The Loran Integrity Performance Panel

Sherman Lo, Per Enge, Lee Boyce, *Department of Aeronautics and Astronautics, Stanford University*
Ben Peterson, *Peterson Integrated Geopositioning*
Tom Gunther, Bob Wenzel, *Booz Allen Hamilton*
Lt. Kevin Carroll, *US Coast Guard Loran Support Unit*
Kevin Bridges, Mitch Narins, *Federal Aviation Administration*

ABSTRACT

LOng RAnge Navigation, Loran, is an attractive candidate to provide redundant services for GPS because of its complementary RNAV, stratum 1 timing, and data channel capabilities. However, for Loran to be accepted as a redundant 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 will follow 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. This paper provides an overview of the LORIPP, the LORIPP process, and the issues being addressed relative to RNP 0.3 accuracy, availability, integrity, and continuity requirements.

The LORIPP's objective is to use rigorous analytical methods, data collection, and modeling to determine if new receiver technology and scheduled Loran station improvements can either mitigate or lower the probability of adverse effects from identified threats. The LORIPP must comprehensively and exhaustively examine every potential threat and prove that Loran, in light of these issues, meets RNP 0.3 performance requirements. Work to date indicates it is highly likely that Loran can meet these requirements.

1. INTRODUCTION

The Federal Aviation Administration (FAA) and the US Coast Guard (USCG) with the support of a team comprising of government, academia, and industry members are conducting an evaluation of the current and potential capabilities of LOng RAnge Navigation (Loran) system. 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.

1.1 A Brief History of Loran:

Loran began as a US military system where it provided all-weather navigation and positioning services. The US Coast Guard, a participant in the development of Loran [1], took overall responsibilities for Loran in the 1960's [2]. In the 1970s, the current implementation of Loran, Loran-C, was designated as an approved navigation system for the coastal modes of maritime navigation. It provided excellent coverage and enjoyed widespread use along all US Coasts and the Great Lakes. However, Loran applications are not limited to marine users. It can and has been developed and used by all modes of transportation as well as non-transportation applications such as radiosondes for weather balloons. Recently, there has also been research in modulating data onto Loran for differential Global Position System (DGPS) corrections and Wide Area Augmentation System (WAAS) broadcast [3, 4, 5].

1.2 Basic Loran-C Operations and Capabilities

Loran-C is a high power, low frequency, hyperbolic, terrestrial radionavigation system operating in the 90 to 110 kHz frequency band. The US Loran-C system, as seen in Figure 1, comprises transmitters, control stations, and System Area Monitors (SAM) [1] [6].

1 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

In current operations, the basic element of the Loran navigation system is a Loran chain. A chain consists of between three and six transmitting stations. Each chain has a designated Master station and several Secondary stations. Some stations have only one function (i.e., to transmit Master or Secondary signal in a particular chain), but many transmitters are dual-rated, meaning that these transmit signals for two different chains. The transmitters in a Loran chain transmit in a fixed sequence, and the length of time in microseconds over which this sequence takes place is termed the Group Repetition Interval (GRI) of the chain. Chains are identified by their unique GRI. Users typically refer to a chain by its GRI.

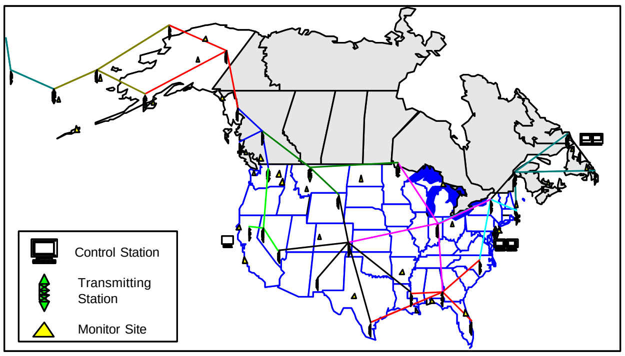

Figure 1. Loran-C System Architecture

1.2.1 Navigation and Positioning

The transmitters emit a set of Loran pulses at precise instances in time. Traditionally, position determination is based on measuring the time difference of arrival (TDOA) of pulses from different stations 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 master independent, multi-chain operations. That is they can determine position using signals from stations in different chains to improve Loran's accuracy, availability, integrity and continuity.

1.2.2 Timing

Precise timing and synchronization is also extremely important to the system's operation, and each Loran-C transmitter incorporates three cesium clocks as standard equipment. The transmitter signals, by law and with the assistance of the US Naval Observatory (USNO), are synchronized to Universal Time Coordinated (UTC) to within 100 nanoseconds. Therefore, Loran-C, like GPS, is a Stratum 1 Timing source[2].

1.3 Loran for Aviation & Other Applications

Before the widespread use of GPS, Loran-C attracted considerable attention from civil aviation users because of its Area Navigation (RNAV) capability. RNAV systems are navigation systems that can, at a minimum, calculate the aircraft position at any point in the service area.

The FAA responded to user demand by working with the US Coast Guard to build four additional transmitting stations to fill the mid-continent gap, thus providing Loran-C coverage across the US. Loran-C was regarded as having considerable utility in flight operations in the en route and terminal phases of flight, and the program included the development and highly visible public demonstrations of Loran-C non-precision approaches (NPAs). However, the system demonstrated several shortfalls that limited FAA acceptance, and attempts to obtain FAA certification for NPA were unsuccessful.

