Loran Integrity Analysis for Required Navigation Performance 0.3

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1 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 the ability of Loran 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. Demonstrating integrity is essential. Furthermore, the parameters set by the integrity analysis affect availability and continuity. This paper outlines the integrity analysis and its results, presenting the means by which it was demonstrated that Loran could meet the integrity requirements.

The integrity design is the first step to the overall requirements analysis since it drives the performance levels and bounds that Loran must meet. The hazards and how they could affect integrity must be articulated. The integrity fault diagram provides this illustration. It also provides for the calculation of the overall integrity by tallying the integrity allocations for each hazard. Various mitigations such as bounding errors or monitoring provide the means for meeting the individual allocations. These mitigations factor into signal availability, receiver cycle integrity algorithms and position bound calculations. These, in turn, determine whether the system is available for use.

2 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 United States 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 United States 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 [2]. 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 of integrity of RNP 0.3 conducted for the Loran evaluation report. Meeting the integrity requirement was seen as the most significant challenge for RNP 0.3. Hence the subgroup of the evaluation team tasked to assess Loran for RNP 0.3 was designated the Loran Integrity Performance Panel (LORIPP).

3 LORAN EVALUATION BACKGROUND

The evaluation assessed the ability to adapt the current Loran system to meet the needs of various modes for providing some form of redundancy to GPS. Hence, the basic Loran system assessed is still 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 [3].

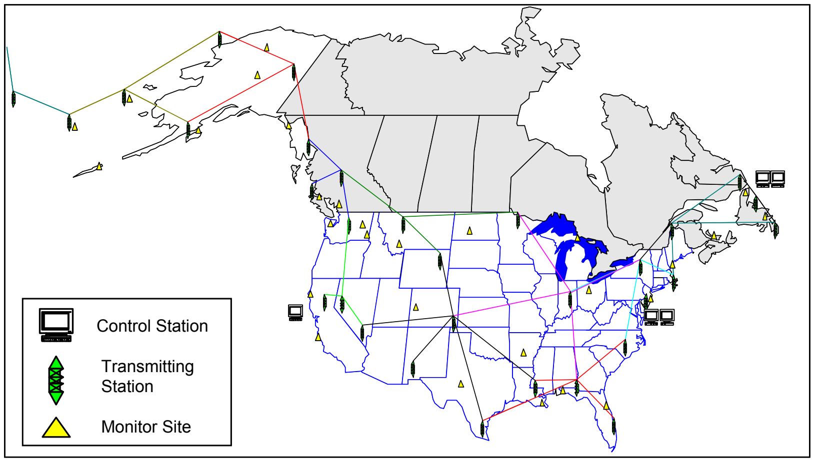

Figure 1. North American Loran-C System

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 [4]. Additionally, it also means changes in areas such as policy and transmitted signal. These changes, discussed in Section 3.2, are necessary to help meet the requirements for RNP. These requirements are quantified in Table 1.

Performance Requirement	RNP Value
Accuracy (target)	307 meters
Monitor/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% over 150 seconds
Continuity (target)	99.99%

Table 1. RNP 0.3 Requirements

The critical issue for RNP 0.3 is demonstrating integrity. 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). All other requirements must be achieved with integrity already met. For example, the integrity analysis provides the confidence bounds on phase or range errors. These confidence bounds are used to generate the horizontal protection level (HPL), an overall confidence bound on horizontal position error (HPE). The system is only available for use if the HPL is less than the alert limit of 556 m. Hence the challenge is have a system that meets integrity requirement while still achieving reasonable availability and continuity.

As such, an iterative design process was utilized to determine the modifications to the system such that integrity is met with reasonable availability and continuity. Meeting integrity requires a comprehensive account of all the hazards that can affect the availability and fidelity of the Loran signal. Much of the design of modernized Loran is made to manage these hazards.

3.1 Tracking the Loran Signal and Hazards

Understanding how a Loran signal is measured is necessary to understanding the Loran hazards. Loran measurements require that the Loran pulse and timing can be tracked. A nominal pulse is shown in Figure 2. A specific tracking point is selected with the point being a balance between signal power and mitigating skywave interference[1]. Typically the tracking point is set around 30 microseconds (or the sixth zero crossing) after the start of the pulse. Noise makes it difficult to identify the start of the pulse (and hence the 30 μsec point) and a two-step process is used to accomplish the tracking. First, the envelope of the signal is used for a "coarse" identification. The goal is identify the correct cycle of the Loran signal to track. Cycle identification, usually using envelope slope, is generally not difficult provided that the signal is not too corrupted by noise. After the desired cycle has been identified, the location of the desired tracking point is determined by examining the zero crossing. This then yields the timing or phase estimate used to determine range.

