2022 IEEE International Symposium on Electromagnetic Compatibility & Signal/Power Integrity (EMCSI) | 978-1-6654-0929-2/22/$31.00 ©2022 IEEE | DOI: 10.1109/EMCSI39492.2022.9889418

Magnetic Field Noise in the Ultra-low Frequency (ULF) Band and Historical Comparisons

Chenming Zhou
National Institute for Occupational Safety and Health
Pittsburgh, PA, USA
czhou@cdc.gov

David P. Synder
National Institute for Occupational Safety and Health
Pittsburgh, PA, USA
fwx4@cdc.gov

Benjamin Epstein
Life Member, IEEE
ECS Federal, LLC
Arlington, MD, USA
benjamin.epstein.ctr@darpa.mil

Zachary T. Robinson
John Hopkins University Applied Physics Lab
Laurel, MD, USA
Zachary.Robinson@jhuapl.edu

George Y. Jin
Johns Hopkins University Applied Physics Lab
Laurel, MD, USA
George.Jin@jhuapl.edu

Priscilla Y. Tang
Johns Hopkins University Applied Physics Lab
Laurel, MD, USA
Priscilla.Tang@jhuapl.edu

Ronald G. Polcawich
Senior Member, IEEE
Army Research Laboratory
Adelphi, MD, USA
r.polcawich@ieee.org

Mike Roper
Chief technology Officer
Vital Alert Communications, Inc.
Toronto, Canada
mike@rfspecialists.ca

***Abstract*—The 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 to 40 years ago suggests that the magnetic field noise has increased substantially (20-30 dB) 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 an essential consideration in the design of future TTE systems.**

Keywords—Low frequency, ULF, electromagnetic noise, ELF, EMN, TTE

I. Introduction

Magnetic field communications at low frequencies (0 to 6000 Hz) has long been an interest of the underground mining community because of the potential for Through-The-Earth (TTE) communications at such frequencies. Some of the earliest 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 [1].

The MINER Act of 2006 created a renewed interest in TTE communications. 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 [2].

With the advancement in digital communications, it was hypothesized that the range and reliability of (TTE) communications could be greatly improved. However, the high amounts of environmental electromagnetic noise (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.

This paper discusses the measurements and comparison methodology of the NIOSH noise survey to the older USBM noise data and the interesting finding that the low frequency noise levels have greatly increased in the last several decades.

II. Historical Perspecive on Ulta Low Frequency (ULF) Noise

The general consensus in the ELF/ULF community is that background noise in this frequency band is dominated by sferic noise, which originates from lightning strikes throughout the world. The strikes are concentrated in the tropical latitudes, with additional strikes in the mid-latitudes during corresponding summer months. According to [3], lightning strikes 60 to 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 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 interest in the historical and possibly growing influence of power line and machinery spectra in EMN measurements over decade-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.

A common view of the EMN in the 1960's resulted from a paper by Macnae et al [4]. Fig. 1, which was reproduced from [4], 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 electromagnetic pulse becomes shaped by various types of propagation channels, resulting in the frequency response shown.

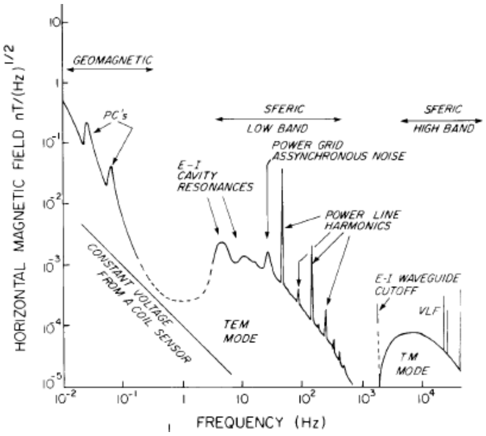

Fig. 1. EMN spectra reproduced from Macnae et al [4]

In [4], 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 1900's and early 2000's, including USBM work from the 1970's. Consequently, NIOSH engineers were expecting to see noise levels in the 10 to 30 femtotesla per root hertz (fT/rtHz) range in their pursuit of TTE systems at or near 1 kHz.

III. Mine Site Noise Surveys and Comparisons Over Time

During the evaluation of the newly developed TTE systems in the 2008 to 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 from 0.3 to 9 kHz at thirty-five locations, primarily underground coal mine sites. The data were collected using a purpose-built Automated Noise Data Acquisition Unit (ANDAU) to capture and store the noise samples across this band of interest for TTE. The ANDAU system was produced and provided by Vital Alert Communications, Inc, in Toronto, Canada.