More recently, however, Congressional interest in Loran-C has increased as a result of concern about the vulnerability of GPS and the consequence of losing GPS on the US critical infrastructure including transportation. Such concerns were detailed in the 1997 President's Commission on Critical Infrastructure Protection [7] and the more recent 2001 DOT Volpe National Transportation Systems Center's GPS vulnerability study [8].

By 1998, the FAA once again became interested in Loran's potential for aviation use. Many of the past Loran-C issues relate to limitations of the system, particular with regards to transmitting equipment and avionics of the time. New technology can eliminate or mitigate these issues. However, the requirements for aviation have evolved into system requirements more rigorous than those contained in the earlier Loran aviation assessments[3]. Today, for Loran-C to be accepted as a redundant navigation source in the National Airspace System (NAS), it needs to provide "chock-to-chock" support for aviation and meet the Required Navigation Performance (RNP) 0.3 requirements for non-precision approaches (see Table 1)[4]

---

[2] A stratum level is a hierarchical structure categorized by the clock source accuracy. A Primary Reference Source (PRS) has a stratum level 1. Stratum 1 is classified as the highest level with an accuracy of 10^{-11} or better. This level requires a Cesium, or a GPS-disciplined oscillator or Loran-C-disciplined oscillator.

[3] Required navigation performance, RNP, is a definition of total navigation system performance. It includes, the navigation system performance, as well as the capability of the pilot and the aircraft to meet specific performance tolerances. RNP is defined in terms of cross-track displacement and along-track position errors relative to a defined flight track. That is RNP 0.3 means that the aircraft must be capable of navigating within 3/10th of a nautical mile on either side of centerline

[4] 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.

Performance Requirement	Value
Accuracy (target)	307 meters
Monitor 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. Minimum and Target Performance Levels for Loran-C

The FAA's evolving RNP 0.3 requirement has become the primary driver for Loran-C research activities, with efforts focused on identifying mitigation strategies for the problems and shortfalls that previously limited FAA acceptance of Loran-C.

The following are generally accepted as Loran's potential benefits and some technical issues that have to be addressed:

Benefits

- Theoretically the most cost-effective redundant radionavigation service.
- Difficult to jam the received signal over large areas due to the high power level (between 0.4 and 1.5 MegaWatts, depending on station).
- Currently provides RNAV capability like GPS-based navigation.
- Currently provides precise time service.
- Potentially an alternate means to broadcast WAAS corrections to multi-modal users.
- Loran-C is unaffected by GPS outages.
- Seamless RNAV transition during GPS outages.

Technical Issues

- The precipitation static needs to be mitigated to achieve the desired availability and continuity of service.
- The effects of atmospheric noise and other interference sources need to be quantified and bounded to insure integrity
- The magnitude and variations in Additional Secondary Factors need to be more precisely quantified
- Transmitter timing and continuity need to be validated

The above issues all related to the integrity of the Loran signal-in-space (SIS)[5]. Determining the integrity of the navigation signal requires rigorous and comprehensive safety analysis.

2. CURRENT FAA LORAN FOR AVIATION EFFORTS

2.1 The Loran Integrity Performance Panel (LORIPP)

The Loran Integrity Performance Panel (LORIPP) is a core team of Loran experts assessing Loran's potential as a redundant navigation system for aviation given current infrastructure modernization plans and new receiver advances. The investigating team comprises researchers from academia, government, and industry operating under the direction of the FAA's Loran program office. It applies engineering and safety analysis principles to build in safety as an integral part of the system design. The principles being used to prove Loran meets RNP 0.3 requirements are similar to those used by the WAAS Integrity Performance Panel (WIPP). The LORIPP will follow a similarly thorough methodology to conduct a rigorous Hazardously Misleading Information (HMI) analysis on Loran.

The Loran program office sanctioned the LORIPP's formation and the team has members with varied expertise crucial to conducting the investigation. Specifically, the LORIPP has experts in: Loran system operation and signal characteristics; WIPP process and WAAS HMI analysis; fault tree analysis and analytical modeling; digital signal processing and all-in-view receiver development; and Loran infrastructure modernization.

2.2 Purpose of the LORIPP

Concerns regarding the Global Positioning System's (GPS) potential vulnerability, and the consequences of losing GPS on the US critical infrastructure, prompted the FAA to study the issue. As a result the FAA determined that the future National Airspace System navigation architecture should retain sufficient legacy ground-based navigation systems to provide redundant navigation services should a GPS disruption occur. Ideally, a redundant navigation system for GPS will have RNP compliant area navigation and approach capability.

The LORIPP's primary purpose is to determine whether or not Loran meets the aviation requirements for an RNP 0.3 navigation system. These are defined in Table 1. Additionally, the team will investigate Loran's potential ancillary capabilities such as maritime harbor approach, precise timing, and data channel for GPS corrections. The LORIPP provides a peer forum based on system safety design process to focus the research program's efforts. This means a comprehensive job of identifying hazards or threats, analysis, and risk assessment. It also means thorough documentation of all findings. This ensures that valid analytical methods are used to arrive at a defendable conclusion on Loran's ability to serve as a redundant navigation system in the National Airspace System. The desired outcome for the LORIPP is to provide a definitive answer (including documentation and substantiating data) to the FAA on Loran's ability to meet RNP 0.3 navigation requirements.

[5] Integrity – The ability of a system to provide timely warnings to users when the system should not be used for navigation. For RNP.3 the system must be able to do this with a confidence of 99.99999% [derived from ICAO Doc. 9613, RTCA/DO-208].

