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A New Apparatus to Measure ELF/VLF Electromagnetic Noise in Coal Mines

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Abstract

Ambient electromagnetic (EM) noise (natural or manmade) is a major limiting factor for the design and operation of many electronic devices, including through-the-earth (TTE) communications and tracking systems. Extensive studies on EM noise were conducted by the US Bureau of Mines in the 1970s and 1980s. Changes in the design and operation of electrical equipment since then, however, have resulted in changes in the EM noise environment. This paper reviews past research on surveying EM noise in the extremely low-frequency (ELF) and very-low-frequency (VLF) bands, which are the operating bands for TTE systems, and introduces a new battery-powered, rugged, portable measurement system for surveying EM noise in mining environments. Examples of surveyed EM noise measurement results in and above an active underground coal mine, using the new system, are presented in terms of absolute magnetic field strength levels. A new metric, average noise level (ANL), is introduced to characterize the noise level relative to a particular frequency band for a specific location. It is found that EM noise in mining environments varies significantly with time and location. EM noise levels at frequencies of 30 Hz that shifted from power harmonics (e.g., 90, 150, 210, 270 Hz) are relatively low and their variation with time can be statistically modeled by a Gaussian distribution. The conclusions and findings presented in this paper can help better design and operate TTE communications and tracking systems in underground mines.

Keywords Through-the-earth · Wireless communications · Electromagnetic noise · ELF · VLF

1 Introduction

Electromagnetic interference (EMI) is a serious and an increasing concern faced by the mining industry as it can cause unexpected malfunctions in electrical and electronic systems that are now used in virtually all aspects of mining. EMI can occur across different frequency bands. In this paper, the focus of the frequency band is from 10 Hz to 10 KHz which fall into the extremely low-frequency (ELF) and very-low-frequency (VLF) bands. The potential systems operating in these bands in the mining industry are mainly through-the-earth (TTE) communications and tracking systems. In addition to ELF and VLF bands, the National Institute for Occupational Safety and Health (NIOSH) also investigates EMI issues occurring at higher frequencies in the mining industry, and results have been documented in other publications. [1–5]

The existing ambient EM noise (i.e., EMI) has been a major limiting factor for the design and operation of TTE communications and tracking systems used in underground coal mines. As a result, it is necessary to know the detailed characteristics of the EM noise in order to design a TTE system that has optimized performance. Additionally, a designed TTE system must be evaluated by using realistic EM noise in order to ensure that the system can effectively work in a noisy mining environment.

EM noise generated in mines is generally a random process. Therefore, statistical analysis is probably the most meaningful approach for analyzing EM noise in mines. In this paper, we first review historical EM noise survey efforts and then introduce a new measurement system for surveying EM noise in mines. EM noise measurement results based on the new system in an active coal mine are presented.

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2 Background: Historical EM Noise Survey Research Sponsored by the United States Bureau of Mines (USBM)

In view of the importance of the ambient EM noise and its impact on communication and tracking systems used in underground mines, the USBM commissioned six contractors in the 1970s to conduct EM noise studies aiming for development of improved TTE systems [6–8]. These efforts have been by far the most comprehensive studies in mining history pertaining to surveying ambient EM noise in coal mines. In the following sections, we will briefly review these historical studies conducted by the six contractors, with a focus on the instrumentation used, locations surveyed, and major results achieved.

National Bureau of Standards (NBS) Researchers from NBS directly recorded magnetic field noise waveforms on analog magnetic tape in the field, then subsequently sampled and converted to digital signals for analysis in the laboratory. A detailed description of the measurement system developed and used by NBS was documented in [9]. The antenna used was an 11-turn electrostatically shielded 30-inch-diameter loop. The locations surveyed included both inside and outside of several active coal mines. In-mine locations surveyed included strategic locations such as in the vicinity of DC trolley lines, electrically powered locomotives, and entrances to AC electric power boreholes, as well as some quiet areas where there were no major noise sources. No data was collected around a working face in those mines. All three components of the B-field were measured. The duration of each recorded noise sample is relatively short, ranging from fractions of a minute to several minutes. EM noise surveying results measured by NBS can be found in a series of technical reports that NBS submitted to USBM, which are now available online [10–13].

