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A Novel System to Measure Composite Electromagnetic Fields in Underground Mines

Ronald D. Jacksha[1], Carl B. Sunderman[1], Dr. Chenming Zhou[2]

[1]Spokane Mining Research Division, CDC NIOSH, Spokane, Washington USA, emails: rjacksha@cdc.gov, csunderman@cdc.gov

[2]Pittsburgh Mining Research Division, CDC NIOSH, Pittsburgh, Pennsylvania USA, emails: czhou@cdc.gov

***Abstract*—Electronic devices and systems used to enhance miner safety and health as well as improve production processes are becoming commonplace in underground mines. The ability of these devices and systems to function properly in each other's presence, and in the presence of legacy electrical systems, in the unique environments of underground mines is not entirely understood. To better understand possible electromagnetic compatibility issues of critical mine electronic devices and systems, researchers from the National Institute for Occupational Safety and Health (NIOSH) are conducting surveys of electromagnetic emissions in underground mines. This paper presents the design of a novel system to measure the superposition of electromagnetic electric fields generated by different sources in underground mines from 10 kHz to 6 GHz —a system which has applications in other industrial settings.**

I. INTRODUCTION

Electrical and electronic systems commonly emit some level of electromagnetic energy into the environment, either intentionally (e.g., radio handsets), unintentionally (e.g., variable frequency drives), or incidentally (e.g., electrical motors). This energy has the potential to adversely impact the operation of other devices or systems—an effect commonly referred to as electromagnetic interference (EMI). To limit the potential for EMI, numerous regulatory requirements and standards have been developed to ensure electromagnetic compatibility (EMC) among electronic devices and systems for most military, industrial, and consumer applications. Examples of EMI/EMC regulatory requirements and standards include: 47 CFR Part 15 – "Telecommunication – Radio Frequency Devices;" MIL-STD-462G – "Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment;" SAE J1113/1™ – "Electromagnetic Compatibility Measurement Procedures and Limits for Components of Vehicles, Boats (up to 15 m), and Machines (Except Aircraft) (16.6 Hz to 18 GHz);" and ISO® 33.100.01 – Electromagnetic Compatibility in General [1-4].

Used for miner safety and health applications such as environmental monitoring, communications, tracking, proximity detection, and much more, complex electronic devices and systems are proliferating in the underground mining environment. However, due to an absence of regulatory requirements, standards, or guidelines for electromagnetic compatibility of electronic devices and systems deployed specifically for use in underground mines, the ability of electronic devices and systems to function properly in each other's presence, or in the presence of legacy electrical systems, is often not ensured or even well understood [5]. A recent example of an instance of EMI in underground mines was that of a personal dust monitor (PDM) causing a proximity detection system (PDS) to malfunction when the PDM was placed in close proximity to a component of the PDS [6].

The potential for EMI among safety-critical electronic systems and devices is a serious concern that needs to be addressed in the mining industry. Research has been conducted to investigate EMI issues in mining around the world. For example, in the 1970s, the United States Bureau of Mines (USBM) awarded a series of contracts to survey the electromagnetic emissions in different mines, in view of the fact that the performance of communication and tracking systems, particularly through-the-earth communication systems, are largely impacted by the electromagnetic "noise" (i.e., interference) existing in the mining environment [7-9]. More recently, discussions of practical examples of EMI associated with underground mining equipment, methods for testing EMI of mining equipment, and EMC test standardization for mining equipment are covered in [10-12]. A comprehensive literature review and practical considerations for EMI in underground coal mines can be found in [13].

To better understand the electromagnetic environment in which critical electronic devices and systems may be operated, researchers from the National Institute for Occupational Safety and Health (NIOSH) are performing surveys of electromagnetic electric field (E-field) emissions in underground mines. The data from these surveys will assist original equipment manufacturers (OEMs) and mine operators in estimating E-field emissions in typical underground mining environments to determine appropriate susceptibility limit levels for electronic devices and systems.

Due to the challenging conditions, there are currently no commercially available systems suitable to measure E-field emissions in underground mines. Consequently, NIOSH researchers developed an innovative system to measure the superposition of electromagnetic electric fields generated by different sources (composite E-field emissions) in such environments. This paper outlines the system's design and presents sample measurement results obtained in an underground mine using the developed system.

