A Time Domain Atmospheric Noise Level Analysis

C.O. Lee Boyce Jr., J. David Powell, Per K. Enge, Sherman C. Lo.

***Abstract*— Lightning and other atmospheric noise interferes with Loran signal reception. This paper develops techniques to improve signal availability under these conditions. While the root-mean square (rms) electric field strengths may be quite large for a given lightning discharge, there is significant time between strikes where the background noise is only modest and signal reception is possible. By implementing a simple non-linear hole-punching algorithm, considerable performance gains may be realized over a linear receiver design. This study uses data from the CCIR to evaluate a hole-punching algorithm in the time domain. Analysis of the data provides justification for a 15dB reduction in the rms noise level when a hole-punch or other non-linear processing is used to mitigate atmospheric noise. With this reduction in noise level the availability and continuity of a Loran receiver will improve. This study constitutes part of the Loran Integrity Performance Panel's on-going analysis of Loran receiver performance for RNP 0.3 approach.**

I. Introduction

Since Loran signals are transmitted pulsed in time rather than on a continuous wave carrier, we need to focus on the timeliness of interference, and hence we are motivated to look at the time domain as well as the frequency domain characteristics of any noise. In the next section, we will examine the time history of atmospheric noise and introduce the concept behind the non-linear hole-punching technique used to mitigate the effects of noise on a Loran receiver. Finally, a brief description of CCIR 322-2 [2], the report used to model atmospheric noise, will discuss the limitations of the report and provide the basis for this paper's analysis.

In the following sections we will explore the effects of a non-linear hole-punching filter on atmospheric noise and the justification for a 15dB reduction in the noise rms electric field strength. Ultimately, this reduction in noise will lead to greater availability and continuity.

A. Atmospheric Noise

Atmospheric noise is generated by electrical discharges between clouds or between the clouds and the ground. The energy from these discharges is wide band and peaks at 10 kHz. Such low frequency waves propagate well over the Earth and can be detected a thousand kilometers from the source.

[7] thoroughly describes various lightning processes and the components of each process that generate atmospheric noise. While there are various types of lightning flashes, the most studied process is the negative cloud-to-ground (CG) flash. The CG flash begins when enough negative charge has been accumulated in the cloud and causes a preliminary electrical breakdown. A stepped leader process follows which occurs as a column of charge makes its way to the ground. The stepped leader gets its name from the way the charge breaks down the air in sporadic steps, pausing between steps for several microseconds before continuing on. As the discharge nears the ground it connects with the potential of the ground and a large current of positive charge rises from the ground up to the cloud. This high current discharge is called the return stroke and is the strongest source of current during the flash. Subsequently, there is a quiescent period that is on average 32 ms in duration. Following this period charge will rearrange itself within the cloud, known as the J&K processes. If sufficient charge is still present in the cloud, a dart leader may form which is similar to the initial stepped leader but is much quicker since the channel is already charged. Following the dart leader, we may get another return stroke and the entire process may repeat a number of times.

A representative time history [7] of the electric fields during the return stroke is shown in Figure 1. Also shown appropriately scaled in time, but not amplitude, is a Loran pulse. As shown, the duration of the return stroke is comparable to the Loran signal. Due to the strength of the return stroke it is expect that the Loran signal will be wiped out should they occur concurrently. However, there are quieter periods, on average of 32 ms, between return strokes where we expect the reception of the Loran signal to be possible. This leads to the basic concept of the analysis.

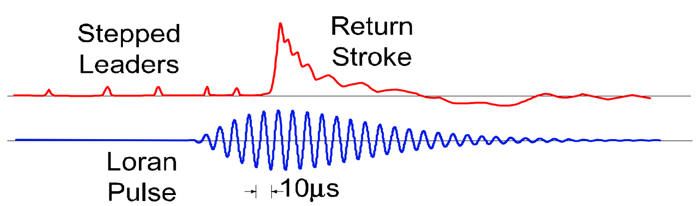

Fig. 1. Time history of a return stroke and a Loran pulse.

We are interested in determining how much quiet time is available between strokes during a storm. In Figure 2, we represent the duration for some of the stepped leaders and the return stroke by a red rectangle and the duration of a Loran pulse by a blue rectangle. Even if the stroke intercepts a pulse in a GRI, we should be able to recover some of the pulses before the next stroke.

