Mitigating Atmospheric Noise for Loran

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ABSTRACT

With its large-amplitude and short-duration pulses, atmospheric noise, produced by electrical discharges within clouds, dominates the low-frequency spectrum. Unless mitigated, this noise, which enters into the Loran band, can distort a Loran signal within a receiver and can induce cycle selection errors resulting in range measurement errors of 3,000 km. Such errors would induce position errors greater than 556 m and would prevent the receiver from meeting the requirements for aircraft non-precision approach (NPA).

In order to evaluate the effectiveness of Loran for non-precision approach we needed to perform two tasks: 1) confirm that the standard model of atmospheric noise, ITU P372-7, despite its caveats against its use in the low-frequency band is indeed valid for Loran, and 2) obtain raw data for use in evaluating non-linear signal processing techniques to mitigate the effects of atmospheric noise.

To accomplish these tasks, we developed atmospheric noise collection equipment and fielded them in Norman, Oklahoma, a location of high storm activity. Since atmospheric noise can be several orders of magnitude larger than a weak Loran signal, our latest receiver design combines a high gain and low gain channel to provide 122 dB of dynamic range while having 12 bits of resolution for the Loran signal.

This paper describes our work on verifying the accuracy of the ITU atmospheric noise model for both long-term and short-term noise. In addition, we extend the ITU model by showing a correlation between the predicted rms noise envelope field strength and the minimum voltage deviation of the noise. These results are important to determining the processing credit for non-linear signal processing. The processing credit can then be use to more accurately show the coverage and availability of Loran for aircraft non-precision approach (NPA).

INTRODUCTION

As more users and services rely on GPS, a need for a backup navigation and timing source becomes more critical. The Volpe Center's report on GPS Vulnerability [3] stressed this need as critical to the safety of life and necessary for the protection of the nation's transportation infrastructure. Presidential Directives [1] and [2] officially reinforce this sentiment adding that the nation's economic and military advantages demand backup systems with failure modes separate from that of GPS. These backup systems provide continuity of economic and safety services in the event of a GPS outage and to deter potential attacks on GPS since a backup is available.

The Federal Aviation Administration (FAA) is charged with the task of examining potential backup systems for GPS for aviation. An aviation backup should allow an aircraft to land safely when GPS is unavailable. Hence, one desire is that it enables NPA and therefore it should meet the specifications known as Required Navigation Performance of 0.3 NM (RNP 0.3) [4]. Meeting RNP 0.3 would allow pilots to use the same RNP 0.3 non-precision approach (NPA) charts that have been issued for other navigation systems such as GPS. The new RNP system allows the pilot to use generic charts for any navigation system which combines any set of sensors for a position solution, provided that the system can meet the requirements of the RNP procedure.

One system the FAA views as a potential candidate for NPA back up is the Long Range Navigation (Loran) System. Loran is a low-frequency radio navigation system that currently provides users with ¼ NM accuracies 95% of the time, and over the short term, can provide 18-90 m of repeatable measurements.

In order to analyze Loran's potential as a backup system capable of non-precision approach (NPA), the FAA created the Loran Evaluation Team: a consortium of academic, government and industry researchers. In 2004, the Loran Evaluation Team published its initial findings in [4]. From their technical analysis, the team determined that Loran had the ability to meet RNP 0.3, 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 [5].

A key component of achieving RNP 0.3 is "availability", the percentage of time that a user may reliably receive a position solution. Since we cannot know when the system will be needed, it is important to understand the availability at even the worst conditions. These conditions are often coincident with inclement weather which are conditions where instrument landings are most necessary. Thus the goal is to have high availability under all circumstances. Hence we have an availability target of 99.9%.

Working as part of the Loran Evaluation Team, we developed models to determine Loran's availability to meet RNP 0.3. From our analysis, we found a high signal-to-noise ratio (SNR) is required to achieve high availability. This is because Loran availability was driven by the number of signals available and usable. A minimum SNR must be met for the signal to be usable. The transmitters are fixed and so the signal strength at any location is fixed. Thus the prime determinant of SNR and hence signal availability is noise. Noise is determined by the level of atmospheric noise at the user location and the user's ability to use signal processing to mitigate the noise relative to our signal. An accurate estimate of availability requires that we have good understanding of atmospheric noise and the effect of signal processing.

