Loran for Required Navigation Performance 0.3: The Current Work of Loran Integrity Performance Panel (LORIPP)

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1 ABSTRACT

Loran, is an attractive candidate to provide backup services for GPS because of its complementary area navigation (RNAV), stratum 1 timing, and data channel capabilities. However, for Loran to be accepted as a backup navigation system for aviation, it must meet the integrity, availability, continuity, and accuracy standards for Required Navigation Performance 0.3 (RNP 0.3). The Loran Integrity Performance Panel (LORIPP) is a core team of experts assessing Loran's potential to meet the RNP 0.3 performance. It applies engineering and safety analysis principles to build in safety as an integral part of the system design. The LORIPP is following safety analysis methods similar to those used by the WAAS Integrity Performance Panel (WIPP) to conduct a rigorous Hazardously Misleading Information (HMI) analysis on Loran.

In order to properly address the RNP 0.3 accuracy, availability, integrity, and continuity requirements, many areas of development and research have been undertaken. Developments include transmitter equipment upgrades, receiver technology, and changes in operating procedures. These changes provide a new enhanced Loran (eLoran). Major areas of assessments include groundwave propagation, precipitation static, atmospheric noise, transmitter, receiver and overall system engineering. The analyses produced by these task areas are then used to determine the integrity, availability, continuity, and accuracy of the enhanced Loran system.

The paper discusses the current progress from each area of investigation. Data collection alone represents a significant undertaking. The groundwave propagation tests require setting up time of transmission monitors at secondary Loran stations. Equipment capable of monitoring time of arrival is also installed at numerous locales. The precipitation static tests involve ground and flight trials. In the ground trial, the aircraft is charged to known levels and then discharged. The atmospheric noise work involves collecting data from adverse weather. This data along with known models is then used to determine algorithms for mitigating this type of noise. Analysis of the data provides the input for the overall system engineering which will integrate the results to determine if Loran meets the RNP 0.3 requirements.

2 INTRODUCTION

The findings and recommendations of the Volpe National Transportation Safety Center (VNTSC) Report on GPS Vulnerability have had tremendous ramifications on the United States Department of Transportation (USDOT) [1]. The acceptance of these findings - specifically the need for a backup to GPS in safety critical applications - by the USDOT has led the various components of the USDOT to evaluate how they propose to meet this requirement.

For the US Federal Aviation Administration (FAA), this means maintaining and upgrading a navigation infrastructure sufficient for sustaining the capacity and efficiency to continue commercial flight operations with dispatch reliability. The ability to for air transportation to continue operations by air transportation in the presence of interference is one of the best deterrent to deliberate jamming.

The LOng RAnge Navigation radionavigation system or Loran is a terrestrial, high power, hyperbolic navigation system operating in the 90 to 110 kHz frequency band. Since the low frequencies signals propagate along the nap of the Earth, it is not line of sight dependent. These characteristics are complementary to those of GPS and make Loran a potentially ideal navigation backup to GPS.

As a result, the paramount FAA Loran issue is whether it can support non-precision approach (NPA). The preferred NPA is Required Navigation Performance 0.3 (RNP 0.3). Thus the FAA and the US Coast Guard (USCG), which operates the US Loran system, with the support of a team comprising of government, academia, and industry members are conducting an evaluation of the current and potential capabilities of Loran system. This group is known as the Loran Integrity Performance Panel (LORIPP) and its primary purposes is to investigate ability of Loran to meet RNP 0.3 using the underlying structure of the current Loran system along with planned upgrades and reasonable modifications. The investigation provides answers that will aid in decisions regarding how Loran can contribute to supporting required navigation services in the National Airspace System (NAS) and possibly other transportation modes.

Meeting Required Navigation Performance (RNP) 0.3 requirements for non-precision approaches means achieving the performance levels shown in Table 1[1].

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

Table 1. Performance Levels for RNP 0.3

The paper highlights the current work of LORIPP. It focuses on some systems level work to provide a conception of the current status. Details of the individual LORIPP efforts will be presented in other papers.

3 LORAN BACKGROUND

This section provides background on Loran operations, signal structure and sources of interference.

3.1 Basic Loran-C Operations and Capabilities

Loran-C is the current implementation of Loran. The US Loran-C system, seen in Figure 1, comprises transmitters, control stations, and System Area Monitors (SAM) [2][2].

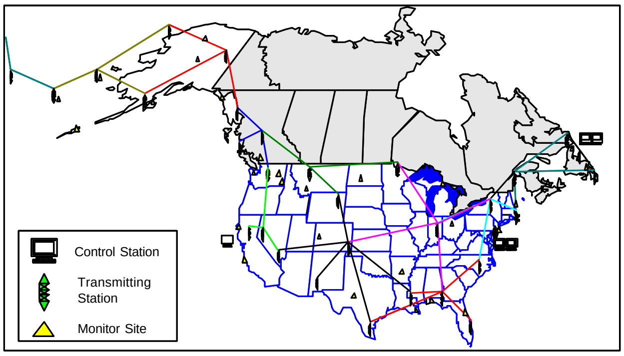

Figure 1. Loran-C System Architecture

Loran stations are grouped together into chains and basic navigation relies on using a specific chain. In each chain, there is a master station and several secondary stations. In Loran-C, each station transmits a group of eight pulses (nine for the master station) at a specified interval. The amount of time between transmissions of the pulse groups, known as the group repetition interval (GRI), is unique to each chain. Hence chains are designated by their GRI. Some stations transmit signals for two different chains. These are termed dual rated stations.

