Overview of the Safety Analysis of Loran for Aviation

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ABSTRACT

The Loran Integrity Performance Panel (LORIPP) completed its 18 month study of the ability of Loran to meet aviation requirements for Required Navigation Performance 0.3 (RNP 0.3) in March 2004. The study examined Loran ability to meet on the RNP 0.3 requirements on integrity, availability, and continuity and provide a design for "enhanced Loran" which would allow Loran to reasonably provide RNP 0.3. This is the first time Loran integrity has been examined in the depth required for aviation. The integrity requirement in turns affects availability and continuity since it sets the acceptable levels of parameters used for determining availability and continuity. The paper presents and details the major results on integrity, availability and continuity of the analysis for RNP 0.3.

The integrity analysis is the first step to the overall requirements analysis since it drives the performance levels and bounds that Loran must meet. The integrity fault diagram illustrates how each hazard could affect integrity. It also provides for the calculation of the overall integrity by tallying the integrity allocations for each hazard. The bounds and parameters used to determine availability are established by the integrity allocation for each hazard.

Using the bounds and performance parameters set by integrity, availability and continuity can be calculated. Since Loran performance can vary significantly from location to location, a coverage tool was developed to carry out these calculations throughout the coverage area. These results represent a statement of the availability and continuity of a Loran system that meets RNP 0.3 integrity requirements. The entire process is iterative. For example, unacceptable availability may lead to a refinement in procedures or allocation so that a lower bound may be achieved while still satisfying integrity.

1. INTRODUCTION

The Global Positioning System (GPS) is rapidly becoming an integral part of the infrastructure of many safety and economically critical operations. While GPS offers significant capabilities over other systems, sole reliance on this system could expose many operations to single point vulnerabilities. Such was the findings of studies such as the Volpe National Transportation Safety Center (VNTSC) Report on GPS Vulnerability [1]. It indicated that the current GPS is susceptible to deliberate or inadvertent interference.

As a result, various agencies within the Department of Transportation (DOT) and Department of Homeland Security (DHS) are examining alternatives to mitigating or overcoming the loss of GPS. One alternative that is being studied is Loran or Long Range Navigation. It is one of the few systems available that can serve the needs of multiple modes of transportation and other economically or safety critical operations.

For the Federal Aviation Administration (FAA), the goal for Loran would be to enable continued commercial flight operations with dispatch reliability in the absence of GPS. Specifically, the objective was to determine the capability of Loran to support non-precision approach (NPA) operations. For this work, the FAA formed a Loran evaluation team with participants from industry, government and academia. The evaluation team also examined the capability of Loran to support other position, navigation and timing (PNT) needs as well.

The Loran evaluation team report was delivered to the FAA on 31 March 2004. Paraphrasing the conclusions, the technical analysis indicated that Loran had the ability to meet Required Navigation Performance 0.3 (RNP 0.3 is equivalent to NPA), Harbor Entrance Approach (HEA) and Stratum 1 frequency standards in the conterminous United States (CONUS). The performance is based on using the underlying structure of the current Loran system along with planned upgrades and reasonable modifications.

This paper presents an overview of the technical analysis conducted for the Loran evaluation report. It will focus on RNP 0.3 but it will also discuss other operations such as HEA and timing and frequency. While the discussion is directed towards RNP, much of it also applies to HEA.

2. BACKGROUND ON THE EVALUATION REPORT

The report presents detailed conclusions on the ability to adapt the current Loran system to meet the needs of various modes for providing some form of redundancy to GPS. The Loran system being assessed will still be a low frequency (LF), terrestrial, pulsed, hyperbolic, horizontal navigation system operating between 90-110 kHz. It will still employ the 24 (29) station sites currently in the US (North American) Loran chain. It will be fundamentally the same system as the current Loran-C and the signal will be compatible with Loran-C users. More details on current Loran-C can be found in numerous papers and books [2]

However, the Loran system assessed has features that distinguish it from the one that exists today. This system is termed modernized Loran designating that all stations will operate with the new equipment currently being installed under programs such as the Loran Recapitalization Project [3]. Additionally, it also means changes in areas such as policy and transmitted signal. These changes are necessary to help meet the requirements for RNP, HEA and timing and frequency.