To give an example of some actual data, Figure 3 superimposes Loran envelope data [6] (green) with distant atmospheric noise data gathered on a typical day (blue). Both are appropriately scaled in amplitude. Near 29.62 s most of the first secondary signal is stepped on by the atmospheric noise. These data points would be discarded by the hole-punch filter to prevent corrupting the running average of the signal.

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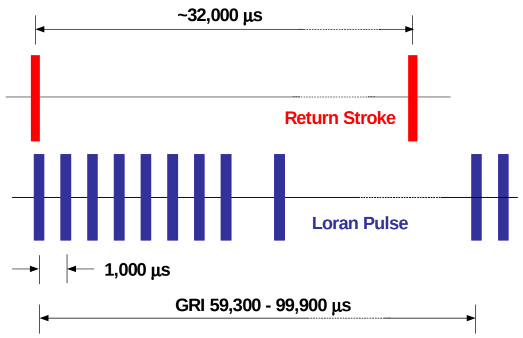

Fig. 2. Diagram of lightning and Loran pulse durations.

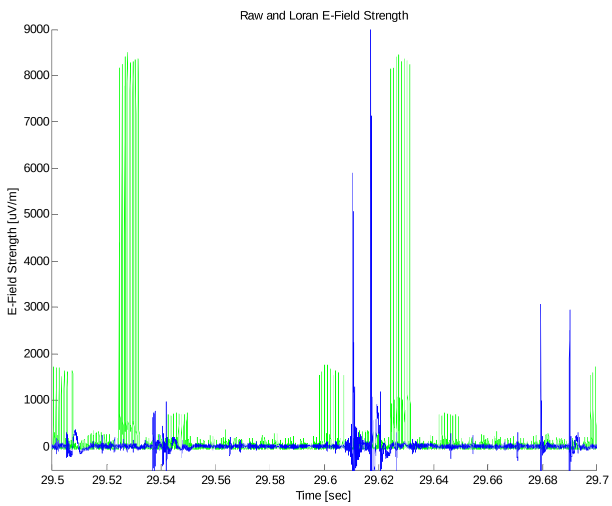

Fig. 3. Superposition of actual lightning data and Loran pulses.

B. Noise Mitigation

A Loran receiver averages the incoming pulses for several phase code intervals (PCIs) to obtain a pulse envelope used in the position calculation. Large amplitude, non-Gaussian variations exhibited by atmospheric noise will skew the envelope values thereby skewing the position calculation. In order to remove the influence of such large variations in our position estimates, we will use a non-linear hole-punching algorithm to eliminate large amplitude noise. The first part of the algorithm will be to set a threshold level; a discussion for what this level should be is presented later in Section II-A. Once an appropriate threshold level is set, any time the signal level exceeds this threshold the data are thrown out and not counted in the averaging process. Our key concerns now become 1) how much of the Loran signal gets suppressed by the hole-punch and 2) what is the resulting level of noise present when the signals are allowed to pass? These questions will be answered in Section II. In order to understand the context of the analysis used in answering these questions, the next section will overview the database used in the analysis.

C. CCIR Data

Of the available methods for describing the noise environment, we chose to use International Telecommunications Union document, ITU P373-7, as the basis of our study. ITU P372-7 is based on an older document produced by the International Radio Consultative Committee, CCIR 322-2. This original CCIR document was based on 4 years of data collected from 1957-1961 at 16 stations around the world. The data consisted of envelope measurements as well as instantaneous voltage measurements with a 200 Hz bandwidth at 13 kHz, 11kHz, 250kHz, 500kHz, 2.5MHz, 5MHz, 10MHz, and 20MHz. In order to more accurately reflect both the annual and diurnal changes of noise levels, the data were organized as four 90-day seasons and by six 4-hour time blocks within each season. [2]

Many statistics were generated to describe the noise recorded by CCIR. Three statistics are of particular importance, the noise factor, the voltage deviation, and the amplitude probability distribution.