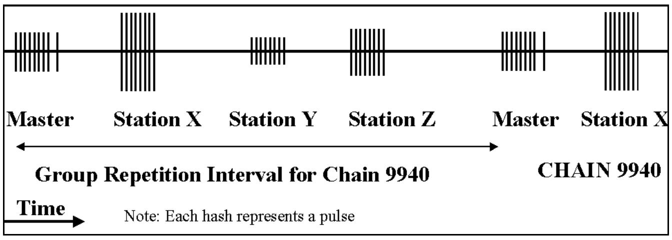

Figure 2. Loran Chain Signals

The GRI is usually expressed as a multiple of ten microseconds, i.e., GRI 7960 = 79600 microseconds. Figure 2 illustrates the 9940 chain transmissions that a receiver may see. Each hash mark represents one Loran pulse (which is 250 microseconds in length). A nominal pulse is shown in Figure 3. The pulse has a specified shape or envelope that aids in tracking the correct cycle. Typically the tracking point is set around 30 microseconds (or the sixth zero crossing) after the start of the pulse. As the signal propagates, the envelope may shift relative to the underlying carrier (and hence the tracking point). This shift is termed the envelope to cycle difference (ECD).

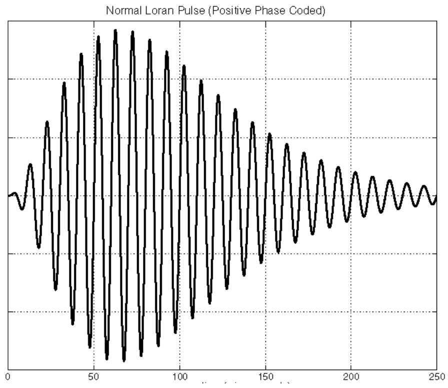

Figure 3. Normal Loran Pulse

The power of Loran transmissions allows users at distances of 800 km or more to receive these signals.

3.2 Navigation and Positioning

The transmitters emit a set of Loran pulses at precise instances in time. Within a chain, the transmission time of each secondary station is specified as an offset from the transmission of the master station. The SAMs regulate the transmission offset. Traditionally, position determination is based on measuring the time difference of arrival (TDOA) of pulses from the master and a secondary station in a chain to create lines of position (LOPs). A minimum of two LOPs are required to determine a position. Newer technology has result in Loran receivers capable of operating without requiring a master station signal. They also can determine position using signals from stations in different chains (all stations in view) to improve Loran performance. These receivers are known as “all-in-view” (AIV) receivers. Processing permits the calculation of a range measurement using the signal time of arrival (TOA) provided that the receiver has rough knowledge of the current time and station identification. Using TOA is akin to using GPS pseudoranges.

3.3 Loran Propagation and Intra System Interference

There are two ways that Loran signals propagate. The signals propagate as a groundwave along the Earth's surface. They also propagate as a skywave by reflecting from the ionosphere. TDOAs are calculated using the groundwaves since they are more reliable and their phase is more stable. Skywave reflections can interfere with the desired groundwave signals much like multipath in GPS. Typical skywaves arrive as early as 32-35 microseconds and as late as 1000 microseconds after the reception of the groundwave [Forssell91]. Since the groundwave from a station can interfere with the groundwave of another station if they are not in the same chain. This type of interference is called cross rate interference since it is due to stations transmitting at different rates.

The propagation speed of the Loran groundwave is dependent on factors such as ground conductivity. These properties change the signal propagation speed from the speed of light. Typically, two factors are used to arrive at the correct propagation time. The primary factor (PF) is the increment of time for traversing an all seawater path. Second is additional secondary factor (ASF), which accounts for propagation delays over heterogeneous earth. PF is solely dependent on distance while ASF need to be measured or modeled. More accurate models or measurements result in more accurate range measurements and hence more accurate position solutions.

4 SYSTEM ENGINEERING FOR RNP 0.3 REQUIREMENTS

The current LORIPP system engineering task is to analytically demonstrate that Loran meets RNP 0.3 requirements.

Providing integrity means that the system provides no hazardously misleading information (HMI) to the user. For Loran RNP 0.3, an HMI occurs when the horizontal position error (HPE) is larger than the horizontal protection level (HPL). The HPL is the bound on position calculated by the user from a prescribed algorithm. This is known as the integrity or HPL equation and will be shown in Section 5.2.1.

Availability is the probability that the system provides a solution that can be used for a RNP 0.3 approach.

Continuity is the probability that, given a solution is available at the beginning of the approach, it will be available throughout the approach (150 seconds). Hence, if a Loran RNP 0.3 solution is not available at the beginning of the approach, the loss of the signal is considered a loss of availability rather than a loss of continuity.