Numerous guiding principles that were used by the evaluation team to determine the changes that should be made. Some basic ones enunciated in the report include:

- Minimal effect on legacy users.
- Minimal modifications are needed to existing transmitting infrastructure—recapitalize or modify existing infrastructure vice creating a new infrastructure.
- No or minimal change in spectrum is required.
- Capability will be included as a separate sensor in an integrated navigation and timing/frequency receiver.
- Signal performance parameters are defined at the base of the receiving antenna vice at the base of the transmitting antenna. Properties of the transmitted signal associated with transmitting stations, propagation (including signal and phase distortion), monitor and control stations, receivers, and intentional errors (jamming/spoofing) must be considered.

These guiding principles form the fundamental basis of the design process and constrained the changes that were deemed acceptable. They also dictated some of the analyses that were necessary.

Another major guiding principle is that the system must be designed for international acceptance. This means that the modifications can be made worldwide and that the system can coexist with existing extensions on Loran-C such as Eurofix [4].

A system design that is compatible with international is important for many reasons. Loran is operated both in Europe and East Asia by the Northwest European Loran-C System (NELS) and Far East Radionavigation Service (FERNS), respectively. As PNT applications become more integrated in commerce, many nations have expressed increased interested in developing redundancy to their use of GPS. For example, one interest of some FERNS member states is the use of Loran for maritime redundancy to GPS. If the system is designed such that it can be easily implemented and adopted internationally, it could provide significant benefits to other nations as well as significant ancillary benefits for the US. International adoption provides increased coverage as well as greater incentive and market for new Loran products. Thus, a design is compatible with international equipage and standards will greatly aid in the adoption and use of *e*Loran, the implemented form of modernized Loran.

2.1 Requirements

The RNP and HEA requirements are shown in Table 2. Integrity is the fidelity of the system. It is the ability of the system to alert a user when a signal or a solution should not be used. This must occur within the time to alert (TTA). Hence, for the solution to be available, it must have already met integrity requirements. The system is available if the integrity bound on the position solution is below the alert or alarm limit. Continuity is the probability that the system remains available for the duration of the operation presuming that availability initially exists.

Performance Requirement	RNP Value	HEA Value
Accuracy (target)	307 meters	20 m, 2 drms
Monitor/Alert Limit (target)	556 meters	50 m, 2 drms
Integrity	10^{-7}/hour	3×10^{-5}
Time-to-alert	10 seconds	10 seconds
Availability (minimum)	99.9%	99.7%
Availability (target)	99.99%	
Continuity (minimum)	99.9% over 150 seconds	99.85% over 3 hours
Continuity (target)	99.99%	

Table 1. RNP 0.3 and HEA Requirements

An assessment of whether the system can meet the requirements for RNP 0.3 and HEA can be made once the hazards that can affect the signal are identified.

2.2 Hazards

There are numerous hazards that can affect the precision of the ranging measurement as well as the overall availability of the signal. Measuring the Loran pulse is a two part process: first, the correct cycle of the pulse is found; second, the zero crossing of that cycle is determined. Some hazards affect the ability to measure the envelope, resulting in incorrect cycle determination (with an accompanying large range error). For example, the envelope shifts relative to the underlying carrier (and hence the tracking point). This shift is termed the envelope to cycle difference (ECD). Significant variations of ECD from nominal could result in cycle errors. Some hazards, such as noise, affect the phase measurement by obscuring the location of the zero crossing or delaying the overall signal. Other hazards, such as transmitter outages, precipitation static or early skywave, make the signal unavailable for use.

