loran integrity equation (seen in Equation 3). Additionally, algorithms such as the cycle confidence algorithm were developed to support integrity [6][7]. Significant improvements in accuracy were determined to be cost prohibitive compared to benefits.

For maritime HEA, the integrity requirement is not as strict and the accuracy requirement is significantly higher when compared to NPA. To meet accuracy requirements, a more proactive approach to eliminating major sources of error was necessary. Hence, differential Loran (dLoran) corrections generated by local monitors will be used to reduce error on Loran measurements, particularly ASF and its temporal variation. Additionally, the provision and use of ASF grids encompassing the entire approach is mandated. This grid sets a nominal value and accounts for the spatial ASF differences. Hence the HEA user will experience significantly smaller residual ASF than NPA. This improves accuracy and reduces the likelihood of incorrect cycle selection. The differential correction will also account for the effects of early skywave, thus mitigating this hazard. The treatment of ASF, seen in Table 3, is a primary difference between *eLoran* for NPA and HEA. The coverage tool accounts for such differences in its assessments.

Hazard Type	Aviation (NPA)	Maritime (HEA)
Nominal ASF	Published table of nominal ASF(s) at airport	Published table of grid of nominal ASFs along harbor approach
Temporal ASF Variations	Model bounding temporal variation of ASF about nominal value	dLoran corrections account for variation
Spatial ASF Variations	Model bounding spatial variation of ASF from nominal on approach	Spatial variations account for by grid
Early skywave	Message warns of extent of early skywave	Effects corrected by dLoran broadcast

Table 3. Differences in treatment of hazards between NPA and HEA

LORAN COVERAGE TOOL OVERVIEW

A coverage tool is needed to assess the ability of *eLoran* to meet the requirements as this depends on its performance characteristics which are location dependent. Specifically, LCAST analyzes the relationship between the protection or accuracy level and the availability or continuity. For example, the tool can determine the availability at a specified HPL. When LCAST is used with the specified HPL at the HAL requirement, the availability calculated is the system availability. Conversely, it can determine the achievable HPL given a specified availability level.

HPL and accuracy are related because the calculations of these two rely on similar inputs. The models used for the calculation are different as one is an integrity bound and the other is an accuracy statistic. This will be discussed next. Availability and continuity, as seen from its definition, are closely related as well. In fact, LCAST calculates continuity from availability from scenarios where different sets of stations are transmitting.

AVAILABILITY & NOISE

The availability of a Loran signal depends primarily on signal to noise ratio (SNR). Noise is the dominant factor as signal strength is relatively constant. Noise levels can vary significantly over time and location. This leads to variations in the availability of stations and *eLoran* for the desired operations. Hence, our determination of availability hinges on noise level.

Fortunately, the International Radio Consultative Committee (CCIR), now known as the International Telecommunications Union (ITU), performed extensive monitoring of atmospheric noise. The result of their first efforts, conducted in the late 1950s, was published as CCIR Report 322. The report generated statistics on atmospheric noise level describing the maximum value at different percentiles (50th, 80th, 95th, etc.). It described these values for each of the six 4-hour time blocks within a day for each of the four seasons. Shown in Figure 2 is a composite of the 99% level over all seasons and over all hours of the day. More details on the ITU noise model are given in [9].

The ITU data determines the availability setting since noise level governs station availability. For example, 95% availability for NPA means that NPA requirements were met when the noise level was at the 95th percentile.

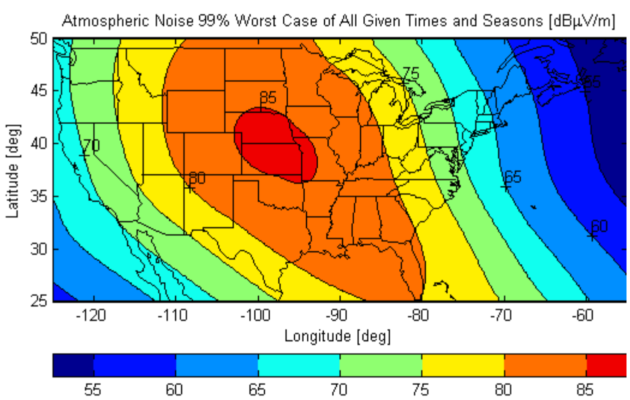

Figure 2. 99th Percentile Atmospheric Noise (Worst Case over all times)

BASIC CALCULATION OF PROTECTION LEVEL & ACCURACY

The essence of the coverage tool is its calculation of the HPL or accuracy. This is accomplished in a two step process. The first step is to determine if the correct cycle on the Loran signal is being tracked to an adequate degree of confidence. The second step is then the calculation of the error bounds and statistics that contribute to the HPL and accuracy, respectively.