Accuracy is a measure of the system's calculated location versus true location. The difference between these two quantities is known as the navigation system error (NSE).

Coverage is a measure of the geographic area where specified levels of each requirement is met. Since Loran signals vary from location to location, the level of performance also varies. Determination of these capabilities throughout the US is necessary to understanding the coverage provided by the system.

4.1 Assumptions

The major assumptions made in the work of the LORIPP can be divided into three categories – assumptions concerning the Loran system design and its operations, Loran user equipment, and policy and operations.

Loran system design and operations assumptions concern the state and operations of the Loran transmitters and monitors. The transmitters are assumed to be all solid-state transmitters (SSXs). This is currently not true but under the Loran Recapitalization Project (LRP) [3], older tube transmitters will be upgraded to new SSXs. Each station is assumed to be under time of transmission (TOT) control synchronized to Universal Time Coordinated (UTC). This method enables a more precise time of transmission determination by users vis-à-vis the current System Area Monitor (SAM) control. Other potential changes may include dual rating all stations and adding a station identification code onto the Loran signal.

With new transmitter equipment and procedures, the operations of the system will be more efficient. Momentary outages from switching to redundant equipment are reduced to three seconds. Operational procedures include coordinating scheduled maintenance to minimize effect on aviation users of Loran.

Loran user equipment assumptions include requiring the use of all-in-view (AIV) receiver with a magnetic field (H-field), software steered antenna. H-field antennas offer mitigation to a form of weather related noise (precipitation static) hence increasing availability. Software steering provides additional processing gain. It is assumed that cross rate interference is cancelled or blanked. It is also assumed that if the Loran signal is modulated, it does not affect navigation performance. The receiver is also assumed to be capable of coasting through a three second outage.

There will be many assumptions made in the operations and procedures utilized by the receiver. The receiver will utilize a current ASF table. The receiver will also have a cycle resolution algorithm that can achieve the performances determined by the LORIPP. Other requirements for other hazards may be added as the LORIPP investigation continues. These operations could form the basis for a Loran RNP 0.3 receiver MOPS.

The justifications for these assumptions come from various sources. Some assumptions result from current plans. Others derive from the analysis. Some will have to be validated.

4.2 Hazards List

The hazard list is an enumeration of anomalous phenomena that may effect Loran's ability to meet RNP 0.3 requirements. A phenomenon that causes signal loss, distortion of the signal envelope or distortion of the signal phase (or timing) is a hazard. Thus hazards result in errors in tracking the Loran signal or measuring the TOA or TDOA of the signal.

Signal loss affects availability and continuity. It can be caused by phenomena that increase the noise level such that the receiver cannot track the signal. It can also be caused by outages at the transmitter that result in the signal going off air.

Envelope distortion generally affects integrity and accuracy. Loran receivers use the envelope to determine the desired zero crossing or cycle to track. If the envelope is too distorted, the wrong cycle may be tracked resulting in a significant position error. If the error is not detected, an integrity failure results. Noise, interference and transmitter equipment failures can cause envelope distortion.

Phase distortion generally affects integrity and accuracy. It can cause phase or timing error since phase measurements are used to determine timing. Inaccuracies in phase measurements result in position errors. If the phase error is unmodeled or undetected, it could result in an integrity failure. Noise, interference and transmitter equipment failures can cause envelope distortion.

As mentioned, there is some intra system interference in the form of skywave and cross rate signals. Skywave interference occurs when the transmitted Loran pulse reflects off of the ionosphere and interferes with the groundwave signal. This interference typically arrives 50-60 microseconds after the arrival of the ground pulse and is part of nominal system operations. The Loran pulse shape was designed to mitigate typical skywave. A much less typical occurrence has been observed in high latitude locations such as Port Clarence, Alaska, where the skywave may arrive as early as 25-30 microseconds after the groundwave [5]. This is an anomalous occurrence termed early skywave.

As described earlier, cross rate interference (CRI) is when pulses of the different GRIs interfere with each other. CRI is part of nominal system operations. Modern receiver designs blank or process out cross rate interference since it is predictable.

Hazards include receiver platform noise, distortions due to propagation, aircraft dynamics, and transmitter failures. In addition, weather related noise such as atmospheric noise (from lightning), precipitation static (P-static) also impacts receiver performance. Early skywave is another hazard. These hazards to Loran navigation integrity, availability and continuity are pictorially represented in Figure 4 and discussed in greater detail in [6]. Table 2 lists these hazards and the requirements to which they pose a significant issue.