Institute for Telecommunications Sciences (ITS) The noise survey effort made by the ITS was mainly based on a magnetic tape recorder, and the results were useful for characterizing the long-term behavior of both atmospheric and man-made EM noise [14]. However, most of the locations surveyed were not at a mine site, and the primary field of interest was the vertical component of the E-field. Three components of magnetic field noise were measured in an operating mine on only one occasion. Consequently, the results collected by ITS have less relevance to ELF and VLF EM noise measurements at a mine site, which is the focus of this paper.

Westinghouse Georesearch Laboratory (WGL) WGL's main objective was to gather data under the relatively quiet conditions that are likely to exist following a disaster when the mine main power is shut down [15]. As a result, data collected by WGL were mostly in mines under non-operating conditions. The vertical component of the B-field was measured on the surface, and the horizontal component of the B-field was measured underground. There were two sets of instrumentation used by WGL for surveying B-field noise. The first set was a 24-inch square, 1000-turn loop antenna connected to a manually tuned wave analyzer. The second set was a few loop antennas connected to a 10-bit A/D converter through a long cable [14, 15].

West Virginia University (WVU) WVU was the only contractor that has surveyed the EM noise at relatively higher frequencies from 2k to 200k Hz [15]. The instrumentation was centered around a conveniently portable, manually tuned, frequency-selective voltmeter which had not been calibrated by placing it in a known uniform field. Measurements were made of the horizontal and vertical magnetic field components of the EM noise at a number of strategic locations including near AC and DC power centers, near high-voltage power cables, near trolley lines, and in the vicinity of a continuous miner.

Colorado School of Mines (CSM) CSM surveyed the EM noise on the surface (above working faces) at a number of operating mines in Colorado, Illinois, and West Virginia. The major instrumentation used was a 13-bit A/D converter where signals were sampled, digitized, and fed into a mini-computer that computed noise histograms. Band-pass filters were added before the A/D converter to select the frequency band of interest. Unfortunately, the results surveyed were uncalibrated results with a unit of gamma/meter that cannot be directly compared to other standard magnetic field measurement results. In addition, the B-field sensor used was a 1000-foot perimeter loop laid on the ground. Such a large loop tends to average out or mask spatial variations of the B-fields which are not likely to be uniform over the area of the large loop [14, 16].

Arthur D. Little, Inc. This contactor did not directly contribute to any instrumentation development and noise measurements. Instead, they surveyed what the other five contractors had done and summarized the findings to draw conclusions and make recommendations for USBM [15].

A comparison of the measurement effort from different contractors is given in Table 1. After sponsoring considerable studies in EM noise measurement and analysis, in order to optimize the return of its research investment, USBM directed NBS to review what the other five contractors had done and summarize the results with a comprehensive report. The overall conclusion resulting from this survey was that, at the time, there was not sufficient knowledge of EMI in mining environments to design a reliable communication system, and thus, future work is needed. Some recommendations made by the NBS for future EM noise

Table 1 A comparison of the EM noise survey efforts made by different contractors of USBM in the 1970s

Contractor	Frequency (Hz)	Magnetic field component	Unit	Instrumentation		Calibration	Locations
				Receiver	Antenna		
NBS	20-20 k	Three components (in sequence)	dB A/m	Analog tape record		Yes	Surface and underground (operating coal mines)
ITS	20-20 k	Three components B-field (one measurement)	dB mA/m	Analog tape record		Yes	Most not at mine sites, with only one occasion in an operating mine
WGL	20-5 k	Vertical component (surface), horizontal (underground)	dB µA/m	Narrow band receiver	24-inch square, 1000-turn shielded loop, 1-foot diameter air-core loop, ferrite-core loop	Yes	Surface and underground
WVU	2 k-200 k	Three components	dB (reference to 0.35 V)	Amplifier + Voltmeter	50-turn unshielded air-core loop with an area of 1.3 m^2	No	Surface and underground
CSM	20-20 k (eight secondary bands)	Vertical	Gamma/second	Wideband filter + A/D converter		No	Surface (above working faces), near a power station
Arthur	N/A	N/A	N/A	N/A	N/A	N/A	N/A

survey efforts, based on the work done by the other contractors [13], included:

