Measurement of Ambient Magnetic Field Noise for Through-the-Earth (TTE) Communications and Historical Comparisons

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***Abstract*—Recent results of low-frequency (<6 kHz) magnetic field noise measurements at underground coal mines are presented. A comparison of these results to measurements made 35–40 years ago suggests that the magnetic field noise has increased substantially since this period of time. The ambient noise level is an important factor in the operation of through-the-earth (TTE) communications systems, and the data presented herein are a consideration in the design of future TTE systems.**

***Index Terms*—Electromagnetic (EM) noise, EMI, low frequency, through-the-earth (TTE), ultralow-frequency (ULF), very-low-frequency (VLF).**

I. Introduction

ELECTROMAGNETIC (EM) environments in the ultralow-frequency (ULF) and very-low-frequency (VLF) bands exhibit a rich variety of naturally occurring EM phenomena [1], [2]. This variety of signals, while interesting to some of the scientists studying the processes occurring in the ionosphere and magnetosphere [3], [4], constitutes an interfering signal to communication systems operating in the low frequency band. A knowledge of the undesired interfering signals present in the EM environment would be critical in designing a communication system that can reliably operate in the intended EM environment. Due to advantages such as its low attenuation rate, high reliability (no multipath “fading”), and good penetration capability (can penetrate seawater and soil with relatively low loss), VLF and ULF bands have been used for military global, submarine and subterranean communications. As a result, there has been a strong interest in characterizing EM environments and investigating the effects of EM noise (EMN) on performance of military radio communications systems in these bands [5].

In addition to military applications, magnetic field communications in the frequency range from 0 to 6000 Hz has long been an interest of the underground mining community because of the potential for through-the-earth (TTE) communications and tracking systems at such frequencies [6], [7]. A reliable TTE communications system would be a highly desirable post-disaster communications mechanism, as it has the highest potential for the communications link to survive the disaster event. Unlike other communications systems which require considerable in-mine infrastructure, a TTE system only requires a portable transceiver and antenna inside the mine, and a corresponding pair on the surface [8], [9], [10].

Some of the earliest TTE research and systems development work were performed by the United States Bureau of Mines (USBM), which developed a trapped miner location system in this frequency band. As part of their research in the 1970s and early 1980s, 93 mine sites were visited. A prototype system was evaluated, and magnetic field noise measurements were made at the mine sites [11].

In view of the importance of the ambient EMN and its impact on communication and tracking systems used in underground mines, USBM commissioned six contractors in the 1970s to conduct EMN studies that were aimed at developing improved TTE systems. These efforts have been by far the most comprehensive studies pertaining to surveying ambient EMN in coal mines and have generated a wealth of publications available to the public. For example, contract reports submitted by individual contractors can be found online (e.g., [12]). Some of the results have also been published in IEEE journals [13]. In addition, the USBM directed the U.S. National Bureau of Standards (NBS) to review the EMN work completed at the time, resulting in a comprehensive report summarizing the efforts from all five major USBM contractors [14].

The MINER Act of 2006 created a renewed interest in TTE communications. With the advancement in digital communications, it was hypothesized that the range and reliability of TTE communications could be greatly improved. However, the

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high amounts of environmental EMN below 6-kHz limits the improvement that could be achieved. The National Institute for Occupational Safety and Health (NIOSH) therefore commissioned a noise survey to try to characterize the noise levels that need to be accommodated for future underground mine TTE communications systems.

There are several major contributions from this article. First, this article summarizes our recent measurement results from extensive magnetic field noise surveys conducted in 35 mines and facilities from 2015 to 2018. Second, these recent results, along with the methodology, are compared to the older USBM noise data, and the interesting finding that the low frequency noise levels have greatly increased in the last several decades is presented. In addition, the calibration and validation of the developed magnetic field measurement system are discussed in detail in this article.

The rest of the article is organized as follows. First, some published research work related to measuring magnetic field noise is reviewed in Section II. The data collection system along with the calibration and validation of the system are described in Section III. Data processing methods and some sample results are given in Section IV. The magnetic field noise measurement results from 35 mines and facilities are summarized in Section V. In Section VI, comparisons are made between our measurement results and some historical measurement results reported in the literature. Finally, Section VII concludes this article.