Noise factor, Fa, is a bandwidth independent measurement that can be used to calculate the rms electric field induced on a vertical monopole antenna above a perfect conducting ground plane [2]. The relation between Fa and the rms electric field is given by Equation 1.

$$A_{rms} = F_a + 20\log_{10} f_{MHz} + B - 92.5 \text{ dB}\,\mu\text{V/m} \tag{1}$$

The voltage deviation, V_d, is the ratio of rms envelope voltage to average envelope voltage expressed in dB as shown in Equation 2. V_d gives a measure of the "impulsiveness" of the noise. Using this metric it may be seen that a few large values will increase the rms voltage more than they will increase the average voltage, thus raising the V_d value.

$$V_d = 20\log_{10}\left(\frac{\text{rms envelope voltage}}{\text{average envelope voltage}}\right) \text{dB} \tag{2}$$

As a practical example, take an instantaneous noise voltages whose magnitude follows a Gaussian distribution and whose phase is uniformly distributed, then the in-phase and quadrature measurements of this instantaneous voltage would also be Gaussian. The envelope may then be calculated by the root-sum-square of the in-phase and quadrature channels, thus it will always be a positive number that follow a Rayleigh distribution. For Gaussian noise, $\tilde{}N(0,1)$, the envelope will follow a Rayleigh distribution. From [4] the mean of the resulting Rayleigh distribution will be $\sqrt{\pi/2}$ while the rms value will be $\sqrt{2}$ thus, $V_d = 1.05$.

The difference between instantaneous voltages and envelope voltages obfuscates much of noise literature, and we will attempt to clarify any ambiguity when possible. To reiterate for clarity, instantaneous noise voltages which follows a Gaussian distribution, yield instantaneous envelope values that are always positive and Rayleigh distributed. So the terms Gaussian noise or Rayleigh noise are typically used interchangeably depending on whether the context is instantaneous voltages or envelope voltages.

To get a sense of how often a particular level of noise is exceeded, the CCIR gives amplitude probability distributions (APDs) for atmospheric noise. The APD is equivalent to 1 – CDF, the more commonly recognized cumulative distribution function. Typically the APD is also drawn with the axes switched from the CDF, as shown in Figure 4.The x-axis of the APD lists the probability that the y-axis value, Δ, is exceeded. In addition, the x-axis is scaled by $\frac{1}{2}\log_{10}[-\ln(P[\Delta\ Exceeded])]$ [1], therefore Rayleigh distributed data which has a $V_d = 1.05$ would appear as a straight negatively sloped line on this plot. This characteristic makes it easy to determine the extent that the noise voltage is Gaussian or equivalently to what extent does the noise envelope follow a Rayleigh distribution. Furthermore, the APDs in the CCIR are for Δ, the difference between the envelope voltages, A, and the rms envelope voltage, A_0; thus the rms envelope voltage would be at $\Delta = 0$ dB.

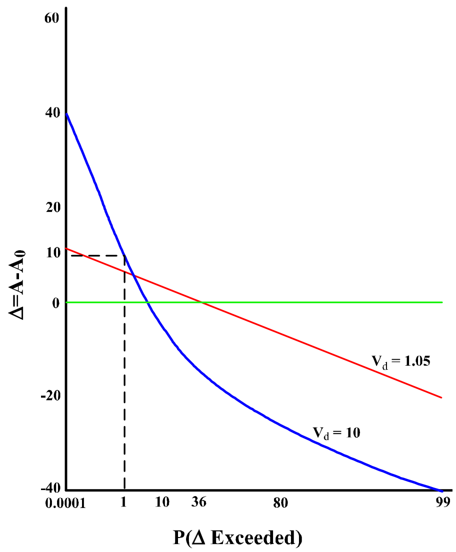

Fig. 4. APD for $V_d = 10$.

One use for the APD is to see what is the probability that the instantaneous envelope voltage, A, will exceed a given value. For example, as shown in Figure 4 the APD shows that the instantaneous envelope voltage will exceed the rms value by more than 10dB about 1% of the time.

While the data collection effort to compile CCIR 322-2 was extensive, there were limitations as to the use of the equipment. Only average background noise data were gathered. Local thunderstorms close to the receiving stations were not included since there was corona discharge on the antenna in the presence of a storm [5]. This leads to some ambiguity as to establishing values for the noise seen during a thunderstorm [2].