- The result should be presented with a unit of either (a) A/m, or (b) (A/m)/ $\sqrt{Hz}$.
- Calibrated instrumentation should be used so the results are directly related to B-field and can be compared to each other.
- Three components of the B-field should be measured.
- Small loop antennas should be used. The loop antenna should be small enough for taking convenient measurements in mines. In addition, another reason for avoiding using large loop antennas for an EM noise survey is that large loop antennas remove the spatial variation of the B-field.

3 New Measurement Instrumentation

Earlier data collected by various USBM contractors in the 1970s was based on a variety of equipment and measurement methods making the data analysis complex. With the advancement in sensors and computing technologies, it was necessary to develop a modern measurement system to survey some recent fresh data to be used for evaluating the performance of TTE systems.

In view of the need for such a new noise survey system, NIOSH contracted with Vital Alert Inc., a commercial TTE system manufacturer, to develop a battery-powered portable system to capture and store noise samples. This system is referred to as the Automated Noise Data Acquisition Unit (ANDAU) system and will be briefly described in this paper.

First, to minimize the self-inflicted EMI generated by the circuits (e.g., the power supply circuits) of the ANDAU system, the new system was separated into two units: the sensor unit and the data acquisition unit, as shown in Fig. 1. The two units are hosted in two waterproof plastic cases with an identical size of 16 in. x 12 in. x 7 in. The data acquisition unit is the brain of the system which contains the system battery power supply, single-board computer, analog-to-digital converter (sampling rate: 100K samples/second), removable storage media, and status indicators. The sensor unit contains a three-axis antenna formed by three ferrite rod antennas and the corresponding amplifiers for the three antennas. The two units are connected by a long (>3 m) multi-conductor shielded cable. It should be

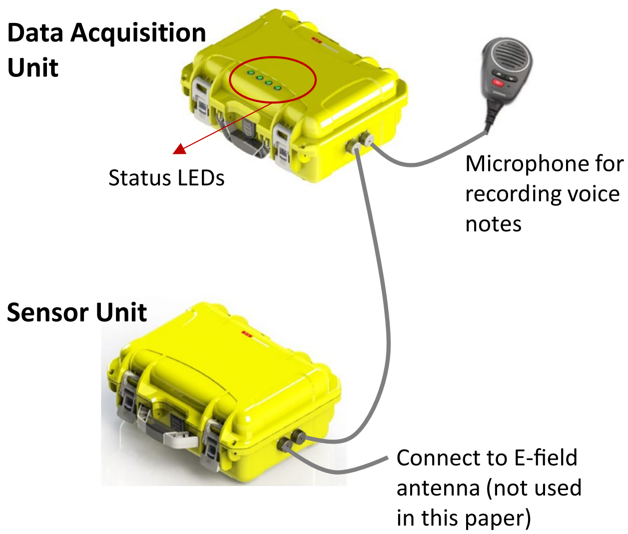

Fig. 1 The developed noise survey system (the ANDAU system) consists of two units: a data acquisition unit and a sensor unit

Fig. 2 ANDAU system was placed near a ventilation fan for an underground coal mine to survey the ambient EM noise in the fan area

noted that this new system is also equipped with two E-field electrodes that can be externally connected to the sensor unit via shielded wires. As a result, the system can be used to simultaneously survey the E-field and B-field noises in the ambient environment. Both E-field and B-field antennas were carefully calibrated so that the results collected by this system could be represented by the corresponding absolute field values. For the results reported in this paper, the E-field electrodes were not used, so only B-field results were collected as an illustrative example.

For each channel, two filters have been added to the system. The first one is a low-pass filter for anti-aliasing purpose which has a 3-dB attenuation at 17.5 kHz. The other one is a high-pass filter which has a 3-dB attenuation at 220 Hz and is mainly for attenuating the power of the 60-Hz signals to prevent a system saturation caused by 60-Hz signals. The effects of these filters have been calibrated through a system calibration to ensure that these filters shall not affect the measured magnetic field levels.