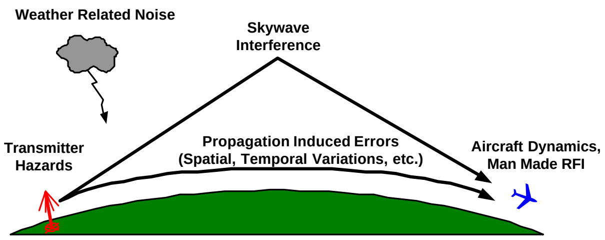

Figure 4. Loran Hazards

Hazard	Integrity	Continuity	Accuracy	Availability	Coverage
Temporal variation of ECD	x				
Temporal variation of phase	x		x		
Temporal variation of SNR				x	
Spatial variation of groundwave phase along approach path		x			X
Weather related noise				x	
Early skywave	x				
Aircraft dynamics		x			
Man-made RFI		x		x	
Transmitter Hazards		x		x	X

Table 2. Hazard-Requirement Matrix

5 INTEGRITY ANALYSIS PROGRESS

Current work on integrity is proceeding with data collection and analysis of the major integrity hazards of groundwave propagation and early skywave. This section begins with a quick description of the Loran integrity fault tree.   It serves as a road map for the work to date.

The integrity fault tree allocates the acceptable error probabilities for each fault or hazard with regard to the integrity requirement. It provides bookkeeping for a thorough accounting of all hazards.

The integrity fault tree is shown Figure 5 and described in greater detail in [7]. It first divides the integrity faults in two basic categories – faults due to Cycle Error and faults due to Phase/Timing Error (All Cycles Correct).

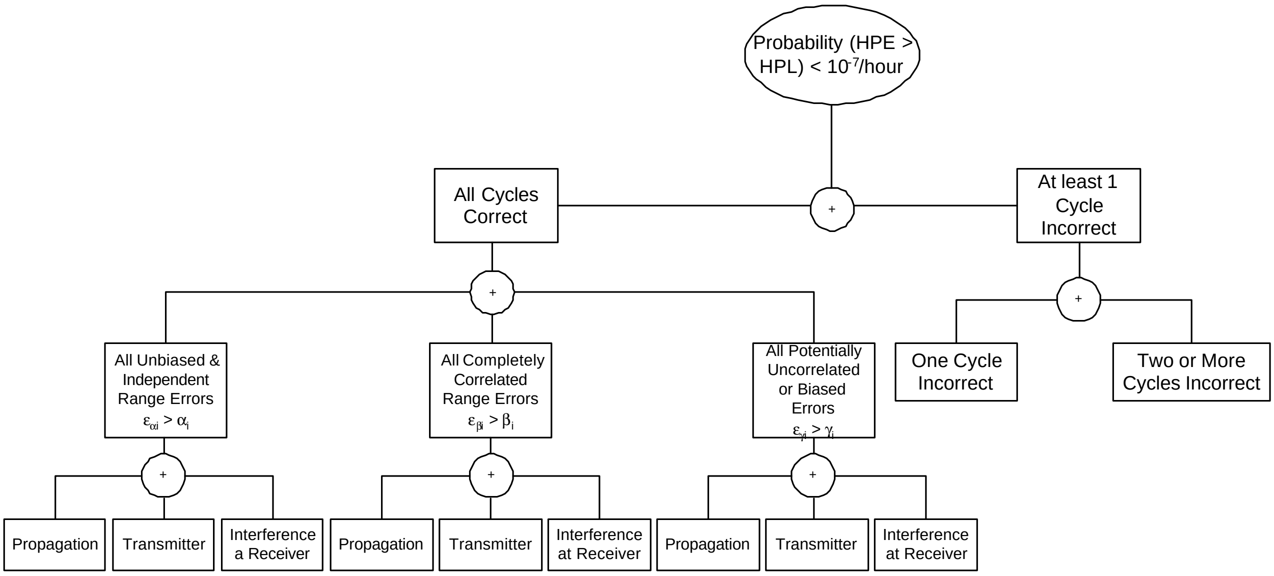

Figure 5. High Level Loran Integrity Fault Tree

5.1 Current Effort on Cycle Error

Tracking the wrong cycle will result in a ranging error of a Loran wavelength (three kilometers) or more. If the error is undetected, it will result in an integrity failure. Since the envelope shape is used to determine the location of the zero crossing for the expected tracking point, a large ECD may lead the receiver to unwittingly track the wrong zero crossing. Hence, a greater the variation in ECD results in a greater likelihood of tracking the wrong cycle. Determination of integrity risk requires a good understanding of ECD variations, particularly due to propagation. A cycle error detection algorithm is being to developed and validated to ensure that integrity requirements are met. It uses redundant measurements to increase the certitude of tracking the correct cycle. The design is discussed in [8].

5.1.1 Determination and Validation of ECD

An understanding of ECD bias and variations is necessary to determine the risk of tracking the wrong cycle. The variation of ECD, while dependent on other factors as well, is generally a function of signal to noise ratio (SNR) as seen in Equation (1.1). The bias in ECD is dependent on factors such as propagation distance, transmitter biases, etc. This value may be modeled or bounded. In practice, Loran receiver will be able to estimate its ECD. This estimate or a bound may be used with the model of ECD variation to aid in cycle error detection.

$$s_{ECD} = \frac{M \; m\mathrm{sec}}{\sqrt{N \; * \; SNR}} \qquad (1.1)$$

where: *N* is the number or pulses averaged
M is dependent on the receiver. *M* = 42 for the Austron 5000 Loran receiver

Since these models account for only nominal ECD changes, collected data is being used to supplement the model. The groundwave data collection effort has produced data on ECD measurements in many location of the country. This data is currently being used to refine *a priori* ECD statistics and produce bounds for ECD. It is also used to identify anomalous occurrences that may cause ECD to deviate from predictions.