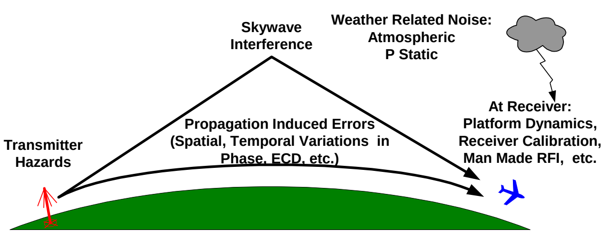

Figure 1. Loran Hazards

Category	Hazard
Transmitter	Timing and Frequency Equipment Transmitter and Antenna Coupler Transmitter Equipment Monitoring
Propagation	Spatial variation of phase along approach path Temporal variation of phase Spatial variation of ECD along approach path Temporal variation of ECD Temporal variation of SNR
Receiver	Platform dynamics Atmospheric Noise Precipitation Static Skywaves Cross-Rate Interference Man-made RFI Structures Receiver Calibration

Table 2. Hazards and What They Affect

The evaluation team had to identify and assess each of these hazards to determine their effect on the system. The hazards are listed in Table 2 and pictorially depicted in Figure 1. This paper will not detail the hazards which are described in other papers [5].

2.3 Assessment Process

Loran evaluation team assessment proceeded by understanding the system characteristics and hazards of Loran for aviation. Design changes (system assumptions) were added or modified in order to meet aviation requirements. These changes were subject to the guiding principles discussed earlier. Changes were classified into four categories or trade spaces:

1. Radionavigation Policy which involves areas of radionavigation policy and statements of performance, certification, calibration, funding, and other issues addressed at the policy level.
2. Operational Doctrine which involves areas of operational performance employed in managing and controlling Loran-C operations.
3. Transmitter, monitor, and control equipment which involves the equipment used for signal generation, monitoring, and control.
4. User equipment which involves the sensor specification, antenna types, and algorithms used to define and implement user equipment.

Some major additions/assumptions include the addition of a communications channel ("ninth pulse"), all in view receivers, use of calibration points, enhanced antennas, and upgraded transmitter equipment.

The modifications occurred as the team iterated through the integrity, availability, continuity and accuracy analysis. For example, additions included early skywave monitors and communications channel for integrity flag (for skywave). It was discovered that early skywave could have a significant adverse effect on availability unless a warning message was available. The rest of this paper provides an overview of the assessment of these requirements. Figure 2 shows the overall evaluation process for aviation. Similar processes were carried out for maritime and timing with coordination between the evaluations. This ensured that there were no discrepancies and resulted in a coherent system design that met all three needs.

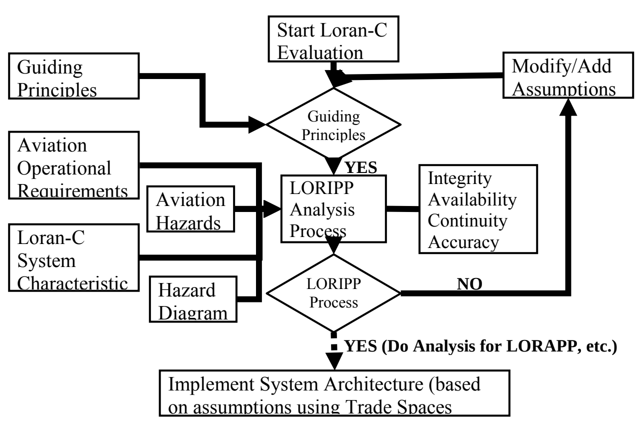

Figure 2. Overall LORIPP Evaluation Process

3. INTEGRITY ASSESSMENT

Providing a position solution with integrity is paramount to the mission of Loran as a backup for GPS. Hence, integrity must be first demonstrated. Integrity requires providing bounds for hazards that will affect the position solution. It also requires monitors and alerts for hazards that cannot be reasonably bounded.

3.1 Fault Diagram and Integrity Allocation

Demonstration of integrity started with the integrity fault diagram. This diagram lays out the significant phenomenon or threats that can result in a loss of integrity. The high level fault diagram is shown in Figure 3. The diagram systematically lays out all integrity threats of concern and helps to tabulate the overall integrity based given these threats. Each threat is given an allocation partly based on analysis of the ability to provide integrity covering each threat. The current allocation is shown in Table 3. Since determining Loran position requires cycle determination and phase determination for the calculation of range and position, allocations have to be provide for both cycle and phase.