Another nice feature of the ANDAU system is that a voice recorder is built into the system so that the operator can conveniently record the location and other details related to the environment (e.g., whether there are any power center or mining machines nearby that can potentially generate strong EM noise) for each measurement. The recorded voice message will be saved as an audio file using the same file name as the collected noise data. The data recording starts after the voice note is completed and automatically stops when 20-min data samples are collected.

As shown in Fig. 1, the two units are housed in two waterproof cases that can be conveniently carried around and used in rugged mining environments. All connectors used externally are military style metal connectors, waterproof to IP-67.

The ANDAU system has been calibrated in an RF anechoic chamber where EM noise from the environment is shielded. The calibration was done by immersing the ANDAU system (the sensor unit) in a known uniform magnetic field generated by a Helmholtz coil. The details of the calibration will be documented in a separate publication, which will be [17]. The ANDAU system well addresses the four recommendations made in the previous section which were drawn from the historical EM noise survey efforts.

4 Measurement Setup

Using the newly developed ANDAU system, NIOSH researchers surveyed EM noise at the four following locations in an operating coal mine:

- Quiet entry (underground): A relatively quiet location in the underground without any significant noise sources nearby.
- Open field (surface): A wide-open area on the surface without any significant noise sources nearby.
- Fan area (surface): As shown in Fig. 2, the measurement was taken near a high-power fan motor.
- Production hoist area (surface): The measurement was taken near a production hoist area where high-power electric motors were present.

Figure 2 shows the experimental setup for surveying the EM noise in the fan area. The fan motor on a walkway is about 10-ft high. Measurements were taken from the ground directly underneath the walkway. The fan was in the middle of a large open area. The variable frequency drives (VFDs) were inside a building located at some distance (greater than 100 ft) away.

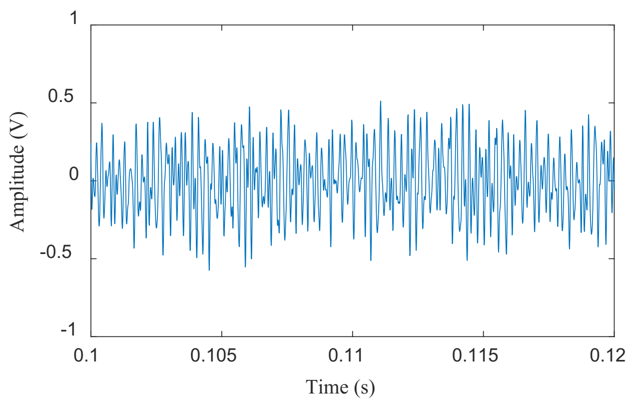

Fig. 3 A small section of the raw data recorded by the ANDAU system in the fan area

5 Measurement Results

Time Domain Result (Raw Data) As an illustrative example, Fig. 3 shows a small section (0.02 s out of a 20-min data set) of the data that was converted from the raw data recorded by the ANDAU system. This result corresponds to the time domain voltage signals recorded by one of the three orthogonal ferrite rod antennas (after amplification) when placed near the exhaust fan area on the surface of the mine surveyed. It should be noted that the true raw data out of the ANDAU system is a series of multi-channel binary data after analog-to-digital converters (ADC) without any unit. These binary data first need to be converted into floating points in volts corresponding to the voltage signal at the input of the ADC. The data shown in Fig. 3 is the converted data that is ready to be further processed with Matlab or any other signal processing tool. We consider this converted data as the raw data with respect to the further data processing to be applied to the data.

