Loran for RNP 0.3 Approach: The Preliminary Conclusions of Loran Integrity Performance Panel (LORIPP)

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ABSTRACT

Loran, is an attractive candidate to provide backup services for GPS because of its complementary RNAV, stratum 1 frequency stability, precise timing, and data channel capabilities. However, for Loran to be accepted as a backup navigation system for aviation, it must meet the accuracy, availability, integrity, and continuity 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 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 accuracy, availability, continuity and integrity of the enhanced Loran system.

The paper shows the preliminary conclusions of the LORIPP study on Loran RNP 0.3. It also will discuss the current results from each area of investigation. Ground and flight tests have been conducted to collect data. Analysis of data for ground propagation, atmospheric noise, precipitation static and platform noise is currently being conducted and preliminary results and conclusions can be drawn. Ongoing analysis of the transmitter is conducted to determine transmitter availability and signal integrity. Other work involves an examination of skywave, continuous wave and cross rate interference. Finally, receiver algorithms are being completed that will incorporate interference from atmospheric noise.

1. INTRODUCTION

The Global Positioning System (GPS) has become integral to many applications critical to the nation. The national infrastructure for applications such navigation (aviation, terrestrial and maritime) and timing has becoming increasingly dependent on GPS. Studies such as the Volpe National Transportation Safety Center (VNTSC) Report on GPS Vulnerability illustrates the need for redundancy, particularly in safety critical applications [1]. As such, the agencies responsible for different components of national infrastructure are determining effective means of providing the desired redundancy. For the Federal Aviation Administration (FAA), this means developing a back up infrastructure capable of sustaining the capacity and efficiency to continue commercial flight operations with dispatch reliability. One system being considered to provide this capability is Loran.

Loran is well suited for the role of back up to GPS. It is a terrestrial low frequency navigation system that utilizes whose signal pulses are high powered and not line of sight dependent. Hence it is not susceptible to the same vulnerabilities as GPS while being able to provide similar capabilities in both navigation and timing/frequency services. One drawback for aviation is that Loran has never been certified for approaches and prior attempts in the late 1980s to certify Loran for approach failed due to several deficiencies in the system. New technology and upgrades to the system has mitigated or eliminated all of the noted deficiencies. The FAA has chartered the Loran Integrity Performance Panel (LORIPP) to determine if Loran can meet the aviation requirements for Non Precision Approach (NPA) in light of new technology and reasonable system changes. The preferred NPA to Required Navigation Performance 0.3 (RNP 0.3)

Currently, the LORIPP is more than half way through its investigation of Loran for aviation, which will be presented to the FAA in March 2004. This paper will discuss the findings to date.

The background section covers the operations of Loran for aviation and the hazards to meeting RNP 0.3 requirements. The reader should read other papers such as [2,3] for more background information on Loran and the various components that will go into a Loran for RNP 0.3.

2. BACKGROUND

Simply stated, the LORIPP is determining whether Loran can meet the integrity, accuracy, availability and continuity requirements for RNP 0.3 (See Table 1). Integrity is the requirement on the fidelity of the system. In Loran, integrity is provided by a bound horizontal position error (HPE) known as the horizontal protection level (HPL). The requirement is for the probability of hazardously misleading information (HMI) to be 10^{-7}/hour or less. An HMI event is one where the HPL exceeds the HPE. Availability is the probability that the user has a solution that can be used for the desired approach. For a position solution to be available, the HPL has to be below the horizontal alert limit (HAL) of 556 meters. Continuity is the probability that a system can be used to complete an approach if it is available at the start of the approach. Accuracy, as described in the table, represents the 95-percentile level of horizontal position error (HPE). In order to determine the ability of Loran to meet these requirements, one has to understand the hazards to these requirements and their effects.

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. RNP 0.3 Requirements

The first two subsections provides background on the assumed Loran system, user equipment and receiver operations for RNP 0.3. This discussion leads to the last two subsections, which overview the hazards to meeting the RNP 0.3 requirements and how the hazards affect each requirement.

2.1 The Loran System and User Equipment for RNP 0.3

The operation of the Loran for RNP 0.3 involves some changes to the commonly known Loran equipment and operations of today.

Loran transmitters will be upgraded. Under the Loran Recapitalization Program (LRP) and other US Coast Guard initiatives, Loran transmitters are being upgraded to Solid State transmitters (SSX) with new timing and frequency equipment (TFE), switch cabinets, universal power supplies, and lightning resistant equipment [4]. The TFE suite will allow each station to transmit independently by being synchronized to and with respect to universal time coordinated (UTC). This is known as time of transmission (TOT) or time of emission (TOE) control and is essential for reducing uncertainty in the Loran measurement. Other equipment reduces outage times due to loss power, lightning strikes or switches to alternate equipment. Switch times are reduced to three seconds from 20 seconds (average).

User equipment will include all in view receivers, digital signal processing and magnetic loop (H-field) antenna. These technologies will allow for more signals to be available and used for position solutions thus increasing availability. A database of propagation delays known as additional secondary factor (ASF) will be utilized.

2.2 Loran Receiver Operation & Introduction to Hazards

An understanding of Loran RNP 0.3 receiver operation will describe some of the receiver requirements and introduce many hazards to Loran. Providing guidance for RNP 0.3 means that the receiver has to provide position solutions in the terminal area or roughly 10-20 miles of an airport. To generate a position solution, the Loran receiver needs to acquire and process an adequate number of Loran signals. These signals must be strong enough (relative to noise and interference) such that an accurate time of arrival (TOA) can be determined. Anything that affects signal availability is an availability and/or continuity hazard.

