Noise Assessment and Mitigation for Loran for Aviation

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ABSTRACT

The United States released the technical report on the ability of Loran to mitigate the effects of a GPS outage in December 2004. The report indicated that the current Loran system, with reasonable upgrades and modifications, could provide backup to GPS for aviation, maritime and timing users. The conclusion was based on the results of the analysis of many significant hazards to Loran usage. One critical factor is atmospheric noise, particular at extreme conditions. Atmospheric noise results from lightning discharge and as such, it can vary greatly from moment to moment. High levels of atmospheric noise, above the 95th percentile, are of great concern. The International Radio Consultative Committee (CCIR) noise model indicates some extremely high values for high levels of atmospheric noise. While these values still generally result in acceptable availability of the Loran system for aviation, actual performance is suspected to be better. This is because the CCIR data collection equipment differed substantially from those of a typical Loran receiver. Hence, it is necessary to conduct data collection to supplement the knowledge found in CCIR.

A data collection system was developed to collect atmospheric noise data. Data were collected at two areas of known high atmospheric noise - Socorro, NM, and Minneapolis, MN during the summer of 2004. Further data collection will be conducted in 2005. The data were first used to assess the reasonableness of the CCIR noise values. An additional use will be to refine the CCIR noise model for the Loran band. This will include developing a statistical model for lightning. In addition to studying the noise, its statistics, and characteristics, it is also important to understand how to mitigate its effects. This paper discusses the data collection set up and presents the preliminary analysis of the data collected at various sites.

1. INTRODUCTION

Robustness and redundancy have always been important features of position, navigation and timing (PNT) service. They are more paramount as the number of users of Global Positioning System (GPS) steadily increases and as GPS becomes increasingly integrated into society and critical infrastructure. A robust PNT infrastructure provides users back up capability in the event that GPS is unavailable. This is achieved by having redundant system(s) capable of providing efficient means of retaining much of the safety or economic benefits derived from GPS. System vulnerabilities are mitigated if the redundant system has different failure modes than GPS. Mitigating system vulnerabilities reduces economic and safety risks due to outage or deliberate interference. Furthermore, having a redundant system acts as a deterrent against malicious interference. These thoughts are echoed in the Volpe National Transportation Safety Center (VNTSC) Report on GPS Vulnerability [1]. Its recommendations include examining various alternatives to provide redundancy to GPS, particularly in safety critical applications.

The Long Range Navigation system, or Loran, is one of the systems being considered for providing redundancy. It is one of the few systems being evaluated that is capable of meeting this need across many modes of application. The system was the topic of a multi-year study conducted under the direction of the Federal Aviation Administration (FAA). The evaluation report from this study was delivered and released in 2004. Paraphrasing the conclusions, the technical analysis indicated that Loran had the ability to meet Required Navigation Performance 0.3 (RNP 0.3 is equivalent to NPA), Harbor Entrance Approach (HEA) and Stratum 1 frequency standards in the conterminous United States (CONUS). The performance is based on using the underlying structure of the current Loran system along with planned upgrades and reasonable modifications and evaluating the system's performance in light of various threats [2]. The source and categorization of the threats are broken down in [2] and a number of different threat assessments are treated in references [4-8]

One critical ongoing study assesses the impact of atmospheric noise on a receiver's ability to receive and track Loran signals. Atmospheric noise is generated by electrical discharges such as lightning, and is a major source of interference over a wide bandwidth that includes the Loran band. The analysis conducted for the Loran report utilized the generally accepted International Radio Consultative Committee (CCIR) model for atmospheric noise defined by CCIR Report 322 [9] which was later superseded by ITU-R P.372-7 [10]. In addition, other sources such as the National Lightning Detection Network were utilized to give lightning return stroke distances and strengths.

The data collection for CCIR is extensive; however, the application of the data to determine system performance at the worst-case levels of noise is left to the discretion of the reader. For our application of aircraft navigation in close proximity to electrical storms, there are two major questions raised as to the applicability of the CCIR data to Loran navigation signals. The first issue is that the original CCIR data collection equipment was not useful for monitoring nearby lightning storms. Second, the data collection system used by CCIR was a narrow band receiver. The intended application was for evaluating atmospheric noise on narrow bandwidth communications channels. Narrow bandwidth refers to the bandwidth of the channel being much smaller than the center frequency, usually by an order of magnitude. Loran, centered at 100 kHz and being 35 kHz wide, does not fall under this definition.