Another potential limitation of the data is inherent in their hardware implementation. The bandwidth of their receivers was narrow $\mathcal{O}(200Hz)$ with respect to that of atmospheric noise $\mathcal{O}(20MHz)$. A Loran receiver typically has a bandwidth of $\mathcal{O}(30kHz)$. While there are tables provided by CCIR to convert between bandwidths of receivers far larger than a Loran receiver, there may be some question as to the validity of the APDs for Loran receivers. More will be said about this in Section V.

II. Analysis

Given that atmospheric noise follows the APD listed in CCIR, the analysis required to answer the questions of how much signal is suppressed and the resulting rms value of the noise after the hole-punch is straightforward. We may now address the questions 1) how much of the Loran signal gets suppressed by the hole-punch and 2) what is the resulting level of noise present when the signals are allowed to pass?

A. Signal Suppression

By examining when does the APD deviate from a Rayleigh distribution, which is a straight negatively sloped line, we can look to the x-axis at that point to see what percentage of time does the noise differ from a Rayleigh distribution. This will allow us to separate the time the noise is Rayleigh distributed from the time that it is non-Rayleigh. By hole-punching when the signal is non-Rayleigh, only the Rayleigh like noise will be allowed to pass.

For our analysis, we will use the point at which the APD deviates from the straight line portion by more than 3dB as our criteria for when is the noise non-Rayleigh. This point is easy to quantify and the resulting distribution will be nearly Rayleigh. We can now use the APDs listed in CCIR 322-2 to determine approximately the amount of time the noise is Rayleigh when the linear estimation techniques will work well and the amount of time the signal will be suppressed.

As a practical consideration, we will monitor the incoming signals when there are no Loran pulses to gather information as to the quality of the noise. From these data, we can measure V_d and then approximate the noise as following the CCIR APDs. In practice, we may choose the threshold level to be set a few dBs above the expected Loran signal strength rather than the 3dB point as mentioned above.

Figure 5 shows an example of this technique using an APD for a V_d of 10. By drawing a construction line tangent to the Rayleigh portion of the APD, we can approximate the point at which the APD exceeds a Rayleigh distribution by 3dB. The result is that both the noise and desired signal would be punched out or suppressed 55% of the time. This may be represented by a loss of 3.5dB due to signal suppression. In this manner, signal suppression values for each of the APD curves up to a V_d of 16 were plotted on Figure 6. The best-fit line shows a reasonable linear relationship, and thus signal suppression of the signal may be approximated by –0.3*V_d dB. Thus for any V_d value, we can directly determine how much signal would be lost if we hole punched whenever the noise was non-Gaussian.

B. Gaussian Noise Level Gain

Next, we wish to determine what is the level of the passed noise, which is approximately Rayleigh, relative to the original rms noise value. To determine the rms values of the resulting noise after hole-punching, we again construct a straight line tangent to the Rayleigh section of the APD. By measuring the difference between the 1-σ point (approximately the 36% probability) of the construction line and that of the 0 dB level on the graph, we obtain the difference between the rms value of the passed noise from that of the overall noise. Extending the example from the previous section, Figure 7 shows that the noise after hole-punching would be 20dB below the original

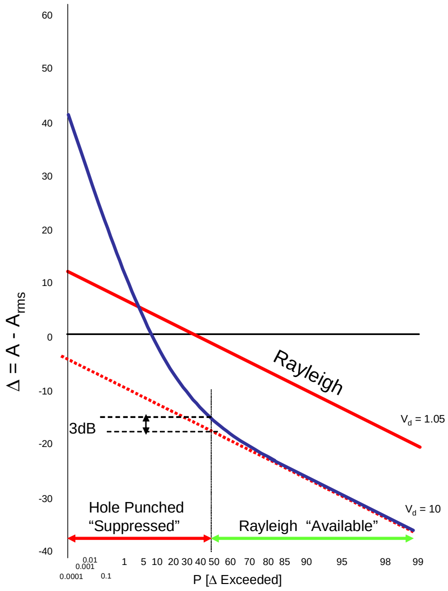

Fig. 5. Signal suppression based on APD.

