Effects of Lightning on Low-Frequency Navigation Systems

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ABSTRACT

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Low Frequency (LF) navigation systems operate in the frequency band from 30 to 300 kHz. In this frequency band, the effect of atmospheric noise caused by lightning is one of the primary contributors to the noise floor as observed by a receiver. This Thesis investigates the effects of lightning on the Long Range Navigation (Loran-C) system which operates at 100 kHz with a 20-kHz bandwidth. Flight test data were collected and analyzed for both normal and lightning conditions for electric field (E-field) and magnetic field (H-field) antennas. It was found that both the E-field and H-field antennas are affected similarly by lightning-induced noise. Pulse durations due to lightning discharges are on the order of 0.1 to 0.6 ms, both during normal and thunderstorm flight test conditions. The average number of noise pulses per second during normal conditions was approx. 111 pulses for both antennas. During thunderstorm conditions, the average number of noise pulses per second increased by a factor of three for both antennas compared to the number during normal conditions. By discarding Loran pulses affected by lightning, an improvement in SNR was achieved for both E-field and H-field antennas.

Approved: _____________________________________________________________

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I would like to dedicate this Thesis to my Grandfather who was truly an inspiration to me. I would like to thank my parents, Anwar and Talat Latif for always being there for me in good and bad times: this thesis would not have been possible without all your prayers, support and encouragement.

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<td>LOng RAnge Navigation</td>
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<td>GRI</td>
<td>Group Repetition Interval</td>
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<tr>
<td>SNR</td>
<td>Signal- to-Noise ratio</td>
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<td>RMS</td>
<td>Root Mean Square</td>
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<td>eLORAN</td>
<td>Enhanced Loran</td>
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<td>CW</td>
<td>Continuous Wave</td>
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<td>RF</td>
<td>Radio Frequency</td>
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<td>s</td>
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<td>rad</td>
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<td>ms</td>
<td>Millisecond</td>
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<tr>
<td>µs</td>
<td>microsecond</td>
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<td>LOP</td>
<td>Line of Position</td>
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<td>GPS</td>
<td>Global Positioning System</td>
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<td>Emission Delay</td>
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<td>RF</td>
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<td>IFR</td>
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<td>AEC</td>
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<td>ADF</td>
<td>Automatic Direction Finding</td>
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<td>ITU</td>
<td>International Telecommunication Union</td>
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1 INTRODUCTION

Low Frequency (LF) navigation systems operate in the frequency band from 30 to 300 kHz [1]. In this frequency band, the effect of atmospheric noise caused by lightning is one of the primary contributors to the noise floor as observed by a receiver [2]. At the time of this writing, the Long Range Navigation (Loran-C) system is the only LF navigation and timing system operational in the world. Therefore, this thesis focuses on the effects of lightning on the Loran-C receiver.

Loran-C is a ground-based radio navigation system which operates in the radio frequency band of 90-110 kHz. The Loran-C system as it exists at the time of this writing provides better than 0.25 nautical mile horizontal positioning accuracy (95%) and 10-100 ns timing accuracy for users within the Loran-C coverage areas [3]. Loran-C provides service to land, maritime, and aviation users. For aviation, it is approved for en-route flight under both Visual Flight Rule (VFR) and Instrument Flight Rule (IFR) conditions. During recent years, several Loran-C performance enhancements have been implemented, including solid state transmitters, improved monitoring of the signal broadcast and improved timing. Additional improvements are being investigated to increase the Loran-C timing and positioning performance. The resulting system is referred to as enhanced Loran or eLoran [4]. Some of the additional improvements under consideration are:

- **Loran Data Channel (LDC)** The addition of a data channel to broadcast corrections or warnings through the use of pulse position modulation of the broadcast signal [4].
• **Time of Transmission control (TOT)** This method of timing control of the Loran transmitters does not rely on remote monitor sites. In addition to Master Station synchronization to the Universal Coordinated Time (UTC), all Secondary Stations will also be synchronized to UTC. This change will improve Loran receiver timing performance and will also improve absolute positioning accuracy for users that are not close to the existing monitor sites [4].

Enhanced Loran (eLoran) incorporates the latest receiver, antenna and transmission system technology to enable Loran-C to serve as a high-accuracy navigation and timing system. For example, eLoran enables two-dimensional positioning accuracies of 8-20 meters (2 drms, or twice the radial distance root-mean-squared) for harbor entrance and approach. eLoran can also function as an independent, accurate source of Universal Time Coordinated (UTC).

Loran error sources include atmospheric noise, man made noise, precipitation static and continuous wave interference [5]. Atmospheric noise is dominated by lightning discharges produced by thunderstorms all over the world. Atmospheric noise increases when lightning discharges occur closer to the receiver, which is generally the case during the summer. In order to improve the performance of the Loran receiver in the presence of lightning discharges, the effects of lightning on the received signal structure must be characterized. This information can then be used to design and evaluate receiver processing algorithms that operate effectively in the presence of lightning.