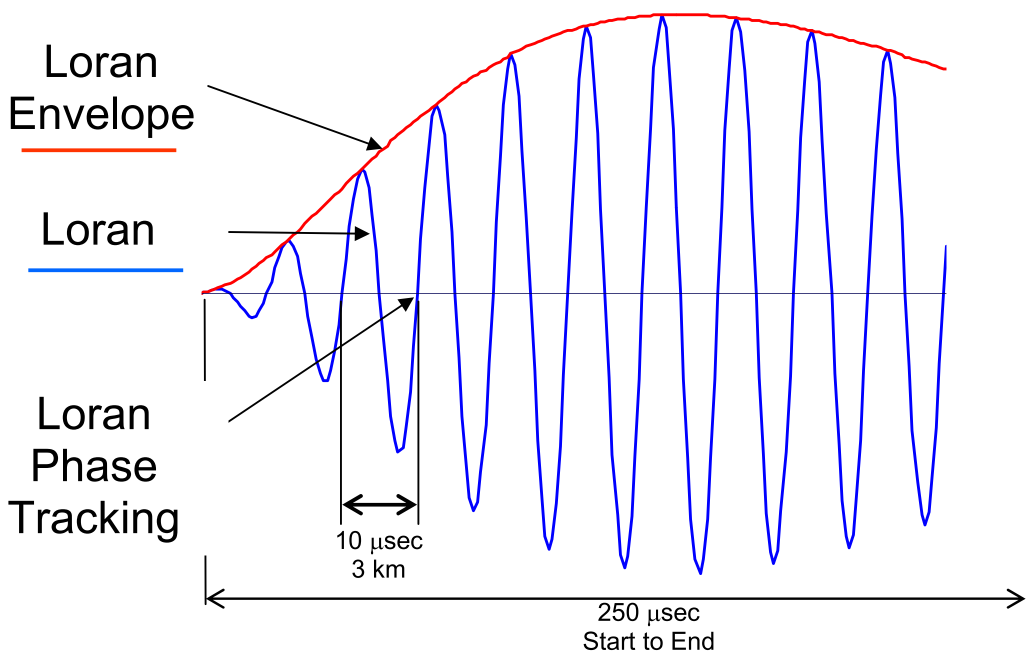

Figure 2. Normal Loran Pulse

There are numerous hazards that can affect the precision of the ranging measurement as well as the overall availability of the signal. Some hazards affect the ability to measure the envelope, resulting in incorrect cycle determination (with an accompanying large range error). For example, the envelope may shift relative to the underlying carrier (and hence the tracking point). This shift is termed the envelope to cycle

[1] Skywave interference comes from ionospheric reflections of the Loran signal. It is akin to GPS multipath.

difference (ECD). There is always some ECD but much of it is predictable. If the ECD is not well known, this could lead to cycle selection error. Some hazards, such as noise or propagation effects, 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.

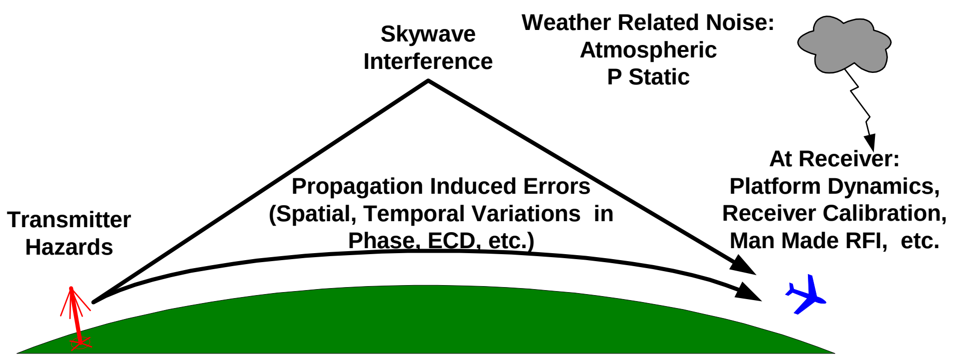

Figure 3. Loran Hazards

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

Significant Loran hazards are listed in Table 2 and pictorially depicted in Figure 3. The mitigation of these hazards will be detailed in this paper.

3.2 Modernized Loran

The Modernized Loran system designed by the evaluation team is based on mitigating all significant hazards in order to meet the requirements of RNP 0.3 as well as Harbor Entrance Approach (HEA) and Stratum 1 frequency. It is based on the design and infrastructure of the current Loran system. The changes from the current system are categorized into four areas: radionavigation policy, operational doctrine, transmitter, monitoring and control equipment and user equipment. While the changes are numerous, most of the changes are achievable with existing equipment and planned upgrades. Table 3 lists some of the major changes made for RNP. The rational for some of these changes will be discussed in the paper.