II. Historical Perspective on ELF/ULF Noise

The general consensus in the extremely low frequency (ELF) /ULF community is that background noise in this frequency band in remote areas is dominated by sferic noise, which originates from lightning strikes throughout the world. Due to the low propagation loss (on the order of 2–4 dB per 1000 km [15]) associated with ELF/ULF waves, noise generated by lightning strikes can be detected in locations very far away. The strikes are concentrated in the tropical latitudes, with additional strikes in the mid-latitudes during corresponding summer months. According to [16], lightning strikes 60–100 times per sec worldwide. Lightning strikes include cloud-to-ground (or, some argue ground-to-cloud), which have a strong vertical current flow orientation, and cloud-to-cloud, which is a mix of horizontal and vertical orientations. Other EMN sources, including solar, cosmic, tectonic, etc. have been accounted for, but are much lower in amplitude.

Man-made noise from electrical power lines, motor vehicles, and other machinery are likewise considered to have lower amplitude when distant from the measurement site. The 50/60 Hz signals and their harmonics are often considered manageable since they can be filtered out by applying notch filters at known frequencies. Nevertheless, the effects of these spurs on measurement receiver electronics should not necessarily be ruled out.

While there is an interest in the historical and possibly growing influence of power line and machinery spectra in EMN measurements over decades-length time spans, any systematic study of the evolution of such noise sources over decades appears to be lacking in the literature. Reports of changes in the amplitude of EMN over time are mainly confined to seasonal or diurnal measurements.

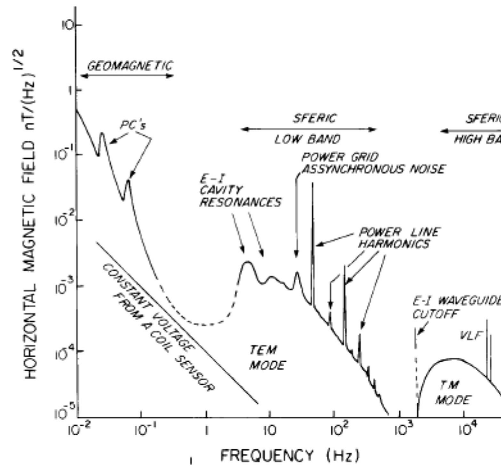

Fig. 1. EMN spectra reproduced from Macnae et al. [17].

A common view of EMN in the 1960s resulted from a paper by Macnae et al. [17]. Fig. 1, which was reproduced from [17], shows the nominal EMN levels based on their data and analysis of the impact of sferic noise on observed EMN. The figure shows how an originating EM pulse becomes shaped by various types of propagation channels, resulting in the frequency response shown.

In [17], no information was provided on how the data were obtained, nor how the plot was constructed; thus, any numbers drawn from the graph should not be considered definitive. However, for the TTE frequency range of interest (0–6000 Hz), the values indicated for the noise levels are consistent with other papers on the subject from the mid to late 1900s and early 2000's, including the USBM work from the 1970s. Consequently, NIOSH engineers were expecting to see magnetic field noise levels in the 10–30 femtotesla per root hertz (fT/rtHz) range in their pursuit of TTE systems at or near 1 kHz.

III. Mine EMN Measurement System, Calibration, and Validation

During the evaluation of the newly developed TTE systems in the 2008–2012 timeframe, widely varying ranges of performance of the systems were observed. The performance varied as both a function of location and time. As a result, the NIOSH engineers were interested in understanding the variation in noise levels. NIOSH sponsored the measurement of the EMN at 35 locations, primarily underground mine sites.

A. Measurement System

The data were collected using a purpose-built Automated Noise Data Acquisition Unit (ANDAU) to capture and store the noise samples across frequencies of interest for TTE [18]. The ANDAU system was produced and provided by Vital Alert Communications, Inc, Toronto, Canada.

As shown in Fig. 2, the ANDAU system is a battery-powered rugged system designed for use in harsh mining environments.

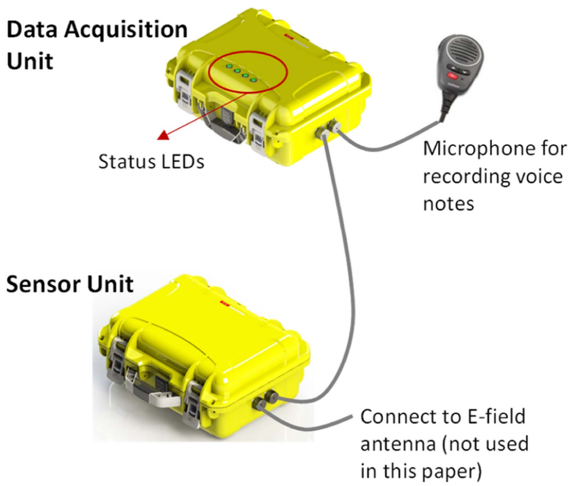

Fig. 2. Measurement system (i.e., the ANDAU system) for surveying EM noise in mining envionrments.