The combination of uncertainty in the accuracy of CCIR data with regards to nearby storms and the questionable applicability of the data to our wide bandwidth channel precipitated our need for taking atmospheric data of our own. This paper describes our data collection efforts and some of our preliminary results. Furthermore, these preliminary data are compared to that of CCIR. The comparison indicates that the CCIR models are accurate for describing some of the noise parameters in the Loran system.

A deeper examination of atmospheric noise is necessary to better understand Loran availability. Our process of recording and analyzing atmospheric noise will help refine the CCIR model as it is applied to Loran. It is also necessary to develop mitigation techniques that are better suited to the characteristics of this noise. Overall, the work is valuable in increasing Loran availability and increasing our knowledge of noise in the Loran band.

2. BACKGROUND

2.1 Atmospheric Noise Background

Atmospheric noise is the predominant noise source in the low frequency spectrum. The noise is generated by electrical discharges within clouds, between clouds, and between the clouds and the ground (e.g. lightning). This noise is often present to some degree since the conductive characteristics of the Earth [7] cause the ground to act as a waveguide, allowing this low-frequency noise to propagate for thousands of kilometers. The LORIPP utilized the generally accepted International Radio Consultative Committee (CCIR) model for atmospheric noise.

In addition, data has been taken from other sources such as the National Lightning Detection Network (NLDN). The NLDN is a series of over 100 sensors distributed across the United States and maintained by Vaisala, Inc. The sensors are GPS-synchronized, and use model-based estimation algorithms and time of arrival information to predict the location and strength of lightning return strokes. We used this information in the calibration of our sensors.

2.2 CCIR Background

The International Radio Consultative Committee (CCIR), later renamed the International Telecommunications Union (ITU), distributes the reports that combine the efforts of many years of atmospheric noise monitoring.

The CCIR performed its initial work on CCIR Report 322 on atmospheric noise from 1957 to 1961. They collected data for four years using 16 stations around the globe in eight frequency bands: 13 kHz, 110 kHz, 250 kHz, 500 kHz, 2.5 MHz, 5 MHz, 10 MHz, and 20 MHz. The primary data measurement made was external antenna noise factor, *Fa*, the power received through a loss-free antenna values over a 15-minute period. Some additional high-speed data were taken in order to relate the instantaneous noise envelope to that of the average external antenna noise factor. These data were used to produce the amplitude probability distributions (APDs).

Since atmospheric noise is a non-stationary process, the CCIR broke down their data into several categories in an attempt to make the statistics more stationary. The categories divided the statistics into different values for each of the four seasons and each of six 4-hour time blocks within a day. The values derived from the worst season and the worst time block were the basis of the LORIPP integrity and availability analyses.

Figure 1 depicts the expected median, or 50% value, of noise across the country derived from the external noise factor for an ideal monopole over an infinite ground plane. CCIR found the noise data to be log-normal in its distribution, that is, normally distributed if the values are given in log of power. Such a long-tailed distribution leads to very large noise values for rarer events. To illustrate this, Figure 2 shows the expected 99% noise value.