The thesis is focused on the experimental characterization of atmospheric noise. Recorded data from two flight tests are used to gain a better understanding of the effects
of atmospheric noise and to obtain statistics on atmospheric noise. The next chapter provides background information on the Loran-C system, followed by a literature review on Loran noise in Chapter 3. Chapter 4 describes the flight test equipment setup, while the data processing is detailed in Chapter 5. Chapters 6 and 7 present the statistical analysis of the received Loran signal under normal and thunderstorm conditions. Chapter 8 provides the conclusions, followed by recommendations for future research in Chapter 9.
# 2 LORAN-C SYSTEM DESCRIPTION AND ERROR SOURCES

This chapter provides the principle of operation of Loran-C. Loran-C is a land-based two-dimensional positioning system. It can also be used as a timing system. In addition, Loran-C also provides a data broadcast capability. With the development of eLoran, significant improvements can be anticipated in all three areas of positioning, timing, and data broadcast [4].

## 2.1 Loran Signal

An individual Loran pulse is shown in Figure 2-1. The pulse envelope reaches its maximum amplitude in 65 $\mu$sec and at that instant of time, it starts an exponential decay to zero which lasts for approximately 185 $\mu$sec. This results in a Loran pulse that is approximately 250 $\mu$sec in time duration [1]. The mathematical expression for the current that is provided to the Loran antenna is given by [6]:

\[
i(t) = \begin{cases} 
  0; & \text{for } t < \tau \\
  A(t - \tau)^2 \exp \left( -\frac{2(t - \tau)}{65} \right) \sin(\omega t + PC); & \text{for } \tau \leq t \leq 65 + \tau
\end{cases}
\]

where:

- $A$: Constant related to the magnitude of antenna current in amperes.
- $t$: Time in microseconds.
- $\tau$: Envelope to cycle difference in microseconds.
- $PC$: Phase code in radians (0 for positive phase code and $\pi$ for negative phase code).
- $\omega$: Carrier Frequency ($0.2 \pi$ rad/$\mu$sec).
The timing of the Loran pulse is defined relative to the third positive-going zero-crossing of the pulse also referred to as the standard zero-crossing. The third zero-crossing was selected to avoid contamination of the ground wave by a sky wave, while maximizing the received signal strength for the timing measurement [6].

The Loran signal as received by a Loran-C receiver consists of a series of pulses that originate from a Master station followed by additional series of pulses broadcast by Secondary stations. The signal from a Master station consists of a total of nine pulses; eight pulses spaced by 1 ms followed by a ninth pulse that occurs 2 ms after the eight pulse. The Secondary stations broadcast eight pulses spaced by 1 ms. The timing of the Master and Secondary transmissions is implemented in such a way that the pulses do not overlap within the coverage region for a particular chain. A chain consists of one Master station and up to five Secondary stations. Figure 2-2 shows pulse patterns from Master and Secondary stations.
2.2 Loran System Structure

The Loran system is organized in chains of three to six transmitters. The transmitters are generally placed between 500-1000 km from each other. In the hyperbolic mode of operation, each Master-Secondary pair provides one line of position. The line of position is determined by the time difference (TD) of arrival (TDOA) of the pulses from the Master station and a Secondary station. As shown in Figure 2-3, the Master station first transmits its pulses, which are followed by the Secondary station transmissions. The time interval between Master Station pulse group transmissions is called the Group Repetition Interval (GRI). The GRI is specified in microseconds. Each Loran chain has its own GRI for identification of the chain [7].

Figure 2-2 Master and Secondary station pulse patterns.
2.3 Position Determination

In the hyperbolic mode of operation, two-dimensional, horizontal position determination is accomplished using two TDOA measurements between one Master and two Secondary stations. Each TDOA forms a hyperbolic line of position (LOP). The intersection of two or more LOPs in the chain’s coverage area provides the position of the user [1].

Specifically, consider a Master station (M) signal transmission that is received by user (U) and Secondary (S). The time it took the pulses to travel from the Master to the Secondary is defined as the baseline travel time. After reception of the pulses at the Secondary station, it transmits its pulses after a fixed delay, defined as the coding delay (CD). The sum of baseline travel time and coding delay is known as the emission delay (ED). Each Secondary station has its own ED to ensure that pulses from one chain to not overlap within the coverage area of the chain. Figure 2-4 shows the TD measured between the Master and the Secondary station that is used to find the LOP [1].
Figure 2.4 Graphical Description of Computing Time Difference (TD) [1]
2.4 Loran Error Sources

Loran signals experience delays or distortion due to multiple error sources, including transmitter errors, propagation delays, sky waves, receiver errors, and several noise sources. The focus in this thesis is on Loran noise error sources to address the uncertainties related to actual Loran performance during lightning conditions. Loran noise can be separated into five categories. These categories are summarized in the next five sections.

2.4.1 Man-Made Noise

The Loran receiver may experience noise from man-made equipment such as power transmissions, electrical and mechanical machineries in factories, generators, and car ignitions. Man-made noise depends on the area of operation. This type of noise is much higher in urban and industrial areas than in rural or residential areas [8].

A receiver close to a man-made noise source can experience major interference and normal Loran reception can be nearly impossible. Even thousands of feet up in the sky, man-made noise can still cause major interference and make it difficult for the user to navigate, unless the receiver is designed to mitigate this type of noise [8].

2.4.2 Precipitation Static (P-static)

P-static is caused by charged water particles, snow or dust, which cause the aircraft to become electrically charged during flight. Noise is generated as the aircraft discharges to the surrounding air. The faster the aircraft moves, the faster the charge accumulates on the aircraft, which, in turn, causes a stronger discharge noise. A typical charging current for a single engine aircraft is approx. 400µA, 750µA for a twin engine aircraft, and as
high as 1.5 mA for transport category jets [9]. Voltage build-up on the aircraft due to this charging can reach values on the order of 100 kV [9]. Precipitation static is mitigated through the use of magnetic field (H-field) antennas [7].