Determining TOA is a two-part process. Figure 1 shows a Loran pulse and its envelope. Typically timing is determined using a positive zero crossing of the signal. First the receiver uses the envelope slope to determine a coarse estimate of the tracking point. The standard tracking point is usually the sixth zero crossing (30 microseconds after the beginning of the pulse). This point represents a balance between received signal power and skywave interference mitigation. Then the timing is determined using the zero crossing nearest to coarse estimate. Variations in the envelope relative to the carrier may result in a coarse estimate that differs from desired zero crossing by half a cycle or more. The selection of the wrong zero crossing is commonly termed a cycle error. Phenomena that affect signal to noise ratio (SNR) and signal quality (envelope, phase/carrier) are hazards since they affect our ability to accurately track the desired zero crossing.

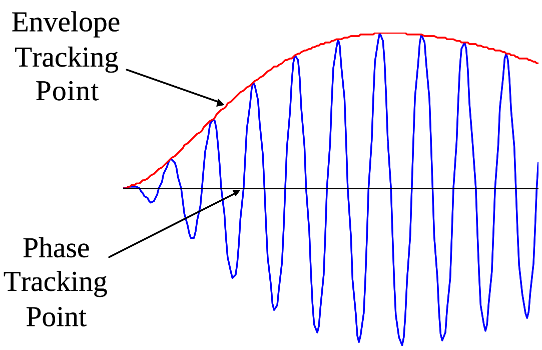

Figure 1. Determining Time of Arrival

Therefore, the critical first step is ensuring that the receiver is tracking the correct cycle. The LORIPP has developed a cycle resolution algorithm using redundant measurements to check cycle [5]. If the cycle is verified to the level specified by integrity, a timing measurement can be taken yielding a range. The receiver needs to adjust the range for propagation delays using an ASF database. The receiver also estimates a bound on the error of the range estimate due to changes in ASF, SNR, transmitter timing, and other effects. This bound is used to generate the HPL.

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 a_i is the standard deviation of the bound on error i. The second and third term correspond to bounds on correlated and uncorrelated biases respectively. The final term, *PB*, is a position bound on errors. This is being considered for spatial ASF variations. A position domain bound is acceptable since the transmitters are fixed thus fixing the geometry matrix at a given location. More details on the Loran Integrity equation will be presented in a future paper.

$$HPL = k\sqrt{\sum_i K_i a_i^2} + \left|\sum_i K_i b_i\right| + \sum_i \left|K g_i\right| + PB \qquad (1.1)$$

As a result, phenomena that affect signal "delay" such as transmitter timing and propagation delays (such as ASF) are hazards. These hazards are often unobservable to the receiver and bounds on the variation of these quantities are modeled using prior data and physical understanding. Deviations that not modeled properly could result in HPE exceeding HPL, representing an integrity hazard.

2.3 Description of Hazards

From examining the determination of TOA, one can classify a hazard as affecting one of three qualities of the signal: availability, strength and quality, and delay. Examining phenomena that affect these quantities leads to the primary hazards to Loran. These hazards are shown in Figure 2 and enumerated below. The following sections will briefly describe each hazard.

1. Temporal Variations of Groundwave
    a. Additional Secondary Factor (ASF)
    b. Envelope to Cycle Difference (ECD)
    c. Signal Strength (SS)
2. Spatial Variations of Groundwave
    a. ASF
    b. ECD
    c. SS
3. Weather related noise
4. Early skywave
5. Aircraft dynamics
6. Man-made RFI
7. Transmitter Hazards

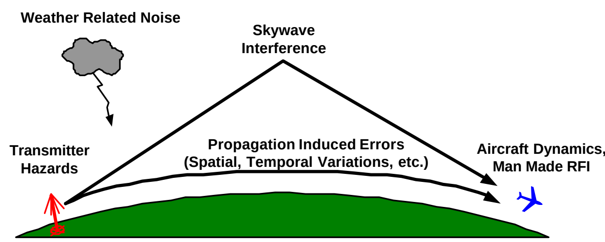

Figure 2. Loran Hazards

2.3.1 Temporal Variation of Groundwave

The Loran groundwave, the signal used for determining TOA, is affected by variations in terrain properties such as conductivity and terrain changes. These terrain properties may change significantly throughout the year, especially during winter months where ground can change from frozen to dry within days. The changes in terrain property affect the propagation delay known as additional secondary factor (ASF) – the additional delay from traversing a terrestrial path vice an all seawater path. It also affects the envelope to cycle difference (ECD) with is the delay of the envelope relative to the carrier. It is basically group delay due to propagation. Finally, the terrain changes can also alter signal strength (SS).

2.3.2 Spatial Variation of Groundwave

Irregular terrain can cause variations in signal properties beyond that predicted from path conductivities. Nearby locations may have quite different ASF, SS, ECD due to variations in terrain.

2.3.3 Weather Related Noise

Much of noise in the LF band is due to weather. There are two primary sources of weather related noise in Loran – atmospheric noise and precipitation static (P-static). Atmospheric noise is noise due to lightening. This noise is omnipresent in the LF band since the noise propagates over long distances and increases as one nears a lightening storm. P-static is noise caused by build up and discharge of the ionized particles on the airframe. Especially present near precipitation, this phenomena cause significant problems to Loran availability in the previous trials of Loran for aviation.

2.3.4 Early Skywave

Skywave is the component of the Loran signal that is directed away from the earth's surface, scatters off the ionosphere, and returns to the earth's surface. The phenomenon is analogous to GPS multipath with the skywave arriving generally after the standard Loran tracking point. Typical skywave is not a problem since the tracking point occurs before the arrival of the skywave. However, skywave is less predictable than groundwave and it can arrive prior to the tracking point. This is known as early skywave and it can affect both the measured envelope and phase (timing) of the Loran signal. Especially problematic is a very low effective ionospheric reflection height in which the difference between the skywave and groundwave path lengths becomes relatively small. With the appropriate phasing and relative amplitudes, the superposition of these two wave components may yield a waveform in which the usual methods of measuring the tracking point from certain envelope values can lead to an erroneous cycle selection. This has obvious implications for Loran integrity.