II. MEASUREMENT SYSTEM DESIGN

A. General Design Considerations

Underground mines present unique challenges when attempting to measure electromagnetic emissions from a given source. Numerous electronic and electrical devices and systems—e.g., power centers, associated electrical and electronic controls, motors, variable frequency drives, etc.—can be placed in very close proximity, often making it virtually impossible to determine the source of emissions of interest. For this reason—and considering the goal of the surveys is to understand the electromagnetic environments in which electronic devices and systems will operate—it was decided to measure the composite E-field emissions in specific areas of interest in a mine. Figures 1 and 2 show a typical area of interest in an underground mine. Figure 1 shows cabinets housing industrial controls and Fig. 2 shows a coal conveyor belt with drive motor (out of sight.)

Figure 1: Cabinets housing industrial controls

Figure 2: Coal conveyor belt with head end drive motor (out of view.)

Given current frequency spectrum allocations, known radio frequency (RF) signal propagation characteristics underground, and practical applications of wireless systems in mines, it was determined that a measurement range of 10 kHz to 6 GHz was adequate [14].

The practical design of the measurement system was driven by the geographic expanse and harsh environment of a typical underground mine. Ruggedness, portability, and ease of transport were the goals. The system needed to be able to survive the harsh environment of an operating underground mine yet be quickly and easily set up for measurements and broken down for transport of equipment. In addition, the system needed to be comprised of minimal components due to the limited space available in vehicles used to transport personnel and equipment in underground mines. Finally, the measurement system needed to require minimal technical expertise to set up and operate being that individuals with limited spectrum analysis experience would be responsible for making the measurements.

B. *Antenna Selection*

The antennas were selected based on the following technical requirements. Omnidirectional antennas were necessary to effectively measure composite E-field emissions in a survey area. Antenna efficiency was crucial as the antennas needed to have reasonable antenna factors to provide for optimal system sensitivity. As previously mentioned, the quantity and size of antennas were considerations due to the challenges of transporting equipment in underground mines.

Four antennas from A.H. Systems were selected to cover the 10 kHz to 6 GHz measurement range of the system. The model numbers, types, and frequency ranges of the antennas are shown in Table 1.

Table 1: Measurement system antennas

A.H. Systems Model Number	Antenna Type	Test System Measurement Span
SAS-550-1B	Active Monopole	10 kHz – 50 MHz
SAS-542	Biconical	50 MHz – 200 MHz
SAS-545	Biconical	200 MHz – 1 GHz
SAS-547	Biconical	1 GHz – 6 GHz

C. *Measurement Receiver (Spectrum Analyzer)*

The primary requirement was that the measurement receiver (spectrum analyzer) be battery powered. Many potential survey areas would not have 120-volt mains power available, and in areas that did, the power may not be properly conditioned and pose a risk of damaging the spectrum analyzer. A battery-powered spectrum analyzer was the only reasonable choice.

Other requirements were that the spectrum analyzer be capable of laboratory quality measurements, have a battery operational time of 6 to 8 hours, and not require an external computer to operate. The 6-to-8-hour battery operational time was desired because some operators of United States coal mines do not allow the changing of batteries in electronic devices underground. The preference for a spectrum analyzer not requiring an external computer was based on the knowledge that the computer would contribute to the composite E-field emissions in a survey area.

The Rohde & Schwarz (R&S®) FPL1000 was selected as it best satisfied all the requirements. The R&S® FPL1000 is capable of both 120-volt mains and battery operation and has an option for dual batteries capable of a total operational time of 6-to-8 hours. It also has excellent performance specifications and does not require an external computer to operate.

D. *Shielded Enclosure*

Based on previous NIOSH research, it was recognized that E-field emissions from a spectrum analyzer can contribute to composite emissions in a survey area [15]. The traditional method to limit E-field emissions from a single device—a portable RF shielded test enclosure—was not practical due to size and weight constraints for transport in a mine [16]. A compact and lighter form of an RF-shielded enclosure was needed.

As a more practical solution, a small aluminum toolbox was modified to serve as a portable RF-shielded enclosure. To provide an electromagnetic seal, knitted wire mesh was installed on the toolbox's top lip which mated against copper foil tape placed on the underside of the lid. In addition, RF absorbing material was placed on the top, bottom, and sides of the toolbox to limit any other potential leakage. Type N and BNC bulkheads were used to connect the spectrum analyzer to the external antennas and to the measurement triggering device, respectively. The triggering device was simply two 1.5-volt AA batteries, a momentary switch, and an indicator LED housed in an aluminum enclosure with a BNC bulkhead. Figure 1 shows the FPL1000 in the portable RF shielded enclosure prior to a measurement with the triggering device shown in the lower right corner. A schematic diagram for the triggering device is shown in Fig. 2. Full information on the design and evaluation of the shielded enclosure can be found in [17].

Figure 3: R&S FPL1000 placed in portable shielded enclosure.