Spectral Density Estimation The time domain data collected by an ANDAU system can be further processed and analyzed based on different approaches and needs. Since the system is calibrated in the frequency domain, it is natural to first transfer the time domain data to the frequency domain and plot the data in terms of the absolute magnetic field strength. Following the recommendations made based on the historical EM noise survey efforts sponsored by USBM, in this paper a spectral analysis has been applied to the time domain data, and the results are presented with a unit of (A/m)/ $\sqrt{Hz}$ to facilitate a comparison with the historical data. The procedures for the spectral analysis are briefly described below:

1. The 20-min time domain voltage signal is split up into a series of ($N = 1831$) segments with an equal length.
2. Each segment of data is then windowed by a standard window function (the Hanning window has been used in this paper as it provides good frequency resolution and leakage protection with a fair amplitude accuracy.). By applying a window function, each data segment is significantly attenuated at the two ends which causes a loss of information. To mitigate the loss, the individual data sets are overlapped (50%) in time.
3. The Fast Fourier Transform (FFT) algorithm is applied to each segment to convert the data from the time domain to the frequency domain.
4. The corresponding calibration coefficients are applied to convert the magnitudes of the spectrum to magnetic field strengths.
5. Repeat steps 2–4 for each of the three-axis data collected.
6. Calculate the vector sum of the magnetic field based on the three-axis results obtained from step 5.
7. Repeat steps 2–6 for each segment of the data and compute the maximum, minimum, and average values of the magnetic field across the different segments.

As an example, Fig. 4 shows the measured noise level in terms of magnetic field strength for the location close to the fan area on the surface. It should be noted that, unless otherwise stated, B-fields presented in this paper are a vector sum of the fields received from the three-axis antenna. The three curves in Fig. 4 represent the maximum, mean, and minimum values of the B-field, respectively, over the 20-min period. As expected, 60 Hz from the main power line and its harmonics dominate the signal, even though the ANDAU system has purposely introduced additional attenuation to the 60-Hz signal to avoid the saturation caused by it. It is also interesting to note that noise at 30 Hz shifted from 60 Hz (and its harmonics) (e.g., 90, 150, 210, and 270 Hz) generally have relatively low strength and thus can be

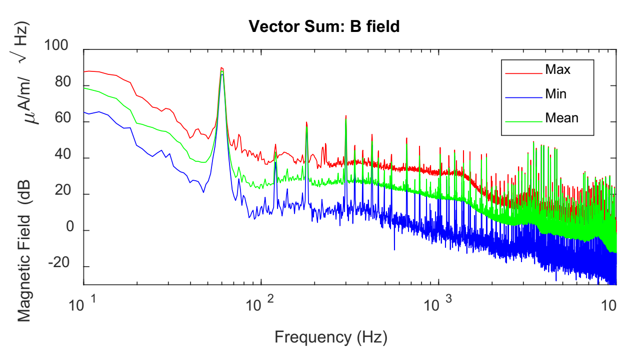

Fig. 4 Measured EM noise (in terms of absolute magnetic field strength levels) in the fan area of the mine

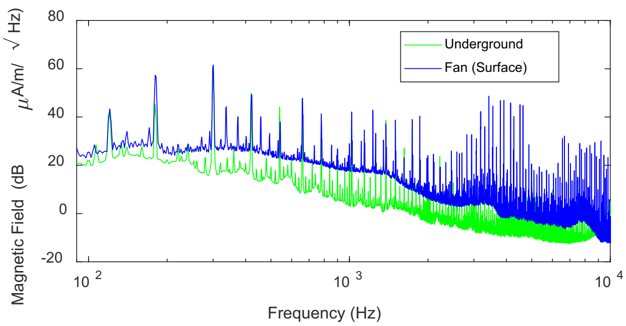

Fig. 5 A comparison of the EM noise (mean value) collected at two locations: the fan area on the surface and a quiet entry in the underground

used for TTE communications and tracking. A comparison of the "max" and "min" values of the B-field suggests that, depending on the frequency, EM noise could vary significantly with time.

Figure 5 shows a comparison of the mean value of the B-field for two locations: a quiet entry in the underground and the fan area on the surface. It can be found from Fig. 5 that the noise in the fan area is much stronger than the noise in the underground for most of the frequency components.