2.3.5 Aircraft Dynamics

Dynamic movements of the aircraft affect the ability of the user to track and average a Loran signal. Doppler effects from aircraft dynamics reduces the averaging time of receivers which effectively lowers SNR by reducing the ability to average down noise. This results in reduced signal availability. Hence aircraft dynamics is an availability/continuity hazard.

2.3.6 Radio-Frequency Interference (RFI)

Radio frequency interference can increase the noise level experienced by the user resulting in reduce availability/continuity. Sources of this interference may be within the aircraft itself (motors, engines, other electrical equipment) or external (other LF transmission, power lines, etc.). This hazard may increase as the aircraft descends closer to man made sources of RFI.

2.3.7 Transmitter Hazard

Transmitter is responsible for the timing, shape and transmission of the signal in space. A fault in the transmitter may cause a signal transmission timing error, a distorted signal to be sent, or prevent the signal from being transmitted. Hence the transmitter may be the source of integrity, availability, continuity and accuracy hazards. However, a Loran transmitter provides guarantees of the signal in space by continuously monitoring the signal in the near field using the automatic blink system (ABS). ABS "blinks" the transmitted signal if it detects any suspect out of tolerance condition. Blink is a method that notifies users that the signal is not good. In Enhanced Loran, blink is defined as removing the signal for a minimum of 10 seconds.

2.4 Relationship between Hazards and Requirements

Determining the performance of Loran relative to the RNP 0.3 requirements requires understanding the relationships between each hazard and the requirements affected by the hazard. It provides guidance for the analysis of the hazard and integrating the results to determine integrity, availability, continuity, and accuracy.

2.4.1 Integrity

The integrity analysis examines hazards whose variation may cause horizontal position error (HPE) to exceed horizontal protection level (HPL). The definition rules out variations of measured quantities such SNR as primary hazards since changes from nominal should be measured and accounted. For the analysis, the hazards are divided into two categories – cycle error and phase error.

Cycle error occurs when the coarse estimate of the tracking point results in the selection of the wrong cycle to track. Tracking the wrong cycle will result in a range estimate that is in error by a multiple of 3000 meter (one wavelength). Such a range error will result in HMI if undetected and hence a critical part of the providing integrity is the cycle resolution algorithm. Cycle error is caused by ECD and distortions in the envelope. Temporal, spatial variations of groundwave, early skywave and transmitter performance affect ECD.

The phase error is timing error. This can result from multiple sources: errors in measured and transmitted timing and difference in ASF from the values used by the user. The transmitter is one source of timing error as is early skywave. The ASF varies temporally and spatially and the actual value may deviate from that used by the user because of both phenomena. Confidence bounds for these variations will have to be estimated. An integrity fault may occur if the actual variation exceeds the bounds.

The division of integrity into cycle and phase integrity occurs because determining range/timing is a two-part process. A valid phase measurement cannot be made before adequate confidence that the correct cycle is being tracked. Noise, which affects both envelope and phase, is a secondary hazard since it is measured.

2.4.2 Availability

Determination of availability involves examining hazards that would prevent the user from using Loran for RNP 0.3. A solution can be used for RNP 0.3 if the HPL does not exceed the HAL. Loss of availability can result from a lack of signals necessary for a solution, a lack of adequate cycle integrity, or a lack of adequate HPL. Thus transmitter availability is one significant hazard and it affects both cycle integrity and HPL. Other primary hazards to adequate cycle integrity are phenomena that affect ECD (spatial, temporal variations, early skywave, aircraft dynamics). Large variations in ASF and low SNR can reduce our confidence in the signal resulting in an HPL that exceeds the HAL. The impact of these hazards depends partially on geometry.

2.4.3 Continuity

Loss of continuity occurs when a position solution previously adequate for RNP 0.3 becomes unavailable. Continuity hazards are similar to those that cause loss of availability though limited to those hazards that can change during the duration of an approach. Hazards include signal availability, noise and interference, and aircraft dynamics.

2.4.4 Accuracy

Accuracy analysis depends on the signals available, the geometry and the nominal errors within the system.

2.4.5 Summary

Hazard	Integrity	Continuity	Availability	Accuracy
Temporal variation of ECD	1		2	
Temporal variation of phase	1		1	2
Temporal variation of SNR	2		1	
Spatial variation of groundwave phase			1	
Weather related noise		2	1	
Early skywave	1			
Aircraft dynamics		1	2	
Man-made RFI		1	1	
Transmitter Hazards	1	1	1	

Table 2. Mapping Loran Hazards to RNP 0.3 Requirements

Table 2 shows a mapping of the hazards to the requirements they most affect. A "1" signifies that the hazard significantly affects the requirement while a "2" designates a substantial, but lesser effect. These assignments are subjective and the performance in one requirement category is coupled with that of the others. However, these designations follow the analysis conducted in determining the ability to meet RNP 0.3 requirements.

3. ANALYSIS OF HAZARDS

This section discusses the work on each of the hazards and current conclusions. The next section will place them in the context of the RNP 0.3 requirements. Other papers and future papers will discuss the details behind the work analyzing each hazard.

3.1 Temporal Variation of Groundwave

TOA and time of transmission (TOT) monitors (TOAM, TOTM) were set up to determine ASF values and measure quantities such as ECD and signal strength. The monitor network density is higher in Northeast US where the variations are historically largest. More details on the data collection are presented in [6].

3.1.1 Temporal Variations of ASF

In the assessment of temporal variation of ASF, one has to examine the quality of the data collected and develop a model for this term. The model terms may then be incorporated in both the analysis and user equipment.