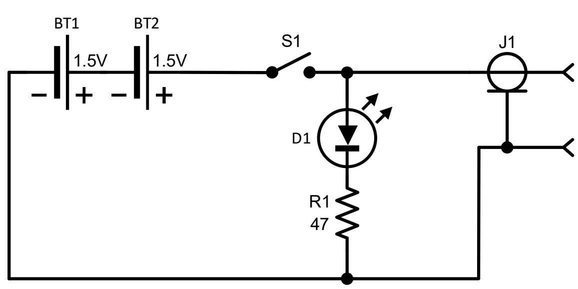

Figure 4: Triggering device schematic diagram.

E. Spectrum Analyzer Trigger Configuration – Spectrum 1

One unusual characteristic of the FPL1000 is the inability to use an external trigger to initiate a single measurement consisting of a predetermined number of sweeps (as described in section F. Spectrum Analyzer Measurement Configurations – Spectrum 2.) The workaround for this issue was to configure the FPL1000 to perform two sequential measurements. This was accomplished by defining two measurement channels (Spectrums), Spectrum 1 and Spectrum 2. Spectrum 1 was configured to Run Continuous with a Sweep Count of 0 and initiated externally using External Trigger 1. The FPL1000's Sequencer function was then set up to run the Spectrum 2 measurement after the Spectrum 1 measurement was completed. Details on configuring sequential measurements can be found in the FPL1000 manual or here [18]. A summary of Spectrum 1 measurement configuration settings is shown in Table 1.

Table 2: Spectrum analyzer configuration – Spectrum 1

Spectrum 1 Preset	
RF Atten	10 dB
Run Cont	
Sweep Count	0
Trigger	External Trigger 1

F. Spectrum Analyzer Measurement Configurations – Spectrum 2

The spectrum analyzer's Spectrum 2 measurement configurations were loosely based on the criteria outlined in MIL-STD-461G sections "4. GENERAL REQUIREMENTS" and "5.18 RE102, radiated emissions, electric field." with consideration of the aforementioned constraints of measuring composite E-field emissions in underground mines [2].

Four measurement frequency spans—10 kHz to 50 MHz, 50 MHz to 200 MHz, 200 MHz to 1 GHz, and 1 GHz to 6 GHz—were configured to the optimize the antenna factors for each span. Each measurement span used the required 6 dB resolution bandwidth (RBW) as defined in MIL-STD-461G "TABLE II. Bandwidth and measurement time." [2].

The spectrum analyzer's internal preamplifier was not used for the 10 kHz to 50 MHz and 50 MHz to 200 MHz spans out of a concern that it could possibly be saturated due to high incidental and intentional radiator emissions in the survey areas. Variable frequency drives (incidental radiator) would quite likely be in any survey area with variable speed electric motors or an area that controlled variable speed electric motors [19]. Radiating coaxial cable communications systems (intentional radiator) operating the 150 to 170 MHz VHF band, used heavily in the mining industry for production and emergency communications, would most likely be present in all survey areas [20].

As a matter of good practice to reduce mismatch uncertainty, 10 dB of spectrum analyzer input attenuation was used for all measurements [21, 22].

The frequency step size (Sweep Points) for each measurement span was a practical determination. Following the required one-half bandwidth increment or less step size as defined in MIL-STD-416G would have resulted in more than 66,000 data points for the four combined measurement spans [2]. For ease of data post-processing and analysis, it was desired to keep the total combined measurement data points to less than 10,000. The FPL1000 uses a 40 MHz measurement bandwidth, and it was felt reducing the sweep points would have minimal impact on the E-field emission survey results. The number of sweep points for each measurement span was based on what was considered a reasonable frequency resolution for the span. The number of sweep points and resultant frequency step for each measurement span are shown in Table 3.

To capture the highest E-field emissions, the maximum trace hold was enabled in each measurement span.

Based on the limited amount of time allowed in a mine and survey area, the number of sweeps (Sweep Count) for each single trigger (Run Single) was calculated so that each measurement span would acquire approximate 60 seconds of data. The calculation was simply 60 seconds divided by the sweep time displayed on the FPL1000. The measurement time for each span was validated using a stopwatch.

A summary of Spectrum 2 measurement configuration settings is shown in Table 3.