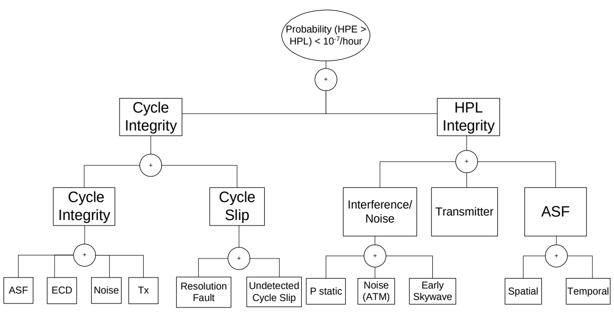

Figure 3. High Level Integrity Fault Diagram

Hazard	Cycle ID Allocation	Phase Allocation	Occurrence Probability
Spatial Phase	0	0	1.0
Temporal Phase	0	0	1.0
Spatial ECD Bias	0	N/A	1.0
Temporal ECD Bias	0	N/A	1.0
Early Skywave	1.04×10^{-5}	1.0×10^{-7}	6.85×10^{-4}
A/C Dynamics	0	N/A	1.0
P Static	0	1.0×10^{-8}	1.0
Tx Noise	1.0×10^{-10}	1.0×10^{-8}	1.0
Tx ECD	1.0×10^{-10}	N/A	1.0
Atm Noise	2.0×10^{-8}	1.0×10^{-8}	1.0
Interference	0	1.0×10^{-8}	0.05

Table 3. Integrity Allocations

The integrity fault diagram tabulation ensures that the overall integrity level is the results from a comprehensive tally. The tabulation is the overall integrity provided that each individual threat allocation is met. This partitions the integrity analysis into discrete examinations of each threat.

3.2 Meeting Integrity Allocations

For each threat, the integrity allocation can be met in many ways. The effects of the threat can be bounded, monitored, and/or flagged. If a bound is used, the bound is set such that the overall integrity requirement is met. Many threats are treated by bounding. The cycle and phase error bounds for the significant hazards are shown in Table 4. Depending on the characteristics of the error, the bounds may be an absolute bound on a bias or a confidence bound on a random error. The bounds are then used to determine cycle integrity and calculate the horizontal protection level (HPL) using the integrity equation discussed in the next section.

Hazard/Process	Type	Cycle ID	Phase
Spatial Phase	Uncorr. Bias	100 m	*PD:* 120 m
Temporal Phase	Corr. Bias	0.3 m/km	0.3 m/km
	Uncorr. Bias	75 m	75 m
Total ECD	Bias	300 m	N/A
-Spatial ECD		60 m	N/A
-Temporal ECD		m	N/A
-Tx ECD		~ 30 m	N/A
-Residual Rx Cal		~30 m	N/A
Noise	Random (1 σ)	$29/\sqrt{Nenv}$ μs	$169/\sqrt{Nph}$ m
Tx Noise	Random (1 σ)	Part of noise	6 m

Table 4. Bounds for Integrity

However, a bound that meets the integrity allocation may prove unacceptably high resulting in high unavailability due to high HPL. In such a case, one can increase the integrity allocation, provide an integrity warning (use/don't use flag), or develop a different technique to meet that bound with the given allocation. For example, the effect of early skywave can be very significant and is not easily bounded. However, since it is a rare phenomenon in the CONUS, an integrity warning is provided in case of occurrence. This is better than an *a* *priori* bound would in essence treat the error as omnipresent. The bounding of spatial phase errors demonstrates an instance where different technique was developed to meet the allocation with an acceptable bound. A position domain (PD) bound and the use of additional calibration points result in a more acceptable bound for the given allocation.

