Statistical Analysis and Modeling of VLF/ELF Noise in Coal Mines for Through-the-Earth Wireless Communications

Lincan Yan, Joseph Waynert, Carl Sunderman, Nicholas Damiano
National Institute for Occupational Safety and Health (NIOSH)
626 Cochrans Mills Road
Pittsburgh, PA 15236, USA
LYan1@cdc.gov, JWaynert@cdc.gov, CSunderman@cdc.gov, NDamiano@cdc.gov

***Abstract* -- The through-the-earth (TTE) wireless communication system, in which the RF signal can directly penetrate the earth separating a transmitter and receiver, is likely to survive a mine disaster because it requires no cabling between the surface and underground. One of the biggest challenges for TTE communication is that the ambient electromagnetic (EM) noise can be significant and impose a limitation on the reception sensitivity. Both underground and surface RF noise characteristics were obtained and analyzed from experimental data collected at several coal mines. The results show the surface has a higher noise level than underground. Moreover, the parameters obtained in an empirical noise model can be used to predict a TTE system's performance at a specific mine site.**

***Keywords* -- VLF/ELF noise; Loop antenna; Mine communication; Magnetic field; Through-the-earth.**

I. INTRODUCTION

Analysis of the electromagnetic background noise of through-the-earth (TTE) communication is important, for it is against this noise background that the received RF signal must be recognized at the earth's surface or in a mine. The range of frequencies of interest in TTE communication with trapped miners is roughly from 10 Hz to 10 kHz. Thus, portions of both the extremely low frequency (ELF) (3 Hz-3 kHz) and very low frequency (VLF) (3 kHz-30 kHz) bands are included. Also, both surface and subsurface noise are important because both uplink and downlink transmission are desirable. By characterizing the noise environment at a mine, it is possible to specify the minimum signal source strength required for a communication system as well as the desirable receiver sensitivity.

During the 1970s, the National Bureau of Standards took wideband noise measurements both within and above numerous coal mines [1, 2]. The majority of these measurements were taken under operational conditions, and man-made noise was generally dominant. One of the characteristics of man-made noise in an operational mine is the 60 Hz harmonics from power lines. Also, there are wideband impulses from machinery. For uplink transmission in which the receiver is located on the surface, the atmospheric noise from lightning is the dominant source [3].

The electromagnetic noise in the mine environment today has changed significantly since what was measured by the Bureau nearly a half century ago, due to the considerably increased electromagnetic activity on the surface and underground. Therefore, it is necessary to measure the noise again at specific coal mines to obtain their RF noise characteristics which will be useful in TTE system design and application.

The VLF/ELF band noise usually consists of two types of source: atmospheric noise and man-made electromagnetic (EM) noise. The atmospheric noise produced by lightning can be characterized as near-field noise from local thunderstorms and background noise from distant thunderstorms. The characteristics of lightning and atmospheric noise are detailed by A. D. Watt [4]. The noise from local thunderstorms tends to be randomly polarized and highly impulsive. There were some atmospheric noise measurements at ELF performed during the 1960s and the 1970s for research in submarine communications [5].

In the references cited previously, most VLF/ELF atmospheric noise has either the vertical electric field or the horizontal magnetic field because they are the dominant components of both the transverse electromagnetic (TEM) or the first-order transverse magnetic (TM) modes in the earth-ionosphere waveguide [6]. However, for TTE communication applications that use horizontal transmit loop antennas, the vertical magnetic field is of interest. The U. S. Bureau of Mines conducted some experiments on the measurement of the vertical component using horizontal loops in selected narrow bandwidths centered on each of the four channel frequencies of 630, 1050, 1950, and 3030 Hz, above 27 coal mines, with the aim of investigating the relationship between vertical magnetic noise and the depth dependence important in the downlink and uplink transmission.

The man-made radio-interference environment is the composite emission from human-produced radio-noise sources. For the mining environment, the EM noise also arises from mining machines, roof bolting machines, power cables, ground transportation vehicles, electric power generators, transmission lines, etc. In general, the level and variability of interference are specifically related to the number and types of unintentional radiation and reception and the nature of the intervening terrain. Skomal gives

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detailed observations and description of man-made RF noise [7].