Radionavigation Policy	• Canadian stations, if operating within the system, will be equipped and operated in the same fashion as the U.S. stations • Airport calibrations for ASF and ECD values and bounds on the associated errors will be used for RNP 0.3 approaches.
Operational Doctrine	• Long-term synchronization to UTC will be maintained using two methods with at least one method being independent of GPS • Taking a station off air will indicate signal abnormality (vice blink) • Signal transmission will use time of transmission (TOT) control • Maintenance and scheduled off airs will be conducted to maximize signal availability
Transmitting, Monitoring, & Controlling Equipment	• All transmitters will be upgraded to the new solid state transmitter (SSX) standards • New time and frequency equipment (TFE) will be installed • New cesium clocks will be installed. • Momentary off-airs will be reduced to 3 seconds or less. • A 9th pulse in each GRI will be broadcast by all stations. It will be modulated. Any modulation will have minimal affect on navigation • A monitoring network will be established for maritime differential corrections and far-field propagation (early skywave, etc.) effects.
User Equipment	• Equipment must verify cycle identification. • Equipment must be able to "coast" through a 3-second outage. • Aviation equipment will use H-field or equivalent antennas. • Equipment must achieve results comparable to at least 12 dB processing gain at the 99th percentile level of atmospheric noise. • Equipment will operate in the all-in-view mode (cross-chain, master-independent) reading and applying 9th pulse information • Equipment must be able to use provided ASF and ECD information • Equipment must process cross-rate interference with performance comparable to that achieved by the LORIPP

Table 3. Assumptions/Modifications for Modernized Loran

3.3 Assessment of Integrity (Outline of Paper)

This paper follows the general process used for conducting the integrity assessment. Figure 4 presents an overview of this process. First, the integrity hazards are identified. The integrity fault diagram is formulated to enumerate the faults that can occur due to these hazards. It is used to allocate integrity failure probabilities. Section 4 presents an overview of the fault diagram and the allocations used for the report. The hazards are analyzed to determine the mitigation necessary to meet the allocations. This analysis is discussed in Section 5. For many hazards, an integrity bound on the error is produced. These bounds are used to determine cycle resolution confidence and HPL. These two integrity algorithms are discussed in Section 6, are created in the process of analyzing hazards. However, for the algorithms to produce meaningful results requires having the meaningful bounds produced by the hazard analysis. These integrity algorithms then are used to help determine system availability. If system availability is acceptable, then the assessment is generally complete. If availability is unacceptable or the integrity allocations cannot be met, modifications to the system, integrity allocation or both may be required. The process is not a static one and analysis of hazards may result in discovery of additional hazards or elimination of a hazard. The fault diagram is modified and the assessment is conducted reflecting the change.

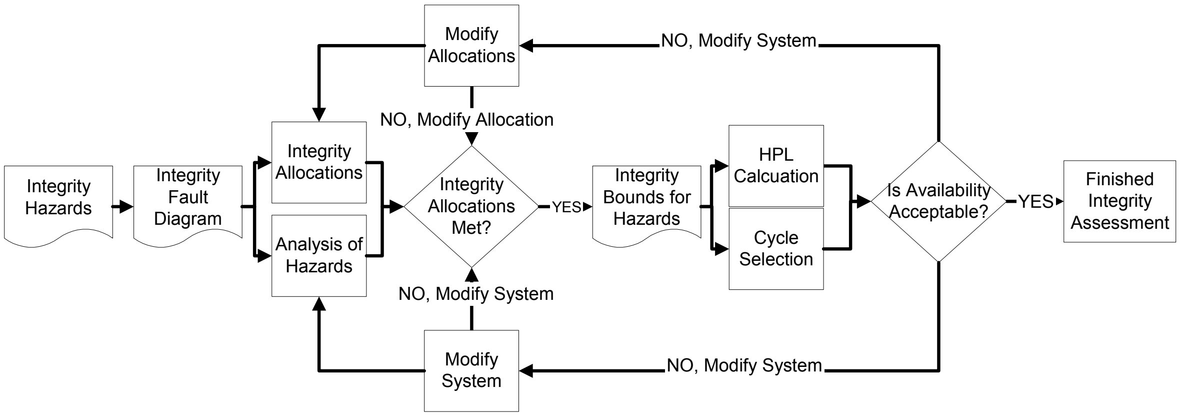

Figure 4. Basic Flowchart for Integrity Assessment

4 INTEGRITY FAULT DIAGRAM AND ALLOCATION

The integrity fault diagram is the system engineering of the integrity analysis. The diagram uses the basic methodology for providing the integrity to the user (cycle and phase integrity) and systematically lays out the effect of all integrity threats of concern relative to the design. It helps to tabulate the overall integrity based given these threats. Since determining Loran position requires cycle determination and phase determination for the calculation of range, a natural division of the integrity fault tree is to separate the analysis into a cycle and a horizontal protection level (HPL) branch. The HPL is an integrity bound on horizontal position error calculated using on bounds for each phase error or hazard. The high level fault diagram and the cycle integrity branch are shown in Figure 5 and Figure 6, respectively.