3.3 Cycle Integrity and the Integrity Equation

As mentioned earlier, determining position is a two step process. First, the cycle must be resolved and integrity requires that cycle resolution is done with adequate integrity. After passing cycle resolution, the range/phase can be measured and these ranges can be used to calculate a position solution with an accompanying HPL. Since cycle resolution and HPL are both required, the total level of integrity is the sum of their integrity levels. The current allocations for cycle resolution and HPL integrity is approximately 7×10^{-8} and 3×10^{-8}, respectively.

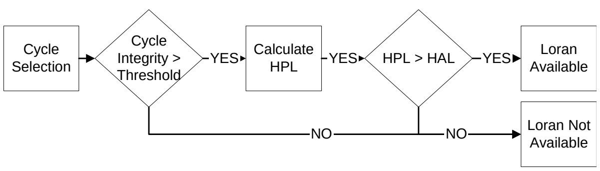

Figure 4. Flowchart for calculating position solution and using Loran for RNP & HEA

The signal to noise ratio (SNR) is the prime determinant of our confidence of correct cycle resolution. For signals with high SNR (generally 4 dB or higher), the signal is of adequate fidelity that the receiver can be confident of tracking the correct cycle to the required level. Since at least three signals are necessary for a position solution, there needs to be at least three such stations. However, there are often instances where that does not exist. Cycle resolution using an overdetermined solution and a residuals test is used to verify cycle selection. The bounds on biases and random errors affecting cycle measurement are used to determine overall confidence. Details on this technique are given in [6]. If the cycle is resolved with adequate integrity, then HPL can be calculated.

The HPL is calculated using the Loran Integrity equation shown in Equation (1.1). The equation divides the error into four components. The first term is a Gaussian bound on random errors where α_i is the standard deviation of the bound on random error *i*. The second and third term correspond to bounds on correlated and uncorrelated biases respectively. The final term, *PB*, is the position domain bound on errors mentioned in Section 3.2. This is used for spatial ASF variations since it can help leverage inherent spatial correlations.

$$HPL = \kappa\sqrt{\sum_i K_i \alpha_i^2} + \left|\sum_i K_i \beta_i\right| + \sum_i \left|K_i \gamma_i\right| + PB \qquad (1.1)$$

Meeting cycle integrity is required for a meaningful calculation of HPL. An HPL below the horizontal alarm limit (HAL) is required for availability. The assessment of integrity provides the bounds necessary for calculating cycle integrity and HPL. This is a necessary step for determining availability.

4. AVAILABILITY ASSESSMENT

The formulation of the integrity algorithm for cycle resolution and HPL allows for the determination of availability and continuity. These algorithms are based on station geometry, station availability, SNR and the bounds determined for integrity. Many of these factors are location dependent and hence the availability need be calculated for each place of interest. A coverage tool was designed to perform the calculation

4.1 Coverage Tool

The basic calculation of the coverage is illustrated in a flow chart form in Figure 5. More details on the coverage tool and the determination of station availability and continuity are presented in [7]. The tool calculates SNR using accepted models for signal strength and noise. Noise levels are based on the widely accepted model from International Telecommunication Union (ITU), formerly the International Radio Consultative Committee (CCIR) [8]. Results from these signal and noise models are shown in Figure 6 and Figure 7, respectively.