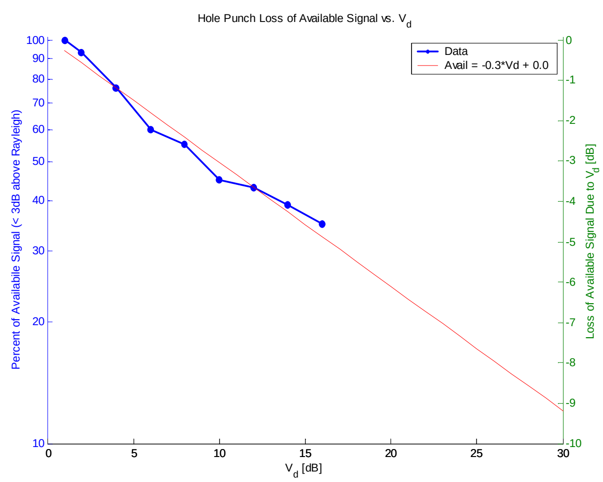

Fig. 6. Signal suppression as a function of V_d.

rms noise level. Thus the effective noise level drops by 20dB from what we had calculated in Equation 1.

Applying this analysis to the APDs listed in CCIR, we produce Figure 8. The best line fit through the points results in a reduction of the noise level that follows Equation 3 of

$$\text{RMS Reduction} = -2.1V_d + 1.8 \text{ dB} \tag{3}$$

Recall that the APD gives the expected noise value relative to the rms value. So we will need to use Equation 1 to calculate the rms value from the noise factor for a vertical monopole antenna over a perfectly conducting ground plane and then apply a correction to account for the suppression of the non-Rayleigh noise in order to get the absolute rms value of the passed noise.

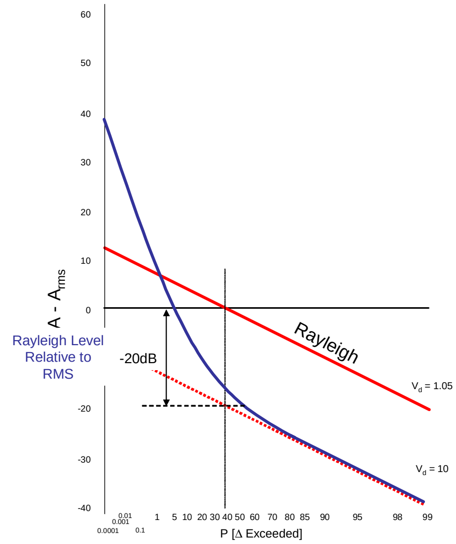

Fig. 7. Example of the rms reduction due to hole-punching for $V_d = 10$.

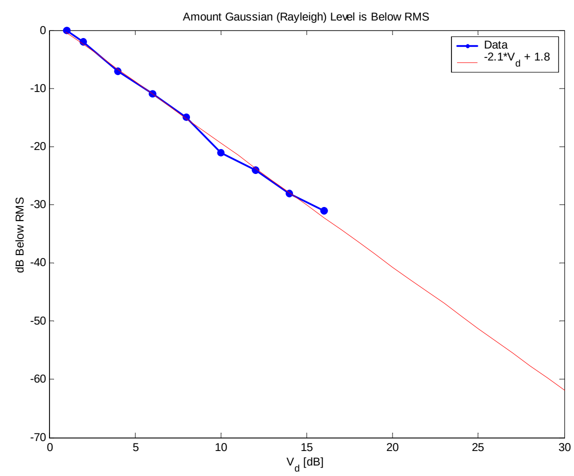

Fig. 8. Reduction of rms electric field value as a function of V_d.

C. *Total Performance*

Now we combine the results derived in the previous two sections. We found that hole-punching suppresses the signal since some of the samples will be thrown out by the non-linear filter when the noise is large. Yet at the same time the filter will reduce the over all rms value of the noise since the less frequent but high level values will be discarded. Equation 4 gives the combined effect on noise for the hole-punching filter given that the noise follows the CCIR APDs; the results are plotted on Figure 9. Notice that in light of a loss due to suppression, the improvement due to the reduction in the rms level will always dominate.

$$\text{Total Noise Reduction} = -1.8V_d + 1.7 \text{ dB} \tag{4}$$

Also shown in green on Figure 9 are analytical results derived for clipping on a Spread Spectrum Multiple Access (SSMA) system. The analysis of an SSMA system would be similar to