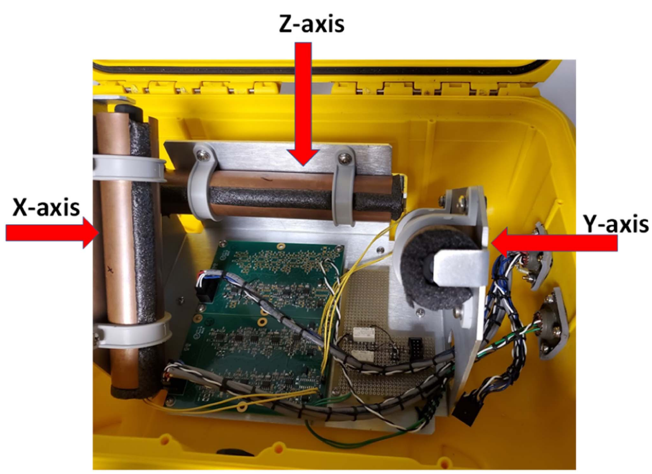

Fig. 3. 3-axis ferrite loop antenna included in the SU of the ANDAU system.

To minimize the impact of the self-generated EM interference (i.e., EM noise generated by the digital electronics of the ANDAU system being picked up by the antennas of the ANDAU system), the system consists of two units—the data acquisition unit (DAU) and sensor unit (SU)—that should be kept some distance from each other when used for recording environmental magnetic field noise. The DAU primarily contains the system battery power supply, analog-to-digital converter (Adc), removable storage media and status indicators. The SU contains a 3-axis ferrite loop antenna. There is an amplifier used for signals received from each individual axis. The two units are connected by a multi-conductor shielded cable.

Fig. 3 shows an illustration of the 3-axis ferrite loop antenna inside the SU of the ANDAU system. To fit the antenna into a compact waterproof case that can be conveniently carried in a mining environment, the *X*- and *Y*-axes of the antenna are placed at a special angle to the horizontal plane. In addition to surveying magnetic field noise, the ANDAU system can also be used to survey electric field noise by connecting the SU to external electrodes. This article only focuses on magnetic field noise, thus the interface for electrodes has been terminated.

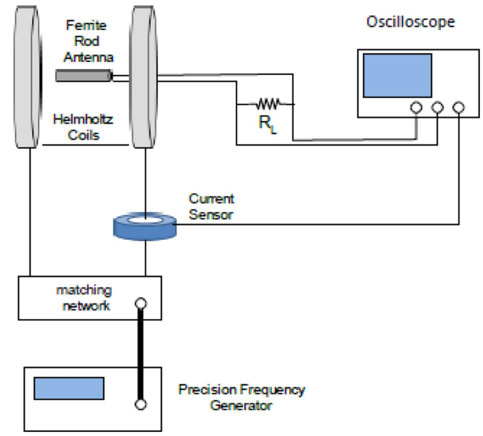

Fig. 4. System setup for calibrating the ferrite loop antennas used in the ANDAU system.

B. Initial System Calibration by Vital Alert

The initial system calibration was performed by Vital Alert using an Helmholtz coil. The system setup used for the initial calibration is shown in Fig. 4. The Helmholtz coil has 40-turns in each coil. The coil radius and separation are set to 23 cm which allows the ANDAU ferrite antennas (17 cm) to fit into the region of uniform field. The field on the axis between the coils varies by less than 1%. A precision frequency generator drives current into the Helmholtz coil via a broadband matching network. The current in the Helmholtz coil is measured using a current sensor connected to an oscilloscope. The output of the ferrite antenna is measured across a load resistor that is equal to the Rx amplifier input impedance (47 kΩ).

During this initial calibration, the antennas were calibrated one at a time. Adding a second and third ferrite at the spacing used in the SU was found to have no measurable effect on the sensitivity or frequency response of the antenna under test. An increase in output was only observed when the ends of all three rods were brought close together ($<$1 cm apart) but the mechanical design of the SU prevents this type of inter-action.

For the initial calibration performed by vital alert, the amplifier used for each axis is calibrated separately from the antenna. The amplifier gain is measured as a function of frequency by driving it with a precision generator and measuring the output voltage. The generator is interfaced to the amplifier via a matching network, which simulates the differential input impedance presented by the ferrite antenna.