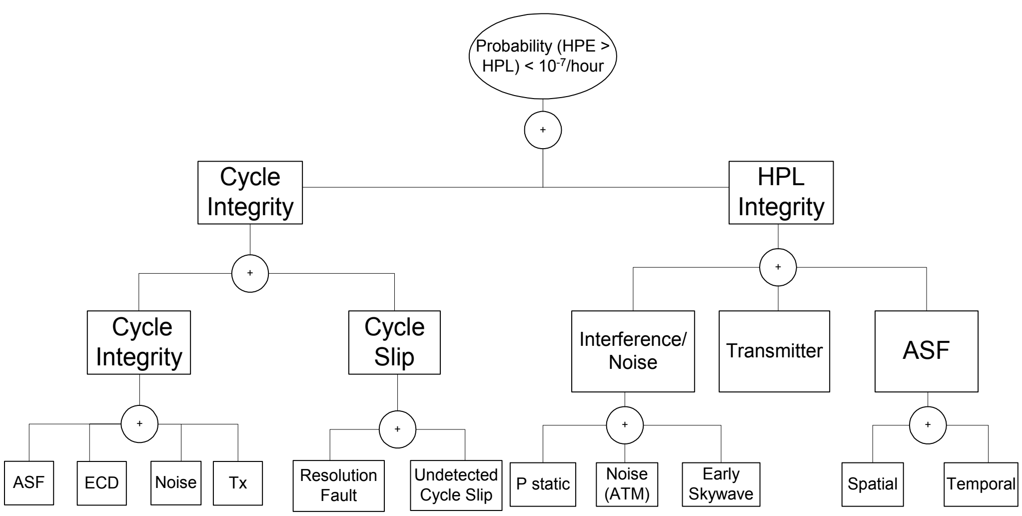

Figure 5. High Level Integrity Fault Diagram

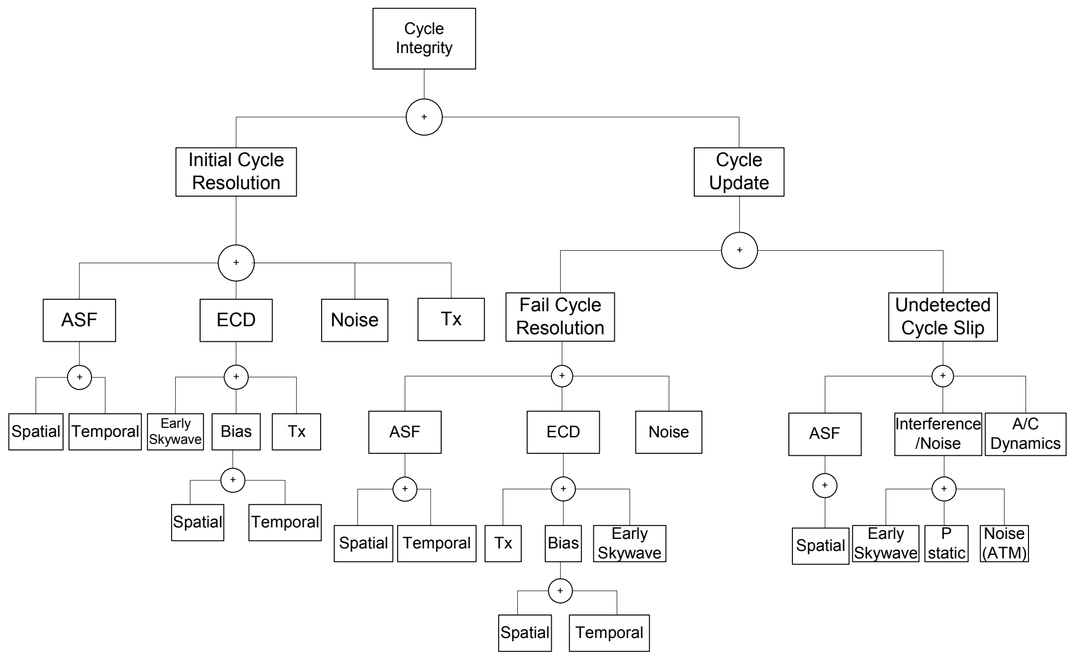

Figure 6. Cycle Integrity Branch of Integrity Fault Diagram

Each threat is given an allocation partly based on analysis of the ability to provide integrity covering each threat. The allocations, which represent the probability that the hazard will cause an integrity failure, are shown in Table 3. These allocations are based on assessments of the hazards. The overall failure probability is the allocation weighted by the probability of the fault occurring. These failure probabilities are tallied to determine the overall failure allocations for cycle resolution and HPL integrity, which are approximately $7x10^{-8}$ and $3x10^{-8}$, respectively. The result is an overall probability of integrity failure of less than 10^{-7} per hour. This overall level is met provided the integrity level specified by each allocation is achieved. The analysis and mitigation of each hazard provides this demonstration.

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	$1.04x10^{-5}$	$1.0x10^{-7}$	$6.85x10^{-4}$
A/C Dynamics	0	N/A	1.0
P Static	0	$1.0x10^{-8}$	1.0
Tx Noise	$1.0x10^{-10}$	$1.0x10^{-8}$	1.0
Tx ECD	$1.0x10^{-10}$	N/A	1.0
Atm Noise	$2.0x10^{-8}$	$1.0x10^{-8}$	1.0
Interference	0	$1.0x10^{-8}$	0.05

Table 4. Integrity Allocations

5 HAZARDS AND MITIGATION

The hazards briefly mentioned may affect integrity, availability, continuity, accuracy and/or coverage. Transmitter outages, for example, have little effect on integrity but it can reduce availability and continuity. This section will detail hazards with significant effect on integrity and how these hazards were treated. The hazards examined are divided into three categories: hazards at the transmitter, due to propagation, and at the receiver.