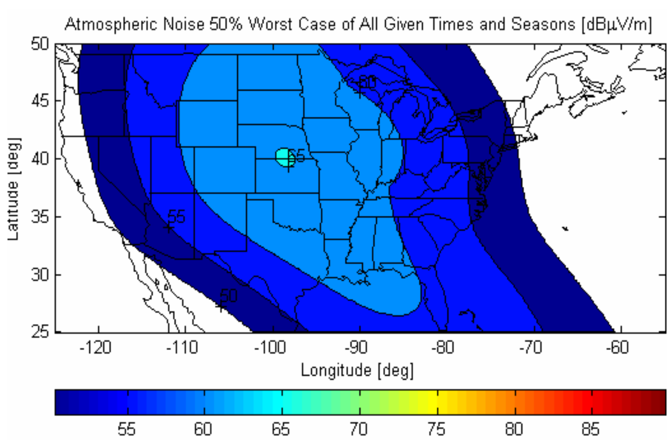

Figure 1. Worst Case Noise: 50th Percentile

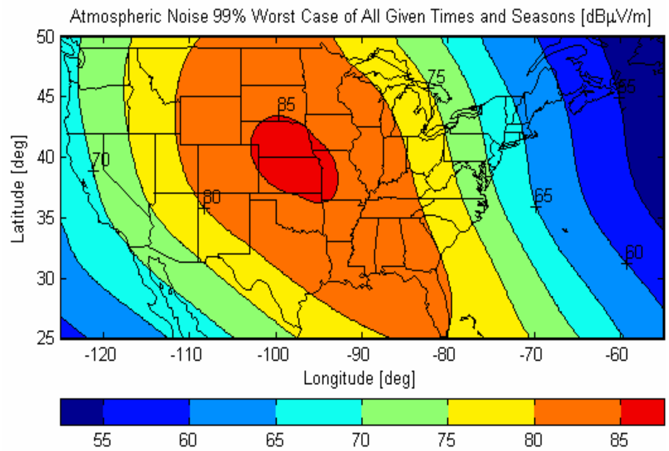

Figure 2. Worst Case Noise: 99th Percentile

CCIR 322-3 and Robert Matheson, the technician who worked on the report, [11] mention the limitations of the ARN-2 Radio Noise instrumentation used for collecting data. The key issue concerning the ARN-2 used in CCIR data collection was that the antenna would go into corona when there were nearby lightning storms. Therefore, the receiver closest to the storm was turned off and not used to measure the noise. The LORIPP was concerned that there may be some levels of noise not seen when nearby storms are present leading CCIR to underestimate the noise values.

As a secondary concern, the ARN-2 collected data at each of the eight frequencies using down-conversion and a 200 Hz bandpass filter. This narrow band receiver design is typical in communication channels. However, Loran is a navigation system with a 35 kHz bandwidth centered at 100 kHz. So there was some concern as to whether or not the translation from a narrow bandwidth to a wider one would be accurate.

Another concern was the lack of time correlation in the CCIR data. Lightning is a "bursty" process. When you have one stroke, there is a higher likelihood of a second or more following. This process may be represented by a two state Markov Chain, as shown in Figure 3. Here the system is in one of two states: the first "quiet" state has no lightning noise and then there is a second noisy "lightning" state. The probabilities are shown where the first and second subscripts indicate the probability for a transition occurring at one state and proceeding into a second state. By adjusting these probabilities, different models may be made to fit the time domain properties of our measured data. In our testing, we were looking to develop the statistics for this time correlation and add that information into the CCIR data.

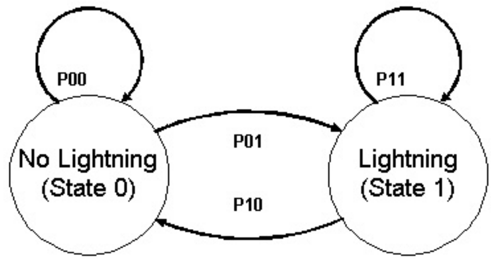

Figure 3. Simple Markov Chain for Lightning

Finally, while lightning has not changed since the writing of the original CCIR reports, electronic processing and data collection systems have changed dramatically. The original ARN-2 used an elaborate method of integrating the charge from the antenna over a 15-minute period. It was our intent to utilize more modern methods and gather high-speed data that could lead to a better understanding of noise and lead to better noise mitigation techniques.

3. TEST SET UP

CCIR predicted noise values that vary across the country and over different seasons. Predominantly, spring and summer contained the most severe weather. Therefore we set out to areas of the country that had large values of noise and could provide a reasonable benchmark to compare the estimated noise values with that of what we measured. We also needed to have the system run remotely, so Internet access was a must. Thus we selected locations and times that yielded high noise values during the spring and summer and that were also readably accessible.