2.3 System Engineering to Meet RNP 0.3 Requirements

Proof that the system meets RNP 0.3 requirements involves accounting for all potential system threats. A comprehensive threat or hazard list is developed and a fault tree for requirements such as integrity and continuity is created. The hazard list enumerates the noteworthy faults that can precipitate integrity, continuity, availability or accuracy failures. The fault tree allocates the acceptable error probabilities for each fault with regard to the requirement. For example, the integrity fault tree list shows the faults that can cause an integrity failure or HMI and the probability that the fault will cause the failure. The probability allocations are selected based on what is known, what can be proven or what is required to meet the overall system requirement. In the case of integrity, the requirement is that the probability of HMI be 10^{-7} per hour or less. 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 proscribed algorithm. The fault tree provides the bookkeeping for a thorough accounting of all faults and tally of total system error. Reductions may be achieved through various means such as monitors, analysis, etc. Thus, the fault tree can be used to suggest where error probability reductions are most efficacious or necessary.

2.4 Cycle & Phase Errors

Building the fault tree requires that we examine and quantify the threats to Loran with respect to each requirement. In Figure 1, we first divided the threats in two basic categories – Cycle Error and Phase/Timing Error (All Cycles Correct). Cycle errors are range errors that results from tracking the wrong cycle. Phase error results from the difference between the measured zero crossing and the actual zero crossing of the Loran carrier. We will consider timing and prediction errors as a subset of phase errors.

The primary cause of cycle error is Envelope to Cycle Differences (ECDs). ECD is the difference between the envelope TOA and the phase TOA. This error results because a Loran receiver first determines the TOA of the envelope. This envelope TOA is then used the select the nearest zero crossing, which determines the (phase) TOA used in the navigation solution. If the total ECD error at the receiver exceeds one half cycle or 5 µsec, then a cycle error of 10 µsec occurs. The total ECD error at the receiver is the sum of:

- Transmitter ECD errors, (both bias and noise.)
- Errors in predicting the change in ECD as the signal propagates from transmitter to receiver (bias).
- Errors in the measurement due to noise and interference (both noise and bias)
- Errors in the calibration of the receiver (bias).

Since tracking the wrong cycle will result in a bias error that is an integer multiple of 10 µsec or 3000 meters, a HMI will occur if a measurement with an uncorrected and undetected cycle error is used in a position solution. Hence, cycle error dominates in this scenario. The main issue associated with analytically proving Loran integrity is sufficient confidence in the correct cycle selection.

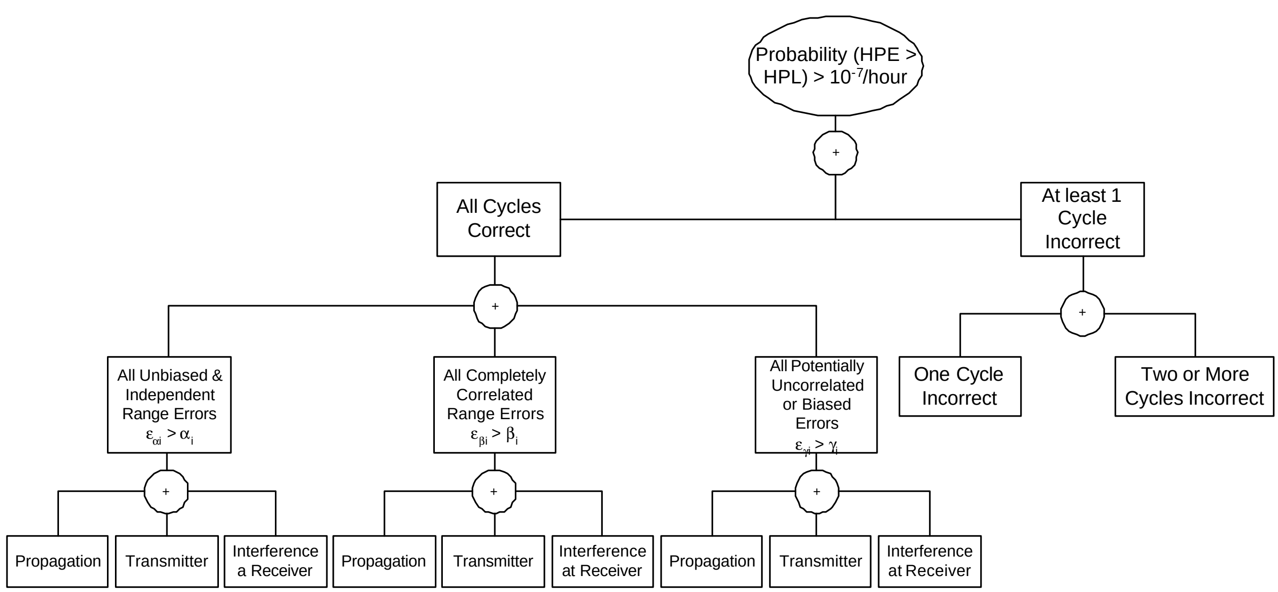

Figure 2. Preliminary High Level Integrity Fault Tree

Within the receiver, there will be a cycle integrity monitor. Because of the importance of not using measurements with cycle errors, redundant information, when available, is used to form an over-determined position solution that allows for the calculation of cycle to a desired integrity. The LORIPP is exploring and testing different algorithms for this monitor. Once a measurement is verified to be on the correct cycle, it still will contain phase and timing errors. The LORIPP will examine the characteristics of these errors and develop bounds consistent with meeting the integrity requirements.