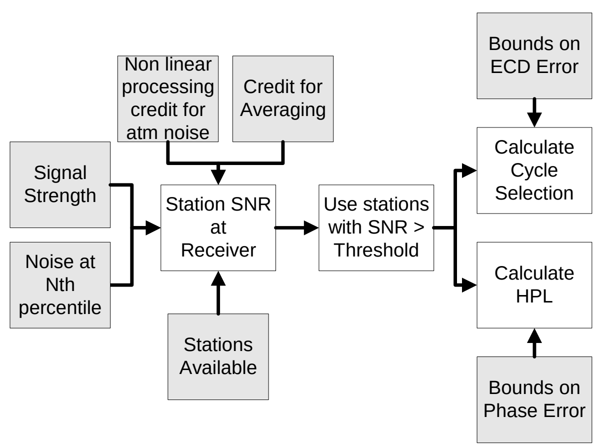

Figure 5. Calculation Process of Basic Coverage Analysis

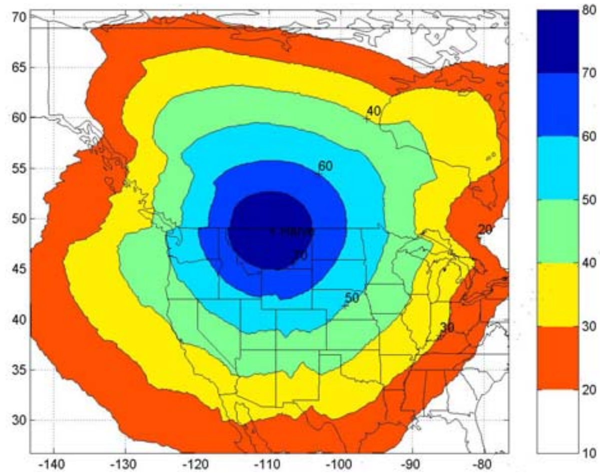

Figure 6. Sample Signal Strength from Havre in dB re 1uv/m for 400 kW

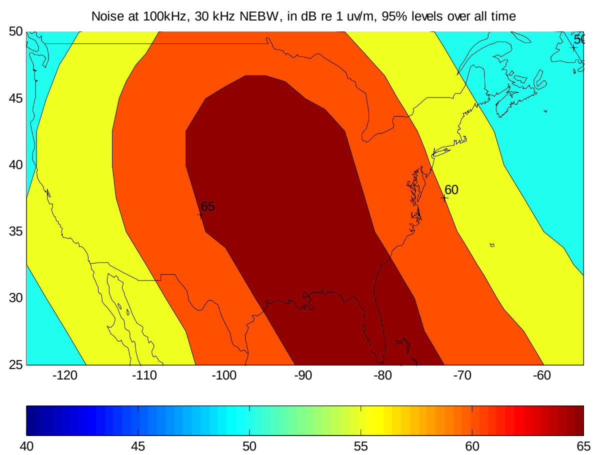

Figure 7. 95% CONUS Noise Map (Annual Average)

However, not all stations will necessarily be transmitting. Each subset of the stations available is examined with the resulting availability weighted by the probability of that subset occurring. Knowing the stations available and their respective SNR, modified by credits and debits for processing and interference, calculations of cycle resolution and HPL can be made.

Process	Type	SNR
Atmospheric Noise: Non-linear Processing	Credit	12 dB (depending on impulsivity of noise)
Precipitation Static (P Static)	Debit	40 dB mV/m
Cross Rate Interference (CRI) Blanking 9th Pulse	Debit	0.5 dB
CRI Canceling	Debit	1.5 dB
Early Skywave	Debit	Loss of Signal
Aircraft Dynamics	Debit	Minimal affect on cycle slip

Table 5. Credits and Debits for SNR

Item	Model Parameter
W/O	With or without Canadian stations
HAL	Horizontal alarm limit
CCR	Credit for clipping
ENB	ECD bias
ETC	Seconds to average envelope
PTC	Seconds to average phase
SPE	Range error for spatial
SRE	Position error for spatial ASF decorrelation in HPL
KCT	Coefficient that scales correlated seasonal phase variation map
KUT	Coefficient that scales uncorrelated seasonal phase variation map
HMN	Threshold of probability for Gaussian noise contribution to HPL
HCY	Threshold of probability of undetected cycle error

Table 6. Parameter Key for Coverage Diagrams

The calculations depend on the bounds and other assumptions used. While the values used represent the current best estimates, these values could change. Furthermore, it would be useful to test the sensitivity of coverage to various parameters. Hence, the coverage tool was designed so that various assumptions and parameters can be changed. Aside from the utility mentioned above, it allows the tool to be used for both HEA and RNP with only minor changes. Table 6 shows some of the model parameters that can be varied within the tool.