5.1 Transmitter Hazards

Transmitter hazards can be divided into three areas: timing and frequency equipment (TFE), transmitter and antenna coupler, and transmitter monitoring and control equipment. The transmitting station signal generation and monitoring equipment is designed to ensure that these tolerances are achieved with a probability of one part in one hundred million (10^{-8}). Hence, the signal generation and monitoring equipment, not the user receiver, is required to detect an error in the transmitted signal due to the transmitter hazards.

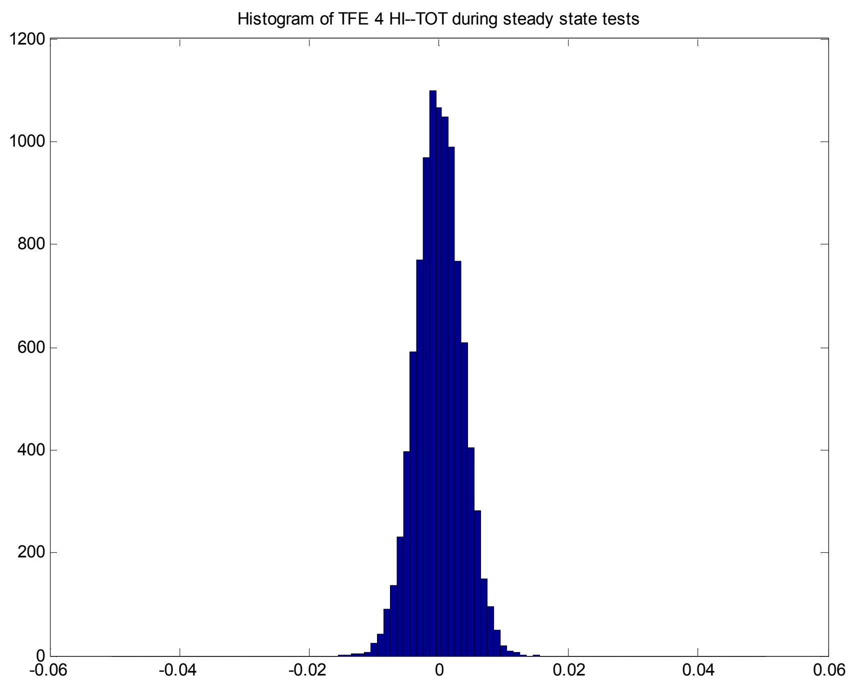

Figure 7. Histogram of TFE timing (microseconds)

TFE is responsible for the timing and frequency stability of the transmitted signal. An ensemble clock based on three HP 5071A cesium clocks is used to provide short term stability in case of GPS outage. For the long term average, synchronization to a common time standard such as UTC will be used. Acceptance testing of TFE has shown that the transmitter jitter from timing can be maintained to less than 100 ns as seen in Figure 7. A one standard deviation value of 20 ns or 6 m currently used for transmitter noise.

Transmitter and antenna coupler equipment are currently being upgraded. This will significantly reduce transmitted phase and signal shape imperfections. Established tolerances for these errors are used in the assessment as part of the transmitter noise and ECD.

Transmitter monitoring and control equipment, based on existing equipment and planned upgrades, will provide assurance that the transmitted signal is within tolerance. The new equipment being installed will significantly reduce transmitted phase and signal shape imperfections. Out of tolerance condition will be indicated by going off air rather than blinking the first two pulses to ensure that a 10 second time to alarm is met.

5.2 Propagation Hazards

While the signal out of the transmitter may be within tolerances, there are many propagation effects that can cause errors for the user. In fact, these propagation effects represent the major portion of the Loran error budget. Propagation effects not only the phase measurement but it also affects cycle identification as well as signal to noise ratio (SNR). The following subsections will detail some of these hazards and their treatment.

5.2.1 Spatial Variation of the Phase

The propagation of the Loran signal over terrain results in delays in both envelope and phase. A standard method for specifying the phase delay has been established [5]. The primary factor (PF) is the propagation time for the signal to traverse the atmosphere. The secondary factor (SF) is the increment of time for traversing an all seawater path. Third is additional secondary factor (ASF), which represents the incremental propagation delay of the Loran signal due to traversing heterogeneous earth vice an all seawater path. PF and SF are solely dependent on distance and can be calculated. ASF can vary with both time as well as location. The location variation may be significant if there is significant terrain change.