5.1.2 Cycle Error Detection

The cycle error detection reduces the integrity risk by providing confidence that the correct cycles are being tracked. It identifies instances when cycle confidence does not meet integrity requirements. The LORIPP is finalizing the overall receiver cycle error detection architecture. It will consist of a cycle validation and a cycle slip or step detection algorithm. The cycle validation algorithm uses a calculated weighted sum square error (WSSE) statistic and *a priori* probabilities to determine the probability of being on a wrong cycle and not detecting the error. The cycle slip detector is used once the cycle has been initially validated.

5.2 Phase/Timing Errors

Even if a measurement is verified to be on the correct cycle, it still will contain phase and timing errors. These errors result in position errors. Confidence bounds on the errors are necessary to allow the receiver to determine the horizontal protection level (HPL) for the position solution. The LORIPP is determining the bounds and a reasonable means to combine them (via the integrity equation) to calculate an HPL that meets the required confidence level without being too conservative.

Some sources of phase/timing error need be corrected. The correction will result in a smaller bound for the error thus reducing the HPL while maintaining the same integrity level. This is necessary since the position solution cannot be used for RNP 0.3 if it has an HPL that exceeds the Horizontal Alert Limit (HAL) of 556 m. A major integrity related task that will provide a timing “correction” is the groundwave propagation.

5.2.1 The Loran Integrity Equation

The Integrity or HPL equation, Equation (1.2), characterizes phase errors into three forms. These are: 1) random, uncorrelated, and unbiased error, 2) completely correlated biases 3) uncorrelated biases. These bounds for these errors are denoted by the Greek letters a, b, g, respectively. The true errors for each type are denoted as e_a, e_b, e_g, respectively. If the phase error bounds are exceed by the actual errors, then there is a potential HMI.

$$HPL = k\sqrt{\sum_i K_i a_i^2} + \left|\sum_i K_i b_i\right| + \sum_i \left|K_i g_i\right| \qquad (1.2)$$

The integrity fault tree utilizes this division of errors. The fault tree then divides the sources of error by where the error enters the Loran signal - transmitter, propagation, and interference at the receiver. This division generally adheres to the divisions of the various LORIPP research tasks. Part of the work of each research task is to determine the error form of the hazard for the integrity equation.

5.2.2 Groundwave Propagation

The groundwave propagation task is one of the most significant efforts being undertaken by the LORIPP. It encompasses the hazards of temporal variations of ECD, SNR and phase as well as groundwave spatial variations. These are the first four hazards listed in Table 2.

The data collection and analysis effort will be briefly described. More details is provided by [9]. Data is being collected by a network of time of transmission (TOT) and time of arrival (TOA) monitors throughout the United States. TOT monitors are located at secondary Loran transmitters and TOA monitors are located at various user locations. These monitors allow for calculation of propagation times that are not adulterated by the control of the system area monitors (SAM) since the SAMs can shift the timing of the secondary Loran transmitters from the nominal transmission time. SAM control can thus mask the ASF.

The data collection gathers information on TOT/TOA, SNR, ECD, signal strength, Loran waveform, and other pertinent data. The ASF is calculated from the TOT/TOA data. A full year of ASF from data collected from all sites will be use to identify the best means of provide ASF and ASF bound to the user. One means to separate spatial and temporal components as seen in Equation (1.3). A least squares estimate of these factors using ASF calculated from the stations monitored at Sandy Hook is shown in Figure 6. These components may be used to generate bounds for the integrity equation.

$$ASF = C_{spatial} * d_{land} + C_{temporal} + ASF_{ave} + e \quad (1.3)$$

where: d_{land} is the distance traversed on land
$C_{spatial}$, $C_{temporal}$ are the spatial and temporal coefficients
ASF_{ave} is some average ASF provided to the user
e is the error

More accurate models for ASF spatial variations are being employed [10]. ASF measurements will be taken in the spring and summer to validate these results and determine a means of bounding the spatial variation.

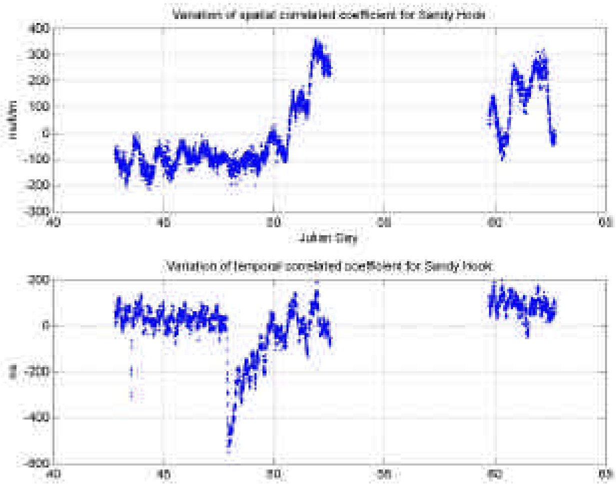

Figure 6. Spatial and Temporal Coefficient for ASF

SNR and ECD data are also collected and analyzed. Since the USCG collects ECD and SNR data from each SAM site, there is significant amount of such data available. The analysis of ECD collected has indicated that some anomalies in ECD variations versus expectations. One potential cause is early skywave.