The HPL and accuracy calculation are valid only if the user is tracking the correct cycle. The typical tracking point is the standard zero crossing (SZC) which is 30 microseconds from the start of the pulse. Incorrect cycle selection results in a one cycle or 3 km range error. The calculation performed in LCAST (and user receiver) determines the confidence that all cycles are correct. If this "cycle confidence", given by a bound on the probability of wrong cycle (P_{wc}) is adequate, then the HPL or accuracy can be calculated. Otherwise, the HPL or accuracy cannot be determined.

Given acceptable cycle confidence, bounds and statistics can be calculated for each source of variation on each Loran signal used. Some of the errors are random and not correlated from signal to signal, denoted by α. This includes noise, transmitter jitter, etc. Equation 1 shows the variance of these effects in meters squared. As implemented in LCAST, the value of N_{pulses} corresponds to the number of seconds of phase averaging and SNR is the SNR of the pulses processed over one second. An alternative formulation is to have N_{pulses} be the total number of pulses used in the averaging and SNR be the SNR of one pulse. Additionally, there are correlated (β) and uncorrelated bias error (γ). The errors on all signals are then combined to determine an overall position accuracy (95% level) or integrity bound (> 99.99999% bound).

$$\alpha_i^2 = c_1 + \frac{337.5^2}{N_{pulses} \bullet SNR} \quad (1)$$

Since the purpose of analyzing HEA accuracy is to calculate the achievable accuracy, it is assumed that the dLoran reference station and user are very close or collocated. Hence, LCAST does not account for errors due to the distance between user and reference station. The result is that Equation 1 is adequate for describing the error on each measurement with c_1 accounting for position independent, generally random errors (transmitter jitter, reference station noise, grid accuracy, etc.). The accuracy is then given by Equation 2 where K_i represents the first two rows of the projection matrix K.

$$accuracy = 2\sqrt{\sum_i K_i \alpha_i^2} \quad (2)$$

The integrity bound for aviation is calculated similarly though with additional terms to account for ASF related variations. The integrity or HPL equation, seen in Equation 3, was developed for this purpose. Again, K_i represents the first two rows of the projection matrix K. Correlated and uncorrelated temporal variations of ASF are treated in the equation by the terms β and γ, respectively. Spatial variations on ASF are treated in the position domain by the position bound (PB). As a result, the c_1 term in Equation 1 only needs to account for transmitter related noise which is nominally 6 m, one sigma. Details on the integrity equation for Loran is given in [4].

$$HPL = \kappa_{RNP}\sqrt{\sum_i K_i \alpha_i^2} + \left|\sum_i K_i \beta_i\right| + \sum_i \left|K_i \gamma_i\right| + PB \quad (3)$$

BASIC AVAILABILITY CALCULATION

Typically, LCAST is used to calculate availability at the horizontal alert limit (HAL) or accuracy requirement level for integrity or accuracy respectively. This yields the system availability.

The basic flow for calculating availability is seen in Figure 3. Assume that we are calculating integrity and hence determining the availability of HPL > HAL. LCAST loads input data and the region (in the form of a grid) about which availability is calculated. It starts at the first location in the map. As mentioned previously, availability calculation is tied to noise level. So the calculation begins by iterating on different noise levels starting at the highest percentile (99.9%) at each location in the coverage area. From the noise level, the stations or signals observable and their corresponding SNR are determined. Next, the procedure described in the section above is followed. First, cycle confidence is calculated. If the confidence is adequate, the HPL is calculated using the error model for each signal. Should cycle confidence or HPL not meet requirements, then the calculation repeats but at the next highest noise percentile. The process stops at the 50% noise percentile. If they both meet required levels, then there is availability at that (noise) percentile.