The source of phase as well as cycle errors can be divided into three error types as shown in the fault tree. The types are derived from the HPL equation, Equation (1.1). Error types 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. Hence, the fault tree examines the probability that each error bound is not exceeded by its corresponding error. Finally, the fault tree divides the sources of error by where the error enters the Loran signal - transmitter, propagation prediction error, and interference at the receiver.

$$HPL = k\sqrt{\sum_i K_i a_i} + \left|\sum_i K_i b_i\right| + \sum_i \left|K_i g_i\right| \quad (1.1)$$

Then, threat mitigation will be examined if they are necessary to meet requirements.

The integrity analysis considers the mix of new and legacy equipment that will remain after the Loran Recapitilization Project (LRP) is completed [9]. The USCG Loran Support Unit (LSU) is coordinating the LRP. The new Loran equipment and its associated control and monitoring systems are being developed to mitigate or eliminate shortfalls identified during the first attempt to certify Loran for NPA and for possible use in the maritime harbor approach environment.

The next section will discuss high-level threats to Loran Phase and Cycle determination and outline the planned mitigation techniques.

3. MAJOR ISSUES & THREATS TO LORAN INTEGRITY

This section provides a description of the main threats and pressing issues for Loran integrity. For clarity, the threats to Loran are divided into three categories based on where the threats or issues exist or derive: from Loran transmitters, from propagation phenomena, and from the user receiver. The categories are seen in Figure 3.

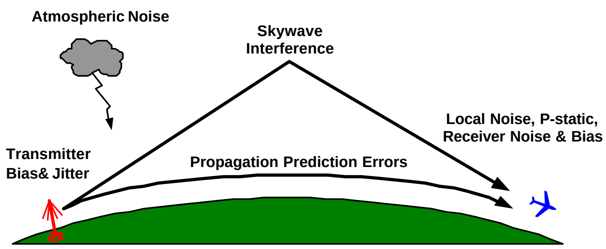

Figure 3. Threats to Loran Integrity

4.1 Loran Transmitter Description & Threats

Loran's ability to meet RNP 0.3 navigation performance begins at the Loran transmitting site. Signal in space integrity is ensured by validating that the signal transmitted from the antenna meets or exceeds the requirements contained in the signal specification [10]. The equipment at a Loran transmitter can be divided into two major divisions: 1) the operational timing and frequency equipment; and, 2) the transmitter and antenna coupler.

3.1.1 Operational Timing & Frequency Equipment

The operational timing and frequency equipment is the heartbeat of the Loran pulse train. Three cesium based frequency standard clocks set the timing reference for the Loran pulse train. As such, equipment failure or clock drift could result in timing shifts. Part of the concern is alleviated by the upgrade to new Agilent 5071A's in 2000. The new cesium clocks have significantly greater stability and accuracy as shown by their average drift rate of less than 7 nanoseconds per day verses the old clocks with rates up to 200 nanoseconds per day.

Another concern is time synchronization to a common clock standard. Discrepancies in timing from station to station will result in range errors. The new Timing and Frequency Equipment (TFE) creates an ensemble from the three frequency standards and synchronizes the ensemble to USNO-UTC via GPS timing signals. The ensemble can freewheel without GPS for nearly two weeks without exceeding the 100-nanosecond goal necessary to maintain the 307-meter accuracy required for RNP 0.3. The LSU is also exploring alternate methods to maintain synchronization to USNO-UTC without using GPS. Each of these time transfer methods being investigated will have an associated integrity analysis with appropriate parameters.

3.1.2 Transmitter & Antenna Coupler

The LORIPP will only perform analysis of solid-state transmitters since the remaining 1960's tube technology stations will be replaced with new solid-state transmitters under LRP. The new solid-state transmitters help alleviate some concerns, such as momentary off airs, brought up in the first certification effort. They have greater reliability and performance that enhance Loran's continuity and availability. Administrative momentary off-airs associated with the solid-state transmitter switch will be far less common and significantly faster[6]. For the thirteen prior generation solid-state transmitters, a new switch cabinet with a revised coupling network will be installed. The new coupling network is capable of switching paths in less than 3 seconds. In addition, the requirement for administrative momentary off-airs is again significantly reduced with the complete redesign of the switch cabinet.

These changes mitigate some reliability concerns. However, since all hardware is subject to failure, hardware faults will have to be examined. Fault analysis for both generations of solid-state transmitter will be conducted. For example, failure of solid-state transmitter hardware such as half cycle generators (HCGs) can cause timing shifts and other errors that result in phase errors at the receiver. Failure of transmitter equipment can also affect ECD.

3.1.3 Transmitter Faults on ECD

Thus far, we have only mentioned the effects of transmitter fault on phase and timing. However, transmitter faults can also result in ECD errors. The Loran Signal Specifications [10] contains the specifications for nominal ECD's as measured in the transmitter antenna current. While ECD is measured at the transmitter, blink[7] is initiated based on far field observations at the System Area Monitor (SAM). Typically blink is initiated manually by the Coast Guard watchstander if the observed ECD varies from the controlling standard ECD (CSECD) by more than 1.5 μsec. The LORIPP will be investigating whether or not transmitter ECD blink will be necessary to meet integrity requirements. In general, it is probably safe to say that much tighter tolerances than 1.5 μsec will be necessary to meet better than 10^{-7} cycle integrity requirements. Present efforts are analyzing the ECD data from current Loran monitors (along with TD signal strength and SNR) and developing a data acquisition program to collect data on the ECD of every transmitted pulse. In addition to ECD analysis, a HMI analysis is being conducted to ensure the Automatic Blink System can detect all possible faults minimizing possible out of tolerance conditions without blink.