Table 3: Spectrum analyzer configurations – Spectrum 2

Spectrum 2 Preset				
Ref Level	-40 dBm			
RF Atten	10 dB			
Preamp	Off	Off	On	On
Freq Start	10 kHz	50 MHz	200 MHz	1 GHz
Freq Stop	50.01 MHz	200 MHz	1000 MHz	6 GHz
Res BW (Mil 6 dB)	10 kHz	10 kHz	100 kHz	1 MHz
Sweep Points	2501	3001	3201	1001
Freq Step	20 kHz	50 kHz	250 kHz	2.5 MHz
Sweep Time (~Secs)	0.126	0.175	0.800	0.050
Trace 1	Max Hold			
Freq Axis	Linear			
Run Single				
Sweep Count	400	300	70	500
Measurement Time (~Secs)	60	60	60	60

III. MEASUREMENT METHODOLOGY

Composite E-field emissions are measured in a survey area as follows. The FPL1000 is placed in the portable RF shielded enclosure. The RF input of the FPL1000 is connected to the Type N bulkhead connector using a 0.5m length of LMR400 coaxial cable, and the rear panel Trigger In is connected to the BNC bulkhead using a 0.5m length of RG-58 coaxial cable. The external triggering device is connected to the BNC bulkhead using 3m length of RG-58 coaxial cable. The FPL1000 is then powered on and allowed to stabilize.

The active monopole antenna is mounted to a carbon fiber antenna stand with the height adjusted to 1m as measured at the ground plane and placed in the approximate center of the survey area. Referring to Fig. 1 and Fig. 2, the antenna would be placed midway between the electrical cabinets and conveyor belt drive motor. The antenna is connected to the Type N bulkhead connector on the portable RF shielded enclosure using a 6m length of LMR400UF coaxial cable. LMR400UF is used for this connection because of its ruggedness, reasonable insertion loss, and flexibility of the outer jacket. The enclosure is then placed a reasonable distance from the antenna.

The preconfigured measurement file matching the active monopole antenna is loaded into the FPL1000 from its internal drive. The lid of the portable RF shielded enclosure is then closed and latched. When ready, the measurement is initiated using the external triggering device, and the measurement time is monitored using a mechanical stopwatch. After 60 seconds, the lid of the enclosure is opened and Spectrum 2's measurement result is saved to the FPL1000's internal drive.

This process is repeated for the remaining three measurement span/antenna combinations with the antennas vertically polarized for the measurements.

The measurement data is later post-processed applying the antenna factors and cables losses to convert from dBm to dBuV/m [23]. Four post-processed measurement files associated with a specific survey area are then concatenated and plotted in a log/log graphical format.

IV. MEASUREMENT SYSTEM EVALUATION

MIL-STD-461G section *"4.3.4 Ambient electromagnetic level."* states *"When measurements are made outside a shielded enclosure, the tests shall be performed during times and conditions when the ambient is at its lowest level."*[2]. However, in a survey area there would not be a single device under test (DUT) or specific piece of equipment under test (EUT), but rather the survey area itself would be considered the DUT or EUT. Therefore, the intent of the measurement system evaluation was to characterize the noise floor of the system so the measured E-field emissions in a survey area could be compared against the characterized noise floor. The measurement system noise floor was characterized by measuring the four frequency spans with a 50-ohm termination on the FPL1000's RF input and with the measurement system configured as it would be for actual measurements in a survey area.

The measurement system evaluation was performed in a 3.0m by 3.5m ETS/Lindgren Series 81 RF shielded enclosure (full-size RF shielded enclosure.) All measurements were made with the FPL1000 inside the portable RF shielded enclosure using the previously described measurement methodology. Any other electronic and electrical devices present in the enclosure during the measurements were powered off and unplugged from mains power.

A. Displayed Average Noise Level – 50-ohm Termination

The first suite of measurements was performed with a 50-ohm termination on the RF shielded enclosure's Type N bulkhead connector. This measurement suite captured the displayed average noise level (DANL) of the FPL1000.

Figure 3 shows the post-processed results for the measurement suite. The DANL of the FPL1000 met or was below the radiated emission limit for "Fixed wing external (2 MHz to 18 GHz) and Helicopters" as defined by "Figure RE102-3. RE102 limit for aircraft and space system applications." in MIL-STD-461G [2].

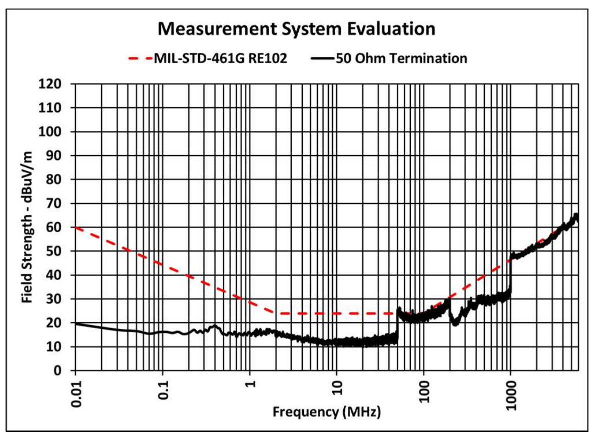

Figure 3: Displayed average noise level (DANL) of FPL1000.