In this paper, the VLF/ELF magnetic noises measured at several operating coal mines are statistically analyzed. The noises are further characterized based on an empirical model.

II. Field Measurement

Electromagnetic noise has been measured at two operational coal mine sites to investigate the effect of VLF/ELF noise on the application and reliability of TTE communication systems. Noise was recorded at WV CM (continuous mining) mine #1 on two separate occasions over the summer of 2012. Surface and underground noise measurements have also been recorded at PA longwall mine #1. The RF noise is suspected to be able to penetrate the earth overburden for both uplink and downlink communications. Noise measurements were taken at the surface and underground at both mine sites during the same shift hours; thus the results described here are applicable for the design of both uplink and downlink electromagnetic transmission systems. The noise was measured with three orthogonal axis ferrite core receiver antennas, which were connected to a LabView data acquisition program through an analog-to-digital converter. The noise was recorded in the time domain with a sampling rate of 50 kb/s. Due to file size limitation; the data were split into a series of files, each of about 90 seconds recording duration.

A. *WV CM mine #1*

WV CM mine #1 is an underground mine that uses continuous mining machines. Noise measurements were taken at both the surface and underground. The earth overburden at the test location has a depth of ~113-119 m (370-390 ft.). Underground noise was recorded on two successive days while the transmitting loop antenna was being set up at the surface. The transmitter (Tx) and receiver (Rx) were then switched for uplink and noise was recorded at the surface while the Tx system was off.

B. *PA longwall mine #1*

This mine has an overburden depth of ~213-229 m (700-750 ft.). Surface noise was recorded. The Tx and Rx were switched for the downlink the second day and noise was recorded underground while the Tx was off.

III. Noise Characterization

A. *Fast Fourier transform (FFT) and Power Spectrum*

Representative noise data at WV CM mine #1 is plotted in Figs. 1 and 2 for surface and underground (FFT), respectively. In those plots, the FFT of the receiving signal (voltage) is converted to magnetic field strength (A/m) using the frequency-dependent antenna factor which is obtained prior to the experiment. Without losing the peaks, data in Fig. 1 and Fig. 2 are averaged over every 10 points to reduce the noise fluctuation, which is reduced from ~20 dB to ~5 dB. In Figs. 1 and 2, the y axis signal is kept unchanged, but the x and z axis signals are shifted by plus or minus 20 dB for clarity. The noise is first recorded with the transmitting antenna powered off, then with the antenna powered on (two transmitting frequencies, 810 Hz and 3330 Hz), to check for any unfavorable reception at the Rx due to the Tx radiation. Based on the FFT plots, the surface has a higher noise level than underground at this mine site.

Man-made noise is generally observed to take the form of power line harmonics. It is stronger at lower frequencies. While atmospheric noise is generally dominant between 10 and 30 kHz (especially in the summer), the power line noise could be dominant at 1 kHz [8]. However, the 1 kHz signal and its harmonics in the FFT plots of some recorded noise data are thought to be caused by data acquisition electronics, especially the laptop which might be close to the receivers.

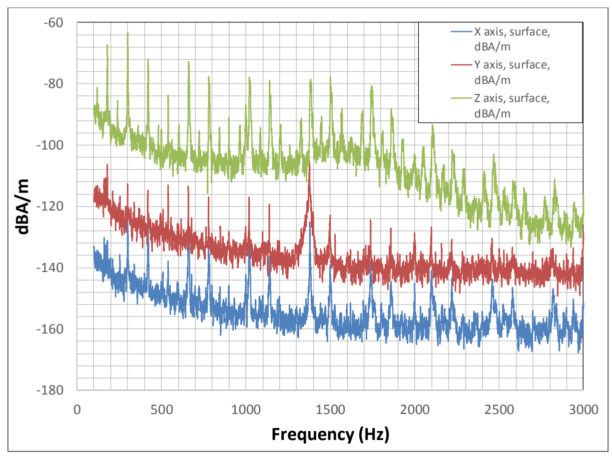

Fig. 1. FFT of **Surface** noise on receiving x, y, and z axis antennas, Tx off. Upper and lower curves are displaced +20 and -20 dB from the middle curve, respectively.