C. System Calibration and Validation by the Johns Hopkins University Applied Physics Laboratory (APL)

In order to confirm the findings of NIOSH and Vital Alert, the APL independently calibrated the ANDAU system and measured its noise floor. The results of these analyses are described here in their respective order.

1) Calibration Procedure: For the APL calibration measurements, a Schwarzbeck Mess-Elektronik HHS 5128 square 10-turn Helmholtz coil with a 1.21 m separation is applied to generate precisely defined magnetic fields. The ARA PLA-2050A 5” passive loop antenna is used as a reference sensor and is placed in the center of the Helmholtz coil to measure the generated field. Antenna factors for the PLA-2050A were taken from the manufacturer's technical manual (published in Jan 1992) and were measured in accordance with the standard defined by SAE ARP-958, a requirement of MIL-STD-461, to which the PLA-2050A conforms.

The ANDAU system is calibrated with all of the magnetic sensing components (magnetometers and preamplifier board) intact and in the same relative orientation as they were delivered. The calibration recordings are taken separately for each of the magnetic field ferrite core antennas (*X*-, *Y*-, and *Z*-axis). For each measurement, the entire SU is oriented such that the magnetometer under test is parallel to the ground (i.e., when the *X*-axis magnetometer is being measured, the whole SU is moved and angled such that the *X*-axis magnetometer is parallel to the ground). The labeling of the magnetometer axes is shown in Fig. 3. During the calibration process, the DAU is placed on a laboratory bench away from the Helmholtz coil.

A signal generator (NI-PXI 4461) is used to drive the Helmholtz coils. The signal generator applies a sine wave across a 620 Ω resistor for 30 s and then waits for 5 s before moving on to the next frequency point. For each axis, approximately 15.17 min of reference data is collected and extracted using a NI-PXI 4462 digitizer with a sampling rate of 50 kilo-samples per second. Only the data from one axis is used from each of the ANDAU recordings since each axis is calibrated separately. The data sections are windowed with a Hann window and the Fourier transform is computed to produce 1-Hz resolution spectrograms.

2) Calibration Factor Calculations: For each axis, the calibration factors are calculated in three different ways. The following sections describe the methods used to find the calibration factors.

1) *Calculation Method 1:* For the first method, spectrograms of the reference antenna and ANDAU recordings are created. The start and stop times for each frequency are manually found from these spectrograms. The first and last frequencies (5 and 11 000 Hz) are discarded. The amplitude of each frequency in root mean square (RMS) counts is determined by integrating over the power spectral density using a bandwidth of 4 Hz for the reference data and 10 Hz for the ANDAU data, then taking the square root of the result.
2) *Calculation Method 2:* The second method of calculating the calibration factors also uses the same start and stop times for each frequency (discarding 5 and 11 000 Hz) manually found from the spectrograms in the first method. For each frequency, the data are mixed down to dc and then resampled to a bandwidth of 4 Hz for the reference data and 10 Hz for the ANDAU data. Next, the median amplitude is taken. Since this is only the positive frequency component of a real signal, each amplitude is multiplied by a factor of 2. To convert to RMS values, the result is divided by the square root of 2.
3) *Calculation Method 3:* The third method also computes the spectrograms of the reference and ANDAU data, but then amplitudes are found automatically. The pulse duration relative to the time axis spacing is determined first. For each frequency, the power spectrum is extracted and converted to dB values. A peak-fitting algorithm is used to fit a rectangular pulse, with the pulse duration found earlier. The algorithm attempts to find the corners of the pulse and extracts the amplitude by averaging the values between the corners and then finding the peak value. To improve the accuracy of this peak-fitting algorithm for the endpoints, one frequency point is added before the first and one more after the last, which then are disregarded.

3) Noise Floor Measurement Procedure: Noise floor measurements are made in a quiet test environment provided by a three-layer MuMetal magnetically shielded chamber. The SU is placed in the center of the chamber. The SU has the same configuration as that used to make the calibration measurements, as shown in Fig. 3. All of the magnetic sensing components (magnetometers and preamplifier board) inside the SU are left intact and in the same relative orientation as they were delivered. The chamber lids are closed and the DAU is placed outside the chamber to collect data.