3.1.1.1 Model for Temporal ASF

The temporal variation in ASF is due primarily to changes in conductivity. A basic mathematical model for ASF temporal variation is seen in Equation (1.2). The equation shows the ASF for each user-transmitter pair. The ASF from station i at time t is equaled to the mean ASF from that station plus a land distance related term $dTOA(t)$ that is the same for all received transmitters, a common mode term $c(t)$, and a residual error term $e_i(t)$. The total land distance to the user from transmitter i is $d_{i,land}$.

The terms are derived from knowledge and observations. The $dTOA(t)$ term derives from the observation that, for a given location, the local land conductivity and conductivity changes should be similar in all directions. As a result, some of the temporal changes in ASF should be common to all stations and related proportionally to the land distance from a station to the user. The $dTOA(t)$

is an estimate of the proportionally factor assuming the relationship is linear in land distance. The term *c(t)* accounts common mode variations such as errors and variations from the TOA monitor clock. These terms cannot account for all the variation in the ASF. As one goes further from the location, the conductivity in one direction becomes more decorrelated with that of another direction. Hence the model contains a residual error term, $e_i(t)$, for each transmitter which accounts for errors not covered by the previous terms.

$$\begin{aligned} ASF_i(t) &= ASF_{i,mean} + dTOA(t) * d_{iland} + c(t) + e_i(t) \\ \Delta ASF_i(t) &= dTOA(t) * d_{i,land} + c(t) + e_i(t) \end{aligned} \quad (1.2)$$

3.1.1.2 Assessing Data and Model

The data collection system was rapidly deployed over the last nine months. The system has been refined over the course of these months to provide data sets that are suitable for analysis. The amount of data, due to the small quantity from the winter, is not currently adequate for a complete picture. However, given the limited amount of time for the analysis, the analysis must begin with the data at hand. The data was filtered to remove obvious instances of error. For example, measurements with unusually poor signal strength or SNR, non-physical jumps or gradients, are thrown out.

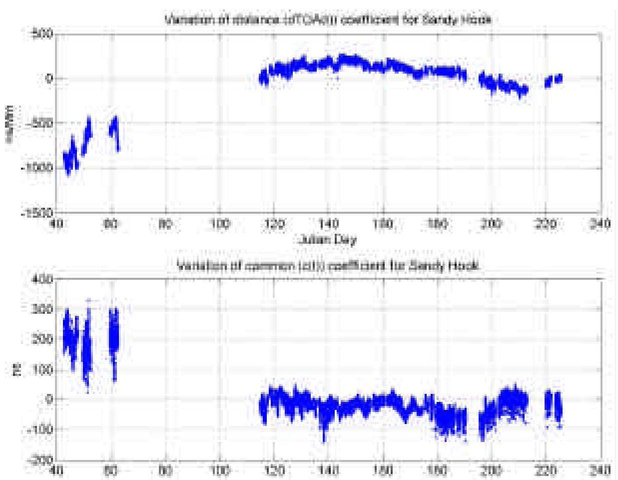

Figure 3. Estimated Values of Distance Related and Common Coefficients (*dTOA(t) & c(t)*)

The resulting data is used to estimate the terms of the model. Figure 3 and Figure 4 show results from the Sandy Hook, NJ monitor. Figure 3 shows the estimates of the distance related and common terms. Figure 4 shows the residual error for the Carolina Beach to Sandy Hook baseline, which was not used to estimate the terms. Currently, most of the data that is adequate for fitting and testing the model is from the spring and summer. However, the primary concern is the winter variations. The current results indicate that the system is operating well and it is hoped that the data from the coming winter will be adequate to determine the magnitude of the variations.

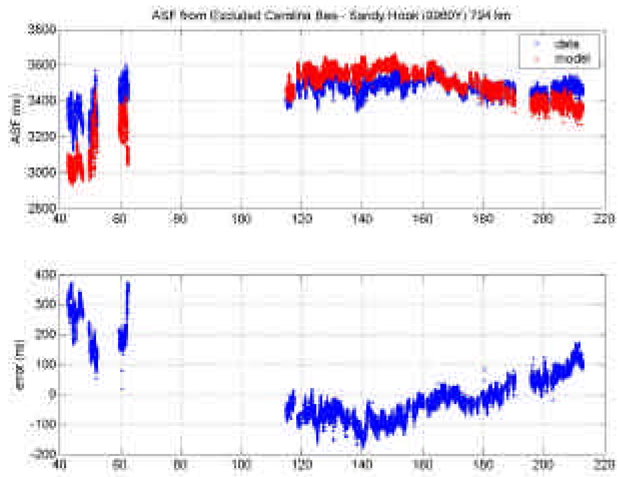

Figure 4. Estimated ASF and Residual Error for Carolina Beach, NC to Sandy Hook, NJ

The cursory evaluation was conducted using the current data using bound values that are roughly 10% greater than the maximum absolute value for the coefficients and residual error. These values were used in the integrity equation to determine HPL. The analysis leads to two conclusions. The residual error, an uncorrelated bias, dominants the distance related error in terms of contribution to HPL. In fact, a bound of 400-500 m for the residual error is on the borderline of achieving an acceptable HPL. And so, it seems that for the Northeast, the conclusion will depend on additional data and our ability to model the temporal ASF changes.