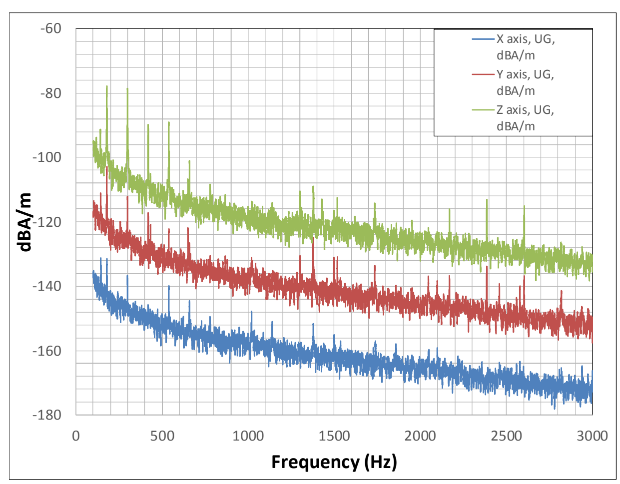

Fig. 2. FFT of **Underground** noise on receiving x, y, and z axis antennas, Tx off. Upper and lower curves are displaced +20 and -20 dB from the middle curve, respectively.

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B. Cross-Correlation between surface and underground

For TTE wireless communication, the uplink transmission will be more challenging than the downlink, because the surface has a higher noise level than the underground and the underground transmit power level is limited by safety considerations.

Moreover, reliability is a challenge for a TTE system. It has been observed that a TTE system may establish a communication link at one time, but perhaps not be able to establish the link a few hours later. One explanation of this lack of repeatability or availability may be the difference in the noise environment due to changes in mining activities. To investigate this possibility, both surface and underground noise at one mine were recorded simultaneously (the surface and underground system computers were approximately synchronized) and then checked for cross-correlation to see if the measured noise, surface and underground, were correlated to each other. In signal processing, cross-correlation is a measure of the similarity of two waveforms as a function of a time-lag applied to one of them. Consider two series *x(i)* and *y(i)* where i = 0, 1, 2, ..., N-1. The cross-correlation R_{xy} at delay time τ is defined as

$$R_{xy}(\tau) = \frac{\sum_i[(x(i)-\overline{x}(i)) * (y(i-\tau)-\overline{y}(i))]}{\sqrt{\sum_i(x(i)-\overline{x}(i))^2}\sqrt{\sum_i(y(i-\tau)-\overline{y}(i))^2}} \qquad (1)$$

where $\overline{x}(i)$ and $\overline{y}(i)$ are the means of the corresponding series. The denominator in the expression above serves to normalize the correlation coefficients such that $-1 \leq R_{xy}(\tau) \leq 1$. The bounds, -1 or 1, indicate a maximum correlation and 0 indicates no correlation. A high negative correlation indicates a high correlation but of the inverse of one of the series, i.e. the two signals are out of phase. The cross-correlation between surface and underground signals is plotted vs. lag time (in units of second) in Fig. 3. The values of $R_{xy}(\tau)$ attain a value of ~0.2 when the transmitter is on (blue line) and are nearly zero for just noise reception. It has to be mentioned that the noise data taken underground and on the surface were taken on different dates, i.e., not simultaneously; not surprisingly, the noise data are uncorrelated.

C. Amplitude PDF Model

There is extensive research and modeling on the first-order amplitude power-density (APD) of atmospheric radio noise [9-15]. One approach to characterize RF noise is through the use of APD spectrums in which the average level of the noise field over some time frame is determined at a series of frequencies. Recently, Chrissan provided a detailed model that incorporates both the α-stable probability density function (PDF) and a Poisson-distributed time of occurrence [16]. Some APD models are based entirely on intuitive reasoning and/or fitting the data to mathematical functions (empirical models based on noise measurements). Other models make assumptions on the noise source distribution and the propagation of noise impulses (statistical-physical models).