3.1 Test Location

Beginning in the summer of 2004, we set out to measure the rate at which atmospheric noise was generated and to determine some of the time correlation properties of the process. The intent was to survey a couple of locations and determine the applicability of the CCIR report when it came to Loran. The first location chosen was Langmuir Laboratory in Socorro, NM run by New Mexico Institute of Mining and Technology (see Figure 4). This facility sits on top of Mt. Baldy at an elevation of approximately 10,700 ft. The location of this facility was chosen since daily isolated thunderstorms are present during the New Mexico monsoon season of July and August. Later on in the summer, we set out for the University of Minnesota and established a data collection system there in order to capture some of the larger storms that occur in August.

Both of these sites used a LRS IIID Loran receiver from Locus outfitted with an electric-field (E-Field) antenna. The raw data from the receiver's radiofrequency (RF) front end was piped to a 2 channel ICS-652 A/D card. The data were digitally mixed with a 100 kHz reference, were filtered and converted to baseband inphase and quadrature measurements (I&Qs). The I&Qs may be root sum squared to get the envelope of the signal. The envelopes is a convenient method for showing the data since it may be down sampled easily and still retain useful information. The system ran under Windows XP using Remote Desktop in order to access the system from California.

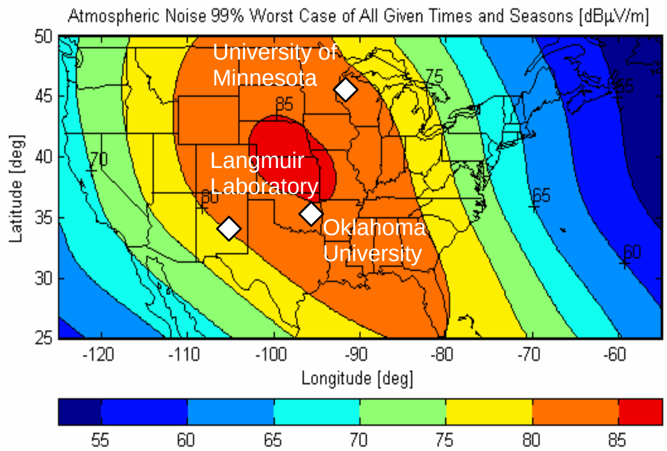

Figure 4. Test Sites (in white) overlaided on map of 99th percentile noise levels from CCIR

While these data were useful in examining the periodicity of lightning, there was a significant limitation in the use of the data for validating the amplitude distribution of the noise. Since the receiver and antenna were designed to capture Loran signals, its dynamic range was not adequate to capture the full power of nearby lightning. As such, the receiver clipped the amplitudes of the close high-powered lightning strikes. While this is not a problem for receiving the timing between strikes, it would skew the amplitude statistics we were trying to validate.

Location	Time Period	Lightning Level	Rate
NSWC Oklahoma City, OK	Early Spring – Early Summer	Extremely High level	Common
Langmuir, Socorro, NM	Summer	Moderate to High	Daily
UMinn/TC Minneapolis, MN	Late Summer	High to Extremely High	Common

Table 1. Test Location and Lightning Characteristics

At the start of 2005 we decided that incorporating amplitude distribution validation data was crucial for improving our model. This led to the development of our own RF front end shown in Figure 5. This front end would have a 35 kHz wide bandpass filter centered at 100 kHz that would be measured directly and down converted to I&Q. This design is representative of a Loran receiver's RF front end. In addition, an envelope detector was available for same signal as a second channel. To make the comparison to CCIR unambiguous, a channel using a 200 Hz wide bandpass filter centered at 100 kHz was added. This channel's data were mixed to baseband I&Q and then recorded. An envelope detector was also present and made a fourth data channel.

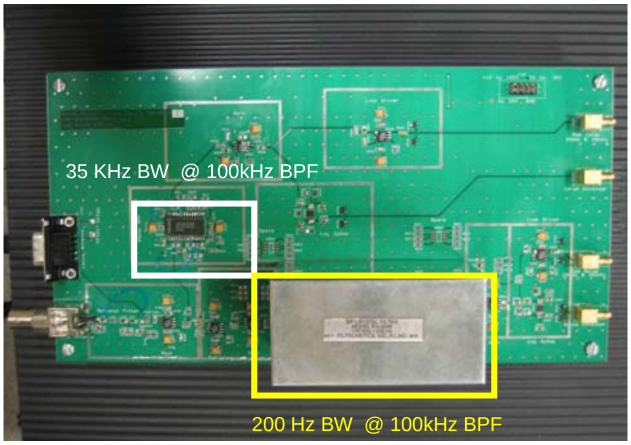

Figure 5. Front End for Noise Data Collection Unit

This system was taken to the University of Oklahoma and set up at the Sarkeys Energy Center in Norman, OK. The antenna used an LRS-IIID Locus antenna similar to the previous year's antenna but had its internal amplifier reduced by 30 dB. The output of the antenna was fed to all channels of the RF front end.