5.2.3 Early Skywave

The other major integrity hazard task is early skywave. Early skywave is a term describing phenomena by which the skywave arrives much earlier, as early as 20 microseconds after the groundwave, than typical. Early arrival affects the Loran phase tracking point and can result in significant errors. Preliminary data from the groundwave data collection shows that early skywave may be present in CONUS and may require mitigation.

Figure 7 shows the ECD time history and ECD distribution for the Carolina Beach Loran station signal at Sandy Hook, New York. It shows large variation of ECD at night. It suspected that early skywave is the cause of the anomaly. Analysis of USCG SAM data will aid in determining the prevalence and likelihood of this unusual variation.

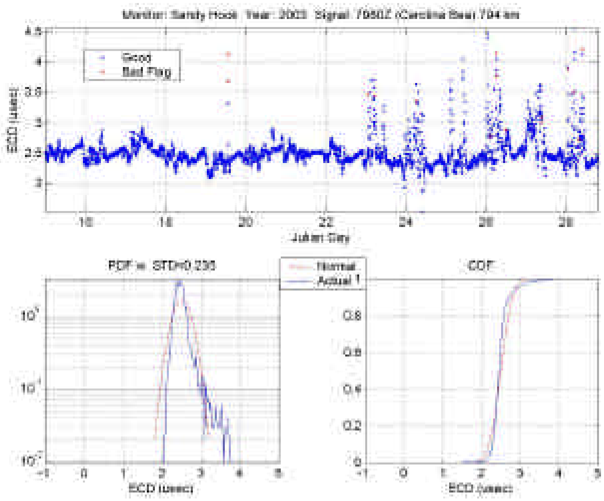

Figure 7. ECD Time History & Distribution

6 AVAILABILITY ANALYSIS PROGRESS

Availability of the Loran solution for RNP 0.3 relies on many factors. Lack of availability may be due to not having adequate signals for a position solution. Hence analysis of signal availability is required. Hazards for signal availability include transmitter hazards, weather related noise, and man made radio frequency interference (RFI). Loss of signal is a hazard for both availability and continuity.

Availability is also dependent on having a position solution with an HPL that is below the HAL. The HPL depends on the bounds developed in the integrity analysis. Finally, the system may lack availability if there is inadequate confidence on the tracked cycles.

6.1 Signal Loss Hazards

One means to lose availability is to lose some or all signals. Transmitter outages, weather related noise, and man made RFI are the major hazards that can result in signal loss.

6.1.1 Transmitter Availability

Transmitter availability is currently being determined using historical data. The data collected from Loran-C Operational Information System (LOIS) is being distilled to determine the outage statistics of the transmitter due to the different sources of outages. An estimate of transmitter availability for the eLoran system is calculated by eliminating those outages sources that have been addressed in the modernization.

6.1.2 Weather Related Noise

Weather related noise such as P-static and atmospheric noise could significantly decrease SNR resulting in an inability to track the signal.

Precipitation static (P-static) is noise caused by the rapid discharging of free charges that build up on sharp edges of the aircraft. Magnetic field (H-field) antennas have been shown to offers mitigation to P-static. They may potentially eliminate the problem. Flight tests are currently being conducted by Ohio University and the FAA Technical Center to quantify the ability of H-field antennas in mitigating P static. In the case of the Ohio University tests, ground data will be taken to eliminate other noise sources such as atmospheric noise.

Atmospheric noise is the noise produced by lightning. Due to the impulsive nature of lightning, the noise is characterized as low-frequency interference band limited to approximately 20 MHz. Since the conductive characteristics of the Earth [11] cause the ground to act as a waveguide, this low-frequency noise may propagate for thousands of kilometers.

Atmospheric noise is primarily an availability hazard. One source of data is CCIR 322-3 [12], which reported statistics on the level of background atmospheric noise. While CCIR can be used as a baseline, the models developed by CCIR are not valid for local storms. Since Loran must operate in locally adverse weather conditions, the CCIR models need to be extended. Hence, it is necessary to determine the atmospheric noise characteristic, particularly during storms, and the means of mitigating the noise.

The work currently has focused on gathering atmospheric noise data and examining mitigation. By modeling the amount of time atmospheric noise interferes with the Loran signal we can evaluate what percentage of the signal gets through. A database of signals gathered by lightning detection sensors across the country and over several years of allows us to determine the performance of Loran in the worst weather conditions and provides a time domain model for atmospheric noise. Figure 8 (a) shows an example of atmospheric noise data (blue) overlaid with appropriately scaled averaged Loran signal data (green). Figure 8 (b) shows in red the section of the Loran signal (green) which would be affected by a simple blanking scheme. Current work examines blanking and clipping as potential mitigations to atmospheric noise.