In order to characterize and compare the overall noise level for different locations, a new metric, average noise level (ANL), is introduced in this paper to represent the noise level over a frequency bandwidth. The value of ANL for a particular frequency band of interest is computed by first integrating the spectral density (e.g., as shown in Fig. 5) over the frequency band and then dividing the integrated result by the bandwidth. Table 2 shows the calculated ANL for different locations. It can be found that for the four locations surveyed, the fan area has the strongest noise level, with the quiet entry in the underground being the "quietest" location. This is expected as high-power motors for the exhaust fan can generate a high level of noise while there were no significant noise sources near the underground quiet entry location. The second "noisy" location is the location close to the production hoist where again high-power motors were present.

Table 2 A comparison of the average noise level (ANL) at different locations

Location	ANL (2 k–5 k Hz) Unit: dB $\mu A/m/\sqrt{Hz}$
Quiet entry (underground)	-2.6
Fan area (surface)	12.2
Production hoist (surface)	7.3
Open field (surface)	-0.9

Amplitude Statistics While Fig. 4 reveals some basic time statistic properties (i.e., mean, maximum, and minimum values) about the strength of the measured ambient B-field noise, it would also be beneficial to study other statistical characteristics of the B-field noise. One example of such a characteristic is its amplitude distribution function. Figure 6 shows the distribution of the magnetic field strength at f=90 Hz. The actual (measured) distribution of the B-field strength over the 20-min window is plotted as a histogram plot which is labeled as "actual distribution." The theoretical Gaussian distribution is plotted as a reference based on the following formula:

$$p(B) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{B-\mu}{\sigma}\right)^2} \quad (1)$$

where μ and σ represent the mean and standard deviation of the variable B. For the curve labeled as "theoretical Gaussian," the values of μ and σ are based on actual mean and standard deviation values of the measured magnetic field over the 1,831 samples with the magnetic field at 90 Hz in each time segment being one sample. For the curve labeled as "Best-fit Gaussian," μ and σ are used as two tuning parameters to best fit the data to the Gaussian function shown in Eq. (1).

It can be found from Fig. 6 that the distribution of the magnetic field at 90 Hz can be well described by a Gaussian function. This is true for many other frequency components (e.g., 150 Hz, 210 Hz, and 270 Hz) where magnetic field strength is low.

6 Conclusions

This paper introduces a portable, battery-powered, compact, and rugged system that is suitable for surveying EM noise in mining environments. The instrumentation used, data

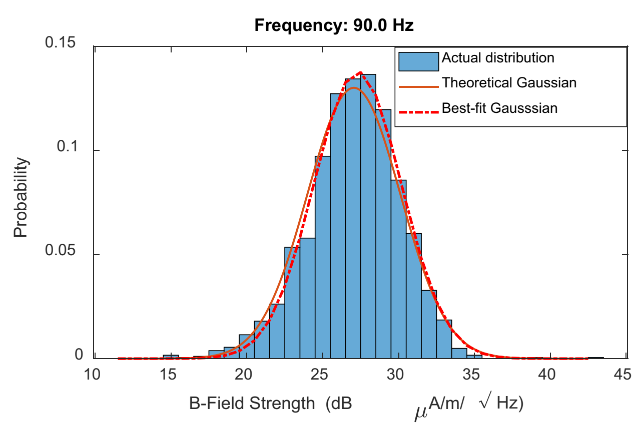

Fig. 6 Distribution of the magnetic field strength at $f=90$ Hz over a 20-min time window

analysis, and some example results collected at a mine site using the new system were presented. The overall conclusion is that EM noise level at a mine site generally varies by location, time, and frequency. The results show that there is strong EM noise present near the exhaust fan on the surface as well as near the production hoist area, possibly due to high-power induction motors used in those areas. 60-Hz and its harmonics dominate the EM noise collected at all four locations. It is also found that EM noise levels at 30 Hz shifted from power harmonics (e.g., 90, 150, 210, 270 Hz) are relatively low, and their amplitude variation with time can be statistically modeled by a Gaussian distribution.