In the Loran Evaluation Team's 2004 report, we used models of atmospheric noise developed by the International Telecommunications Union [6], we discuss the model in the following section. For the effects of signal processing, we made a conservative estimate of 12 dB of credit that we uniformly applied to the SNR at all locations. From these models, we generated coverage diagrams showing percentage of time RNP 0.3 is available across CONUS. The report found that the coverage was generally acceptable when availability was averaged over all seasons and time blocks. However, availability coverage was border-line when considering the worst-case noise time block. When using our conservative estimates for signal processing, the analysis results in Figure 1 shows our coverage prediction of system availability under the worst noise case noise conditions.

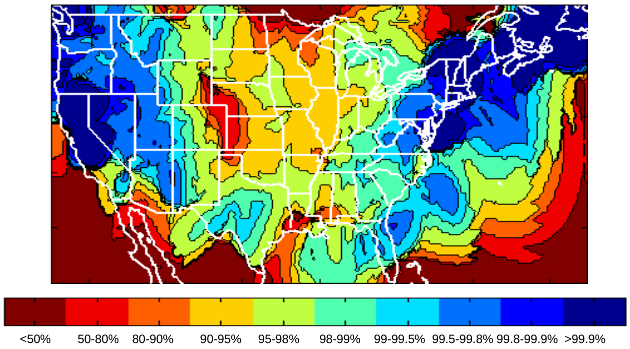

Figure 1 2004 Coverage Prediction for CONUS of RNP 0.3 Availability at Worst Case Noise Periods

However, through an extensive data campaign carried out over 2005 and 2006, we have been able to confirm and to extend our atmospheric noise models and to make a more accurate estimate of non-linear processing credit. This paper describes the initial findings of the 2006 data collection campaign and introduces some concepts which we will use in estimating our non-linear processing credit.

BACKGROUND

Atmospheric Noise

Generated by the discharge of particles within clouds, atmospheric noise is characterized by short-duration, high-amplitude, and consequently wide-band noise. It is highly impulsive and therefore, non-Gaussian in nature. Due to large amplitudes corresponding to high levels of availability, this noise is the dominant noise source within the Loran band and thereby drives Loran's availability of RNP 0.3.

Researchers with the International Telecommunications Union and formerly the International Radio Consultative Committee (CCIR) developed models to describe this non-Gaussian noise in the RF bands [6, 7][1]. The models predict the instantaneous and the long-term rms noise envelope field strengths for various frequencies and bandwidths. The long-term data spanned between 15 minutes and one hour in length, while the short-term records are on the order of seconds to a minute.

To deal with the non-stationary nature of atmospheric noise, ITU gave the noise statistics parameterized by geographic location, season, and hour. Since ITU models are very general, we must adapt them to the Loran band. The original ITU receivers were narrower in bandwidth than Loran receivers, and therefore, the results of the ITU model are not directly applicable. We use the model's formulas to estimate the noise in the Loran band and to evaluate a receiver's performance for the coverage model. Since extrapolation is a potential source of error, we directed the first part of our data collection towards validating our extrapolation of the ITU model.

The ITU model provides a number of different inputs to our coverage analysis. By using the model's long-term rms noise envelope field strength estimates, we can combine them with station signal propagation models and determine the SNR of the stations across the country. Using the SNR and the non-linear processing credit, we may determine Loran's coverage.

To derive the processing credit, we use the short-term noise instantaneous noise envelope field strength probability distributions parameterized by their impulsivity or voltage deviation, V_d [6]. This measure, defined as

$$V_d = 20 \log_{10}(\text{rms field strength/mean field strength})$$

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[1] CCIR became the International Telecommunications Union Radiocommunication Sector (ITU-R) in 1992

coupled with the noise distributions enables us to separate the noise into an impulsive part and a Gaussian part. By suppressing the impulsive part using non-linear processing elements such as hole-punching or clipping, we trade off some signal suppression for noise rejection. We discuss such algorithms in [7] and [9].

Experimental Setup

Over the summers of 2005 and 2006, we collected atmospheric noise data at the University of Oklahoma in Norman, Oklahoma. We intended to verify both the ITU model predictions and to collect enough data to demonstrate the effects of non-linear signal processing.