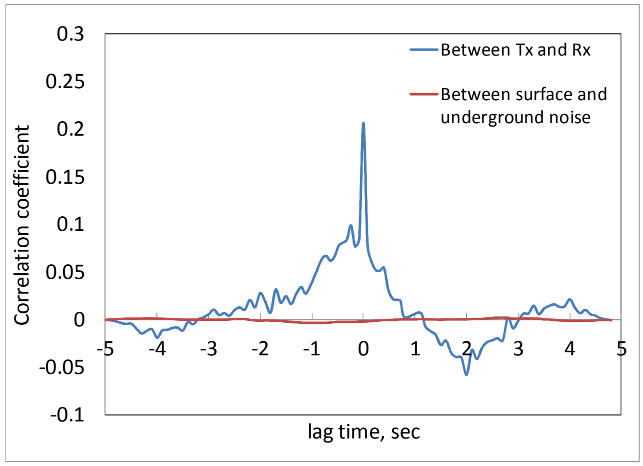

Fig. 3. Cross-correlation between surface and underground noise (red), and between surface transmitting signal and underground receiving signal (z axis) (blue).

Empirical models generally fit a curve to limited data. Some examples are the Hall [17] and Field-Lewinstein models [18]. They are relative simple and more mathematically tractable than other models, but their parameters usually do not relate to the physical processes. Rather than statistical-physical models which may require some unrealistic approximations about atmospheric noise, we use an empirical model to characterize the noise.

Of the commonly known APD models, the Field-Lewinstein (FL) model was chosen in this paper because of its accuracy and relative simplicity (mathematically). In the FL model, the VLF and ELF noise are classified as two components: 1) intermittent, non-overlapping, large pulses, and 2) a more homogeneous background noise. The large pulses are caused by local nearby electromagnetic activities and/or lighting, while the background noise is caused by relatively weak pulses from more numerous and more distant electromagnetic activities and/or lightning flashes [18].

The PDFs of the background noise components x and local impulsive noise component y are denoted by $p_1(x)$ and $p_2(y)$, respectively. The component x can be described statistically as a zero-mean, Gaussian random process with variance ${\sigma_0}^2$. For simplicity, $p_1(x)$ can be represented by a Rayleigh density with average noise power ${R_0}^2 = 2{\sigma_0}^2$. For component y, $p_2(y)$is chosen to be the power-Rayleigh distribution. The latter is suggested by experiment [8]. The standard deviation of the overall noise $z = x + y$ is expressed as

$${\sigma_z}^2 = R^2\left(\Gamma\left(1+\frac{2}{\alpha}\right) - \Gamma^2\left(1+\frac{1}{\alpha}\right)\right) + {R_0}^2\left(1-\frac{\pi}{4}\right) \qquad (2)$$

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The ratio of energy in the impulsive component y to energy in the background component x is defined as

$$\gamma^2 = \frac{E\{y^2\}}{E\{x^2\}} = \frac{R^2\Gamma\left(1+\frac{2}{\alpha}\right)}{{R_0}^2} \tag{3}$$

The APD of $p(z)$ can be obtained through

$$Prob(z > z_T) = \int_{z_T}^{\infty} p(z)\,dz$$

$$= e^{-(z_T/R)^\alpha} + \int_0^{z_T} \frac{\alpha y^{\alpha-1}}{R^\alpha} e^{-(y/R)^\alpha} e^{\frac{-(z_T-y)^2}{{R_0}^2}}\,dy. \tag{4}$$

The values of R^2 and ${R_0}^2$ in (4) are to be determined by solving (2) and (3) simultaneously, given the values of γ and α which are empirically adjusted to fit the observed noise statistics. The parameter α depends on the pulse characteristics of the high-level spiky component, and parameter γ represents the ratio of energy in the impulsive component y to energy in the background component x. Physically, α characterizes the noise spikiness level, while γ measures the impulsivity of the noise.

IV. Results and Discussion

Two sets of the experimental noise data on both the surface and underground were collected at two coal mine sites, and simulated results based on the FL model are plotted in Fig. 4 and Fig. 5. Different combinations of parameters α and γ were tested in the FL model to fit the noise data. The values for best fitting of specific noise data are listed as in Table 1.

