Antenna Arrangement Investigation for Through-the-Earth (TTE) Communications in Coal Mines

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Abstract -- **The MINER Act of 2006 requires the installation of post-accident, two-way, communications and electronic tracking systems for all coal mines. A through-the-earth (TTE) wireless communication system sends its signal directly through the overburden of a mine but can have limitation relative to performance, reliability, and transmission range. The National Institute for Occupational Safety and Health (NIOSH) conducted experiments at a coal mine for different TX/RX antenna arrangements using a NOISH TTE prototype system. This system uses multi-turn, relative small TX loop antenna instead of single turn, relative large TX loop antenna. The objectives of the test are to evaluate the performance of the system, to evaluate the path loss and optimize working frequency for the mine, to characterize surface and underground electromagnetic noise, and to investigate the feasibility of horizontal TTE communication and its advantage over vertical TTE communications. In this paper, the performance of a magnetic loop TTE communication system was evaluated for various antenna arrangements. A fairly large communication range was achieved for horizontal TTE transmission. While vertical TTE communication between underground and the surface may be restricted by factors like deployment challenges of the surface TX antenna and short transmission ranges, horizontal TTE communication within the tunnel can reach relative large distances and can thus establish a more reliable communication. Moreover, the combination of vertical and horizontal TTE communication may provide a way to considerably increase communication range.**

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

I. INTRODUCTION

One of the requirements of the Mine Improvement and New Emergency Response Act (MINER Act) of 2006 is the installation of post-accident, two-way, communications and electronic tracking systems for all coal mines. The magnetic field based through-the-earth (TTE) systems usually utilize a large loop antenna as the transmitter (TX) and a ferrite-core with multi-turn wire wrapped around it as the receiver (Rx). They operate in the very low frequency (VLF) or extremely low frequency (ELF) domains. One big advantage of TTE communication systems is that they do not require extensive mine infrastructure. However, the performance, reliability and transmission range of TTE systems are limited by many factors such as rock conductivity, stratigraphy, background noise, receiver sensitivity, transmitter power, and antenna arrangement. The National Institute for Occupational Safety and Health (NIOSH) conducted experiments at a coal mine for different TX/RX antenna arrangements. The objectives were to test the performance of a NIOSH TTE prototype system, to evaluate the path loss and optimize working frequency at a specific mine for TTE communications, to characterize surface and underground electromagnetic noise, and to investigate the feasibility of horizontal TTE communication and its advantage over vertical TTE communications.

II. NIOSH TTE SYSTEM

In TTE wireless communications, a transmitting loop antenna produces a magnetic field which carries compressed information. The receiving antenna then detects the magnetic fields and receives the signal (Fig. 1). The loop size (the area formed by the loop) is one of the important parameters which will determine the signal strength. A TTE system using a large loop can achieve a larger communication range since it is capable of a greater magnetic moment, M (M = NIA, N is the number of the wire turns, I is the current through a single wire, and the A is the loop area). Some commercial TTE systems use hundreds of feet of single-turn wire to obtain the required M. However, this wire is exposed to machinery and might be damaged during an emergency situation.

Fig. 1. The NIOSH TTE receiving antenna system. It contains a 3-axis Rx, a preamp, an analog-to-digital signal converter, and a computer.

Engineers at NIOSH are experimenting with reducing the loop size and increasing the number of wire turns (Fig. 2) to maintain the magnetic moment required for the TTE

communication. Each two turns of wire are powered independently to reduce the input impedance. Instead of wrapping around a coal pillar, the multi-turn loop antenna can reduce the required footprint to approximately 18 m^2 thus drastically reducing the amount of space required to deploy the antenna. A TTE system, which is comprised of a transmitting and a receiving sub-system was designed and evaluated at an operating coal mine.

Fig. 2. The multi-turn NIOSH TTE transmitting loop antenna with stand.

The inductance of the NIOSH TTE loop was measured with a LCR meter. First, one pair was energized while the rest remained open circuit. Turns were then added sequentially until all 16 turns were connected in series and energized. The inductances were measured versus number of turns at 1 kHz. At other frequencies, the inductance is not appreciably different than at 1 kHz.