We described the experimental set up and initial results of our 2005 data collection tests in [8]. In that year, our receiver had 78 dB of dynamic range which is not wide enough to cover both weak Loran signals and high values of atmospheric noise. Since we were primary interested in capturing the large amplitude atmospheric noise data, we biased our receiver accordingly, and as a result, the incoming Loran signals, which were much weaker than the noise, only fell over the first three bits of our 14-bit analog-to-digital converter (ADC).

Such a gain scheme limited our data to only the high levels of noise and prevented us from confirming the ITU noise model for low noise values. This forced us to simulate Loran signals when evaluating signal processing algorithms [9, 10]. Therefore, for the 2006 summer campaign, we improved the receiver design by adding a second channel with higher gain which was parallel to the first channel. An illustration of the new design is showed in **Error! Reference source not found.**. Multiple unity gain amplifiers are used in the low gain channel to keep the propagation time through the channels identical and keep the data sample synchronized.

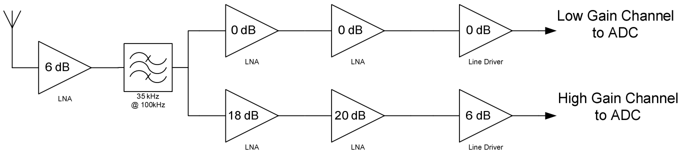

Figure 2 Schematic of 2006 Dual Channel Receiver Design

To combine the data from the two channels to form a single channel, we begin by setting a threshold half way into the range of the high gain channel, approximately at 4,000 ADC counts. We then measure when the data exceeds this threshold. For data below the threshold, we use the high-gain data, and for data above the threshold or when the difference between the two data samples is larger than the gain difference, we use the low gain data. In this manner, we combine the data from two channels to eliminate any artifacts from saturation or clipping and to form a single channel with an effective dynamic range of 122 dB.

We sampled the low and high gain channels at 25.6 MS/s and digitally down converted them to 50 kHz in-phase and quadrature samples using and ICS-652 ADC. We monitored the combined channel data continuously in one minute intervals and recorded the interval's rms, average, maximum, minimum values, and V_d. If the rms value of the data exceeded a set threshold, we saved the data to the hard drive. We later used the saved data for measuring the instantaneous noise envelope field strengths and for evaluating various non-linear processing algorithms.

RESULTS

Long-Term RMS Noise Envelope Field Strength

We used our Loran front end to collect data over a three month period. In order to evaluate the accuracy of the ITU model, we needed to convert our data into a format similar to ITU. First, we combined 15 one-minute data records, to form a 15 minute rms noise envelope field strength measurement to compare to the 15 minute measurements performed by the ITU. Next, we divided up our noise measurements into the time blocks corresponding to the ITU model and calculated the statistics for each time block. We compared the actual data's statistics versus the distribution predicted by the ITU model.

In Figure 3, we show the cumulative distribution function of atmospheric rms noise envelopes for the spring 0000-0400h time block in blue; all time blocks are given in local time. Also shown are the predicted values from the ITU model in red and green. The dashed lines show the ITU model adjusted by a standard deviation.

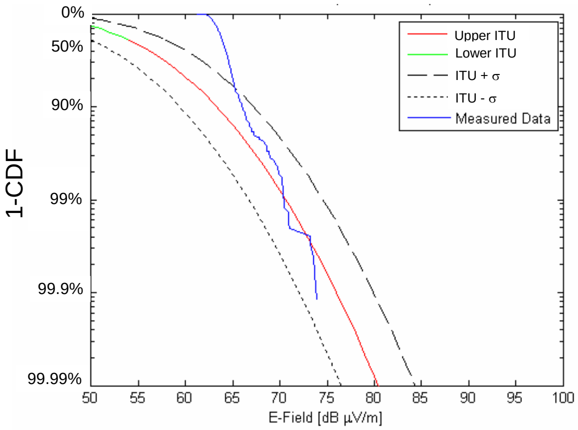

Figure 3 Probability Distribution of Spring 0000-0400h Time Block

We note that our low-end measurements of noise are “corrupted” by the Loran signal present within our band of measurement. However, our data match within 5 dB at the 90-99.9% levels. These levels correspond to the availability probability and are our primary concern when evaluating Loran for RNP 0.3.