Professor William Beasley, of the Meteorology Department, provided a wide bandwidth flat plate antenna. This antenna is roughly one meter square and operates from almost DC to a three dB roll-off at 250 kHz. See Figure 6. Many atmospheric scientists have used wideband antennas and much data have been gathered to describe the expected waveforms seen during a lightning return strokes. This antenna provides us a means of comparing our data to a large existing host of literature and was used to calibrate our system.

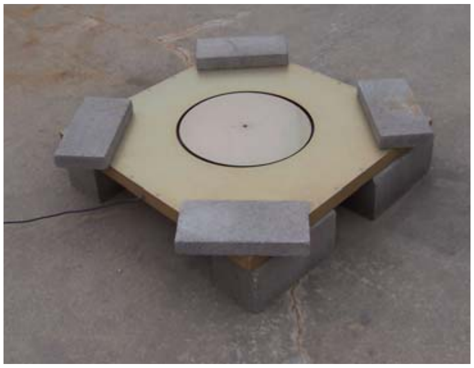

Figure 6. Wide bandwidth Flat Plate Antenna

The data acquisition system used an oven controlled oscillator to drive a synthesizer at 25.6 MHz which clocked the two A/D boards. One board used its two channels to receive the raw 35 kHz and 200 Hz data and a specialized daughter card to down-convert them to 50 kHz I&Q. Data were recorded in five-second continuous files. Maximum, average, and rms values were recorded for each of these files. Only if the rms value of the 5 second file passed a threshold was the file kept.

The second card recorded the 35kHz envelope data on one channel and would have either the flat plate data or the 200Hz envelope data on the second channel. This second card sampled at 1.6 MHz for 0.3125 seconds within the five seconds of the first card due to storage and equipment limitations. The files were time tagged using a GPS true time receiver. The 200 Hz envelope data was recorded for a few storms and then the flat plate antenna was permanently substituted.

4. NOISE CHARACTERISTICS IN LORAN BAND

The current data collection system at the University of Oklahoma went operational at the end of May and has been up for most of June 2005. At the time of this paper, we are in the process of analyzing the results. A more thorough analysis will be presented in a later paper discussing the significance of the results. However, some preliminary results have been obtained and will be presented here.

On June 13, 2005 a large frontal system moved over the Oklahoma site. The envelope data for a five second block of time is shown of the 35 kHz data in Figure 7.

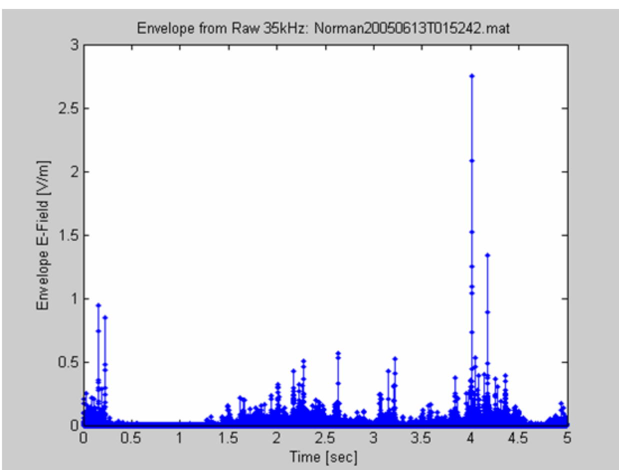

Figure 7. Envelope from 35 kHz data collected June 13 2005 (Oklahoma City)

Note that the scale of the data is in volts/meter. Loran signals are typically on the order of millivolts/meter to microvolts/meter. During the quiet time around 1 second, Figure 8shows an enlargement of the region where the Loran signals are evident. Note the amplitude of the largest Loran signal in the chain is 5.5 mV/m.