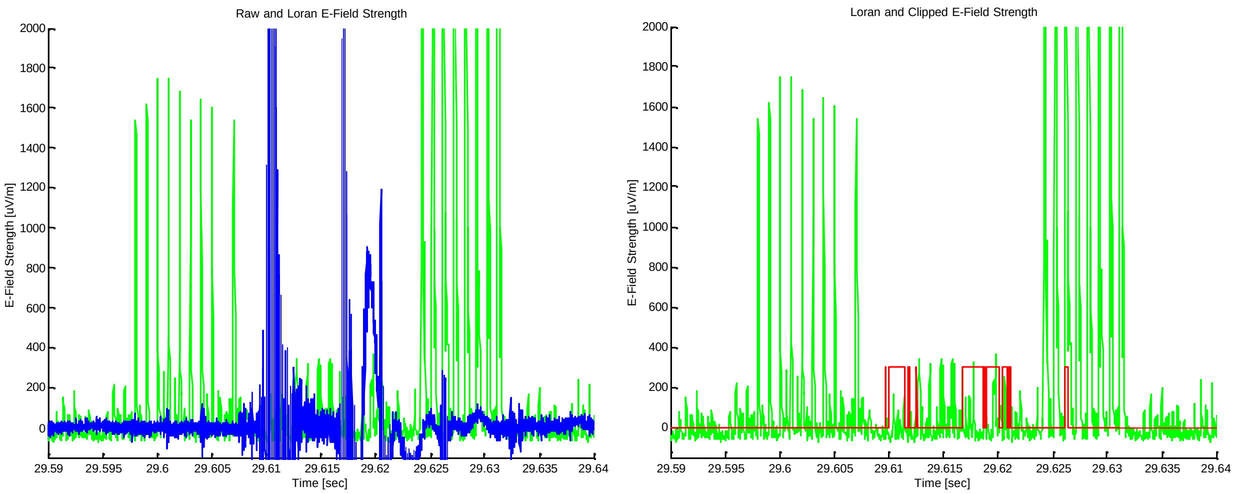

Figure 8. Averaged Loran Signal with Atmospheric Noise (a, Left) and Blanking Scheme (b, Right) Overlaid

6.1.3 Man Made RFI

Man made RFI is another noise source that can result in loss of signals. For some sources of interference, such as power line carriers (PLC), previous literature and research can be used to determine their effects [13]. Other sources such as jamming, re-radiation are currently also being studied.

6.2 Inadequate Confidence in Solution

Availability may also be compromised by poor geometry or signal quality. This results in either an inability to resolve the cycle with the integrity desired or a HPL that exceeds the HAL. These are cases where our confidence that the solution meets the RNP 0.3 approach requirements is not high enough. Since this is geometry dependent, part of the analysis will use the coverage model. The coverage model will be discussed later.

6.3 Loss of Signal and Loss of Availability/Continuity

The loss of one Loran signal does not necessarily result in a loss of the Loran RNP 0.3 solution. There still may be availability and continuity even with the loss of one signal. At least three signal loss cases need to be examined. These are loss of one, two, and all signals. Loss of three or more signals (without having all signals lost) is unlikely since it implies multiple transmitter outages or interference on some signals that do not exist on others.

In the one and two signal loss cases, the concern is about critical transmitters. A “critical transmitter” as follows: If a given transmitter is required for all position solution that meets RNP 0.3 requirements, then the transmitter is critical. In other words, there are no solutions that meet requirements that do not require the measurement from a critical transmitter. In essence, the loss of a critical transmitter results in loss of availability or continuity from inadequate confidence in the solution.

For the loss of all signal cases is due receiver failure or interference, such as atmospheric noise or P-static, that affect all signals.

7 CONTINUITY ANALYSIS PROGRESS

Continuity is the ability to use the navigation system for the entirety of an approach if a solution is initially available. Hence continuity can be lost for the same reasons that availability is lost – loss of cycle integrity, loss of position solution or too large a confidence bound (HPL). Since it is assumed that the system was available initially, the only mechanism by which continuity is lost due to an excessive HPL is signal loss. For continuity, the two major areas are then loss of signal or loss of cycle integrity. The continuity fault tree, created to provide a thorough accounting of all continuity hazards, uses this division of faults.

7.1 Loss of Signal

Just as in the case of availability, one means for the user to lose continuity is for the receiver to lose a Loran signal or signals. This can result from faults at the transmitter station or at the receiver. These hazards were discussed in the availability and will not be discussed here. This section will focus on points specific to continuity.

7.1.1 Loss of Signal at the Transmitter

LOIS data used for availability is also being used to provide transmitter outage statistics. The probability and duration of the different types of outages is used to calculate the probability continuity. It is important to separate the outages by type since some forms of outage are significantly longer than others. Also, the combination of new equipment to reduce equipment switch momentaries to three seconds and the ability to coast through three second outages significantly results in no loss of continuity during momentaries. Since momentaries account for a majority of Loran outages [14], this is significant since these outages no longer pose a continuity threat.