3.1.2 Temporal Variations of ECD and SS

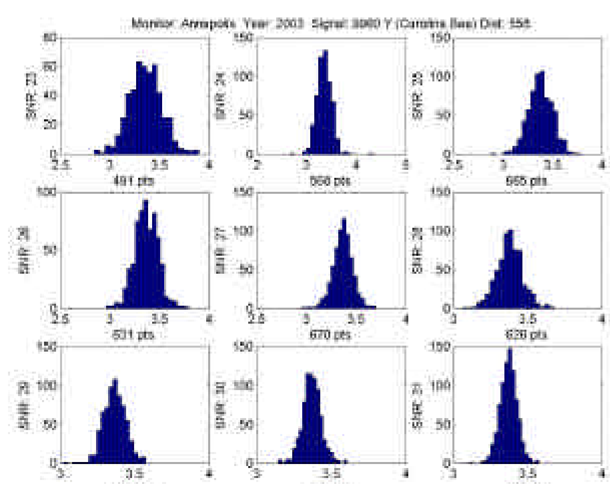

Figure 5. ECD Histogram (for various SNR) for Annapolis-Carolina Beach

The TOA monitors also collect ECD and signal strength data. The data is used to examine the nominal variations of ECD and SS. The receiver uses an a priori model in which the variance of ECD is proportional to SNR. Figure 5 shows histograms of ECD at various SNR for one station and such histograms can be used to examine the validity of the model. It can also indicate anomalies. Large variations in ECD may indicate the presence of early skywave. In addition, signal strength helps determine the quality of the other measurements.

3.2 Spatial Variation of Groundwave

Spatial variation is modeled using the method discussed in [7,8,9]. The model utilizes coastline information, conductivity maps, and accurate terrain databases to determine the propagation delays and attenuation of a signal. Figure 6 shows the spatial ASF variations, generated using the model, of the Nantucket signal near Cape Elizabeth. ME. While the model is the basis of our estimates of spatial variations, flight and ground tests have been conducted to determine the validity of the model [10].

3.2.1 Spatial ASF Contribution to HPL

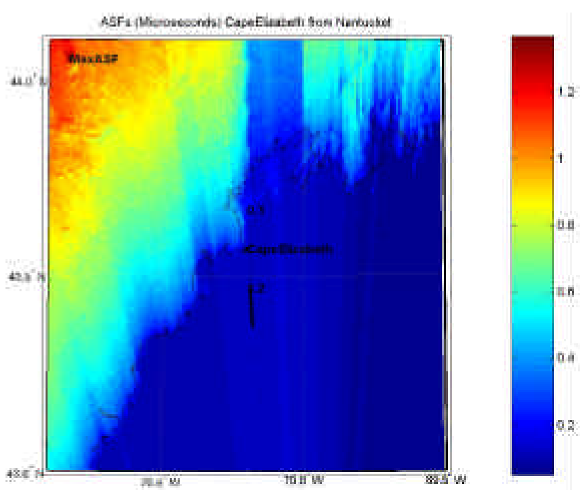

Figure 6. Spatial Variation of Nantucket ASF Around Cape Elizabeth (0.1 microsec, largest deviation 1.2 microsec)

The variation of spatial ASF from the model is used with the HPL equation to determine its effect on integrity and availability. Two methods are tested using ASFs generated by the model. It is assumed that the user has the ASF at the airport and the variation of concern is in the differential ASF. The first method is a range domain bound with one bound on spatial differential ASF for each station. The value depends on the area over which the bound is valid with a coverage radius to 10 to 20 nm typically examined since that represents the maximum extent of the terminal area. The range domain bound must be treated as an uncorrelated error between stations and the bound contribution from each station is added in the worst possible way to determine its contribution on HPL. The result for Cape Elizabeth is shown in Figure 7.

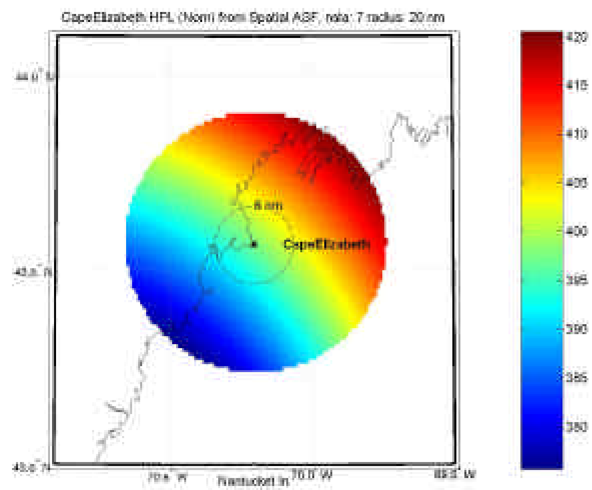

Figure 7. Calculated Nominal HPL Contribution Using Range Domain Bound on Spatial ASF (No Stations Lost)

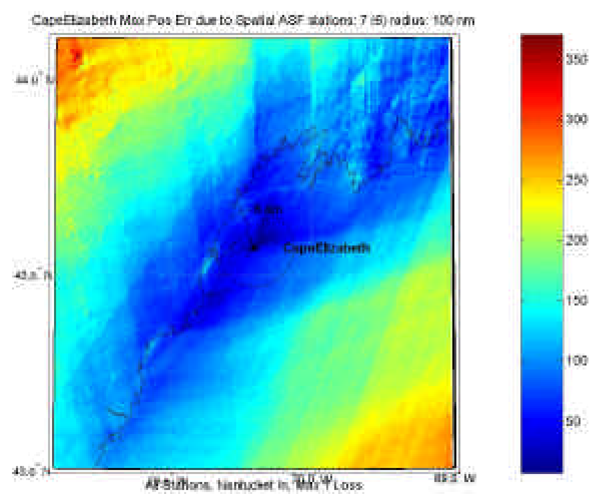

Figure 8. Calculated Worst Case HPL Contribution Due to Spatial ASF Using Position Domain Bound (Up to One Station Lost, Nantucket Always Present)

In fact, the direction of the ASF change is known from the model though providing that information in the range domain requires providing differential ASFs at numerous locations. Hence the second method, a position domain bound, is examined to leverage the known relationship. The receiver uses one bound for position solution per airport terminal area. This simplifies the information the receiver needs – only one bound instead of a bound for each range. It is possible because the stations are fixed and hence the geometry is fixed. The only variation that has to be accounted for is which stations are used for the solution. Thus, to use the position domain bound, the receiver must use only a prescribed set of stations under which the bound is valid. Figure 8 shows an example with the bounds being valid for any solutions containing at least six of seven stations provided that Nantucket is always used. For Cape Elizabeth, the Nantucket signal has the most significant influence to the HPL. While the position domain bound limits the set of stations used, it lowers the HPL by 30% or more vice the range domain bound. This is necessary to achieve availability on some coastal locations.