D. Calibration Results and Comparision

The measured calibration factors from both Vital Alert and APL for each magnetometer are shown in Fig. 5. As seen in these plots, the calibration factors calculated by APL using the three different methods all agree with one another. Additionally, the calibration factors from APL reasonably agree with those from Vital Alert in the frequency band of interest (0–6 kHz). It appears that the *Z*-axis [see Fig. 5(c)] exhibits a relatively greater discrepancy (approximately 5 dB) between the vital alert result and the APL result as compared to the *X*- and *Y*-axes. Several factors could contribute to this divergence, given that the two calibrations were executed using distinct methods. The exact factor responsible for this discrepancy remains undetermined. Consequently, it is possible that the accuracy of the results presented in this article might not be better than 5 dB.

Fig. 6 shows the measured system noise floor of the ANDAU system. The system noise floor for each axis is first measured and then the vector sum is calculated and shown in Fig. 6. It is observed that the ANDAU magnetometers are picking up system noise, which is most likely due to the preamplifier board located close to the antenna.

IV. Magnetic Field Noise Survey: Data Processing and Sample Results

The ANDAU Adc samples the analog voltage data received from each antenna (i.e., *X*-, *Y*-, and *Z*-axes) at a fixed sampling rate of 100 KHz. The digitized time domain voltage data is then transformed to the frequency domain through a fast Fourier transform (FFT) based on Welch's method which is widely used for estimating the power of a time domain signal at different frequencies. A mathematical description and a detailed procedure of Welch's method can be found in [19]. The collected time domain data (with a total length of 20 mins) is split into 1831 sequential overlapping data segments with a segment length of 65 536. Each segment has a window (the Blackman–Nuttal

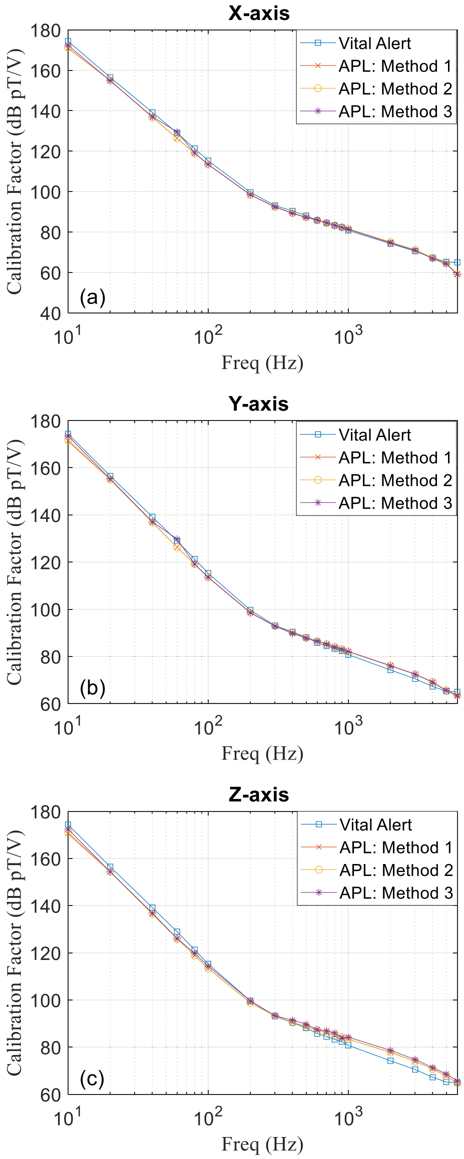

Fig. 5. Measured calibration factor for the *X*-, *Y*-, and *Z*-axes of the ferrite loop antenna used in the ANDAU system, with the corresponding amplifier gain included.

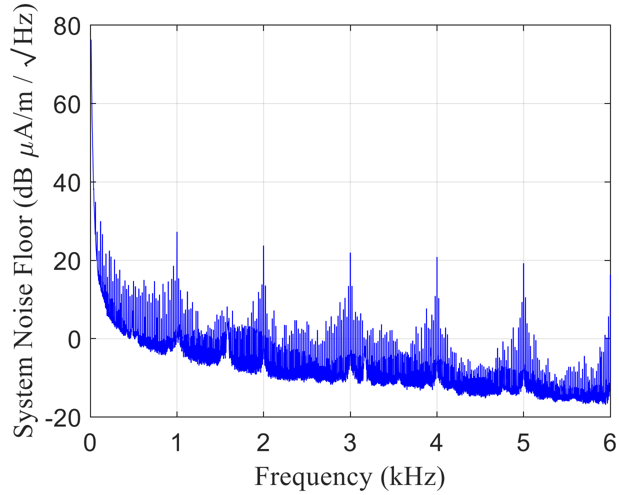

Fig. 6. Measured system noise floor of the ANDAU system.