As shown in Fig. 2, the ANDAU system is a battery-powered rugged system that was designed to be used in harsh mining environments. To minimize the impact of the self-generated electromagnetic interference (i.e., electromagnetic 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 and sensor unit) that should be kept some distance from each other when used for recording environmental magnetic field noise. The data acquisition unit primarily contains the system battery power supply, Analog to Digital Converter (ADC), removable storage media and status indicators. The sensor unit contains a 3-axis ferrite loop antenna, and the associated amplifiers. The two units are connected by a multi-conductor shielded cable.

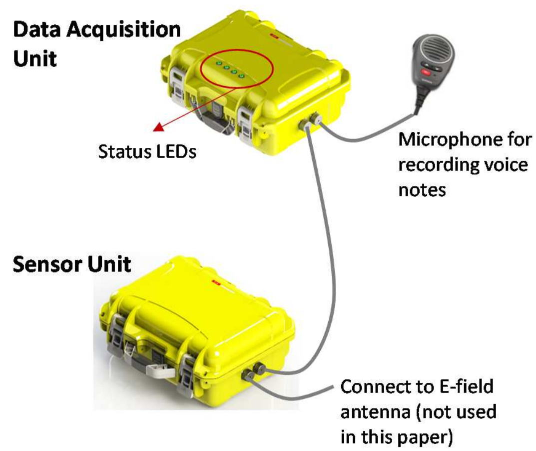

Fig. 2. The pupose-built noise survey system (the ANDAU system) consists of two units: a data acquisition unit and a sensor unit.

In [5], the results of the very low frequency (VLF) noise measurements acquired by using the developed ANDAU system in active mines between 2015 and 2018 under the NIOSH contract were compared with several single frequency measurements made by Durkin in 1980-83 [1]. 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 average noise was higher at the surface than in underground locations, where the mine overburden attenuated the atmospheric noise. The measurements in the 1980's were consistent from an order of magnitude perspective with the values from [4] and other earlier studies.

Surprisingly, the comparison showed that the 2015-2018 measurements were an order of magnitude higher than Durkin's 1980s results. The comparison is illustrated in Fig. 3, reproduced from [5], which summarizes the two sets of survey results.

The comparison in Fig. 3 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. 3 suggests that the noise is not predominantly atmospheric, but the data are insufficient to draw a definitive conclusion.

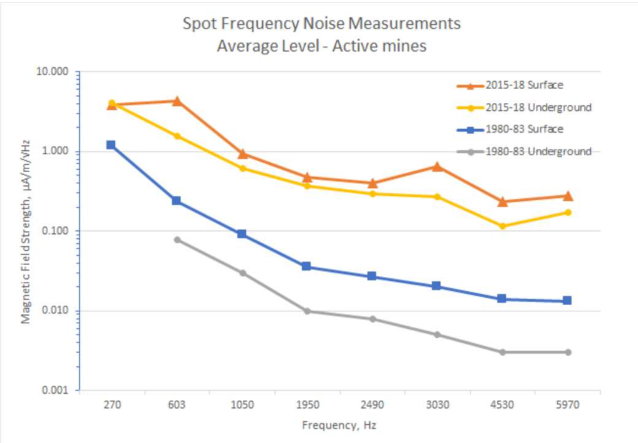

Fig. 3. A comparision of recent EMN levels (measured based on the ANDAU system from 2015 to 2018) with the measured EMN levels reported in [1].

IV. Mine Measurement System, Calibration, and Validation

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 the Johns Hopkins University Applied Physics Laboratory (APL) to assess the accuracy of the ANDAU system calibration. APL's independent assessment of the ANDAU system found that the ANDAU measurements are generally accurate in the frequency range specified (0 - 6 kHz). The details of the comparison are planned to be documented in future papers. APL also participated in additional testing at the Pittsburgh Mining Research Division test mines as discussed in the next section.

V. Comparison of Mine EMN Measurements to Historical Ambient Measurements

The authors recognized that the conclusions in this report could be quite controversial, 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 1 provides a compelling argument that the EMN has increased in the band of interest. The table was developed by comparing the values measured at 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 have the lowest atmospheric noise relative to other parts of the frequency band of interest for TTE communications. For completeness, the United States National Bureau of Standards (USNBS) studies from a series of measurements in the 1970s (Grace [6], Itmann [7] , and Robena coal mines [8]) are included. However, these studies are intended to investigate the impact of mining machinery noise on background electromagnetic noise, thus higher than usual magnetic noise levels are reported.

The last line in Table 1 show measurements that were made by APL using their own calibrated systems. The results were very similar to 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 Hz to 5970 Hz in active mines are 20 to 30 dB higher than the average noise levels measured by Durkin [1] about 35 years earlier.