2.4.3 Atmospheric Noise

Atmospheric noise is one of the major noise sources encountered by low frequency navigation systems. Atmospheric noise is generated by electromagnetic discharges produced by thunderstorms all over the world. Sky wave propagation allows these high power electromagnetic signals to be received by users located thousands of kilometers from the source [8]. The closer the receiver is to a thunderstorm the higher the level of atmospheric noise. The level of atmospheric noise also depends on location and time of the year. Atmospheric noise levels are much higher during summer nights in tropical regions and much lower during winter nights in a polar regions [8].

2.4.4 Cross-rate Interference

Cross rate interference is caused by transmissions from other Loran chains. By design, within the coverage region for a chain, the pulse transmissions from the transmitters for that chain do not overlap. However, transmissions from other chains are based on different Group Repetition Intervals (GRI) and, on a regular basis, these pulses will partially or fully overlap with the desired pulses.

2.4.5 Continuous Wave Interference (CW)

CW interference is caused by transmitters that broadcast in or near the Loran frequency band from 90 to 110 kHz. The signal strength of the interfering signals depends on both
distance and propagation characteristics. At night, CW interference becomes more severe because of increased sky wave propagation [7].
3 LITERATURE REVIEW

As discussed in the previous chapter, the primary noise contributions for low frequency radio navigation systems are atmospheric noise, man-made noise, precipitation static, cross-rate interference and CW interference. Since this thesis investigates primarily the effects of atmospheric noise on a Loran receiver, this chapter reviews the previous work which has been done to mitigate the effects of atmospheric noise on a Loran receiver. In the early 1970’s, Dr. Feldman developed an atmospheric noise model for low-frequency navigation systems [3]. The model was specifically designed to investigate the characteristics of non-Gaussian noise generated by lightning discharges. Using the noise model, the performance of various non-linear atmospheric mitigation techniques was compared. These techniques included clipping, hole-punching, and hard-limiting. Clipping is implemented in a linear receiver by limiting the input voltage between negative and positive thresholds. Hole-punching sets the input signal to zero when it exceeds a positive or negative threshold, while hard-limiting converts the input into a 1-bit representation (either positive or negative one).

The results from simulations show that the analysis of these receiver techniques, using the atmospheric model, provides very close prediction of actual performance of these mitigation techniques. The noise model shows that the hard-limiter technique provides the best performance to mitigate atmospheric noise as well as cross correlation. However, the hard-limiter proofed less resilient against other types of interference like CW. In the 1970’s, hard-limiter receivers were used because of their relatively simple hardware and also low computing power requirements. The downside of the hard-limiter receiver is its
relative low accuracy, long startup time, and, as stated earlier, its susceptibility to CW interference. Linear receivers can largely overcome these shortcomings, but they are much more susceptible to cross-rate interference and atmospheric noise. In today’s era, new and improved linear receivers have tremendous amounts of computing power available, allowing advanced interference mitigation and tracking algorithms. This results in greater accuracies and improved robustness [3].

In 2004, Manish Lad compared three different flight tests in different weather conditions (normal, thunderstorm, and precipitation static) and concluded that E-field and H-field antennas are both affected similarly by lightning-induced noise. The results also showed that the H-field antenna is insensitive to P-static whereas the E-field antenna is pretty much unusable under severe P-static conditions [9, 10].

In 2006, Dr. Wouter Pelgrum documented in great detail the progress to date with both E-field and H-Field antennas for Loran-C [11]. The analysis in his dissertation shows that the most accurate way of determining in-band noise statistics is to first remove all Loran-C signals. He further analyzed and compared the effects of Loran ‘removal’ techniques and suggested that simply discarding (blanking) all tracked Loran signals is the most efficient way to measure noise and the noise amplitude distribution.

Dr. Pelgrum demonstrated that much of the noise in the Loran-C band is not only atmospheric noise; cross rate interference also plays a big role in signal degradation. It was concluded that if the noise sources are not mitigated properly it seriously impacts the performance of low-frequency navigation receivers. He further elaborated that even a single high energy atmospheric noise spike can severely deteriorate the tracking
performance. It was recommended that if the noise pulse hits the Loran pulse’s measurement point (third zero crossing point), the pulse should not be used for tracking whereas if the noise pulse only hits the falling edge (or the tail) of the pulse it can still be used for tracking.

In 2006, Dr. Lee Boyce presented an evaluation of the standard atmospheric noise model developed by ITU being used for Loran, and questioned the applicability of the noise model for a Loran receiver. The evaluation of the ITU model shows that it accurately predicts both the long term and short term time scales for ITU’s 200 Hz narrow-band system, but the ITU researchers gave no assurances that the same data are applicable to the 20 kHz wide band Loran system centered at 100 kHz. The ITU model was also compared with the model developed by atmospheric physicists and agreements were found for both short and long term timescales. A constant non-linear processing gain of 12 dB was estimated when using a non-linear signal processing technique (hole punching or clipping). The result show that when accounting for the non-linear processing gain through the use of the ITU model, the SNR improved by 8 dB and also the coverage increased from 90-95% throughout the US continent [12].