Analysis indicated ASF variations often are too great to yield a bound that will be acceptable for RNP 0.3. Hence, an ASF survey must be performed for each airport approach. The survey provides a reference value of ASF. The receiver will use the reference value, though they will still be residual ASF variations. These variations are significantly smaller and result in acceptable availability for RNP 0.3. One variation is the spatial of variation from being located some distance away from the calibration location. To model this variation, an extensive computation effort using the best available propagation modeling technique was utilized [6]. The results show that, depending on local terrain, ASF could rapidly vary over an approach – particularly on coastal regions near mountains. The large variations have been confirmed at several locations through data collection. The analyses determined that this component could be brought below 100 meters, as an absolute range domain bound, with a single calibration point for a very large percentage of airports. For the locations where a single calibration point is insufficient, the addition of a few additional points was found to be sufficient to meeting the 100 m bound. This range bound is used for cycle resolution. In addition, a position domain (PD) bound of 120 m was established for calculation of the HPL. The use of PD bound leverages known correlations in the spatial variation, resulting in an overall lower contribution to the HPL while meeting the integrity requirement. Similarly, the addition of a few more calibration points may be used for locations where one is insufficient. Details of the analysis are presented in [7].

5.2.2 Temporal Variation of Phase

Temporal variation of ASF is the other component of ASF variation from the reference value. This is the variation in propagation delay due to changing terrain conditions that occurs throughout the year. Two sources of data were used to assess this variation. One was archived data from the United States Coast Guard's (USCG) network of monitor and transmitting station receivers. The other was time of transmission and arrival measurements from a specially deployed data collection network located at transmitter and monitor sites. Both data sets were used for the determination of the ASF temporal variations and a bound model. The temporal variations, seen in Figure 8, vary in size from region to region. They are largest in the northeast United States and Great Lakes.

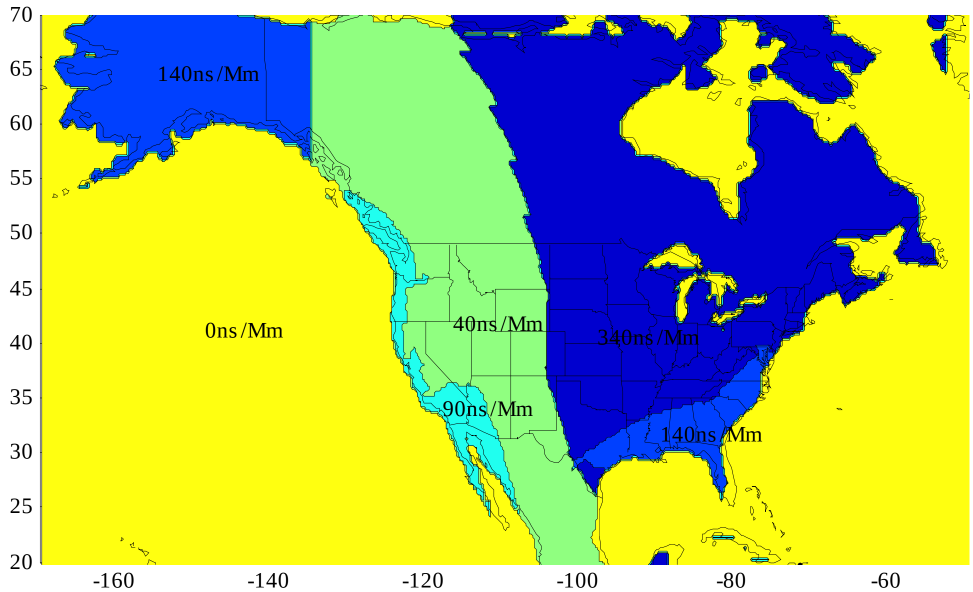

Figure 8. Temporal Variation Regions for the United States

The model for temporal variations is seen in Equation 1. There are three time varying components to this model: a component that varies with land distance (*A(t)*), a component that accounts for common receiver clock error (*c(t)*) and a residual error component ($\varepsilon_i(t)$) that is dependent on the transmitting station *i*. The model essentially divides the error into a component correlated between all measurements (*A(t)*) and uncorrelated component ($\varepsilon_i(t)$). The common term is not significant since it is common to all measurements. Absolute bounds for *A(t)* and $\varepsilon_i(t)$ were established for the Northeast US. This value was scaled based on the variations seen in Figure 8. Again, refer to [7] for more details.

$$\text{Equation 1: } \Delta ASF_i(t) = A(t) * d_{i,land} + c(t) + \varepsilon_i(t)$$

5.2.3 Spatial and Temporal Variation of ECD

The propagation delay of the envelope differs from that of the phase. As a result, there are variations in ECD. This variation has both spatial and temporal components. Knowledge of the expected ECD at any location is required for the cycle selection portion of the integrity calculation. As with phase, calibration values for ECD will be required and used. Spatial variation of ECD was examined using the same propagation program used for spatial phase. The result is that spatial ECD variation should be less than 0.2 μs (60 m).

Since proper ECD knowledge is essential to tracking the correct cycle, this topic has been studied by the USCG for quite some time. Studies from the early 1970s indicated that temporal ECD variations are slightly smaller than, but highly correlated with, temporal phase (ASF) variations. The LORIPP utilized the same two data sources from the temporal phase analysis to determine a model for ECD error. This model, like the temporal phase model, also varies regionally.

Temporal and spatial variations in SNR are predominately hazards that affect availability and continuity and will not be discussed.