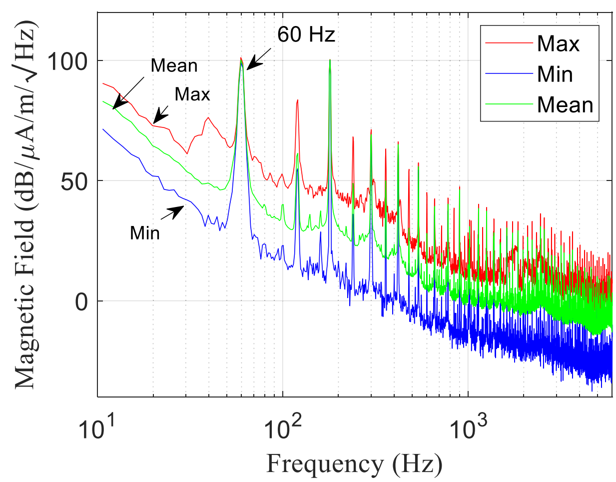

Fig. 7. Sample result showing the magnetic field noises measured above NIOSH's Pittsburgh Experimental Mine.

window has been used in this article) applied to it in order to improve the dynamic range of the spectrum plot before the FFT is applied. Calibration factors are then applied in the frequency domain to each axis to convert the calculated spectrum magnitudes to the corresponding magnetic field strengths. This conversion is important as it extracts the antenna effects from the final results and makes the result independent of the measurement tool used. As a result, we can compare our measurement results (expressed in magnetic field strength) to other measurement results published in the literature, despite the fact that different measurement tools may have been used. The 1831 sequential data segments allow us to calculate the mean, standard deviation, minimum, and maximum value of the magnetic field strength over a 20-min time window.

Fig. 7 shows a sample result of the calculated minimum, maximum, and mean values of the ambient magnetic field noises measured above the Pittsburgh Experimental Mine, located in Bruceton, PA, USA. It is apparent in Fig. 7 that 60 Hz and its harmonics are dominant in the measured magnetic field noises. It is also observed that the magnetic field noise level declines with frequency, most rapidly between 10 Hz and 1 kHz. Above 1 kHz the noise level decays more slowly with frequency.

In Fig. 8, as another sample result, a spectrogram is plotted to illustrate how magnetic field noise varies with time and frequency. For this figure, the raw data was collected by using the ANDAU system at an active coal mine site where variable frequency drives (VFDs) are used for controlling different mining equipment. The interesting frequency "ramping" shown in Fig. 8 (e.g., from 0.7 to 1.8 mins, for frequencies below 1.5 kHz) can probably be attributed to the VFDs used at the mine site. It should be noted that only a "zoomed in" (2 mins out of 20 mins collected data) version of the spectrogram is shown in Fig. 8, to better visualize the variation of the frequency with time.

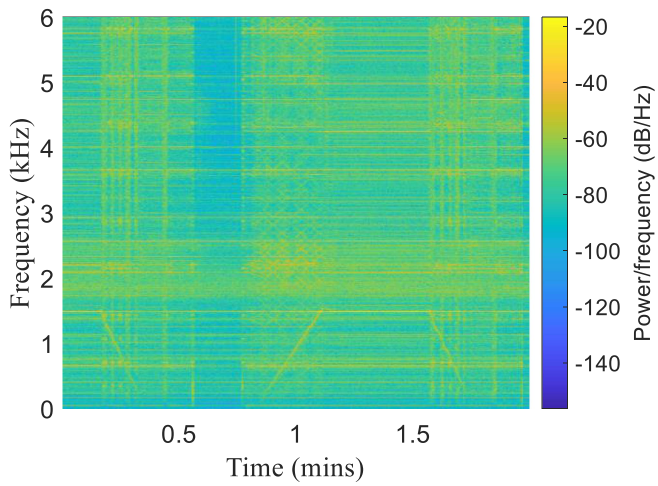

Fig. 8. Spectrogram showing how ambient magnetic field noise (measured above an active coal mine) varies with time and frequency.