The analysis by Pelgrum and Boyce show that properly mitigating atmospheric noise improves the SNR and thereby the Loran coverage. Analysis by Pelgrum shows that using non-linear signal processing techniques such as hole punching or clipping can cause severe discontinuities and it is better to discard the complete Loran pulses that are affected by noise pulses. With the availability of high computing power it is now possible
to detect and discard complete Loran pulses which are affected by noise pulses from averaging and tracking rather than clipping the signal or replacing it with zeros.

The work presented in this thesis describes the characterization of atmospheric noise pulses in terms of width and amplitude, using airborne Loran data collected in the presence of normal and lightning conditions. Comparing the data from both normal and lightning conditions provides insight into the impact of lightning on the performance of a Loran receiver. The SNR is first calculated using the traditional method, and also using a novel method in which the receiver is designed to eliminate the Loran pulses when hit by a noise pulse. The performance of the receiver using both methods is evaluated and the results are compared.
4 FLIGHT TEST EQUIPMENT SETUP

This chapter provides a brief description of the data collection system for the recording of Loran flight data. The main goal of the Loran data collection system is to collect radio frequency (RF) data in the Loran frequency band. The system was designed so that the data being collected look similar to the data that would normally be seen by an advanced Loran receiver [11]. For example, the filtering characteristics of the Loran data collection system are the same as the filtering characteristics of an advanced Loran receiver.

Figure 4-1 shows the Ohio University Douglas DC-3 research aircraft used for collecting airborne data.

Figure 4-1 Ohio University DC-3 Research Aircraft.
4.1 Airborne System

The data collection PC and the chassis containing the Loran equipment are placed on top of each other in a 19-inch rack and the rack is installed on the seat rails of the aircraft [13, 14].

Figure 4-2 shows the data collection system installed in the Douglas DC-3. The E-field and H-field antennas are used in the data collection system and the data collection box consists of Reelektronika’s Data Grabber, used to collect RF data in the Loran band and a GPS receiver to provide the reference position trajectory.

![Data collection system on DC-3](image)

Figure 4-2 Data collection system on DC-3
4.2 Data collection equipment

4.2.1 E-field Antenna

The E-field antenna used in the data collection system is an A16 antenna designed by UPSAT. It is a standard Loran antenna and has a built-in preamplifier. The antenna preamp is powered by an Apollo 618 Loran receiver [14].

![E-Field Antenna](image)

Figure 4-3 E-Field Antenna

4.2.2 H-field Antenna

A modified Automatic Direction Finding (ADF) antenna is used as an H-field antenna for the data collection system. This antenna has two independent loops wrapped around a ferrite core. A custom-made preamplifier is used to combine the output of each loop to form an omni directional phase pattern [15].
4.2.3 *Apollo 618 Loran-C receiver*

The Apollo 618 Loran receiver was built by II Morrow, Inc., and it is used to power the antenna pre-amplifier for the E-field antenna. It is also used to monitor the Loran signal to verify that the installation is working properly [15].

4.2.4 *Data collection PC*

The data collection PC was built by Cyber research. It contains two 933 MHz Pentium III single board computers. These single board computers have the option of supporting a Redundant Array of Independent Disks (RAID) on an IDE bus [14].

4.2.5 *LORADD_DD Data Grabber*

The LORADD_DD data grabber was developed by Reelektronika in The Netherlands. It was designed to collect RF data in the Loran band. The data grabber is capable of sampling two antenna input channels simultaneously at 400 kHz with 16 bits of resolution. The data grabber can be connected to both the E-field and H-field antennas. Data are transferred from the data grabber to the data collection PC via an Ethernet connection [16].
5 DATA PROCESSING

The main purpose of the data processing is to find a simple, efficient and reliable method of characterizing noise pulses and their statistics. In order to determine the noise statistics it is very important that the Loran pulses themselves do not affect the statistics. Different methods for the removal of the Loran pulses are presented in [11]. One efficient method of Loran pulse removal consists of first tracking and then removing all tracked Loran pulses.
5.1 Removal of Loran Pulses

Data collected during the flight tests are recorded at a rate of 400,000 samples per second. These data are processed in 2-second batches as illustrated in Figure 5-1. The next sections provide details on each of the processing steps.

![Figure 5-1 Data Processing (Flow chart).](image)
5.1.1 Identification & Reduction of Continuous Wave Interference

The first step in the processing is the identification and reduction of Continuous Wave Interference (CWI). CWI is removed by using a series of band stop filters each having a bandwidth of 500 Hz. If the same interfering frequency is detected in more than twenty 2-second data blocks, the band stop filter for that frequency is activated for the entire data set.

5.1.2 Identification of Loran Chains

The next step in the processing is to identify all the visible chains and the pulse locations of the Master and Secondary stations. In order to identify all the visible chains, for each GRI a 2-second data block is divided into GRI intervals and then the median value of each of the GRI samples is computed. Median values identify repeating signals from the Loran stations, while at the same time reject noise pulses that do not repeat at GRI rates. Pseudo code for the median processing step is shown below:

For each 2-second block of data

For each GRI

Divide the data block into GRI intervals

Calculate the median value for each GRI sample

End

End

Based on the median values, pulse locations of the Master and Secondary stations are calculated. First, a predicted GRI pulse mask is generated based on the location of the transmitters and the receiver (as obtained from the GPS receiver). The GRI pulse mask is
an array that contains the relative locations of the received Loran pulses. Next, the predicted GRI pulse mask is correlated with the calculated median value of the GRI intervals to obtain the pulse locations. Figure 5-2 shows the flowchart to identify the pulse locations.