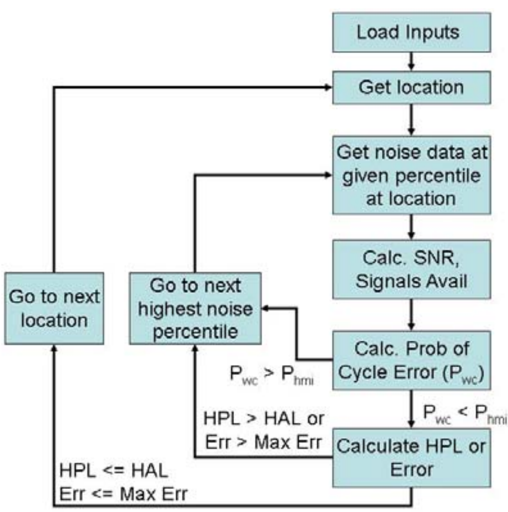

Figure 3. Flowchart for LCAST Calculation of Availability

BASIC CONTINUITY CALCULATION

The continuity is calculated using availability over the set of cases where at most one station is unavailable. Under *eLoran* concept of operations (CONOPS) at most one station within a region should be off air. As such, a user will not experience the loss of more than one usable station. Even without the CONOPS, the likelihood of two stations is very low given historical availability numbers [10].

Continuity is the calculation of the probability of availability throughout an operation given the system is available initially. LCAST starts by assuming that the system is initially available. Then it calculates the user availability over all station states that can be transition to during the operation. A simplifying assumption is that there can only be at most one state transition during the operation. With this assumption, the continuity can be calculated as the expected availability of possible states weighted by (transition) probability of states. This is seen in Equation 4 where the availability without station i is $p_{avail,\, no\ i}$ and its transition probability is $p_{no\ i}$. While this is a simplified model that allows for straight forward calculation within LCAST, it can still be very powerful. The transition probability and the probability of the availability of each state used is based historical data [10].

$$Cont = p_{all}\, p_{avail,all} + \sum_i p_{\text{no } i}\, p_{avail,\text{no } i} \quad (4)$$

LORAN COVERAGE TOOL INPUTS, MODELS & ALGORITHMS

As seen from the last section, the coverage tool incorporates many aspects of the *eLoran* performance from system and environmental conditions to user algorithms. This section will discuss these inputs in more detail and discuss different configuration options.

NOMINAL INPUTS AND PARAMETERS

LCAST uses basic Loran system information and calculates the performance in a grid spanning the desired coverage area. Basic information is stored in various databases by the tool to enable quick computation. Loran station parameters as well as grid-referenced database of noise, ASF, SNR, signal strength, etc. are used. This section will discuss each of these inputs.

The Loran station database contains the station locations, transmission power, group repetition rates (GRIs), etc. The location and power information are used to calculate signal strength at each grid point when used in conjunction with the Millington model for calculating signal attenuation due to propagation. This calculation is done prior to running LCAST and stored in a database. In addition, another database is generated that indicates the stations visible for given noise levels and SNR thresholds. The GRIs provides the number of pulses per second and is used to determine the signal processing gain from averaging.

LCAST uses a grid that covers user locations in the coverage area and a database of Loran stations. The nominal user grid is ¼ degree latitude by ¼ degree longitude. The grid spacing can be increased in to decrease computation time. Pre-calculated data such as nominal ASF map, station signal strengths, etc. are referenced to the nominal grid. Noise data, stored in several databases depending on noise percentile and other factors, is also referenced to the grid. LCAST currently incorporates the grids and accompanying data for conterminous United States (CONUS) and Alaska.

ASF maps, based on historical data and worked conducted by the evaluation team [11], are used by LCAST. One nominal ASF map is used to by the tool to calculate signal strength attenuation via Millington's method. Another ASF map is used to calculate the components of the bound on temporal variation of ASF. The bound models are detailed in [5] and discussed in a later section. In the 2004 report, these two maps were identical. Later refinements in the bounding technique resulted in a weather-based model for bounding temporal ASF and a different map for the bound.