VI. Implications for TTE Communications and Future Research

From Table 1, it is clear that from 2015 on, the measured EMN is substantially higher, often exceeding 20 dB or more, than earlier measurements of EMN. Many of the locations where the increased noise levels were observed were at sites with no active mining equipment. Therefore, some explanation other than local machine-generated noise is necessary. Possible explanations for the noise increase include man-made sources (possibly high-tension DC lines at some distance), or natural effects from solar and ionospheric conditions.

Since the measurements in [1] and [5] were focused on East Coast U.S. underground coal mines, one interesting theory 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 1, 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.

Acknowledgment

The authors would like to acknowledge the contributions of NIOSH, DARPA, APL, and Vital Alert Inc. in support of this work. This research was developed with funding in part from the Defense Advanced Research Projects Agency (DARPA).

Disclaimer

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

Distribution Statement "A" (Approved for Public Release, Distribution Unlimited)

References

[1] J. Durkin, "Vertical Magnetic Noise in the Voice Frequency Band Within and Above Coal Mines," *Report of Investigations 8828, United States Department of the Interior, Bureau of Mines,* 1983.

[2] NIOSH. "Advanced Tutorial on Wireless Communication and Electronic Tracking: CT System Survivability, Reliability, And Availability." https://www.cdc.gov/niosh/mining/content/emergencymanagementandresponse/commtracking/advcommtrackingtutorial4.html (accessed 2021).

[3] A. Meloni, C. Bianchi, G. Mele, and P. Palangio, "Background electromagnetic noise characterization: the role of external and internal Earth sources," *Annals of Geophysics,* vol. 58, no. 3, p. 0330, 2015.

[4] J. C. Macnae, Y. Lamontagne, and G. West, "Noise processing techniques for time-domain EM systems," *Geophysics,* vol. 49, no. 7, pp. 934-948, 1984.

[5] M. Roper, "Electromagnetic Noise Data Acquisition for the Evaluation of TTE Communications in Coal Mines: Phase 4 Data Analysis Report," *NIOSH BAA Contract Report (Contract No 211-2014-59075),* 2018.

[6] J. W. Adams, W. Bensema, and M. Kanda, "Electromagnetic Noise in Grace Mine," in *Final Report Submitted to U.S Bureau of Mines*, 1974: US National Bureau of Standards.

[7] W. Bensema, M. Kanda, and J. W. Adams, "Electromagnetic noise in Itmann mine," in *Final Report Submitted to US Bureau of Mines*, 1974: US National Bureau of Standards.

[8] W. Bensena, M. Kanda, and J. Adams, "Electromagnetic noise in Robena No. 4 coal mine," in *Final Report Submitted to US Bureau of Mines*, 1974: National Bureau of Standards.

[9] E. Maxwell and D. Stone, "Natural noise fields from 1 cps to 100 kc," *IEEE Transactions on Antennas and Propagation,* vol. 11, no. 3, pp. 339-343, 1963.

[10] J. Meloy. "What and Where is the Natural Noise Floor?" http://www.vlf.it/naturalnoisefloor/naturalnoisefloor.htm (accessed 2021).

[11] J. W. Adams, W. Bensema, and N. Tomoeda, "Surface magnetic field noise measurements at Geneva Mine," in *Contract Final Report submitted to the United States Bureau of Mines*, 1974.

[12] D. Chrissan and A. Fraser - Smith, "Seasonal variations of globally measured ELF/VLF radio noise," *Radio Science,* vol. 31, no. 5, pp. 1141-1152, 1996.

TABLE 1 Comparison of Historical Magnetic Field Noise Levels at 1kHz

SOURCE	SEASON & LOCATION	$dB\left[(\mu A/m)/\sqrt{Hz}\right]$	$fT/\sqrt{Hz}$
MAXWELL & STONE (1963) [9]	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) [10]	Spring, Winter various times	-32	31.6
	Spring, night	-38	15.8
ITMANN COAL MINE, WV (1974) [7]	Range of values - Near Noisy Machinery	8 to 23	3.2K - 18K
ROBENA COAL MINE, PA (1974) [8]	Underground - Near Noisy Machinery	10 to 45	4K - 223K
GRACE COAL MINE, PA (1974) [6]	Underground - Near Noisy Machinery	0 to 25	1.3K - 22K
	Underground - no machines nearby	-15	223.5
GENEVA COAL MINE, UTAH (1974) [11]	Surface, daytime	-40	12.6
	Surface, 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) [1]	Average over mines and time	-21	112.0
	Range of values	-38.3 to -7.5	15.3 to 529.9
CHRISSAN & FRASER-SMITH (1986-93) [12]	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 & 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) [5]	Surface, afternoon avg	18	9981.8
	Surface, afternoon low	0	1256.6
PITTSBURGH EXPERIMENTAL MINE (2019)	Oct., Surface (minimum)	-12	316.0
	Oct., Surface (~avg)	-2	1000.0