Figure 5-2 Loran Pulse Locations (Flowchart).
5.1.3  Pulse quality measurement

The next step is to measure the quality of the Loran pulses from the transmitter with the strongest received pulses. This transmitter will be used for the timing correction of the receiver clock. The quality is determined by using the envelope of each pulse. The envelope of the pulse is calculated by computing the In-phase and Quadrature phase components of the pulse. The equations for computing the envelope for the Loran pulse are given below:

\[
I = y \cdot \cos(2\pi f_c t)
\]

\[
Q = y \cdot \sin(2\pi f_c t)
\]

And, \( Envelope = \sqrt{I^2 + Q^2} \)

where \( y \) are the data points and \( f_c \) is 100 kHz (Ideal carrier frequency)

The envelope is used to find the pulses that are distorted. A pulse is determined to be distorted if the pulse maximum location (65\( \mu \)s) point is 10 samples greater or less than the theoretical pulse offset, or the maximum amplitude of the pulse is 0.25 greater than the median value of all the pulses. The quality factor, \( Q_p \) is calculated as follows;

\[
Q_p = \frac{\text{total no of pulses} - \text{no of distorted pulses}}{\text{total no of pulses}}
\]

Figure 5-3 provides an example of the quality factor for a data set consisting of 163 2-second time intervals for one particular transmitter. The quality factor is used to identify distorted Loran pulses during the precise GRI integration step (see Section 5.1.5).
5.1.4 Time Correction

The time correction is used to correct the drift of the receiver clock based on the strongest transmitter. The change in the receiver clock is calculated from the difference of the arrival time of the strongest transmitter in the second 2-second data block and the arrival time in the first 2-second data block. The change in clock or clock drift is calculated for every 2-second data block. It is noted that this method has a small error due to the velocity of the aircraft. This error is not significant as the typical aircraft speed is 60 m/s, resulting in a maximum range error of 120 m over the 2-second data block, which is much less than the 3,000 m Loran wavelength.
5.1.5 Precise Group Repetition Interval (GRI) Integration

With the knowledge of the receiver oscillator drift, the measured data set is corrected for the oscillator drift and the GRI integration process is repeated. Pseudo code for the GRI integration step is shown below:

*For each 2-second block of data*

*For each GRI*

*Divide the data block into GRI intervals*

*Calculate the median value for each GRI sample*

*Calculate integration offsets by correlating predicted GRI with medians.*

*Check quality*

*If (quality > 0.6)*

*Integrate 2-second GRI interval.*

*End*

*End*

*End*

The quality of each 2-second GRI interval determines whether or not it is used in the signal integration. If the quality is below 0.6, which means that more than 40% of the Loran pulses are distorted, then a 2-second block is not used for integration. Figure 5-4 shows the result of integration of the first five strongest chains in the data.
Figure 5-4 Integration Results of Strongest Chains.
5.1.6 Removal of Loran pulses

The final step in the data processing is to remove the Loran pulses that can affect the noise statistics. The Loran pulses are identified by setting the samples that correspond to Loran pulses to zero in the data file. This process will also remove pulses due to noise that coincide with the Loran pulses. The latter is acceptable as long as the time interval between successive noise pulses is not of interest. For the analysis in this thesis, the emphasis is on the determination of the number of noise pulses per unit of time, and the length in time of these pulses. These statistics are not affected by the removal of the samples that contain Loran pulses since the Loran pulses and the atmospheric noise pulses can be assumed to be independent.

5.2 Noise Statistics

After the Loran pulses have been removed, approximately 10-15% of the measured data is available for noise characterization. A method was developed to find and record the pulses that exceed a certain threshold. This threshold was set to be 0.1 times the amplitude of the third strongest transmitter present in the recorded data. The choice of this threshold is based on the assumption that on average, noise pulses with amplitudes below this threshold will still allow for acceptable Loran navigation accuracy for aviation applications. A detailed analysis in support of this threshold is beyond the scope of this thesis and is therefore recommended for future research. All samples that exceed the threshold are recorded. Next, the leading and falling edges of the noise pulses as well as their amplitudes and time durations are determined from the recorded samples. Finally,
noise pulses that are adjacent to Loran pulses that were removed are discarded since the
duration of these noise pulses cannot be determined.

### 5.2.1 Signal-to-Noise Computation

SNR in Loran is defined as the ratio of RMS amplitude of the Loran pulse at the standard
sampling point to the RMS value of the noise present at that time [6]. The standard
sampling point is the point on the Loran pulse envelope 25 microseconds after the
beginning of the pulse. For the standard Loran pulse the amplitude at the standard
sampling point is approx 0.5 times the peak amplitude. The signal to noise ratio for each
2-second data block is computed by the two methods shown below:

**SNR Method A:**

In method A, the SNR is calculated based on the ratio of the RMS value of the Loran
pulse to the RMS of the noise samples, taken from the remaining samples after the Loran
pulses are removed.