B. Noise Floor – Full System with Antennas

The second measurement suite was performed using the appropriate vertically polarized antenna for each measurement span. The antennas were placed at one end of the full-size RF shielded enclosure. The portable RF shielded enclosure was placed on a 1m tall table 2m from the antennas. A 6m length of LMR400UF connected the portable RF shielded enclosure and antennas. This measurement suite captured the noise floor of the measurement system only limited by the shielding effectiveness of the full-size RF shielded enclosure.

Figure 4 shows the post-processed results for the measurement suite. It can be observed that from 400 kHz to 6 GHz, the system noise floor measurement closely matches the DANL of the FPL1000. The rise in the noise floor below 400 kHz can be attributed to the lower shielding performance of the full-size RF shielded enclosure.

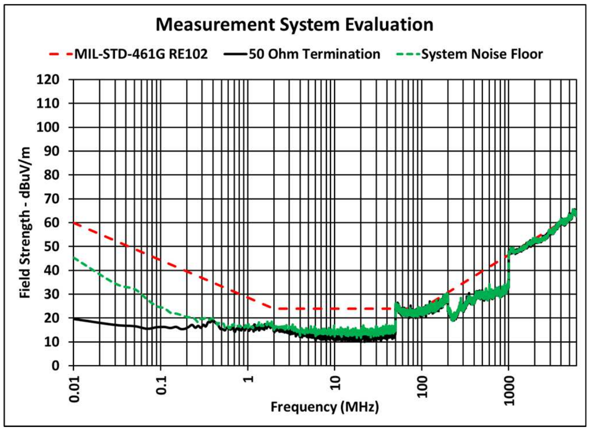

Figure 4: Measurement system noise floor.

V. MEASUREMENT SYSTEM SAMPLE FIELD DATA

Shown in Fig. 5 is a sample of field measurement data taken in an underground coal mine approximately 120m from a longwall shearer. Operating on 4160 VAC, up to 2300 kW, and often weighing in excess of 100 tons, a longwall shearer is a large piece of mining equipment used to cut away a coal seam in an underground mine [24-26]. Figure 6 shows the cutting drum of a longwall shearer which is typically 1.6m-3m in diameter.

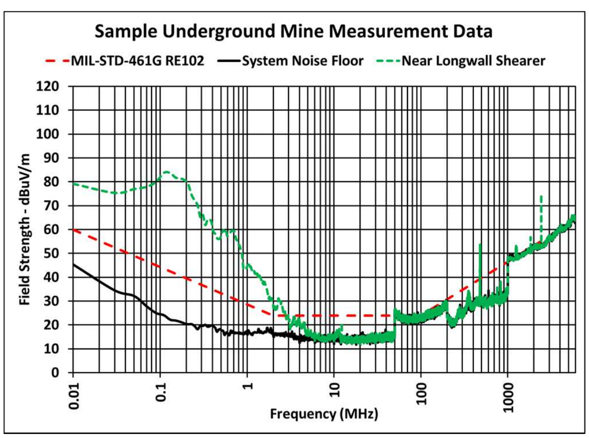

Figure 5: Sample field measurement data.

While a discussion of the results is beyond the scope of this paper, it can be noted that above 12 MHz, the measured composite E-field emissions are limited by the measurement system noise floor. Two discrete RF signals are present in this area, one from a radiating coaxial cable communications system operating in the ultra-high frequency (UHF) band and a Wi-Fi signal operating in the 2.4 GHz industrial, scientific, medical (ISM) frequency band. The rise in E-field emissions below 10 MHz is due to the extremely high amount of power used by the longwall shearer.

Figure 6: Longwall shearing cutting drum. (Credit Getty Images)

VI. SUMMARY

Complex electronic devices and systems are becoming ever more present in underground mines, yet the electromagnetic environment in which they need to function is, for the most part, an unknown. Measurements of characteristic composite E-field emissions at various locations in underground mines can provide original equipment manufacturers and mine operators with valuable data that will help inform them of potential EMI issues when designing and deploying electronic devices or systems. To gather electromagnetic E-field emissions data, NIOSH researchers developed a novel system to measure composite E-field emissions in underground mines. The system is self-contained, portable, rugged, and capable of high-quality measurements. Sample measurements results in an underground mine are presented demonstrating the practical application of the system. The design of the system could serve as a reference for developing similar measurement apparatuses for use in other industrial sectors.

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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 name or product does not constitute endorsement by NIOSH.

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