Generally, spatial ASF does not greatly affect accuracy or HPL in the interior of the United States with the exception of mountainous regions. In those regions, either bound should result in high availability. However, for areas of high spatial ASF variations, the position domain bound may be the only way to provide availability with integrity.

While spatial ASF can be significant, it is our belief that high availability can be provided without having to provide many calibration points. For the worst case regions, using the position domain bound results in a high though generally acceptable contribution to the HPL.

3.2.2 Spatial Variation in Signal Strength & ECD

The model also provides estimates of signal strength variations. The variation of signal strength, if significant, may affect availability by reducing the number of signals usable by a receiver.

The ECD can be estimated using the model analyzed at different frequencies. We are currently assessing the impact of spatial ECD variations.

3.3 Weather Related Noise

Two forms of weather related noise are of concern for Loran. One is atmospheric noise, which is produced 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 [12] cause the ground to act as a waveguide, allowing this low-frequency noise to propagate for thousands of kilometers.

The second is precipitation static (P-static), which is noise due to the build up and discharge of ionized particles on the aircraft. This process often occurs as an aircraft travels through a cloud layer, as may occur on descent. In the past, the increased noise due to P-static has often resulted in blocking out the Loran signal.

3.3.1 Effect of Atmospheric Noise on Loran

Atmospheric noise is generally the primary source of interference while in flight. While the noise may cause increased errors in phase and ECD measurement, the increase uncertainty in these measurements should be accounted by the receiver measurements of SNR. Hence, the primary concern is availability due to the decreased of the number and accuracy of the signals available. The LORIPP analysis was focused on two areas: obtaining a time domain model of atmospheric noise that is consistent with the International Radio Consultative Committee (CCIR 322-2) [13], and using the model to determine the ability of signal processing provide some SNR gain to compensate for the increased noise. The resulting analysis has shown that a SNR credit can be achieved due to the impulsive nature of atmospheric noise.

Low frequency data from lightning discharge was obtained from the National Lightning Detection Network (NLDN). This data helps illustrate the characteristic of atmospheric noise. During the discharge, the atmospheric noise stands a good chance of swamping the Loran signal. Figure 9 is shown a representative Loran signal (green) superimposed on some typical atmospheric noise data (blue). The spikes of Loran data are entire Loran pulses as shown in Figure 1. Atmospheric noise varies between high energy impulses and fairly Gaussian noise between the impulses. The nature of this noise suggests that it is possible to use signal processing to mitigate its effects.

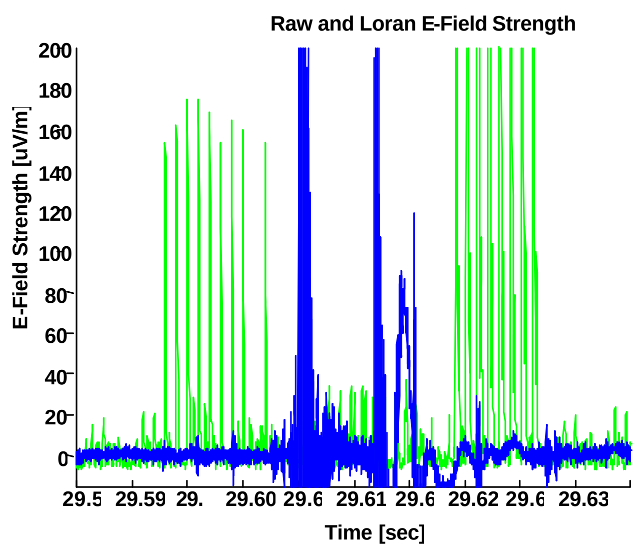

Figure 9. Atmospheric Noise and the Loran Signal in the Time Domain

3.3.2 Mitigation Techniques of Atmospheric Noise

Since this noise is composed of a low-level Gaussian component and an impulsive stochastic process, a typical receiver design using a linear filter will be only marginally effective. However non-linear processes do prove fruitful.

By utilizing either a time-varying filter which will try to estimate the parameters of a canonical model that will be used to represent the noise or by using a less optimal, time-invariant non-linear filter such as a hard-limiter, hole-punch or clipper that either blanks out noisy signals or limits their amplitudes, we can gain a 10-30dB improvement over the linear filter.

A preliminary analysis using a hole-punch or threshold blanking algorithm, showed a 15 dB improvement over the linear filter during severe atmospheric conditions. The improvement results from a loss due to signal suppression when the signal was unavailable due to the level of atmospheric noise, and the gain realized since the rms level of the Gaussian background noise is significantly lower than the rms level of the overall atmospheric noise. This gain increases as the noise becomes more impulsive.

The effectiveness of the filter was parameterized by the voltage deviation, V_d=20log$_{10}$ (rms noise value/avg value). V_d gives a measure of how "impulsive" or "non-Gaussian" the noise is. From the data provided by the CCIR 322-2, V_d and the rms noise level are independent of each other so the effects of non-linear filtering may be taken separately from the overall noise level. Also, shown in the above plot is a comparison of this hole-punching technique with a clipping algorithm used in a spread spectrum multiple access (SSMA) system.