The RMS value of the pulse is calculated by using the amplitude of the Loran pulse at the
standard sampling point: $N_{LP} = (0.506 \times PeakAmplitude)$

$$\text{RMS}_{\text{Loran Pulse}} = N_{LP_{rms}} = \sqrt{\frac{1}{l} \sum_{i=1}^{l} N_{LP_i}} = \sqrt{(N_{LP_1}^2 + N_{LP_2}^2 + \ldots + N_{LP_l}^2) / l}$$

Where $l$ is the total number of Loran amplitude values.

$$\text{RMS}_{\text{Noise}} = X_{rms} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} x_i^2} = \sqrt{(x_1^2 + x_2^2 + \ldots + x_n^2) / n}$$

Where $n$ is the total number of noise samples after removal of the Loran pulses, and $x$ is
taken from the measurement samples that remain after Loran pulse removal.
Method A provides the SNR without taking credit for the removal of known noise pulses.

**SNR Method B:**

In method B, the SNR is calculated based on the assumption that all noise spikes that exceed the threshold affect the Loran pulses. The corresponding Loran pulses are removed from the Loran processing. The SNR is calculated using the following equation:

\[
SNR_B = SNR_{spikes\_rem} - 10 \log_{10} \left( \frac{1}{1 - (N_{spikes} \times \tau_{spikes})} \right)
\]

Where, \(N_{spikes}\) is the number of noise spikes per second, and \(\tau_{spikes}\) is the mean duration of the noise spikes.

\(SNR_{spikes\_rem}\) is calculated using Method A, where the noise samples do no include the noise pulses that were removed. Method B takes advantage of a lower background noise floor since the noise pulses that exceed the threshold have been removed, but at the same time, the Loran power is reduced by the number of Loran pulses that were removed due to overlap with noise pulses.
6 FLIGHT TEST I (NORMAL CONDITIONS)

This chapter will discuss the noise statistics of the flight test performed in normal weather conditions. The flight test Loran data were collected on July, 12 2005 in Florida. The data recorded from the flight test were processed using the technique described in chapter 5. Data from both E-field and H-field antennas were processed and the results were examined and compared.

6.1 E-field Antenna Processing

Figure 6-1 shows an example of E-field antenna data before and after Loran pulse removal processing.

![Figure 6-1 Example of E-field antenna data before and after Loran pulse removal processing (Normal conditions)](image-url)
6.1.1 E-Field Results

As a result of the removal of the Loran pulses, 86.9% of the total samples were removed in this data set. The remaining 13.1% of the data (approx 17 million samples) was used for noise statistics.

Figure 6-2 shows the histogram of the width in seconds of noise pulses that exceeded the threshold.

![Histogram of duration of noise pulses in E-field antenna data](image)

**Figure 6-2 Histogram of duration of the noise pulses in E-field antenna data**

*(Normal conditions)*

Figure 6-2 shows that most of the noise pulses had a width of approx. 40-80 samples with a mean duration of 237.9 µs. There were 471916 samples that exceeded the
threshold in this data set for the E-field antenna. This represents 2% of the total number of samples which were used for statistical analysis.

Figure 6-3 shows the histogram of relative amplitude of the noise pulses.

Figure 6-3 shows that most of the noise pulses had amplitudes of 40-70 A/D level. Some of the noise pulses exceeded 1000 A/D level. The average number of noise pulses exceeding the threshold for 13.1% of the data is 15.2 pulses, which means that the number of noise pulses per second equals $\frac{15.2}{0.131} = 116$.
6.2 H-field Antenna Processing

Figure 6-4 shows an example of the data before and after Loran pulse removal processing.

![Before and After Processing Graph](image)

Figure 6-4 Example of H-field antenna data before and after Loran pulse removal processing (Normal conditions)
6.2.1 H-Field Results

As a result of removing Loran pulses 85.4% of the total samples were removed in this data set. The remaining 14.6% of the data (approx. 19 million samples) was used for noise statistics.

Figure 6-5 shows the histogram of the width in seconds of the noise pulses that exceeded the threshold.

Figure 6-5   Histogram of duration of the noise Pulses in H-field antenna data

(Normal conditions)
Figure 6-5 shows that most of the noise pulses had a width of approx 40-80 samples with a mean duration of 169.2 µs. There were 342315 samples that exceeded the threshold in this data set for the H-field antenna. This represents 1.7% of the total number of samples which were used for statistical analysis.

Figure 6-6 shows the histogram of relative amplitude of the noise pulses.

Figure 6-6 Histogram of relative Amplitude of the noise Pulses in H-field antenna data (Normal conditions)
Figure 6-6 shows that most of the noise pulses had amplitudes of 10-12 A/D level. The average number of noise pulses exceeding the threshold for 14.6% of the data is 15.5 pulses, which means that the number of noise pulses per second equals 15.5/0.146 = 106.

6.3 SNR calculation for Flight Test I

The SNR for the strongest transmitter was calculated using both method A and method B as explained in section 5.2.1. Based on the location of the flight test, the Southeast Chain was the strongest chain and Jupiter was the strongest transmitter in the chain. Therefore SNR was calculated for Jupiter. Figure 6-7 shows the configuration of the Southeast Loran Chain.