3.1.4 Transmitter Equipment Monitoring

The Remote Automated Integrated Loran (RAIL) system monitors and controls all of the Loran transmitting equipment within the station. RAIL allows remote operators to switch to redundant equipment if the need arises. The majority of the equipment at each transmitting station is fully redundant of its own right and will automatically switch over to the backup side when fault conditions arise. The equipment will report faults and current status to the station personnel and the remote operator both via RAIL. The Equipment Control and Monitoring system constantly tracks status of vital facility systems such as the back-up generators and the two UPS systems that provide continuous power to the transmitter and TFE. Finally, the Automatic Blink System provides the integrity monitor for the transmitted signal by blinking the Loran signal during out of tolerance conditions[8].

The LORIPP team will examine whether the control and monitoring devices installed in the Loran transmitting site will meet the RNP 0.3 requirements.

3.2 Propagation Prediction Error

3.2.1 Additional Secondary Factors

Loran-C is accurate only to the extent the groundwave time of arrival can be transformed to geodetic distance to the transmitting antennas. Since its inception, the Loran-C groundwave propagation time has been defined as the sum of a primary factor (PF), a secondary factor (SF), and an additional secondary factor (ASF). If there is no range error, then Equation (1.2) gives the relationship between these factors and the true propagation time.

$$\begin{aligned} \text{True Propagation Time} &= PF + SF + ASF \\ ASF &= \text{True Propagation Time} - PF - SF \end{aligned} \quad (1.2)$$

Both these first two terms can be easily calculated and are functions only of distance. However, since groundwave propagation speed varies depending on the terrain features that the signal traverses from the antenna to the receiver, an additional term is necessary. Hence ASF, the third term, is the difference between the true propagation time

6 Administrative off-airs will be monthly to quarterly versus every two weeks with the tube transmitters. Additionally, switching time to the redundant equipment will be reduced from 14-22 seconds to 3 seconds.

7 Blink is the turning on and off of the first two pulses of a GRI. This feature alerts users to out of tolerance conditions at the transmitter.

8 A proposed policy change is to have a station cease transmitting if an out of tolerance condition is detected. In an all-in-view environment an off-air is easier to detect and aids in meeting the time to alarm function for the RNP 0.3 requirement.

and the first two terms. ASF can, in theory, be calculated. However, there have always been difficulties in getting enough information to fully characterize the propagation path. Besides the fact that there are no published ASFs over United States land, studies under this effort have shown available ASFs barely meet ¼-nm 2drms accuracy requirement. Without more accurate ASFs, ASF prediction error is potentially a large source of range error.

The LORIPP is performing a regional ASF data collection effort to better model ASF propagation errors. The hypothesis is that Loran accuracy can be improved to 307 meters by significantly reducing ASF errors. This calibration, unlike past efforts, must recognize ASFs can have significant seasonal variations. An accurate calibration also requires that a constant time of transmission (TOT) timing control be used. Currently, Loran transmitter timing is controlled by System Area Monitors (SAMs), which regulate the transmission times of secondary stations relative to the master station. Since the SAMs are not collocated with the transmitters, the monitoring is affected by unknown and non-constant propagation and transmission delays. Under TOT control, each transmitter uses a common time standard for transmission. This method enables a more precise time of transmission determination by users vis-a-vis SAM control.

While the equipment for TOT has been specified, such a system has not been deployed in the US and will not be fully deployed for at least another two years. The calibration must start before then so special equipment and methods are being developed and installed. The current plan is to deploy data collection equipment by early 2003.

3.2.2 Other Prediction Terms

In addition to having accurate ASF predictions for range measurements, there may also be a need to examine ECD predictions. Cycle error will result if ECD prediction errors are too great. A better model for ECD prediction should reduce the probability of cycle error.

ECD prediction is necessary since the ECD changes from the time the Loran pulse leaves the transmitter. The near far field signal is essentially the time derivative of the antenna current and therefore its ECD is approximately +2.4 μsec relative to transmitted ECD. The ECD changes in the negative direction as the groundwave propagates. This change is because the group (or envelope) velocity differs from the phase (or zero crossing) velocity. The difference is due to different phase velocities at the different frequencies within the Loran band. In order to meet cycle integrity requirements, it is anticipated that certified receivers will have to predict these changes and compare predicted to observed ECD in the cycle selection process. One effort to predict these changes in ECD as a function of ground conductivity using a large quantity of flight data collected throughout CONUS is documented in [11].

Signal strength is used by the receiver to determine the reliability of a measurement. It is also used in the LORIPP analysis for coverage prediction. The effects of terrain on signal strength or ASF may also need to be examined [12, 13]

3.3 Interference at the Receiver

Interference at the receiver can come from many sources. There are natural sources of interference such as atmospheric noise and static discharge, Loran generated interference, and other man made interference.

3.3.1 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 [14] cause the ground to act as a waveguide, this low-frequency noise may propagate for thousands of kilometers.

With the Loran signal centered at 100 kHz, atmospheric noise tends to be a primary source of interference while in flight. The addition of noise on the signal will impact the position solution by introducing an additional phase offset and if the noise is severe enough may even cause the receiver to track the wrong cycle.