5.3 Receiver Hazards

The category of receiver hazards is meant to cover all hazards that “enter” at the receiver. Some of these hazards are caused by the receiver or the platform on which the receiver operates. However, others, such as interference and atmospheric noise, originate for other sources.

5.3.1 Atmospheric Noise

Atmospheric noise is the predominant noise source in the low frequency spectrum. The noise is generated by lightning, i.e. electrical discharges between clouds and/or between the clouds and the ground. This noise is often present to some degree since the conductive characteristics of the Earth [8] cause the ground to act as a waveguide, allowing this low-frequency noise to propagate for thousands of kilometers. The LORIPP utilized the generally accepted International Radio Consultative Committee (CCIR) model for atmospheric noise. In addition, data has been taken from other sources such as the National Lightning Detection Network (NLDN). Examination of data suggests that the CCIR values may be high for worst case levels of noise. However, the CCIR is used until more empirical data can be collected.

The NLDN and other time domain lightning data were used to examine techniques to mitigate the effects of atmospheric noise. Mitigation depends greatly on the impulsivity of the noise which is quantified by figure denoted V_d [9, 10]. On the basis of analysis of non linear processing such as clipping, it was determined that a 12 dB clipping credit represents a conservative estimate for high levels of noise (higher than 80 percentile). These situations typically have V_d around 12. Figure 9 shows clipping credit as a function V_d.

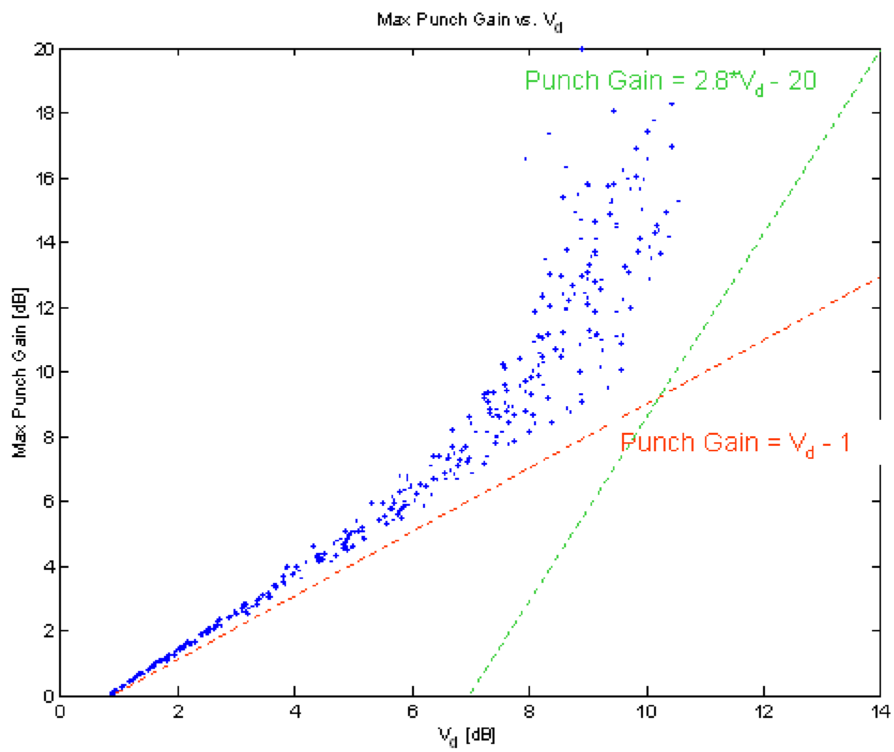

Figure 9. Processing Gain vs. V_d (dB)

5.3.2 Precipitation Static

Precipitation static (p-static) is noise caused by the discharge of charged particles that can build up on the skin of an aircraft as it passes through areas of adverse weather. The phenomenon can be greatly reduced through the installation of static dischargers and with good airframe maintenance. Tests at Ohio University and the FAA technical center demonstrate that H-field antennas significantly decrease the effect of p static. The performance model uses a 40 dB above 1 microvolt per meter noise (over a 30 kHz noise equivalent bandwidth) component to emulate the effect because tests show this is a very conservative bound.

5.3.3 Skywaves

The Loran signal generally propagates along the ground and this is typically the signal used by the receiver. Skywave is a copy of that Loran signal that has propagated by reflecting off the ionosphere. This signal is delayed from its groundwave equivalent and could interfere with that signal. The interference from most skywaves can be mitigated or eliminated through signal design and processing. However, early skywave, which have delays of less than 30 microseconds, can have deleterious effects on signal timing and ECD.

Examination of prior work and analysis leads us to believe that the smallest (and, hence, most dangerous) skywave delays occur as a result of solar proton events that cause excess ionization in the auroral and polar D-region ionosphere. In CONUS, these early skywaves are rare with probability of occurrence around 10^{-4}. Thus they still pose an integrity threat. Since they are not easily detected by a receiver, system wide monitoring of early skywave was deemed necessary. The user warning would be provided using a communication channel on an additional pulse - ninth pulse communications [11, 12]. Other mitigation techniques are possible but they involve more significant changes to the signal.