TABLE I
LOCATIONS WHERE A NOISE SURVEY WAS CONDUCTED USING THE DEVELOPED ANDAU SYSTEM

Location Type	Active	Inactive
Coal mines	6	7
Hard rock mines	3	14
Other facilities	4	1
Total	13	22

V. Noise Surveys in 35 Mines and Facilities and Comparisons Over Time

The developed ANDAU system has been used as a tool for surveying the ambient magnetic field noise levels in a wide range of mines and facilities (e.g., underground tunnels). As given in Table I, the total number of locations surveyed is 35 which can be divided into three categories based on their location types. It should be noted that surveys performed in locations other than active coal mines (often educational underground facilities or museums) with little or no high-power mining equipment operating are of interest because they are likely more representative of a practical "post-disaster" EM environment than a fully operational mine. It took about three years (from 2015 to 2018) to complete the surveys in these 35 locations. This effort, to our best knowledge, represents the most recent and comprehensive series of measurements for surveying ambient magnetic field noise in the VLF band.

Averaged results of the VLF noise measurements acquired by using the ANDAU system between 2015 and 2018 under the NIOSH contract were compared with several single frequency measurements made by Durkin in 1980–1983 [11] and the results are shown in Fig. 9. The measurements made by Durkin were obtained at frequencies that avoided capturing any man-made noise at 60 Hz and its associated harmonics. The broadband noise measured at these inter-harmonic frequencies was asserted by Durkin to be predominantly due to atmospheric noise. This conclusion is supported by the observation that the

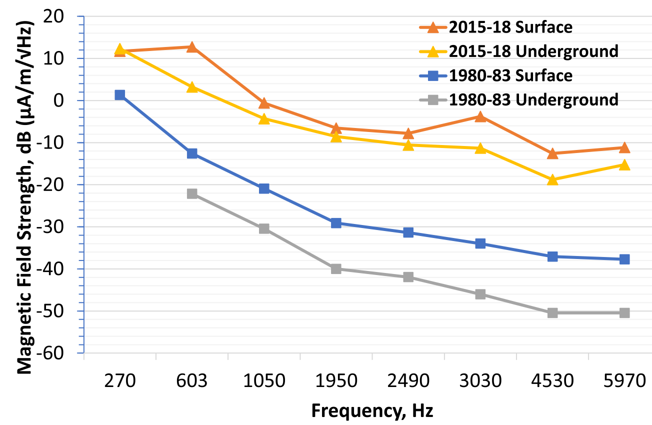

Fig. 9. Comparison of recent EMN levels (measured based on the ANDAU system from 2015 to 2018) with the measured EMN levels reported in [11].

average noise was higher at the surface than in underground locations, where the mine overburden attenuated the atmospheric noise. The measurements in the 1980s were consistent within an order of magnitude perspective with the values from [17] and other earlier studies.

Surprisingly, the comparison showed that the 2015–2018 measurements were over an order of magnitude higher than Durkin's 1980s results. The comparison illustrated in Fig. 9 is reproduced from [20], which summarizes the two sets of survey results.

The comparison in Fig. 9 also shows that the difference between surface and underground noise levels in the 2015–2018 measurements is far less than that observed in the 1980–1983 timeframe. This new result, while not definitive, is inconsistent with the conclusion that the noise is primarily environmental surface noise. The average depth of underground mines has significantly increased in the last 30 years, so one would expect that the difference between surface versus underground noise would have also increased, as a result of the additional attenuation from the increased mine overburden, assuming the noise was primarily surface noise. Fig. 9 suggests that the noise is not predominantly atmospheric, but the data are insufficient to draw a definitive conclusion.

VI. Comparison of Mine EMN Measurements to Historical Ambient Measurements

The authors recognized that the conclusions in this report could potentially lead to more questions, so additional comparison and testing were conducted using the ANDAU system. The comparison substantiated that the magnetic noise measured in 2015 and later is on average substantially higher than historical magnetic noise measurements. Admittedly, these comparisons are difficult to make given the wide variation in locations and measurement techniques. Nonetheless, the comparison below in Table II provides a compelling argument that the EMN has increased in the band of interest. The table was developed by comparing the values measured around 1 kHz from the various studies. The 1-kHz frequency was selected because of availability of data, and Fig. 1 suggests that this frequency should