The ITU noise model previously discussed utilizes several parameters in addition to selecting season and time block. At each noise percentile, there are two additional parameters that need to be described to get the noise level. The first is the antenna noise factor (Fa) confidence level. This is the confidence of the value at a given noise percentile and for typical assessment, the median value (50%) is used. The second is the impulsivity or voltage deviation (V_d) percentile. V_d describes the impulsiveness of the noise and typically the 50% level is used. The greater the V_d, the more processing gain is possible. Results from [12] indicate a relationship between noise level and V_d and this model is incorporated within LCAST as an option. More details on the ITU model are given in [13][14]

STATIONS SETTINGS AND AVAILABILITY

While the station database may contain data for all stations in the system as well as potential new stations, not all stations can or should be used in the calculation. LCAST divides the available station set into CONUS, Alaska, Canadian, and potential additional stations. The division allows for testing of different scenarios. One scenario is *eLoran* performance if the Canadian stations are slow to upgrade. Another scenario is the performance with additional stations, particularly in areas with known deficiencies.

LCAST sets a threshold on SNR to determine if a station is available at a given location. There are two other settings that can affect the availability of a station's signal for a given location. The first is restricting users to stations within 800 km. The effects of early skywave interference occur on signals at distances greater than 800 km [15][16]. The early skywave warning message will disallow use of signals from that range or greater. This range limit simulates the effect of an early skywave warning for the entire coverage. The second setting allows for the examination of station outage and will conduct the availability analysis for all cases of one station off-air.

The probability of station on air (available) and station continuity are also factors that need be set. Probability of station availability is needed to calculate the system availability weighted by different stations transmitting scenarios. The probability of station continuity (1 – transition probability) is needed for the overall continuity calculation as mentioned previously. Both probabilities are given one value each that applies to all stations.

RECEIVER PROCESSING

Receiver processing in LCAST models two effects. First is the increase in signal power from averaging. This is done both for the signal envelope and phase. The Loran envelope is used to determine the SZC through the estimate of the envelope to cycle difference (ECD). Increased averaging improves the ECD calculation and increases the confidence of having the correct cycle. The model used for ECD variation (in microseconds) in seen in Equation 5 where the SNR of that of a single pulse. The factor k_{ECD} assumed for a modern receiver is 29 microseconds [17]. Once the correct cycle is tracked, phase can be determined. Phase averaging improves our estimate of the time of arrival of the signal. The phase noise is given by the second term in Equation 1. ECD is only needed occasionally, such as upon acquisition and so long averaging times may be used. Phase measurements are continuously needed and relate to current position. So its averaging time cannot be as great. For example, envelope and phase averaging in NPA is 20 and 2 seconds, respectively.

$$\sigma_{ECD}^2 = \frac{{k_{ECD}}^2}{N_{pulses,env} \bullet SNR} \quad (5)$$

The second is noise processing credit – the ability to attenuate noise, particularly impulsive noise. The processing credit depends on the impulsivity of the noise. The standard taken is 12 dB based on analysis of typical high noise impulsivity. This was used for the 2004 report. However, as discussed earlier, there are multiple models for impulsivity. LCAST includes two models (conservative and median) developed by Boyce based on studies of atmospheric noise impulsivity. Another model is based on the median ITU value. With these three models, the credit varies depending on noise level instead of a fixed 12 dB value. As such, LCAST incorporates four options for noise processing credit.

CYCLE CONFIDENCE & INTEGRITY

The output of the cycle confidence calculation is to determine the probability of wrong cycle (P_{wc}). The calculation of P_{wc} depends on various inputs such as ECD, ECD bias, scalar ASF bias, and the acceptable probability of false alarm of cycle error (P_{fa}). The last three are parameters that can be set in LCAST while the first is modeled. ECD bias is the maximum bias in the ECD calculated and depends on receiver performance. ASF bias is the maximum residual ASF.

A weighted sum squared error (WSSE) algorithm is used to determine the P_{wc} for a given P_{fa}. Two weighting options are possible, as discussed in [7], resulting in two algorithms. One weighting combines all bias and random errors and treats the whole as random. This was used for the 2004 report. The more recent algorithm retains the separation resulting in more complicated non-central χ^2 distributions. This algorithm has more provable integrity and is less conservative when biases are large [8].

Given the inputs and parameters previously discussed, there are only a few remaining inputs that affect integrity. The first is the position domain error resulting from spatial ASF. Based on analysis, this is set at 120 meters for an aircraft on approach. The second is the HAL which is different depending on the operation desired. For analysis of Loran for aircraft enroute navigation, the HAL is set at 1853 m.

ASF is a significant source of variation and the integrity equation incorporates a model to bound its effects. Two temporal ASF models are incorporated. The "2004 ASF model" based on historical data was developed and used for the 2004 report. The "weather based ASF model" refined this model using regression analysis on weather data and improved fidelity and resolution. Both models are incorporated into LCAST.