Figure 6-7 Southeast Loran Chain

During processing of the Loran data, the peak amplitude of the strongest transmitter Jupiter was recorded. The peak amplitudes were used to calculate the RMS of the Loran pulse. The RMS of noise pulses were calculated for each 2-second block after the removal of the Loran pulses using the root mean square method described in section
5.2.1. The Average SNR value for Jupiter was computed using both methods as shown in Table 6-1:

<table>
<thead>
<tr>
<th>Antenna</th>
<th>SNR (dB)</th>
<th>SNR (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Method A</td>
<td>Method B</td>
</tr>
<tr>
<td>E-field</td>
<td>28.5</td>
<td>35.6</td>
</tr>
<tr>
<td>H-field</td>
<td>28.3</td>
<td>32.3</td>
</tr>
</tbody>
</table>

Tables 6-1 shows that using method A, the average SNR value during the flight for both E-field and H-field antennas are almost equal. Using method B, the results show that the average SNR for the E-field antenna is increased by 7.1 dB and for the H-field antenna by 4.0 dB.

6.4 Comparison of the E-field and H-field Antenna for the Flight Test I

The noise statistics of the E-field and H-field antennas shows similar behavior in terms of noise pulses. Most of the noise pulses in both the antennas lasted between 0.1 and 0.5 ms. The amplitude of the noise pulses in the E-field antenna data was much higher as compared to the H-field antenna data. This is because of the different antenna characteristic of the E-field and H-field antennas. The number of noise pulses found per second was almost the same: 116 for E-field and 106 for H-field. Calculated average
SNR values using the traditional method A for E-field and H-field antennas were 28.5 dB and 28.3 dB, respectively. The fact that these values are almost equal shows that during normal conditions both antennas have similar performance. Method B, shows SNR improvements for both the E-field and the H-field antennas.
7 FLIGHT TEST II (LIGHTNING CONDITIONS)

This chapter will discuss the noise statistics of the flight test performed in lightning conditions. The flight test data were collected on July 13, 2005 in Florida. The data taken from the flight test were processed using the technique described in chapter 5. Data from both the E-field and the H-field antennas were processed and the results were examined and compared.

7.1 E-field Antenna Processing

Figure 7-1 shows an example of E-field antenna data before and after Loran pulse removal processing.

![Figure 7-1 Example of E-field antenna data before and after Loran pulse removal processing (Lightning conditions)]
7.1.1 E-Field Antenna Results

As a result of removing the Loran pulses 88.4% of the total samples was removed in this data set. The remaining 11.6% of the data (approx 15 million samples) was used for noise statistics.

Figure 7-2 shows the histogram of the width in seconds of the number of noise pulses that exceeded the threshold.

![Histogram of duration of the noise pulses in E-field antenna](image)

**Figure 7-2 Histogram of duration of the noise pulses in E-field antenna (Lightning conditions)**

Figure 7-2 shows that most of the noise pulses had width of approx. 60-80 samples with a mean duration of 275.3 µs. There were 1479413 samples that exceeded the threshold in
this data set for the E-field antenna. This represents 9.3% of the total number of samples which were used for statistical analysis.

Figure 7-3 shows the histogram of relative amplitude of the noise pulses.

![Histogram of relative amplitude of noise pulses](image)

**Figure 7-3** Histogram of relative amplitude of the noise Pulses in E-field antenna data (Lightning conditions).

Figure 7-3 shows that most of the noise pulses had amplitudes of 80-90 in A/D levels. There were few noise pulses which exceeded 10000 in A/D levels. As the aircraft is closer to the lightning strikes, the amplitude of the noise pulses increases. The average number of noise pulses that exceeded the threshold for 11.6% of the data is 41 pulses, which means that the number of noise pulses per second equals \( \frac{41}{0.116} = 353 \).
7.2 **H-field Antenna Processing**

Figure 7-4 shows an example of the data before and after Loran pulse removal processing for the H-field antenna during lightning conditions.

![Graph showing data before and after processing](image)

**Figure 7-4** Example of H-field antenna data before and after Loran pulse removal processing (Lightning conditions)
7.2.1 H-Field Results

As a result of removing Loran pulses, 86.7% of the samples was removed in this data set, the remaining 13.3% of the data was used for noise statistics.

Figure 7-5 shows the histogram of the width in seconds of the noise pulses that exceeded the threshold.

Figure 7-5 Histogram of duration of the noise pulses in H-field antenna data

(Lightning conditions)

Figure 7-5 shows that most of the noise pulses had width of approx 60-80 samples with a mean duration of 193.9 µs. There were 1012579 samples that exceeded the threshold in
this data set for the H-field antenna. This represents 5.6% of the total number of samples which were used for statistical analysis.

Figure 7-6 shows the histogram of relative amplitudes of the noise pulses.

![Figure 7-6 Histogram of relative amplitude of the noise pulses in H-field antenna data (Lightning conditions)](image)

Figure 7-6 shows that most of the noise pulses had amplitudes of approx. 10-12 in A/D level, but some of the noise pulses exceeded 1000-1200 A/D level, which is caused by lightning strikes close to the receiver. The average number of noise pulses that exceeded...
the threshold for 13.3% of the data is 40 pulses, which means that the number of noise pulses per second equals $40/0.133 = 301$

7.3 **SNR calculation of Flight Test II**

The SNR for the strongest transmitter is calculated using both method A and method B as explained in section 5.2.1. Based on the location of flight test II, the Southeast Chain was the strongest chain and Jupiter was the strongest transmitter in the chain. Therefore SNR was calculated for Jupiter. The configuration of the Southeast Loran Chain was shown in Figure 6-7.