TABLE II
COMPARISON OF HISTORICAL MAGNETIC FIELD NOISE LEVELS AT 1 KHZ

Source	Season and Location	$dB[(\mu A/m)/\sqrt{Hz}]$	$fT/\sqrt{Hz}$
MAXWELL and STONE (1963) [24]	Winter, Colorado	-40	12.6
	Summer AM, Colorado	-30	39.7
	Summer, California – Range of Values	-60 to -45	1.3 to 7.1
MELOY (CURVE FIT OF M &S) [25]	Spring, Winter various times	-32	31.6
	Spring, night	-38	15.8
ITMANN COAL MINE, WV (1974) [22]	Range of values – Near Noisy Machinery	8 to 23	3.2K – 18K
ROBENA COAL MINE, PA (1974) [23]	Underground – Near Noisy Machinery	10 to 45	4K –223K
GRACE COAL MINE, PA (1974) [21]	Underground – Near Noisy Machinery	0 to 25	1.3K – 22K
	Underground – no machines nearby	-15	223.5
GENEVA COAL MINE, UTAH (1974) [26]	Surface and daytime	-40	12.6
	Surface and nighttime	-14	250.7
	Average over mines and time	-22	99.8
	Range of values	-40 to -14	13 to 250
DURKIN STUDY (1980–83) [11]	Average over mines and time	-21	112.0
	Range of values	-38.3 to -7.5	15.3 to 529.9
CHRISSAN and FRASER-SMITH (1986–93) [27]	Stanford CA, average all times	-33	28.1
	Stanford CA, month range of values	-35 to -30	22.0 to 40.0
	Arrival Heights, Antarctica range of values	-66 to -53	0.6 to 2.8
PITTSBURGH EXPERIMENTAL MINE (2014)	Surface (~avg)	-12	300.0
YAN and SUNDERMAN (NIOSH) 2014	Western mine	-32	30.0
VITAL ALERT MINE DATA (2015–18) [5]	Surface, various mines (Low to High)	-10 to 8	377.0 to 3141.6
BROCKVILLE TRAIN TUNNEL (2018) [20]	Surface, afternoon avg	18	9981.8
	Surface, afternoon low	0	1256.6
PITTSBURGH EXPERIMENTAL MINE (2019)	October, Surface (minimum)	-12	316.0
	October, Surface (~avg)	-2	1000.0

have the lowest atmospheric noise relative to other parts of the frequency band of interest for TTE communications. For completeness, the NBS studies from a series of measurements in the 1970s (Grace coal mine [21], Itmann coal mine [22], and Robena coal mine [23]) are included. However, these studies are intended to investigate the impact of mining machinery noise on background EM noise, thus higher than usual magnetic noise levels are reported.

The EMN levels of the latest mine survey measurements were so much higher than the historical measurements, that the authors wanted to rule out the possibility of calibration or other systemic error. NIOSH collaborated with JHU APL to assess the accuracy of the ANDAU system calibration. As shown in Section III, JHU APL's independent assessment of the ANDAU system found that the ANDAU measurements are accurate in the frequency range specified (0–6 kHz). APL also participated in additional testing at the Pittsburgh Experimental Mine. The last two lines in Table II show measurements that were made by APL using their own calibrated systems. These results were very similar to those of the ANDAU system, giving the authors further confidence in the validity of the ANDAU measurement system results and the assertion that the average levels of broadband magnetic field noise across the frequencies 270 to 5970 Hz in active mines are 20 to 30 dB higher than the average noise levels measured by Durkin [11] about 35 years earlier.

Since the measurements in [11] and [20] were focused on East Coast U.S. underground coal mines, one interesting explanation is that the increased noise may be limited to the eastern U.S. and that the increased noise may be attributed to the expansion of the U.S. power grid along the east coast. A few measurements were made that appear to support this hypothesis, as can be observed from the "western mine" test result in Table II, which has lower noise levels consistent with the 1980s levels. Future research could include ambient noise measurements in the central and western part of the U.S. to determine if those noise levels are similar to the eastern U.S. or if they are substantially quieter. If found to be quieter, then some regional explanation is needed.

It is important to acknowledge that the present article has its limitations, specifically in relation to limited data. Due to constraints such as time, resources, and access to mine sites, the researchers were restricted in their ability to gather a more extensive dataset. Moreover, the historical comparisons were made using data published in existing literature, the accuracy of which cannot be independently verified. The findings presented should be interpreted with caution.

VII. Conclusion

A portable battery-powered system (i.e., the ANDAU system) was developed to survey ambient magnetic fields in mines and facilities. This article introduces the ANDAU system and describes system calibrations and data processing. Some sample results collected at different mine sites are given. The averaged measurement results collected from 35 mines and facilities using the ANDAU system are compared to historical ambient magnetic field noise measurement results published by other researchers. It is found that the measured EMN is substantially higher, often exceeding 20 dB or more, than earlier measurements of ambient EMN. Many of the locations where the increased noise levels were observed were at sites with no active mining equipment. The results and findings in this article may help design future TTE systems to operate reliably in a postdisaster environment.

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