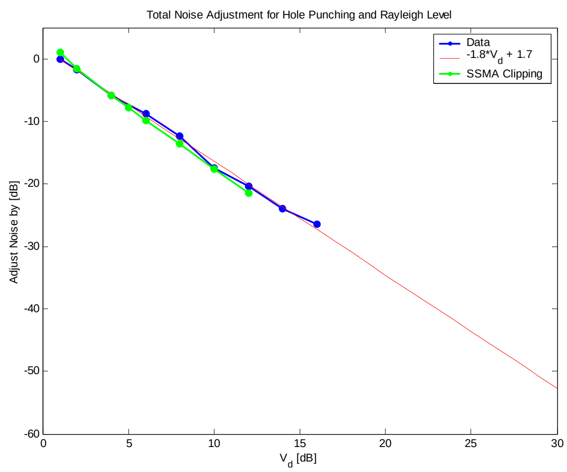

Fig. 9. Plot of total noise reduction as a function of V_d (blue). SSMA noise reduction due to clipping (green).

Loran since both systems employ bursts of pulses rather than continuous wave modulation. The steeper slope of the SSMA system shows that the processing technique used was more efficient at reducing noise, but not much more than this hole-punching method.

III. Results

The performance of a receiver rests on the signal-to-noise ratio (SNR). If we were to use only a linear receiver, we would use the rms values derived from Equation 1 to determine our SNR. By employing the non-linear hole-punching filter first we can greatly reduce the noise level and thus increase our SNR.

To determine receiver performance, we first need to choose a rms noise level and a V_d condition that we wish to evaluate. Here we will choose the median 95% level and the median value of V_d from CCIR 322-2. Figure 10, shows the median 95% noise level of rms electric field at 1800h local time in summer for a monopole above a perfectly conducting ground plane. That is, if we were to sample the rms level of the electric field at 1800h on a number of summer days and to make a histogram for each day of these noise levels then on average half of days will have their 95 percentile value below this value.

Also from CCIR we can get a median percentile value of V_d. The Loran Integrity Performance Panel (LORIPP) determined that the median 50% value of V_d most accurately matches our definition of availability, and so we will use this value of 14 dB for the analysis.

Using a V_d of 14dB, we find that the effects of signal suppression will be a loss of 4.2 dB while the reduction in noise from median 95% rms value to the rms value of the hole-punched data will be 27.6dB. Thus the total effect of the hole-punching will reduce the noise by 23.4 dB. Since V_d has no spatial variation, our improvement in performance may be applied across any region on interest. The effective noise after clipping is shown in Figure 11.

Due to the approximate nature of this analysis, the LORIPP has chosen to take only a 15dB credit for hole-punching. This would be a conservative approach which will hopefully be verified by future testing.

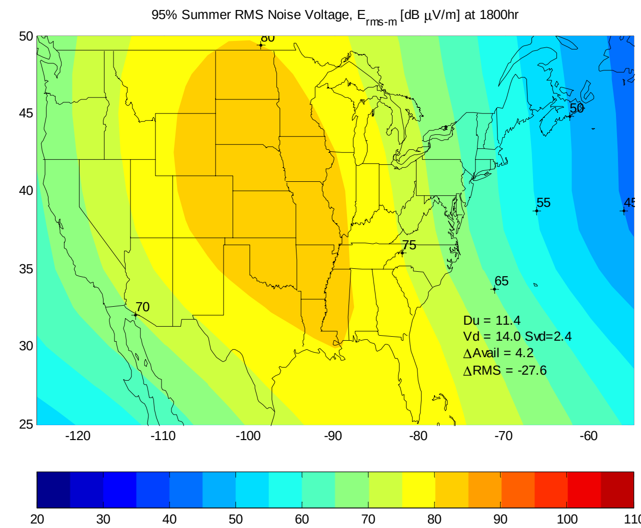

Fig. 10. Median 95% noise values for summer at 1800h local time.