SUMMARY

Table 4 summarizes the options and parameters available in LCAST. Table 5 summarizes the major models in LCAST.

Parameter	**Variable/ Example Value**	**Description**
Noise parameters	Fa, Vd, Season (or worst case)	Various parameters to describe ITU noise model
Noise averaging	Nph = 2, Nenv = 20	Sec averaged for phase, ECD Npulse = Tave*pulse per sec
SNR threshold	SNRthreshold = -15 dB	Threshold for acceptable SNR for station to be useable
Station options	No Canadian, Add'l potential stations	Stations available (i.e. Canadian, Alaska, potential)
Range Limit	N/A	Only stations < 800 km
Prob. of wrong cycle threshold	Praim, threshold	Max acceptable prob of cycle error over all signals (after cycle algorithm)
Probability of false alarm	P_{fa} = .001	Probability of false alarm on wrong cycle
ASF position error	120 m	Position domain bound on spatial ASF
Scalar ASF bias	100 m	Scalar ASF value for cycle confidence
ECD bias	1.0 microsec	Maximum receiver bias error on ECD
ECD processing	K_{ph} = 29 microsec	ECD variance

Table 4. LCAST Options and Parameters

Model/Algorithm	**Variants**	**Calculation**
Signal strength	1	SNR
Noise Processing	4	SNR
Cycle Confidence	2	Cycle
ECD	1	Cycle
Transmitter noise	1	Cycle, HPL/Accuracy
Spatial ASF	1	Cycle, HPL
Temporal ASF (correlated & uncorr.)	2	HPL

Table 5. LCAST Models/Algorithms

EXAMPLE OF LCAST PERFORMANCE

In this section, we present the use of LCAST for the analysis of different scenarios. These cases are meant to illustrate the utility of LCAST and how it has been used. Four different scenarios are shown:

- Basic analysis from 2004 Loran technical evaluation
- Changes in requirement: Enroute from RNP 1.0
- Changes in model: Noise processing and ASF
- Changes in system: Additional Stations

2004 TECHNICAL REPORT

LCAST provided the necessary coverage analysis for the 2004 FAA Loran technical evaluation report. In this section, coverage results of the availability & continuity of NPA integrity and HEA accuracy are shown.

Determining the performance of a modernized or enhanced Loran system for NPA (or RNP 0.3) requirements is a primary purpose of LCAST. Figure 4 and Figure 5 show the expected NPA availability over CONUS. The first figure shows the result given noise percentiles that are averaged using all four hour time blocks through all four seasons. While this is useful in understanding performance, aviation is primarily concern is the worst case. Figure 5 shows the availability if the noise percentile is at its worst (highest) case four hour time block for each given location.

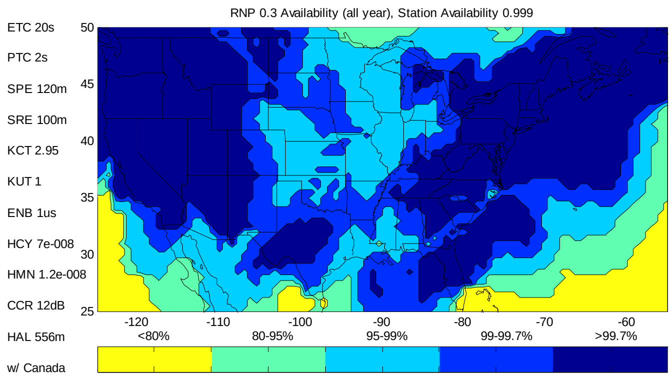

Figure 4. Expected NPA Coverage (Availability Averaged Over Year)