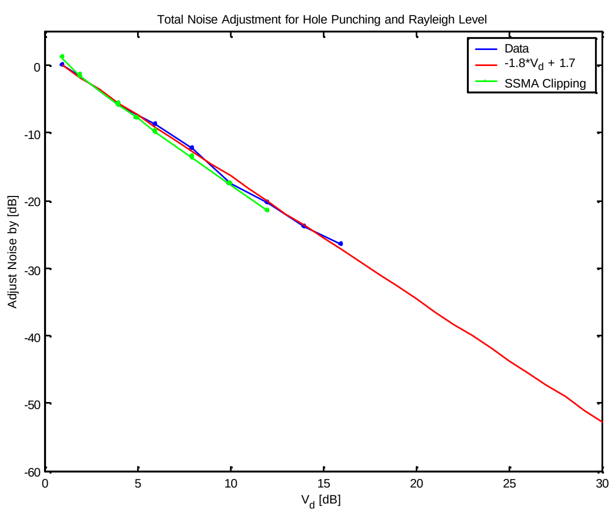

Figure 10. Gain from Using Threshold Blanking as a Function of Impulsiveness (V_d)

The result is that for the 99-percentile noise level, the analysis validates a claim of 15 dB of credit. This credit is used in the availability analysis. More weather related data will be collected in a series of flight trials conducted by Ohio University (OU). It is hoped that these trials provide additional validation.

3.3.3 Precipitation Static Data Collection

One primary purpose of the OU flight trials is to examine P-static. The flight hardware will include an E-field antenna and an H-field antenna and data will be sampled at 400 kHz, two-channel data grabber. The setup provides the ability to quantify the improvement that the H-field antenna will provide in P-static situations. Tests are currently on going and results will be presented at the 32nd Meeting of the International Loran Association (ILA 32).

In addition to flight and ground testing conducted by OU, the FAA Technical Center will also collect data on P-static in three stages. Data will be collected from static ground charging and discharging, natural P-static in flight, and, possibly, charging in flight.

It is believed that H field antenna and proper installation nearly eliminates the P-static problem. The results of the tests will help quantify the performance.

3.4 Early Skywave

Early skywave can have deleterious effects on signal timing and ECD. While skywave delays of less than 30 microseconds are rare in the 48 contiguous states, research indicates phenomena do exist which can cause it to occur. We are currently studying the worst-case effects of early skywave and will soon set up monitors to determine its frequency and magnitude in conterminous US (CONUS) and Alaska.

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. Associated with these events are geomagnetic storm-related enhancements of the ring current that cause the plasmapause and auroral boundaries to move equatorward. While these are rare events in CONUS, they are frequent relative to the integrity requirements to merit examination.

Detection and mitigation of the early skywave hazard is important. If it can be detected, it becomes an availability issue. Mitigation options include: altering the pulse envelope to produce a faster rise time, exclusion of path lengths greater than a certain threshold, and receiver detection/elimination. For CONUS, it is possible for monitors to detect solar proton events well in advance of their effect. Analysis of this work is ongoing and more will be presented at a paper presented at the ILA 32.

3.5 Aircraft Dynamics

Longer integration time can be achieved by using a good estimate of the aircraft dynamics in the tracking loop. This can be achieved by integrating other sensors such as low grade inertials or using Loran Doppler. An implementation of using Loran Doppler to estimate velocity is being developed. Dr. Ben Peterson has shown that it is possible to use the full Loran pulse and this provides significant benefits [6].

One test of the efficacy of the designs is to use the Loran simulator and simulate sample flight patterns. The dynamics limits from Section 2.1.2.5 of the WAAS MOPS will be used as reasonable limits for dynamical maneuvers [14]. The current belief is that it is possible to use these techniques to achieve the desired averaging time on a dynamic platform.

3.6 Radio-Frequency Interference (RFI)

The RFI hazard broadly defines many sources of interference. One source is from the aircraft itself. While the noise source is aircraft and installation specific, an idea of achievable performance can be determined from calibration tests on the weather noise flight tests. From such measurements, maximum level of acceptable aircraft noise can be determined and prescribed. The OU flight test data can be processed to remove the Loran signal. This will provide some measurements of aircraft noise as well as CW interference. Other sources of interference, such as power line carriers (PLC), are analyzed by examining previous literature and research [15].

3.7 Transmitter

The transmitter is the source of the Loran signal. As such its performance affects the integrity, availability, continuity and accuracy of the system. The integrity of the transmitted Loran signal is checked by the automatic blink system (ABS). This system verifies that the signal timing and ECD is within a specified tolerance. In Enhanced Loran, the timing tolerance will more in likely be set at 100 nanoseconds (maximum).

Integrity analysis examines the probability of an ABS failure. ABS takes near field measurements of the Loran signal and verifies that the timing is within specified tolerance. ABS monitors the timing of the signal and ensures correct phase code of the Loran group. The probability of integrity failure is a combination of the probability of a failure that causes the system to exceed tolerance and the probability of ABS failing to detect the failure. The probability of equipment failure can be determined from the historical data used for transmitter availability analysis. Analysis of the ABS system will help determine the probability of ABS failure. Given that the equipment failure is around .001 or less, the probability of a transmitter integrity failure is probably well below 10^{-7}.

Transmitter availability analysis uses historical data from the Loran-C Operational Information System (LOIS). Since the Enhanced Loran system includes upgraded equipment and procedures, the effects of these changes had to be estimated and incorporated. A notable change is the reduction momentary outages due to equipment switches from a minute to three seconds. Since new receivers will coast through a three second outage, equipment switch outages will not result in a loss of continuity. In addition to overall availability, the statistics on the number and distribution of outages and outage times is required to determine continuity.

Table 3 shows a comparison of the estimates for availability with the current and new system. Table 4 shows the outage statistics on a per station basis. The outages are separate into four categories: momentary blink (blk), momentary off air (oa), unusable time (UUT) blink and unusable time off air. Since the LOIS records outages rounded to the next minute, the mean times to repair (MTTRs) are not known precisely and are slightly overestimated.