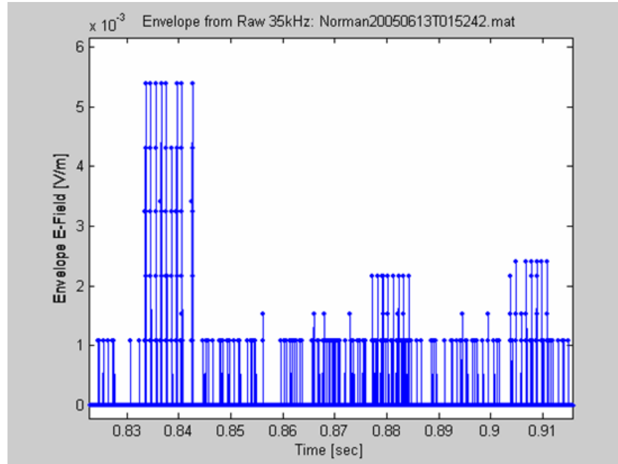

Figure 8. Zoomed View of Envelope from 35 kHz data collected June 13 2005 (Oklahoma City)

To make the data more apparent, it is replotted in Figure 9 on a log plot and the units are now in dBμV/m. The red line shows the expected 99% noise value of 85 dBμV/m derived from CCIR.

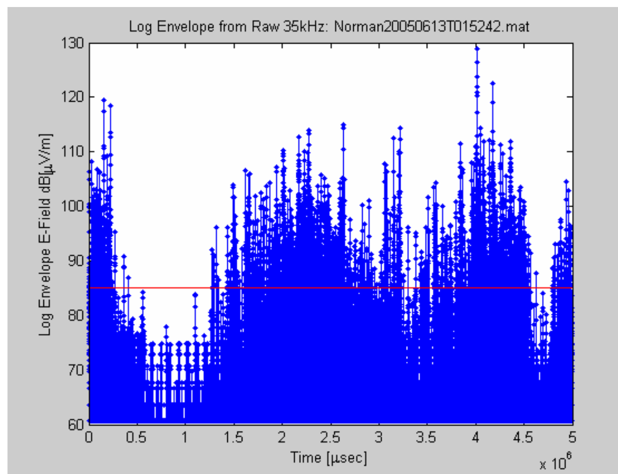

Figure 9. Log Envelope from 35 kHz data collected June 13 2005 (Oklahoma City)

The signal is evident around 1, 3.5, and 4.6 seconds. One would not anticipate being able to see the signal given the expected 99% noise value. However, since the noise is highly correlated, quiet times are present in the data. This noise characteristic suggests that utilizing signal processing techniques such as clipping or hole punching would allow us to significantly mitigate the effect of noise. For example, hole punching captures the signal between lightning bursts thus reducing the effective noise. That is where we would set a threshold of the expected signal strength and suppress the signal when the noise was too high. Since the signal would be kept when only when the noise was low, we can trade noise power for duty cycle. Future work includes examining the effectiveness of such an algorithm.

5. COMPARISON WITH CCIR

There are two metrics that we may easily compare our data with CCIR. First, we compare the average root mean squared (rms) values obtained by averaging 15-minute blocks of data. Due to our receiver being designed for large amplitude noise, the dynamic range limits lower amplitude values. Therefore, only the upper median values of noise are used. CCIR gives curves for both the upper (red) and lower (green) median values of noise. Note that since upper and lower distributions differ, the overall probability density function (PDF) is discontinuous at the median value. The estimated CCIR results are shown for a 200 Hz and a 35 kHz bandwidth with the data in Figure 10 and Figure 11 respectively.