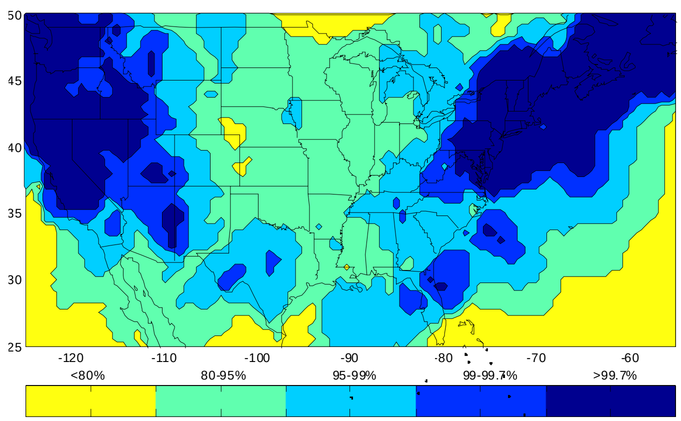

Figure 5. Expected NPA Availability worst case time of year

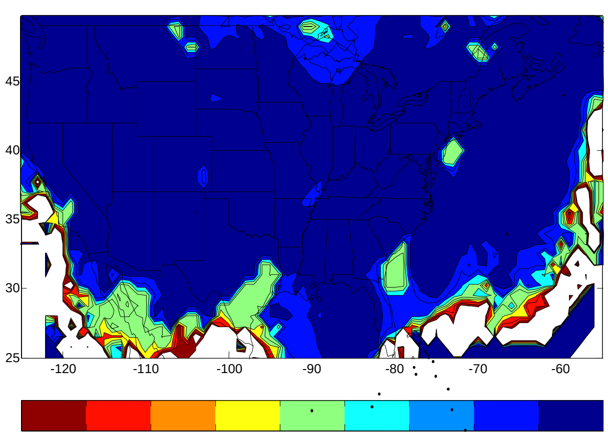

Figure 6. Expected NPA Coverage (Continuity Contours in Percent at a 0.999 Station Continuity)

Figure 6 shows the expected continuity of NPA under *eLoran* given 99.9% station availability. The continuity is very good for a couple of reasons. First, the system must be available at the start of an operation. Second, given the station continuity (transition probability), the likelihood of the lost of a station leading to a loss of availability is low.

Expected *eLoran* HEA performance is shown in the next three figures. Figure 7 shows the expected HEA availability given a 20 m accuracy requirement. The noise levels used again are based on year round averages. Since the exact accuracy requirement may vary based on harbor channel, the accuracy at given availability level is also examined. Figure 8 shows the corresponding accuracy for HEA at 95% availability.

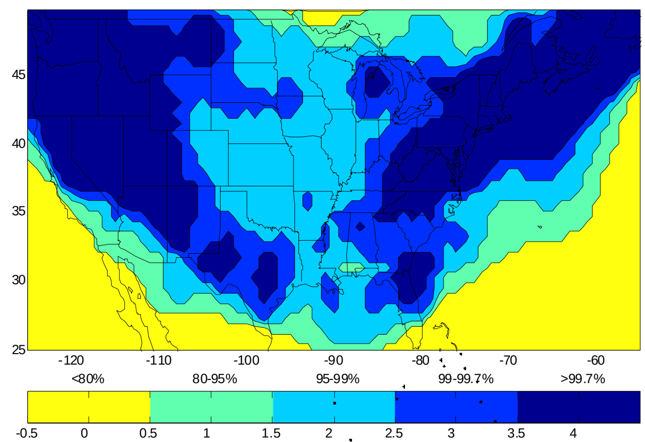

Figure 7. Expected HEA Availability (20 m) averaged over year

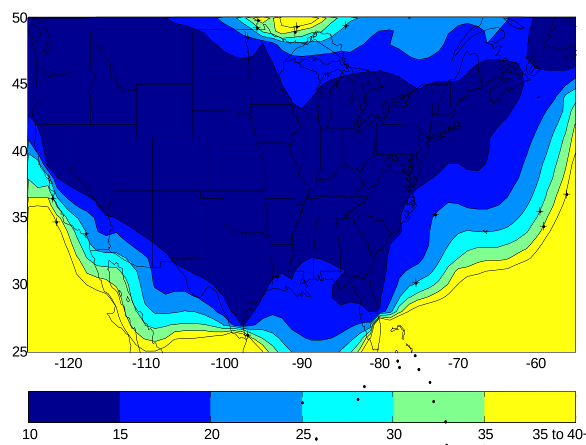

Figure 8. Expected HEA Coverage (Accuracy in Contours in Meters at the 95 Percent Noise Level)

Figure 9 shows the expected continuity of HEA under *eLoran* given 99% station continuity. The station continuity is lower since an HEA operation is three hours versus 150 seconds for NPA. The overall continuity is generally lower than for NPA but still very high.