Station	GRI	Current	New
Malone	*8970 W*	*99.845%*	*99.888%*
Malone	*7980 M*	*99.844%*	*99.900%*
Seneca	*8970 X*	*99.888%*	*99.915%*
Seneca	*9960 M*	*99.882%*	*99.917%*
Baudette	*8970 Y*	*99.890%*	*99.921%*
Baudette	*8290 W*	*99.899%*	*99.931%*
Boise City	*8970 Z*	*99.904%*	*99.932%*
Boise City	*9610 M*	*99.883%*	*99.951%*
Gillette	*9610 V*	*99.923%*	*99.964%*
Gillette	*8290 X*	*99.926%*	*99.955%*
Las Cruces	*9610 X*	*99.895%*	*99.924%*
Raymondville	*9610 Y*	*99.851%*	*99.894%*
Raymondville	*7980 X*	*99.841%*	*99.890%*
Grangeville	*9610 Z*	*99.827%*	*99.907%*
Grangeville	*7980 W*	*99.823%*	*99.902%*
Havre	*8290 M*	*99.946%*	*99.965%*
Jupiter	*7980 Y*	*99.838%*	*99.886%*
Carolina Beach	*7980 Z*	*99.867%*	*99.906%*
Carolina Beach	*9960 Y*	*99.875%*	*99.911%*
Caribou	*9960 W*	*99.896%*	*99.917%*
Nantucket	*9960 X*	*99.820%*	*99.850%*
Total		*99.874%*	*99.915%*

Table 3. Estimated Transmitter Availability

Type	Number/Station/Year	Mean Time To Repair (MTTR) in minutes
Mom (blk)	72.83	< 1
Mom (oa)	66.41	< 1
UUT (blk)	8.15	9.6
UUT (oa)	5.77	62.6
Total	153.16	3.7783

Table 4. Station Outage Statistics (does not include the removal of upgrade times)

4. RNP 0.3 REQUIREMENTS

The final product of the LORIPP analysis is the determination of the integrity, availability, continuity, accuracy and coverage of Loran for RNP 0.3. As such, the analysis of the hazards has to be folded back to the system requirements.

4.1 Integrity

Proving integrity on means assuring that the HPL calculated is not exceeded by the HPE with probability greater than 10^{-7}/hour. For Loran, this means proving that both the cycle integrity algorithm and the components of the integrity equation have that level of integrity. This is the first such integrity analysis conducted for Loran and our determination will depend on data collected, historical data and physical models.

Passing cycle integrity means that the signals can be used to calculate a position solution. Passing a signal with an incorrect cycle will undoubtedly result in HMI (HPL > HPE) due to the size of a cycle error. Hence we must make sure that the a priori values used in the cycle integrity check are valid. This means that the ECD variations due to SNR, temporal and spatial changes, skywave must be validated. There is still significant work to accomplishing this task.

Given that the correct cycles are being tracked, integrity failure can also be caused by not having properly bounding to phase error. The bounds currently are being estimated using data and models. These represent our best evaluation of the variation of each error and in the analysis; we will include an appropriate margin for error. This is especially important for error sources that affect the uncorrelated component of the bound since errors in modeling is amplified the most. The Position Bound is in another such situation since there is weak correlation.

4.2 Availability

Availability depends on various factors such as geometry, signal availability, noise, interference, and variations in ASF. The dependence on geometry necessitates the calculation of availability for every location of interest using a coverage tool. At each location, there will be different signals available, noise, and ASF.

Peterson has used a coverage tool to examine availability at various levels of noise (95%, 99%, etc.). In addition, he has also used the tool to examine availability with one station out. The results of these studies show that RNP 0.3 using Loran is available for most of CONUS at 99% or higher noise levels even with one station out. The analysis has a couple of caveats since it currently uses a simple model for residual temporal ASF and spatial ASF errors. Also, it does not incorporate station availability. The ASF issue should not change the results for much of the country. However, the availability for Northeast U.S. and some coastal and mountainous regions may be impacted given the current levels being obtained in the ASF analysis. With station availability projected to be at least 99.9%, this should not significantly affect the results. Future analysis should incorporate station availability.

4.3 Continuity

The continuity analysis proceeds along lines similar to that of the availability analysis. The main consideration is the analysis of those factors that can change during an approach that changes the system to unavailable. This happens by either having the HPL exceed the HAL or by having loss of cycle integrity.

Factors could result in a change HPL during an approach include increase in noise, interference changing geometry, loss of station. The primary noise of concern is weather related noise, particularly P-static. The magnitude of this hazard on continuity is yet to be determined. Interference, only be a significant factor if there is a local source of interference.

Geometry changes and station loss is examined using the coverage tool. Most locales seem tolerant of the loss of one station.

4.4 Accuracy

The accuracy analysis is conducted using the same coverage tool. Nominal conditions and values of each error are used for the analysis. The accuracy requirement is generally easily met at most locations provided a local ASF value is provided. However, as seen in the position bound shown in Figure 8, there are some regions where the accuracy level is close to exceeding the requirement (with a lost station). Such conditions will be examined though it is expected that, under nominal conditions, this is not an issue. Since accuracy is an aggregate value, the nominal result will dominate.

5. PRELIMINARY CONCLUSIONS

The preliminary conclusions of the LORIPP is that for much of the country, Loran should be able to meet much of the RNP 0.3 requirements. However, there are still many limiting factors and caveats.

A known limiting factor in is for areas of high ASF variation, spatial or temporal. These areas may have reduced availability since bounding the residual ASF to results in high contributions to HPL. The LORIPP is examining options to reduce the bounds.

The integrity bound represents the best information that we have to date. However, it is impossible to characterize bounds on ASF and other errors with the fidelity necessary based on a few years worth of data. The margins that will be built into the analysis hopefully will provide the necessary guarantee.

Furthermore, there is still work to do in analyzing many areas, such as P-static. The P static tests are currently being conducted. Other areas of work, will not finished, are nearing completion.

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