Proper modeling of atmospheric noise is also important. When these effects are evaluated analytically, they have been shown to be inversely proportional to the square-root of the signal-to-noise ratio (SNR) [15]. These SNRs are in turn used for the coverage analysis and HPL calculations. If the noise calculations lack adequate conservatism, we may overestimate coverage or calculate an HPL that is not adequate for the desired level of safety. Therefore, the accuracy of our integrity calculation inherently resides in the accuracy of the noise value.

An additional complication of atmospheric noise is its impulsive nature. Thus it is very different from white Gaussian noise. Since a typical receiver is optimized for white Gaussian noise, performance can be severely degraded when the noise is impulsive [16]. [16] also shows that by better characterizing the noise environment with an analytical model, a non-linear adaptive filter may be designed to greatly improve the performance of a receiver over the typical matched filter.

3.3.2 P-Static

Another important natural noise source in the VLF/LF bandwidth is "Precipitation Static" or P-static [17, 18]. P-static is cause by the rapid discharging of free charges that build up on sharp edges. For aircraft, there are several charging mechanisms: frictional charging, engine charging, and exogenous charging[9].

P-static comes in three forms – arcing, streaming and corona. The discharge can significantly increase the noise level and significantly decrease SNR. The reduced SNR can cause greater phase error and potential cycle error. P-static also can result in a loss of signal availability.

Aircraft can reduce P-static effects by including static dischargers, usually mounted on the trailing edges of the aircraft. Traditionally, Loran users have used simple "whip" or "wire" E-field antennas that sense vertically polarized electric fields. These antennas are effective in maritime and terrestrial applications. However, on aircraft, where there is no convenient access to electrical grounds, their high impedance allows charge to buildup.

An H-field antenna offers mitigation to P-static interference. H-field antennas have one or more loops of wire in which a current is induced by the horizontally polarized magnetic field components of the Loran signal. Such antennas have relatively small effective heights and low impedance. Galvanically connected to the aircraft, they are not subject to the electrostatic field of the free charges, and are much less sensitive to P-static. Disadvantages of the H-field include requiring "steering circuit" logic and a very low noise, high gain pre-amplifier. In addition, the receiving system is very sensitive to antenna placement to avoid "accidental" noise from the aircraft. Such placement can require careful "skin mapping" exercises. The current FAA effort is committed to developing practical H-field antenna/receiver sets and testing their effectiveness. Several of the receivers being developed and tested in this project are using H-field antennas developed by Megapulse and Locus.

To date, tests have been performed by charging aircraft parked in or just outside a hangar. Preliminary tests show that receivers using input from an E-Field antenna have shown more than 20 dB degradation in SNRs while receivers using the H-field antenna showed no degradation [19]. The remaining tests will focus on duplicating such measurements at the FAA's William J. Hughes Technical Center both on the ground and in the air.

3.3.3 Interference from Loran Signals

<u>Multipath – Structures</u>

As with GPS, there is a multipath problem for Loran-C. In rare occasions, structures with ungrounded metal of lengths that are significant when compared to Loran-C's 3 km wavelength can cause some discernible "re-radiation" effects. Such structures (suspension bridges or very long electrical transmission spans) are generally not located near airports and the effect tends to be localized. The mitigation would be to check airport approaches for such effect during the procedure design/calibration.

<u>Multipath – Skywave</u>

Another multipath problem for Loran-C is "skywave" interfering with the navigation signal. The principal signal used for Loran navigation is the signal that travels to the user along the ground, i.e., the "groundwave." The same transmitted signal can be reflected by the ionosphere, or even be reflected off the ionosphere, then the ground, then the ionosphere again. These lead to so-called "first hop" or "second hop" (or higher order) skywaves. "Multiple hop" skywaves can cause long delays in which a skywave version of the first pulse can "run into" later groundwave pulses. The Loran-C phase code mitigates this because its autocorrelation function is zero for all such delays[10]. Another problem is early skywave. This is mitigated by having a pulse shape that allows sufficient groundwave energy to be processed before significant skywave energy is received. However, studies indicate, that at high latitudes, skywave delays can be significantly shorter than specified in past government minimum performance standards (MOPs) [20]. An effort is planned to explore this issue and determine requirements for higher performance receivers to detect, and possibly eliminate, such problems.

<u>Cross-Rate Interference</u>

A final interference source is referred to as "cross-rate interference." Stations on different chains transmit at different rates or GRIs. Since all Loran-C chains share the same frequency band, when these signals arrive at a user simultaneously, they interfere with each other. Some mitigation is provided by the phase code, but that is not its primary purpose. There is an inevitable short-term interference effect, and even a long-term effect because

[9] Frictional charging results when aircraft pass through ice crystals and/or dense clouds. Engine charging stems from ionization in engine exhaust that produces outflowing positive ions, thus leaving negative charge on vehicle Exogenous charging occurs when aircraft passes through the electric field set up between two oppositely charged clouds

[10] The initial phase of a Loran pulse can be either 0 or 180 degrees. The initial phase of a set of Loran pulses over two GRI is selected so that this set has an autocorrelation function of zero with any delayed version of the pulses. This is known as phase coding and it allows the receiver to filter out long delay skywave.

the code is not balanced [21]. Linear processing is necessary to achieve some of the advantages of modern hardware. Linear processing requires some method of cross-rate interference elimination. Simple “blanking” or “hole punching” is effective in some, very low vehicle dynamic applications. However, in aviation, another method is necessary. An innovative solution to this problem that effectively eliminates the interference is described in [21]. The method uses narrow notch filters to eliminate cross-rate interference. It will have to be refined if significant modulation is broadcast on the signals, but it is expected any RNP 0.3- certified Loran avionics would employ an implementation of this method.