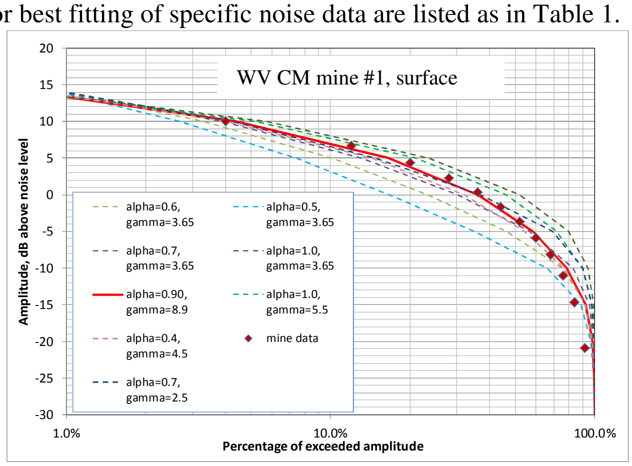

Fig. 4. Surface experimental mine data and FL model predictions based on various α and γ values. Noise measurements were taken at WV CM mine #1.

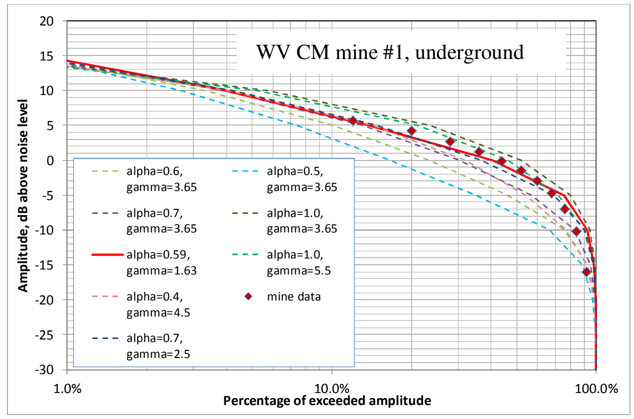

Fig. 5. Underground Experimental mine data and FL model predictions based on various α and γ values. Noise measurements were taken at WV CM mine #1.

TABLE 1
Noise Characteristics at WV CM mine #1 and PA Longwall mine #1

	Coal mine	*Date on*	α	γ
Noise at surface	WV CM mine #1	6/26/2012	0.90	8.9
	WV CM mine #1	8/30/2012	0.95	9.0
	PA longwall mine #1	8/19/2013	0.98	15.8
Noise underground	WV CM mine #1	6/26/2012	0.59	1.63
	WV CM mine #1	8/30/2012	0.53	1.5
	PA longwall mine #1	8/19/2013	0.99	8.3

As seen in Table 1, for noise measurements taken at the WV CM mine #1, both the α and γ values underground are smaller than those for the surface. The value of α underground is about half of that on the surface. The γ value underground is 1/4-1/5 of that on the surface. This suggests that the noise level is greater at the surface than underground at this mine site, at least during the time period measured.

At PA longwall mine #1, γ for the underground noise is about half of that of noise at surface, which suggests there is much more impulsive noise due to local electromagnetic activities and/or lightning flashes at the surface than underground. However, unlike WV CM mine #1, α value for underground is about the same as for the surface. PA longwall mine #1 is a larger coal mine compared with WV CM mine #1, so there are many more mining activities underground. Moreover, the underground sampling location at PA longwall mine #1 is closer to the longwall than at WV CM mine #1.

V. Conclusions

Atmospheric and man-made VLF/ELF noises were measured at different operational coal mines for both the surface and underground environments. To characterize the

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measured noise, statistical analysis based on an FFT and the power spectrum was performed. Furthermore, cross-correlation analysis suggests that noises at the surface and underground are not correlated for different time period at the specific coal mines.

Following analysis of measurements, an empirical model (the FL model) was utilized to characterize the noise to obtain parameters α and γ for each mine site. The results confirm the phenomenon that the surface (high α and γ value) has a higher noise level than underground (small α and γ value) for both mines; hence, it will be more difficult to establish the uplink TTE communication than the downlink because of the greater noise level at the surface. Moreover, the parameters α and γ can be used to create an initial evaluation of a TTE system's performance at a specific mine site if there is no noise measurement information available before system installation.

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DISCLAIMER

The findings and conclusions in this paper are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health (NIOSH).

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