In order to provide a bound on all possible noise, we use the ITU model to predict the worst case noise over all seasons and time blocks, and call this the worst-case time block. For Norman, Oklahoma the worst-case time block is the spring 1600-2000h time block. We plot all of our time block data against the ITU noise predictions for this worst case block in Figure 4 since we want to see if the ITU model over bounds the data.

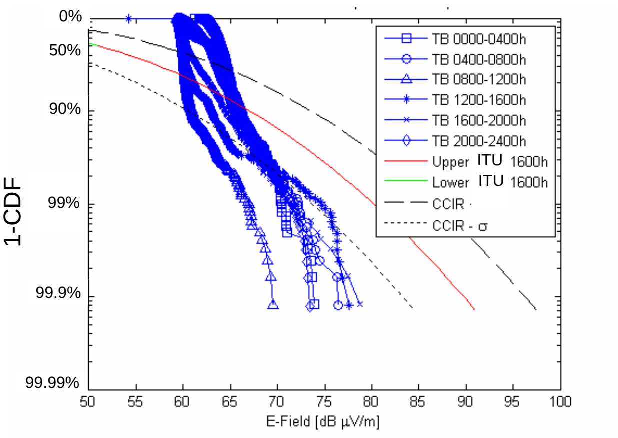

Figure 4 All Data versus Worst Case Probability Distribution of Spring 1600-2000h Time Block

We find the data are bounded by more than 5 dB to the worst-case time block for the season. Incidentally, 2006 was a quiet one in terms of storms, which may explain why the bound increases to over 10 dB at higher values.

From the figure, we see that after the 99.9% probability, the noise rolls off. We suspect that this is part of the physical mechanism of lightning, which limits the strength of the electric fields from following the log-normal distribution predicted by ITU.

Instantaneous Noise Envelope Field Strength

The previous section showed long-term data comparison to the ITU model. These data showed the distribution of measurements taken over the summer in 15 minute intervals. However, the time constants for aviation and maritime receivers are much shorter, on the order of seconds. Since the statistics of short-term data can affect receiver performance, the ITU took some high speed data to generate instantaneous noise distributions. Moreover, the ITU researchers found that voltage deviation alone dictated the noise envelope distribution.

Rather than using the cumulative distribution function (CDF) to view the distribution of instantaneous noise envelope field strengths, we use the historic convention of the amplitude probability distribution (APD) which is 1-CDF. Figure 5 shows the APD of the instantaneous noise envelope field strengths for a single one minute data record. The black line shows the probability distribution of the noise predicted by ITU given the voltage deviation calculated for the data record, while the blue shows that our data corresponds closely to the predictions. This graph is typical, and goes to confirm the predictions of the ITU noise model for instantaneous noise envelope field strengths and its dependence on V_d.

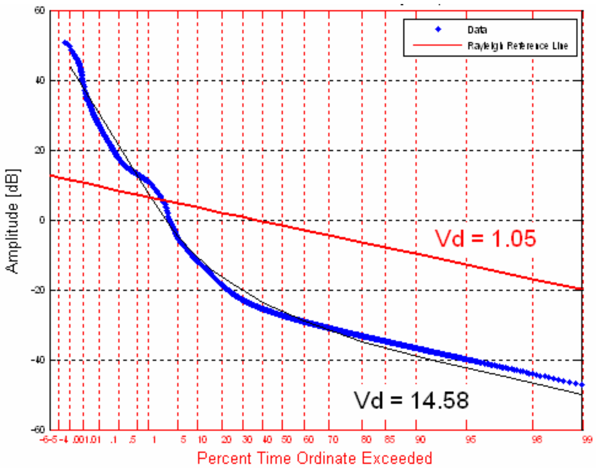

Figure 5 Predicted and Actual Instantaneous Noise Envelope APD

The overall comparison between our data and that predicted by ITU is quite good and we confirm that the distribution is well parameterized by the voltage deviation of the data record itself. Consequently, for any short-term data record, if we measure its voltage deviation, then we have an accurate representation for its amplitude distribution. We will leverage this powerful result in future signal processing algorithms.

In examining these data, we found that there were two phenomena that skewed our data from the ITU model. First, we suspect corona discharges from nearby antennas generated a bump in the distribution at the 2% probability. Second, each Loran tower is present approximately 1% of the time. Since multiple towers are present at a range of distances, this effects the distribution between the 1 and 10% probabilities, depending on the over all strength of the noise. If the Gaussian component of noise is strong enough, it wipes out the Loran signals, so the Loran signals have less of an impact on the overall distribution.