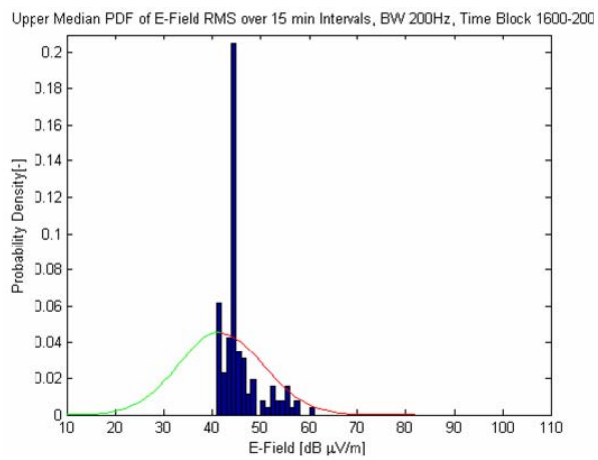

Figure 10. Comparison of Upper Median PDF for 200 Hz Bandwidth from CCIR and Data Collected from Oklahoma City June 2005 (Using E Field Antenna)

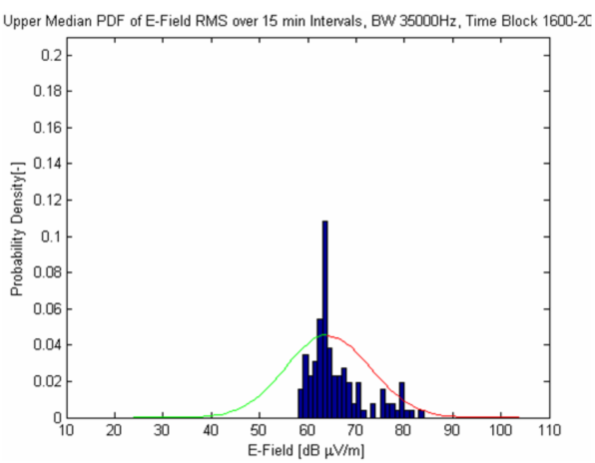

Figure 11. Comparison of Upper Median PDF for 35 kHz Bandwidth from CCIR and Data Collected from Oklahoma City June 2005 (Using E Field Antenna)

What seems apparent is that the CCIR estimate of the data bounds and the actual data are comparable. Therefore, it seems that CCIR accurately predicts the bounds on the rms noise values.

The other CCIR metric that we may compare to is the amplitude probability distribution (APD). The APD is one minus the cumulative distribution function. The APD gives you the percentage of time that the ordinate (noise amplitude) is exceeded. The APDs in CCIR are referenced to the rms value. Therefore, it shows the deviation from the rms in dB. To further describe the data, CCIR measured the envelope voltage deviation, V_d, which is the ratio of the rms to the average envelope values in dB. The V_d of the data from the five-second data file is 15.682. If the data (blue) are plotted on the expected distribution (black), the similarity of the results is striking. The plot is shown in Figure 12. Once again, only the upper median values are used.

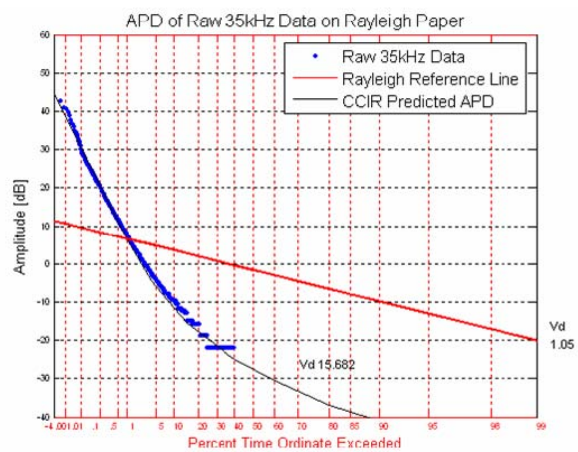

Figure 12. Comparison of CCIR and Collected APD in a 35 kHz bandwidth

6. CONCLUSIONS

Our preliminary results from examining rms averages and APD strengthens our confidence in applying the CCIR to the Loran band. Furthermore, the data collected provides a time history for the behavior of the noise. Time histories have been useful in testing mitigation techniques. However, there is still much work to be done analyzing the vast amount of data collected over the course of this test program.

Since CCIR appears valid, other signal processing techniques mentioned in References [3, 4, 13] will probably hold. They predict anywhere from a 10 to 30 dB improvement in signal to noise ratio if nonlinear signal processing techniques are used. What remains to be finalized is the combining of this information into an effective signal processing strategy for Loran, but our preliminary estimate of 12 dB for signal processing gain to our signal to noise ratio (SNR) seems reasonable [8].

7. ACKNOWLEDGMENTS

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