4.2 Results

One output of the coverage tool is availability plots for RNP or HEA, an example of which is shown in Figure 8. This plot represents the expected availability for RNP 0.3 using noise levels averaged throughout the year. From the results, one could expect Loran, on average, to perform with at least 95%, though more often 99% or higher, availability throughout CONUS.

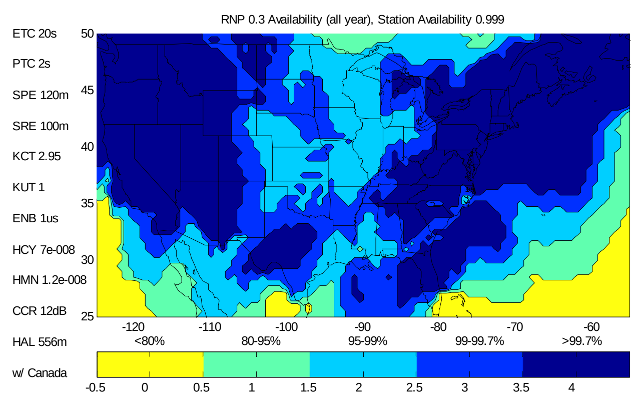

Figure 8. Expected RNP 0.3 Modernized Loran Coverage (Availability Contours in Percent) in CONUS with Existing Infrastructure

One coverage plot does not tell the entire story. A major concern is performance during the worst time intervals. The noise levels can vary significantly from time period to time period with the highest levels generally occurring in summer afternoons. An examination of that case shows that the Midwest suffers significant availability issues with around 80% availability in some significant areas. However, the noise model for these worst case instances is thought to be significantly high. Additionally, CCIR confidence bound on the worst case values is large. This implies that the actual noise could be significantly less. Refinements to the noise model (through additional data collection) and additional signal processing is expected to result in more acceptable availability. Several partners of the evaluation team including Ohio University and Stanford University are engaging in this effort.

Results from the coverage tool show that the principal determinant of availability is the ability to resolve cycles with adequate integrity. This implies that greater availability can be achieved if there were more signals available. Hence a reduction of noise level would have a significant effect. The implication is that if the worst case noise level were found to be lower, this could result in significant increases in availability.

5. CONTINUITY ASSESSMENT

Calculation of availability leads naturally to the assessment of continuity. Calculation of continuity begins by examining all conditions where there is availability and determining the probability that availability will be lost some time during an approach. For RNP, that approach lasts 150 seconds; for HEA, that approach lasts 3 hours. The calculation currently focuses primarily on station continuity though the inclusion of events such as the sudden appearance of interference could be added. So far, these events seem to be insignificant relative to the level of continuity being calculated.

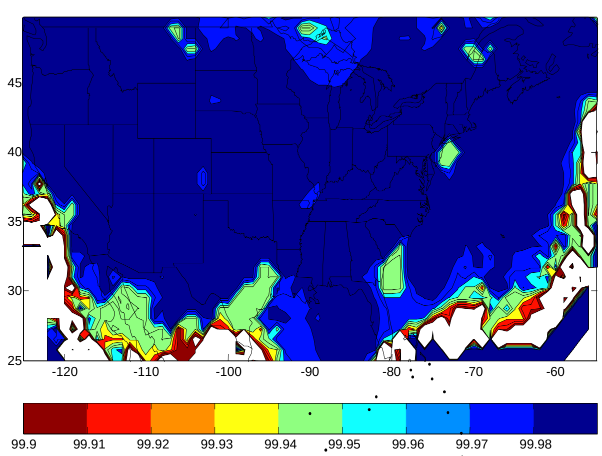

Figure 9. Expected RNP 0.3 Modernized Loran Coverage (Continuity Contours in Percent at a 0.999 Station Availability) in the CONUS with Existing Infrastructure

The results generally demonstrate that in locations where availability is reasonable, continuity should be good as well. For a given location, continuity is generally higher than availability.