5.3.4 Cross-Rate Interference (CRI)

A major source of interference on Loran is other Loran signals. Each station transmits pulses at the same frequency. Transmissions from different stations within a chain (a grouping of stations) are time multiplexed such that they do not interfere with each other within the coverage area. However stations operating in different chains transmit signals that will periodically interfere with each other. This is known as cross rate interference. Digital signal processing methods were developed in the 1990s to effectively eliminate the effects of this interference [13]. These include cross rate blanking and cross rate canceling. Cross rate blanking, which eliminates all signals with cross rate interference, greatly reduces the amount of usable signals. Cross rate cancellation or equivalent technique will be used by receivers so that a reasonable number of signals are available. Cross rate blanking will be employed for the ninth pulse modulation since the modulation results in a pulse timing that cannot be determined *a priori*.

5.3.5 Man-Made Radio Frequency Interference (RFI) & Structures

Both these hazards can result in additional noise and interference on the Loran signal. For the most part, continuous wave interference (CWI) is too insignificant to model, provided that the receiver properly address the potential hazard. Radiation from power lines and re-radiation can be detected during approach surveys. Analysis of malicious interference concluded that this would be difficult to do without detection.

5.3.6 Receiver Calibration

An improperly calibrated receiver produces hazards for phase and ECD. The largest part of the phase offsets is common from one signal to another and only affects the timing estimate. It does not affect the navigation or frequency estimates since this is should be factored out in the solution. Second and third order effects on the phase result because signals being received over different propagation paths have different degrees of distortion and the receiver responds to each differently. These effects are incorporated in the analysis model.

The ECD estimates are inherently more sensitive measurements because the effective SNR is about 50 times less than for the phase. Since common errors represent the largest receiver calibration error component, two methods were examined to eliminate these errors. An over-determined solution (for cycle) and "calibration" of the receiver ECD using the strongest signal can be used to eliminate induced errors that are common on all signals. After employing at least one of these solutions, residual ECD receiver calibration error is assumed to be roughly 0.2 μs.

5.4 Meeting Integrity Allocations

For each hazard, mitigation was provided if deemed necessary. Some hazards resulted in measurement errors. The effects of these measurement errors were bounded. Other hazards were mitigated through processing and the effects of the mitigation incorporated into the error model. Other hazards were monitored and flagged when they posed a significant threat. The bounds were set such that the integrity allocation should be met. The cycle and phase error bounds for the significant hazards are shown in Table 5. 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). Mitigation of various interference sources results in some increase in noise, lowering the SNR. This SNR "debit" as well as receiver processing credit is shown in Table 6.

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		< 180 m	N/A
-Tx ECD		~ 30 m	N/A
-Residual Rx Calibration		~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 5. Bounds for Integrity

Process	Type	SNR
Atmospheric Noise: Non-linear Processing	Credit	12 dB (for worst case)*
P Static	Penalty	40 dB mV/m
CRI Blanking 9th Pulse	Penalty	0.5 dB
CRI Canceling	Penalty	1.5 dB
Early Skywave	Penalty	Loss of Signal
Aircraft Dynamics	Penalty	Minimal affect on cycle slip

Table 6. SNR Credit/Debit for Hazard Mitigation

6 INTEGRITY ALGORITHM

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 bounds, confidences and other mitigations determined in the assessment of each hazards feed into the determination of cycle integrity and HPL.

Applying the bounds determined to meet the integrity allocation is the final step in the integrity analysis. This is important since, while the bounds selected may meet the integrity allocation, it may result in a low availability due to low probability of passing cycle integrity or a high HPL. If that exists, one must either determine a means to achieve a lower bound that still meets the integrity allocation or modifying the allocation.

6.1 Cycle Resolution

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 over-determined 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. This sets the bias and variation on each measurement. All measurements are used together to form an over-determined solution. This solution combines the statistics from each measurements and forms noncentral chi squared statistic. This distribution is used to determine whether cycle resolution has the required integrity. Details on this technique are given in [14]. If the cycle is resolved with adequate integrity, then HPL can be calculated.

6.2 HPL

The HPL is calculated using the Loran Integrity equation shown in Equation 2. 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*. These are errors such as noise. 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 5.2.1. As mention previously, this is used for spatial ASF variations since it can help leverage inherent spatial correlations.

Equation 2: $HPL = \kappa\sqrt{\sum_i K_i \alpha_i^2} + \left|\sum_i K_i \beta_i\right| + \sum_i \left|K_i \gamma_i\right| + PB$

7 CONCLUSIONS

The integrity analysis represents new territory for Loran. The analysis conducted represents the most detailed examination of Loran integrity for aviation. The integrity analysis needs to be conducted in concert with studies of availability and continuity. The availability and continuity assessment is detailed in [15]. For a system to have value, it must have good availability while maintaining integrity. The result of the analysis shows that Loran can achieve a useful level of performance while still meeting integrity requirements in CONUS. While some modifications to the system are necessary to achieve this, the modifications are reasonable.

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