V_d and E_{rms}

Thus far we have shown that the ITU model accurately predicts the noise distribution of the long-term rms noise envelope and instantaneous envelope field strengths. We will now show an extension of the ITU model which will allow us tie the predicted rms noise envelope value to the voltage deviation.

In taking three months of summer storm data, we collected enough data to show the correlation between the impulsivity of the noise and the magnitude of the noise strength. This relationship is a key result since it demonstrates that as the noise gets stronger, it must also be more impulsive.

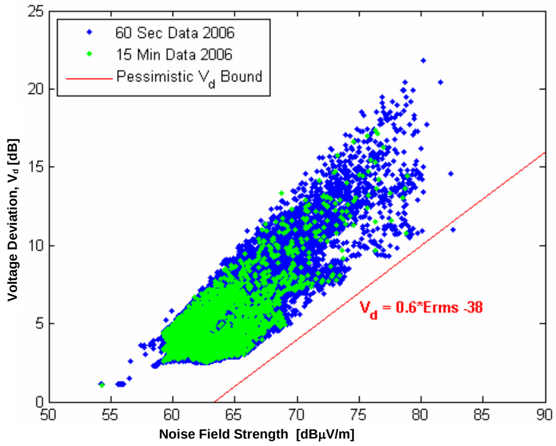

Figure 6 Correlation of Voltage Deviation and RMS Envelop Field Strength (E_{rms})

This is significant since in [9] we find the more impulsive the noise, the easier it is to process out the large spikes, leaving lower noise behind. From Figure 6, we can create a lower bound, which we will call the "pessimistic bound", for the minimum voltage deviation given rms noise envelope strength. We will describe this bound by

$$V_d = 0.5\ E_{rms} - 38$$

Where, V_d is the minimum voltage deviation in dB and E_{rms} is the rms noise envelope field strength in dB[uV/m].

Using the results of [9] and [10] we can more accurately predict the performance of non-linear processing since we can tie the processing credit to the predicted noise level. The details of the calculations will be discussed in a future paper.

CONCLUSION

From Figure 3 and Figure 4, we conclude that the ITU model accurately predicts the long-term rms noise envelope field strength at the 90 – 99.9% availability level. We suspect that the physical mechanisms involved in the lightning process roll-off faster than the predicted log-normal distribution of the ITU model which limits the accuracy of the model above the 99.9%. For our data, the model corresponding to the worst case time period conservatively over bounded our data by up to 10 dB.

Furthermore, the ITU model accurately predicts the distribution of instantaneous noise envelope field strength of data records below one minute in duration. Most of the differences between the ITU predictions and the actual data stem from the Loran signal present in the band or from noise due to corona discharge by antennas co-located with our experimental setup.

In this study, we also show that the long-term rms noise envelope field strength correlates with the voltage deviation. Therefore, as the strength of the noise increases, it becomes more impulsive. Using our data, we produced a lower bound on voltage deviation, thus giving a measure as to the minimum impulsivity for predicted rms noise envelope field strength at a given level of availability.

FUTURE WORK

With a high confidence in the ITU model, the next step is to examine the impact on non-linear signal processing and ultimately, availability. Given our lower bound on V_d, we may apply the processing methods outlined in [10], and predict the amount of signal processing credit we may achieve through non-linear signal processing. By applying this new processing credit to our coverage model, we can determine the improvement to SNR and ultimately to coverage. These steps will be examined more thoroughly in an upcoming paper.

High amplitude atmospheric noise determines Loran reception availability, and from our work we have shown that the ITU models well represent the noise from 90% to the 99.9% probability levels. However, from an academic perspective, we wish to know if the models accurately reflect the noise at probability levels below 90%. Since we took data within the Loran band, we were unable to verify this since the power from the Loran towers skewed the statistics below the 70% level. Therefore, future measurements should be considered just off of the Loran band to prevent such contamination.

Furthermore, we have only this one season of data with a large dynamic range to determine our lower bounds on V_d and E_{rms}. To validate this bound, we should take data at more locations and show that it holds, over many storm years in Oklahoma.

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