3.3.4 Other Issues

Loran-C shares the low frequency (LF) band with communications and other navigation system transmitters. In North America, the 90-110 kHz frequency band is reserved for Loran-C. Since the Loran pulse has energy outside this band, receiver front ends must remain wide to minimize shape distortion. However, this design also lets in interference from other LF sources. The effects can be mitigated by the use of notch filters which, themselves, will introduce second order effects such as phase delay and phase modulation (spectral asymmetry). These phase effects can be calculated and compensated for using digital filters.

Spurious emissions from other aircraft systems are a concern, especially for H-field antenna systems. Appropriate shielding, grounding, and bonding can mitigate the effects.

In relatively rare cases, receivers can be adversely affected by accidental or deliberate interference from ground sources, as is a major concern for GPS. However, efficient LF transmitting systems at Loran frequencies are not easy to build. Such interference would cover a large region and would be relatively easy to detect though they are so rare that they can initially be mistaken for other effects. The Coast Guard has had success with this problem. It maintains a substantial monitor receiver network and, accordingly, has developed and maintained some engineering-level expertise in receiver performance characteristics.

The interference forms described above can cause receiver errors in phase measurements and ECD. Ref [22] analyzes ECD measurements with noise and cross rate interference. It is fairly straightforward to conclude from [22] that achieving the required cycle integrity in a three station (or triad based) fix will be very difficult and that algorithms that verify cycle using redundant information will be necessary. One mitigation technique is to use long averaging times to reduce ECD errors to a tolerable level. This may be possible using Doppler or inertial sensors. However, continuous wave (CWI) and cross rate (CRI) interference also contain synchronous components that show up as ECD bias [22] independent of averaging time even after canceling or notching has been applied. Early skywaves can also cause bias in the ECD measurement. A study where this problem was particularly acute is in [20]. Mitigation for these ECD errors will be examined since due to the importance of tracking the correct cycle.

3.3.5 Receiver Calibration

While not a major threat, there should be some consideration given to receiver calibration. The receiver software needs to know exactly what the radio frequency (RF) front end has done to the Loran pulse in order to make an accurate measurement of ECD. Narrow band, high Q, analog bandpass and notch filters can change characteristics with time and temperature. This can be solved by occasionally having the receiver self calibrate. An alternative approach is to implement the notch and bandpass filters in software.

4. INTEGRITY & AVAILABILITY

There is an inherent trade off between integrity and availability. For example, in the HPL equation, we can set very large error bounds. This would certainly increase integrity by reducing the probability of HMI. However, it decreases availability since fewer solutions will meet the RNP 0.3 requirements on the position error bound.

The Loran program is facing an integrity/availability issue relative to ASF prediction errors. The basic presumption is that for aviation use integrity is the more important requirement. Therefore, because of current uncertainties in ASF errors, meeting the 10^{-7} integrity requirement results in large areas of the Midwest falling below the 99.9% minimum availability requirement due to conservative assumptions in the analysis. The ASF characterization effort will greatly reduce, but may not eliminate, ASF as an error source leading to an improvement in availability. However, small pockets of the country may still potentially experience periods when availability is less than 99.9% due to a combination of factors (particularly atmospheric noise) described in previous sections of this paper. The Loran program will definitively address whether or not this is the case.

There are two potential mitigation alternatives if an availability issue exists. The first is to add another Loran station in Iowa and the Yucatan penninsula at about nine million dollars (US) each. These stations will ensure an overdetermined solution in areas where geometry, number of usable stations, SNR, etc. are a problem should a station go off air.

The second alternative is to accept short periods where small areas of the country experience something less than

99.9% availability. The policy question is whether or not this is acceptable for a back-up navigation system. The answer to this question appears to be yes given other proposed back-up navigation architecture alternatives. Loran will provide higher availability than the other navigation alternatives.

5. ACCURACY

In the course of the LORIPP analysis, the issue increasing Loran accuracy also arises. While the LORIPP envisions that Loran will meet the RNP 0.3 accuracy requirements with improved ASFs, there is also a need for Loran to serve harbor/harbor approach. As a result, the Loran Accuracy Performance Panel (LORAPP) has been formed to examine issues related to increasing Loran accuracy for maritime activities.

6. LORAN DATA CHANNEL

The LORIPP is also examining the use of the Loran data channel. No decision has been made concerning the data channel and its implementation. The preliminary view on the data channel is that, if implemented, its primary purpose is to broadcast data, such as station identification or time tag, which would aid in achieving RNP 0.3 integrity requirements. Since the data is either constant or have long time constants, the data requirement is minimal and additional data bandwidth can be used for other uses such as increasing accuracy. However, the LORIPP viewpoint is that the data channel is first and foremost to be used to serve Loran integrity.

7. CONCLUSIONS

The trials conducted during the 1980's identified several shortfalls that prevented Loran from achieving certification for non-precision approaches. Since then, new receiver, antenna, and transmitter technologies present an opportunity to mitigate each shortfall identified. The LORIPP is investigating these new technologies against the more stringent RNP 0.3 requirements for non-precision approaches in the future National Airspace System.