A curve fit to the data yields the following result, in which L is the loop inductance in units of H, and N is the number of turns [1]. The loop inductance (H) changing with number of wire turns is plotted as in Fig. 3. During operation, the transmit current is sensed with an AH Systems BCP-510 current probe.
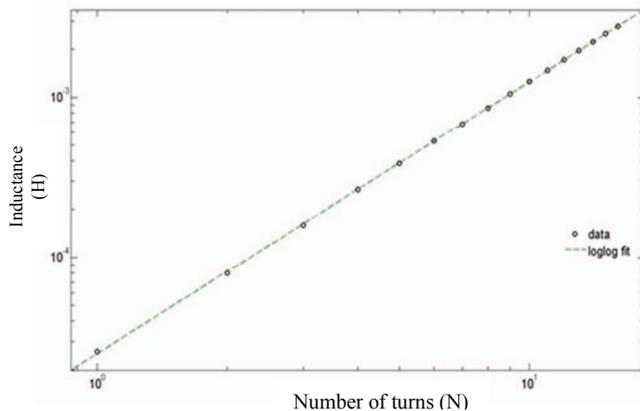
$$L = 10^{-4.60} * N^{1.70} \qquad (1)$$

Fig. 3. Inductance of NIOSH transmit loop versus number of turns at 1 kHz.

The receiver (RX) is composed of a foldable PVC frame

holding three orthogonally mounted ferrite core antennas (Stormwise AF22T-300H-3K). Each antenna is separated by a minimum of 1 meter from the others to avoid significant cross axis magnetic coupling. The output of the antenna is buffered and amplified by a preamplifier. The signal is then digitized by a National Instruments NI9239 analog input module at 50,000 samples per second and processed by LabView software. The LabView software computed a 50,000 point Hanning window Fast Fourier Transform (FFT) voltage spectrum for each channel, yielding a 1 Hertz bin resolution. The FFT datum of the frequency under test is displayed on a real-time waterfall diagram for visual interpretation, while the entire time domain data series is stored to hard disk for post-processing.

III. ANTENNA CALIBRATION

The ferrite rods used in the Stormwise antennas are 61 cm (2 ft) in length; therefore, in order to accurately calibrate these antennas, they need to be placed within a region of uniform magnetic field at least as long as the ferrite. A Helmholtz coil is used to calibrate the Stormwise antennas. Helmholtz coils can be easily constructed, and the fields easily calculated. This makes them especially useful in calibrating low frequency magnetic field testing applications.

The magnetic field on the central axis is given by the following equation [2].

$$B_x = \frac{\mu_0 M}{2r}\left(\frac{1}{\left(r^2 + r + \frac{5}{4}\right)^{\frac{3}{2}}} + \frac{1}{\left(r^2 - r + \frac{5}{4}\right)^{\frac{3}{2}}}\right), \qquad (2)$$

where B_x is the magnetic field in Tesla, M is the magnetic moment in ampere turns, and r is the radius. A Helmholtz coil could have approximately 1 percent error in magnetic field within the central 1-m region of the coil. A coil radius of 1.521 m (5 ft) radius was designed and constructed to yield a 1.2% error. The Helmholtz coil produced a B-field that was measured by use of the NARDA magnetic field sensor. The error bounds of the NARDA sensor are +/-1dB. In order to validate the absolute field strength to greater accuracy, a small 17-turn, 2.28-inch-diameter, air core loop was constructed. A measurement with this small loop was made at the center of the Helmholtz coil. An error of around -2% was observed. Next the Stormwise antennas were calibrated to approximately +/- 2% error.