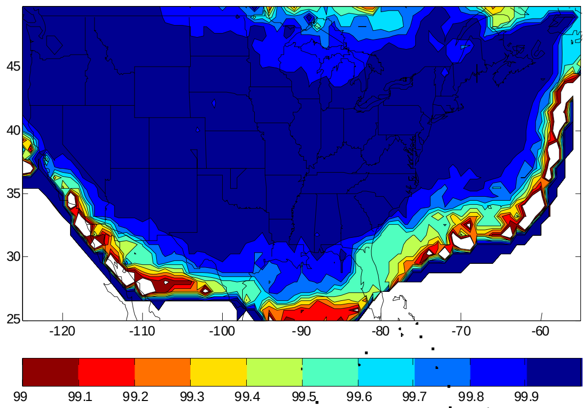

Figure 9 Expected HEA 20-Meter Modernized Loran Coverage (Continuity Contours in Percent for Station Continuity of 0.99)

ENROUTE AVIATION

LCAST was modified to analyze changes in requirements. An example is seen in the analysis of enroute navigation which has a required HAL of 1853 m. This operation also implies a change in user performance as the user will not be as close as to the airport in NPA. The result is that the airport ASFs (and possibly ECDs) are not as applicable. Larger ASF and ECD bounds are incorporated to account for the increased variation. The scalar ASF bias used for cycle confidence is increased from 100 m to 1000 m and the spatial ASF position domain bound is increased to 240 or more meters. Increases in ECD allowance are also tested. One result is seen in Figure 10. Details of the analysis seen in [18].

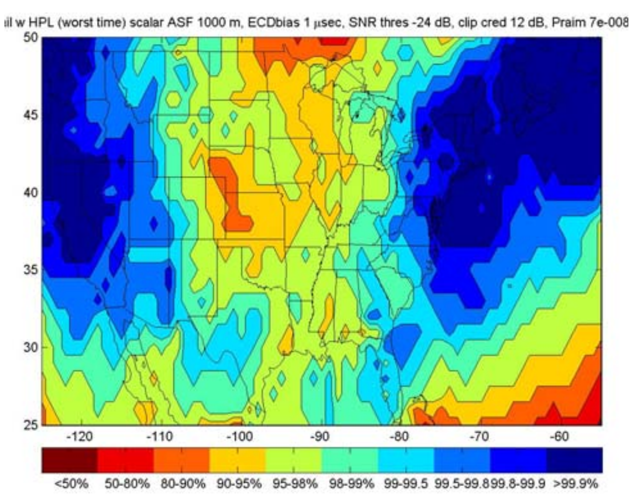

Figure 10. Expected Enroute (RNP 1.0) Availability worst case time of year [18]

This work also examines model/algorithm changes. The cycle confidence algorithm is changed here to one that is based on separating bias and random error (1-σ). This is because the original algorithm for the 2004 report resulted in very conservative performance when handling large biases. More importantly, as mentioned earlier, the algorithm used has integrity that is more provable. Details of the cycle algorithm used are given in [8].

CANDIDATE NOISE PROCESSING & ASF MODEL

LCAST has also been used to assess potential changes in models and algorithms. A refined noise processing model was created by Boyce. The effects of the new model were tested using LCAST. Additionally, the weather based ASF model is also tested. Figure 11 shows the NPA availability coverage change expected from a conservative version of the refined noise model with the 2004 ASF model. If the actual noise processing is better approximated with the Boyce model, the coverage of Loran for both NPA and HEA could be significantly better than stated in the 2004 report. Figure 12 shows the NPA availability with the conservative refined noise processing and weather based ASF model. The weather model provides improved resolution while not significantly changing the NPA coverage shown in the 2004 report.

Another result of the analysis is that LCAST shows that the weather based ASF model does not cause any significant changes in availability results from the 2004 report. The validity of the report results still hold with the weather ASF model.