6. ACCURACY ASSESSMENT

The accuracy assessment was conducted using a variety of techniques. Historical measurements of Loran accuracy indicate that Loran can meet aviation accuracy specifications. However, HEA requirements are much tighter. The simplest and most obvious manner is to take field measurements, either in static positions or versus some truth reference such as GPS/WAAS. Participants such as the US Coast Guard Academy and Peterson Integrated Geopositioning have taken measurements of the performance of Loran and differential Loran [9].

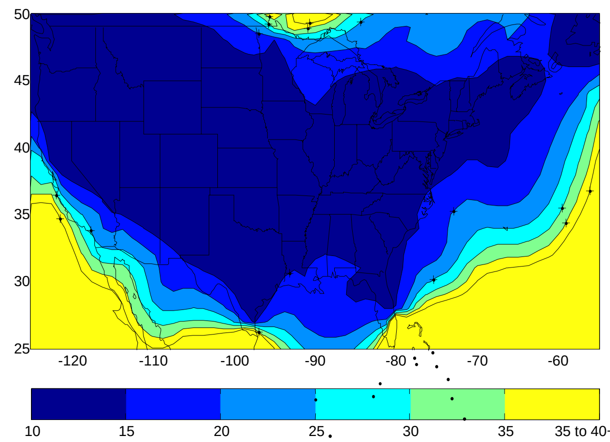

Figure 10. Expected HEA Modernized Loran Accuracy (Accuracy in Contours in Meters at the 95 Percent Noise Level) in the CONUS with the Existing Infrastructure

However, these measurements only provide accuracy estimates in select locations. The coverage tool is used to provide an analytical assessment of accuracy throughout CONUS. Models for Loran errors were developed in the integrity analysis of error bounds and statistics. These are employed in the model and used to predict accuracy. Results have shown good correlation between data and prediction. Figure 10 shows its use in predicting HEA accuracy provided that differential Loran stations and correction broadcasts are established.

In the next step, it is envisioned that accuracy and integrity measurements will be made a fixed sites to validate the integrity results. The triangle chart, developed for the assessment of the Wide Area Augmentation System (WAAS) can be used for the assessment.

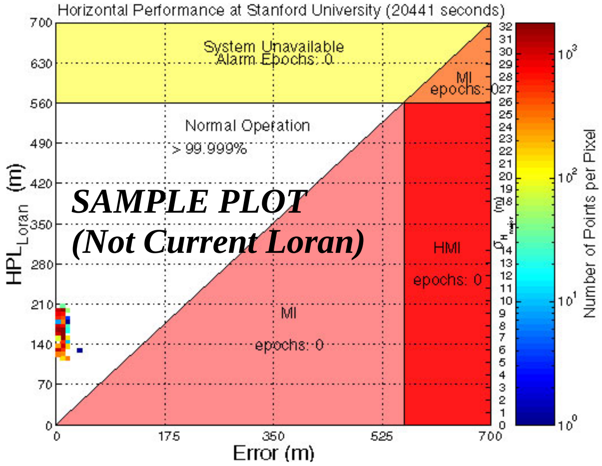

Figure 11. Sample Triangle Chart for Assessing Loran Integrity and Accuracy

7. CONCLUSIONS

The conclusions of this paper are well summarized by the conclusions of the Loran evaluation report states:

"The evaluation shows that a modernized Loran-C system could satisfy the current NPA, HEA, and timing/frequency requirements in the conterminous United States and could be used to mitigate the operational effects of a disruption in GPS services, thereby allowing the GPS users to retain the benefits they derive from their use of GPS [10].*"*

The report represents the most significant and thorough integrity analysis performed on the Loran system for supporting aviation and maritime. It followed many of the procedures and processes used to assess GPS/WAAS. The evaluation team assessed the primary hazards for aviation in detail. The work lays the groundwork for the analysis necessary for certification. There are some issues, such as worst case atmospheric noise, that remain to be resolved. However, the results of the evaluation reflect an understanding that these issues can be reasonably solved.

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