The HMI analysis results to date provide a very strong indication that Loran can meet the RNP 0.3 requirements for accuracy, availability, integrity, and continuity. However, the investigation is not yet complete. There is still significant work remaining to develop the substantiating data needed to prove Loran can meet the RNP requirements. At this point, the two largest issues appear to be atmospheric noise and ASF propagation corrections that impact availability and accuracy, respectively. The LORIPP is addressing these and other issues through testing and a rigorous analytical methodology using the GPS WAAS model.

Loran theoretically is an ideal redundant navigation system for GPS if it can satisfy RNP 0.3 requirements. The outcome from the LORIPP investigation will be a definitive answer on Loran's ability to meet RNP 0.3 navigation requirements for aviation.

REFERENCES

[1] Willoughby, Malcolm F., "U.S. Coast Guard in World War II", USNI, 1957.

[2] Bragaw, Louis K., "Managing a Federal Agency: Hidden Stimulus," John Hopkins University Press, Baltimore, 1980.

[3] van Willigen, D., "Eurofix: Differential Hybridized Integrated Navigation," Proceedings of the 18th Annual Symposium of the Wild Goose Association, Hyannis, MA, November 1989.

[4] Peterson, B. B., Boyer, J. M., Schue, C. A., and Betz, J. R., "Enhanced Loran-C Data Channel Project," Proceedings of the International Symposium on Integration of LORAN-C/Eurofix and EGNOS/Galileo, March 2000, pp. 186-197.

[5] Lo, S., and Enge, P., "Broadcasting Data from an SBAS Reference Network over Low Rate Broadcast Channels," Proceedings of the International Symposium on Integration of LORAN-C/Eurofix and EGNOS/Galileo, March 2000, pp. 199-209.

[6] FAA (AND-700) report to DOT, An Analysis of Loran-C Performance, its Suitability for Aviation Use, and Potential System Enhancements, July 2002.

[7] "Critical Foundations: Protecting America's Infrastructures, The Report of the President's Commission on Critical Infrastructure Protection," October 1997.

[8] "Vulnerability Assessment of the Transportation Infrastructure Relying on the Global Positioning System," John A. Volpe National Transportation System Center, August 20, 2001.

[9] Weeks, G. W., and Campbell, M., "Status of the Loran Recapitalization Project (The Four Horsemen and TOC)", Proceedings of the ION Annual Meeting, Albuquerque, NM, 24-26 June 2002.

[10] U. S. Coast Guard, Specifications of the Transmitted Loran-C Signal, COMDTINST M16562.4A, 1994.

[11] Peterson, B. and Dewalt, K., "Analysis of Envelope-to-Cycle Difference (ECD) in the Far Field," Simulation, Vol. 60, No. 5, pp. 327-334. May 1993.

[12] Peterson, B., Bruckner, D., Danish, M., and Morris, P., "Analysis of Terrain Effects on DGPS and LORAN Signals," Proceedings of the Institute of Navigation National Technical Meeting, Anaheim, CA, January 2000, pp. 258-267.

[13] Last, D., Williams, P., and Dykstra, K., "Propagation of Loran-C Signals in Irregular Terrain – Modelling and Measurements: Part 1: Modelling," Proceedings of the 29th Annual Meeting of the International Loran Association, Washington, DC, November 2000.

[14] Uman, M. A., "The Lightning Discharge", Dover Publications, Inc., Mineola, NY, 2001.

[15] Peterson, B. et. al., "Hazardously Misleading Information Analysis for Loran LNAV", Proceedings of the International Symposium on Integration of LORAN-C/Eurofix and EGNOS/Galileo, June 2002

[16] Middleton, D., and Spaulding, A. D., "A Tutorial Review of Elements of Weak Signal Detection in Non-Gaussian EMI Environments", NTIA Report 86-194, US Department of Commerce, May 1986.

[17] Morris, P.B., Gupta, R.R., and Warren, R.S., Creamer, P.M., "Omega Navigation Course Book," Prepared for the U. S. Cost Guard Navigation Center, July 1994, Chapter 12.

[18] van Grass, D. H., and van Grass, F., "Aircraft Loran-C Dual Loop Antenna System Design and Flight Test,", Proceedings of the ION National Technical Meeting, San Diego, CA., 22-24 January 2001.

[19] Schick, P., Hannon, P., Ren, Z., and Weikert, J., "Use of a Single Analog-to-Digital Converter for Dual-Loop Loran H-Field Antenna," Locus, Corp. Proceedings of the 29th International Loran Associating Meeting, Washington, DC, November 12-15, 2000.

[20] Peterson, B., Gross, K., Chamberlin, and Sheppard, E., "Port Clarence Skywave Interference Study," presented at the 22nd Annual Wild Goose Association Technical Symposium, Santa Barbara, October 1993.

[21] Peterson, B., Gross, K., and Bowen, E., "LORAN Receiver Structure for Cross Rate Interference Cancellation," Proceedings of the 22nd Annual Wild Goose Association Technical Symposium, Santa Barbara, CA, 1993

[22] Peterson, B. B., Thomson, T. N., and Riffe, J., "Measurement of LORAN-C Envelope to Cycle Difference in the Far Field," Proceedings of Wild Goose Association, 20th Annual Technical Symposium, Williamsburg, VA., Oct. 1991. Also NTIS report number PB92-128909/AS.

DISCLAIMER