7.1.2 Loss of Signal at the Receiver

The receiver may not track a Loran signal even though it is transmitted and has adequate signal strength. These are the same issues being examined for availability.

7.2 Loss of Cycle Integrity

Lack of adequate cycle integrity on a signal is another reason why the signal from a normally available transmitter cannot be used. If the cycle integrity on at least three transmitters cannot be guaranteed in the middle of an approach, the approach must be terminated. There will be two primary ways of losing cycle integrity. The first way is with a cycle slip that cannot be corrected. Another possibility is if cycle validation fails during an approach. Note that if cycle validation fails at the beginning of an approach, the approach cannot be started and that is an availability issue.

7.3 Analysis

The continuity analysis is determining the probability that each hazard discussed causes a loss of continuity. Likely combinations of hazards are also considered. This result then forms the probability used in the fault tree. Previous research, such as that done by Volpe [14], examined continuity primarily from transmitter standpoint. The LORIPP initially used the transmitter statistics compiled by Volpe for [14, 15] and analyzed continuity in light of transmitter upgrades and the capability of AIV receivers. The results indicate that, with regards to only transmitter hazards, continuity failure of 10^{-4} per approach is achievable. In the next iteration, the LORIPP will refine the transmitter analysis as well as examine combination of faults where the combination, rather than one hazard, results in loss of continuity.

8 ACCURACY PROGRESS

The accuracy increase in RNP 0.3 will result primarily from the issuance of ASF tables. It is expected that meeting the other three requirements will result in meeting the accuracy requirement. However, measurements will be taken to validate performance. Additionally, the Loran Accuracy Performance Panel (LORAPP) has been formed to determine means to increase accuracy needs for harbor entrance approach (HEA) which has an accuracy requirement of roughly 10-20 meters.

9 COVERAGE

The system coverage is being analyzed using the model tool developed for the LORIPP. Figure 9 shows one coverage result with a given set of assumed values for performance. As the assessment of the hazards, transmitter performance and receiver performance continues, the values used will reflect those results.

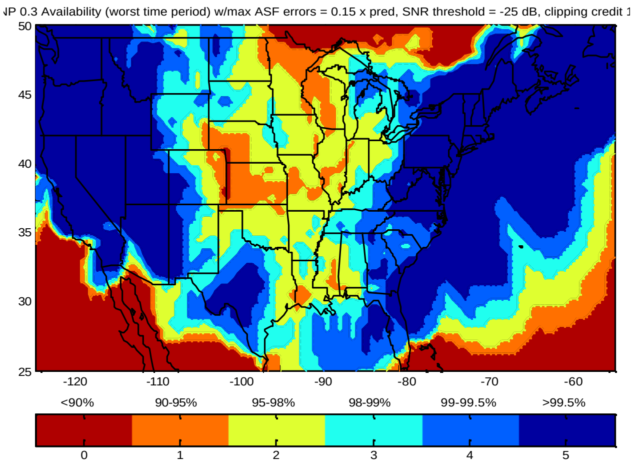

Figure 9. Coverage & Availability for RNP 0.3 (2000 and 250 pulses averaged for envelope and phase tracking, respectively)

Numerous analyses can be conducted using the model. One is a determination the number and location of critical stations. In addition, various scenarios can be tested in the model. The determination will be used in the availability and continuity analysis. A scenario is an examination of effects of different station outages. Another is an examination of the benefits of an additional mid continent station.

10 OTHER RESEARCH AREAS

The USDOT has requirement to provide GPS backup in other modes of transportation. One application is harbor entrance approach (HEA). This application requires greater accuracy than RNP 0.3. Hence, the LORAPP has been formed to examine these accuracy issues in parallel to the LORIPP. Another parallel group is investigating Loran for frequency and timing backup. These groups have many members in common and are coordinating work efforts to see that the needs of each application can be met without adverse effect on other applications.

11 CONCLUSIONS

Progress is being made by the LORIPP in its design and analysis of Loran for RNP 0.3 approaches. The hazards and tasks have been laid out and work is advancing in each individual area. Data collection is well under way and some analysis has been started. It is still a long road to completion and much work lies ahead. It is hoped that results for both Loran RNP 0.3 integrity and continuity should be forthcoming within the following year.

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DISCLAIMER

ENDNOTES

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[1] Availability and continuity are expressed in a range of values from minimum to maximum. The "target" requirements listed in the table are derived from the U.S. standard for GPS that the Loran program is trying to achieve. The "minimum" requirements represent the ICAO standards that must be met.

[2] The SAMs are fixed, unstaffed sites that continuously measure the characteristics of the Loran-C signal as received, detect any anomalies or out-of-tolerance conditions, and relay this information back to the control station so that any necessary corrective action can be taken. 99.9+% of the time the SAM "sees" no abnormalities or out–of tolerance conditions, but provides measurements to allow (within tolerance) corrections to secondary transmission time and clock drift. Of the remaining < 0.1% of the time, the control station could take corrective action without the SAM another 99.9% of the time