During processing of the Loran data, the peak amplitude of the strongest transmitter Jupiter was recorded. The amplitudes were used to calculate the RMS of the Loran pulse. The RMS of the noise pulses were calculated for each 2-second block after the removal of the Loran pulses using the root mean square method described in section 5.2.1. The average SNR value for Jupiter was computed using both methods, and the results are shown in Table 7-1.

<table>
<thead>
<tr>
<th>Antenna</th>
<th>SNR (dB) Method A</th>
<th>SNR (dB) Method B</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-field</td>
<td>14.3</td>
<td>28.7</td>
</tr>
<tr>
<td>H-field</td>
<td>13.0</td>
<td>24.7</td>
</tr>
</tbody>
</table>
Tables 7.1 shows that using method A, the average SNR value during the flight for both E-field and H-field antennas are almost equal. Using method B the results show that the average SNR for the E-field antenna is increased by 14.4 dB and for the H-field antenna by 11.7 dB.

7.4 Comparison of the E-field and H-field antenna for Flight Test II

The noise statistics of the E-field and H-field antennas showed similar behavior. Most of the noise pulses lasted 0.2 to 0.6 ms but there were few noise pulses which exceeded 1 ms in duration for both the E-field and H-field antennas. The amplitude of the noise pulses in the E-field results was much higher compared to the amplitude of the noise pulses in the H-field results. Most of the noise pulses in E-field results have amplitudes of 80-90 and some pulses exceeded the 10000 mark in A/D levels, whereas for the H-field results, the amplitudes of the noise pulses were 10-12 A/D level and some of the noise pulses exceeded the 1000 A/D level. These differences are primarily due to different RF designs for the two antennas. Calculated average SNR values using method A for E-field and H-field antennas was 14.3 dB and 13 dB, respectively, which demonstrates that during lightning conditions both the antennas are affected similarly. Using method B shows significant improvements for both the E-field and H-field antennas.
7.5 Comparison of Flight Test I & Flight Test II

Based on the results from the flight test data collected during normal and thunderstorm conditions, it was found that data from the E-field and H-field antennas are similar in terms of noise statistics. During thunderstorm activity the amplitude of the noise pulses increased in the data from both antennas. During lighting conditions the average number of noise pulses found per second was almost identical for both antennas: 353 for E-field and 301 for H-field. Comparison of the SNR for both flight tests shows that the SNR calculation using method B significantly improves the average SNR. Table 7-2 shows the comparison of SNR between the two flight tests.

Table 7-2 Comparison of SNR for Jupiter during Flight Test I&II

<table>
<thead>
<tr>
<th>Antenna</th>
<th>Flight Test I</th>
<th>Flight Test II</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SNR (dB) Method A</td>
<td>SNR (dB) Method B</td>
</tr>
<tr>
<td>E-field</td>
<td>28.5</td>
<td>35.6</td>
</tr>
<tr>
<td>H-field</td>
<td>28.3</td>
<td>32.3</td>
</tr>
</tbody>
</table>

Note that although flight tests I and II took place in approximately the same geographical area, the SNRs cannot be compared since the locations were not identical. However, the
change in SNR can be compared between the two flight tests. When the noise pulses are
discarded (Method B), the E-field SNR increased by 7.1 dB during normal conditions and
14.4 dB during lightning conditions. Similarly, the H-field SNR increased by 4.0 dB
during normal conditions and 11.7 dB during lightning conditions. Furthermore, since
Method B discards noise pulses that exceed 10% of the amplitude of the third strongest
transmitter, positioning accuracy should also be improved by Method B compared to
Method A. The quantitative evaluation of Method B accuracy improvement is
recommended for future research.
8 CONCLUSIONS

Based on the research documented in this thesis, the following conclusions are provided:

1) Both the E-field and H-field antennas are affected similarly by lightning-induced noise.

2) Loran pulses which are affected by noise pulses should not be used by the receiver for navigation measurements.

3) Pulse durations due to atmospheric noise are on the order of 0.1 to 0.6 ms, both during normal and thunderstorm flight test conditions. The average number of noise pulses per second during normal conditions was approx. 111 pulses for both E-field and H-field antennas. During thunderstorm conditions, the average number of noise pulses per second increased by a factor of three for both antennas compared to the number during normal conditions.

4) Method B improves the SNR for both E-field and H-field antennas data compared to the traditional Method A. When the noise pulses are discarded (Method B), the E-field SNR increased by 7.1 dB during normal conditions and 14.7 dB during lightning conditions. Similarly, the H-field SNR increased by 4.0 dB during normal conditions and 11.1 dB during lightning conditions. Furthermore, since Method B discards noise pulses that exceed 10% of the amplitude of the third strongest transmitter, positioning accuracy should also be improved by Method B compared to Method A.
9 RECOMMENDATIONS FOR FUTURE RESEARCH

The results obtained in this thesis should be taken into consideration for the design of eLoran receivers to effectively mitigate the effects of atmospheric noise on accuracy and availability. Analyses are recommended to study the threshold to be used for the removal of the Loran pulses from the E-field and H-field antenna data.

It is further recommended that the results from this thesis are used to design a noise model to support the mitigation of atmospheric noise in the Loran band. The noise model should be applied to data collected during thunderstorms and compared with the results obtained in this thesis. The various non-linear atmospheric mitigation techniques: Linear, Hard Limiting, Clipping and Hole Punching should also be simulated. Next, these techniques should be evaluated based on the data collected for this thesis during both normal and thunderstorm conditions.
REFERENCES