The instrumentation along with the data analysis method introduced in this paper provide a convenient and effective approach for surveying EM noise at a mine site which is critical for making performance evaluation of existing TTE receiver designs and for testing noise reduction techniques that may be used to combat this type of noisy environment for those receivers. It should be noted that, in addition to surveying EM noise for which the system was originally developed, the technique can be applied to virtually any applications where there is a transducer delivering a voltage or current signal, such as in the areas of mechanical vibrations, mechanical shock, acoustics, and geophysics. The usage of this new instrumentation in its present state is limited to areas where equipment permissibility is not required as the instrumentation has not been evaluated and approved by the Mine Safety and Health Administration (MSHA) in terms of its permissibility.

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Declarations

Competing interests The authors declare no competing interests.

Disclaimer The findings and conclusions in this paper are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health (NIOSH), Centers for Disease Control and Prevention (CDC). Mention of any company or product does not constitute endorsement by NIOSH.

References

1. Noll J, Matetic R, Li J et al (2018) Electromagnetic interference from personal dust monitors and other electronic devices with proximity detection systems. Min Eng 70(5):61–69
2. Li J, Carr J, Reyes M, Jobes C, Whisner B, McElhinney P (2019) “Mitigation of RF radiation and electromagnetic interference from a lithium-ion battery pack used in wearable safety and health devices in the mining industry,” in *2019 PhotonIcs & Electromagnetics Research Symposium-Spring (PIERS-Spring)*, pp. 3601–3608
3. Li J, Carr J, DeGennaro C, Whisner B, McElhinney P (2020) Shielding material comparison for electromagnetic interference mitigation for the air pump motor of personal dust monitors. Mining Metall Explor 37(1):211–217
4. Zhou C, Reyes M, Girman M (2021) “Electromagnetic interference (EMI) in underground coal mines: a literature review and practical considerations,” presented at the SME annual meeting Denver, CO
5. Girman M, Reyes M, Zhou C (2021) “An overview of existing EMI standards applicable to mining,” in *SME Anual Meeting*, Denver, CO
6. Bensema W, Kanda M, Adams JW. “Electromagnetic noise in Itmann mine,” in *Final Report Submitted to US Bureau of Mines*, 1974: US National Bureau of Standards.
7. Kanda M, Adams JW, Bensema W (1974) “Electromagnetic noise in McElroy mine,” *Contract Final Report submitted to the United States Bureau of Mines*
8. Kanda M (1975) Time and amplitude statistics for electromagnetic noise in mines. IEEE Trans Electromagn Compat 3:122–129
9. Bensema WD (1977) A noise spectrum measurement system using the fast Fourier transform. IEEE Trans Electromagn Compat 2:37–43
10. Bensena W, Kanda M, Adams J (1974) “Electromagnetic noise in Robena No. 4 coal mine,” in *Final Report Submitted to US Bureau of Mines*, National Bureau of Standards.
11. Bensema W, Adams J (1973) “Spectrum measurements of electromagnetic-noise in coal mines,” *Contract Final Report submitted to the United States Bureau of Mines*
12. Adams JW, Bensema W, Tomoeda N (1974) “Surface magnetic field noise measurements at Geneva Mine,” in *Contract Final Report submitted to the United States Bureau of Mines*
13. Adams JW, Taggart HE, Spaulding AD (1971) “Survey report of the USBM electromagnetic noise measurement program,” *Contract Final Report submitted to the United States Bureau of Mines*
14. Little AD (1972) “Assessment of electromagnetic noise measurements taken by bureau of mines contractors,” presented at the Technical Memorandim Report Submitted to United States Bureau of Mines (Contract No.HO122026)
15. Adams JW, Taggart HE, Spaulding AD (1971) Survey report of the US Bureau of Mines Electromagnetic Noise Measurement Program. Technical Report Submitted to Unite States Bureau of Mines (Contract No. HO11019)
16. Lagace RL, Aidala D, Roetter M. *et al.* (1974) “Survey of electromagnetic and seismic noise related to mine resue communications,” presented at the USBM Contract Final Report (Contract No. HO122026)
17. Zhou C, Snyder D, Epstein B *et al.* (2022) “Magnetic field noise in the ultra-low frequency (ULF) band and historical comparisons,” in *IEEE Symposium on EMC, SI & PI 2022*, Spokane