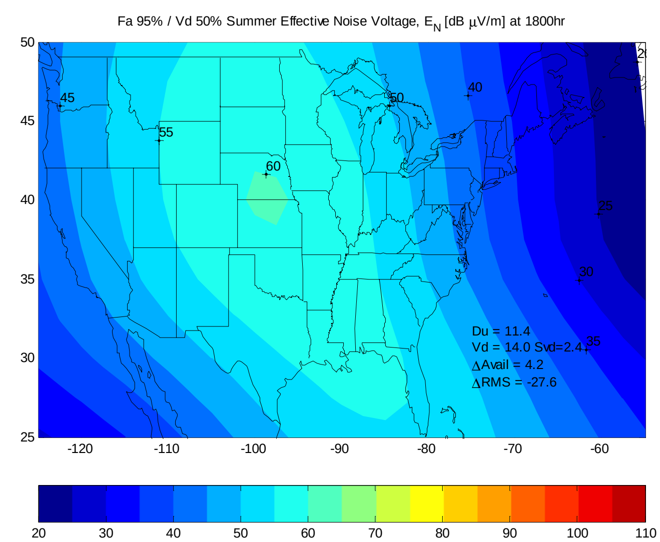

Fig. 11. Effective median 95% noise values for summer at 1800h local time after hole-punching.

This 15dB reduction in noise will directly increase the SNR level by the same amount. Phase noise and ECD errors are both inversely proportional to the square-root of the product of number of signals averaged and SNR. By increasing SNR 15dB, we can effectively reduce the number of signals required to average. This in turn allows for shorter integration times and enables a receiver to track faster vehicle dynamics more easily which can help with continuity. Another benefit of an improved SNR is the inclusion of towers which would otherwise be too weak into our position solution. By increasing the number of towers in our calculations we can improve our error checking algorithms through improved signal geometry and thus increase our availability.

IV. Conclusions

In the previous section we discussed the effects of a non-linear hole-punching filter on rms electric field values of atmospheric noise. The effects of the filter are two-fold: first, a certain amount of the desired signal is suppressed. Second, we get a reduction in the rms value of the noise relative to the pre-filtered levels. The combination of these two effects which are based solely on V_d results in a significant reduction of the rms noise level. Based on the median 50% V_d value, the 15dB credit for hole-punching currently seems justified for the purpose of LORIPP. Finally, this credit can enhance both availability and continuity since with a higher SNR integrity may be met under a larger number of locations and conditions.

V. Future Work

In order to better validate this analysis, it is imperative for the LORIPP to perform some in-band noise tests. Such tests would collect noise data during the spring or summer months in inclement weather to determine that the noise data gathered by a Loran receiver sufficiently follows the APDs given by the CCIR. Of key concern is the validity of the APDs given the wide bandwidth of the Loran receiver.

Also, the CCIR data were taken from ground stations and preliminary data suggests that the noise measured in the air would be significantly reduced in power from that on the ground. Experimental flight and ground tests are planned for 2004 to examine this effect.

VI. Acronym List

APD	Amplitude probability distribution
CCIR	International Radio Consultative Committee
CDF	Cumulative distribution function
CG	Cloud to ground
dB	Decibels
GRI	Group repetition rate
Hz, kHz, MHz	Hertz, kilohertz, megahertz
ITU	International Telecommunications Union
LORIPP	Loran Integrity Performance Panel
NTIA	National Telecommunications and Information Administration
PCI	Phase code interval
rms	Root mean square
s, ms, μs	Second, millisecond, microsecond
SNR	Signal-to-noise ratio
SSMA	Spread Spectrum Multiple Access
μV/m	Microvolts/meter

Acknowledgments

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References

[1] Robert J. Achatz et al., NTIA Report 98-355, *Man-Made Noise in the 136 to 138-MHz VHF Meteorological Satellite Band*

[2] *CCIR 322-2: Characteristics and Applications of Atmospheric Radio Noise Data*, International Radio Consultative Committee, Geneva, 1983.

[3] Per K. Enge and Dilip V. Sawate, *Spread-Spectrum Multiple-Access Performance of Orthogonal Codes: Impulsive Noise*, IEEE Transactions on Communications, Vol. 36, No. 1, January 1988.

[4] Alberto Leon-Garcia, *Probability and Random Processes for Electrical Engineers 2nd Ed.*, Addison-Wesley Publishing Company, Redding Massachusetts, May 1994.

[5] Rober Matheson conversation, 12 August 2002.

[6] Benjamin Peterson, Loran Raw Data Set, 3 January 2003.

[7] Martin A. Uman,.*The Lightning Discharge*, Dover Publications, Inc, Mineola, NY, 2001.