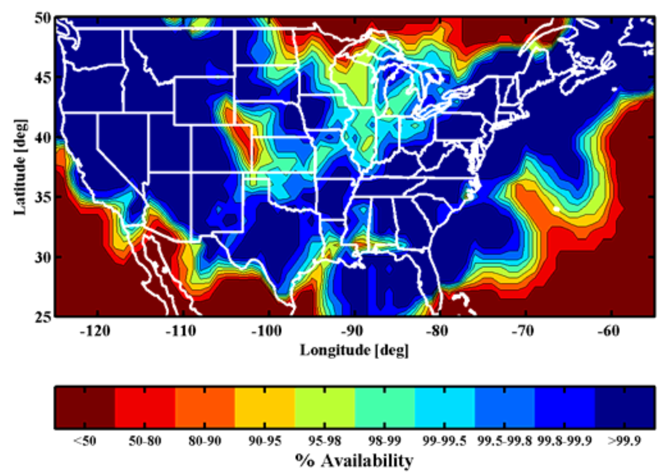

Figure 11. Conservative Refined Noise Model, 2004 ASF Model

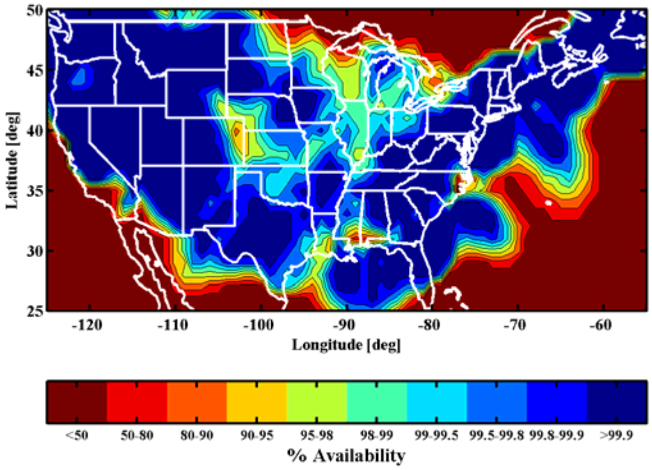

Figure 12. Conservative Refined Noise, Weather ASF Model

ADDITIONAL STATIONS

Changes in system architecture can also be tested in LCAST. The availability of Loran in some regions is known to be limited. This includes southern California and Florida due to the lack of transmitters south of the CONUS as well as the Midwest where an additional station is needed. LCAST was used to assess means of enhancing coverage. One options is having additional Loran stations (such as in Omaha, NE, Yucatan, Mexico, etc.). Another option is using existing smaller, lower power transmitters provide Loran signals in the areas of concern. Figure 13 shows an example of improved NPA coverage with five additional low power (5 kW at Point Loma/San Diego, CA & Miami, FL, 50 kW at other locations) transmitters

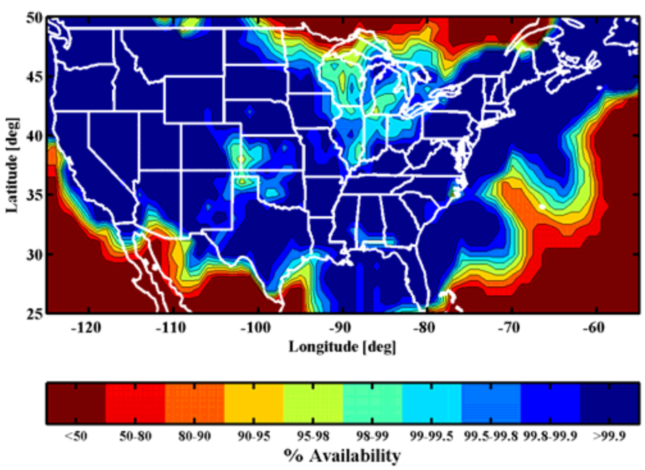

Figure 13. Conservative Refined Noise Model, 2004 ASF Model with additional stations in Glenwood, IA, Bobo, MS, Whitney, NE, Pt. Loma, CA, & Miami, FL

CONCLUSIONS

The Loran Coverage Availability Simulation Tool (LCAST) was developed initially to analyze *eLoran* coverage and availability for NPA and HEA for the 2004 Loran evaluation report. LCAST employs models, algorithms, and results developed by the Loran evaluation team.

We have since developed it into a tool quickly analyze different possibilities of algorithms, requirements, assumptions, and system configuration. As such, it can be used to validate algorithm improvements and suggest directions for system changes. We can use it to conduct sensitivity analysis to show the parameters that most effect availability. In short, LCAST is an integral part of tool set for *eLoran* evaluation

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DISCLAIMER

The views expressed herein are those of the authors 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 or any other person or organization.

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