The calibration ratio of H$_{RX}$/V$_{RX}$ can be generated with the use of a Dynamic Signal Analyzer connected to the Helmholtz coil. A Dynamic Signal Analyzer (DSA) is configured to source a swept sine-wave voltage, which is applied to a power amplifier connected to the Helmholtz coil. The current through the Helmholtz coil, I$_{TX}$, is measured with a current sense amplifier connected to input 1 of the DSA. The current, I$_{TX}$, induces a field, H$_{RX}$, sensed by the antenna

under test. The voltage response of the antenna, V_{RX}, is sensed at input 2 of the DSA. The DSA computes the ratio of V_{RX}/I_{TX}. In post-processing, the product of H_{RX}/I_{TX} and I_{TX}/V_{RX} produces the calibration curve, H_{RX}/V_{RX}. Fig. 4 shows a typical response from a 300-3000 Hz Stormwise antenna. The measured signal (in dBV) is then converted into H-field (A/m) using this chart.
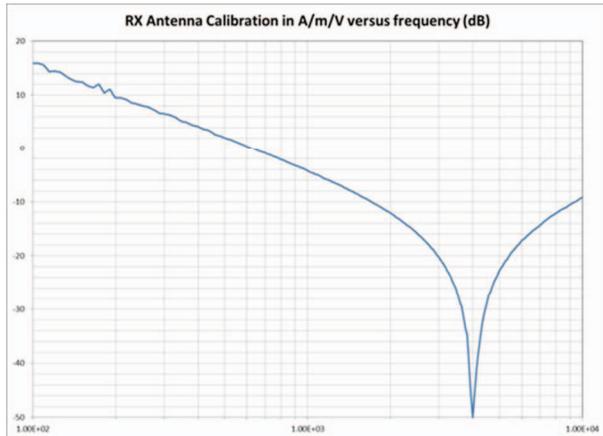

Fig. 4. RX antenna calibration factor plotted with frequency.

IV. FIELD MEASUREMENT

A. Surface and Underground Magnetic Field Noise

RF noise was recorded on the surface and underground at mine entry. Data was recorded in the time domain and converted to the frequency domain using a Fast Fourier Transform (FFT) as shown in Fig. 5. The noise recorded shows the 60 Hz harmonics from nearby power lines. Also observed is increased broadband noise on the surface as compared to the underground for frequencies below 3 kHz. Also, both the surface and underground show a minimum noise spectral density occurring at around 3 kHz. It is against this noise background that the received RF signal must be recognized at the earth's surface or in a mine. By characterizing the noise environment at a mine, it is possible to specify the minimum signal source strength required for a communication system as well as the desirable receiver sensitivity.
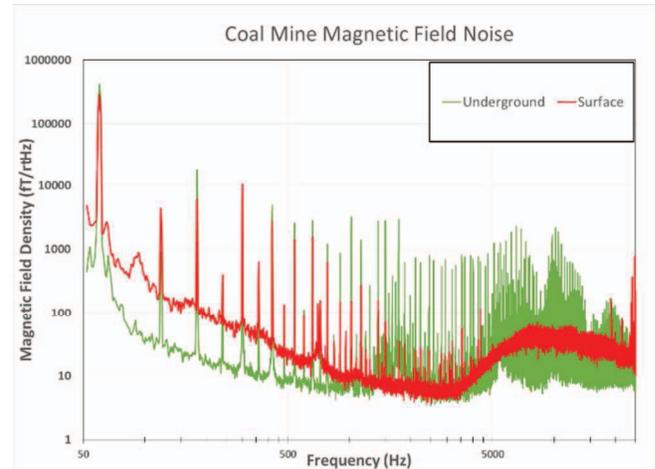

Fig. 5. FFT of noise recorded on surface and underground.

B. Surface-to-Underground (Downlink) Transmission

In a downlink transmission, the TX unit is located at the surface and kept stationary, while the RX unit stays static, underground or moves within the mine entry. The underground unit receives the signal sent by surface personnel. The size of the surface transmitting loop antenna can be fairly large, hence a big magnetic moment, to ensure a successful and stable communication. The transmitted power or current is not limited as it is underground and can be fairly high by comparison.

The underground RX was moved in 50-ft increments away from the surface transmitter, starting from directly beneath the loop antenna. The surface TX was stationary during the test and transmitted at 9 frequencies in the following order at a given RX location: 3150, 1770, 990, 570, 330, 150, 5610, 9810, 3150 Hz. Those frequencies are chosen to avoid the 60-Hz harmonics. Each frequency was transmitted for 3 seconds at each test location. There were 9 frequencies transmitted making each test 27 seconds of transmit time. The first 3150 Hz is at full TX current, and the last 3150 Hz is at half current.

The following is the verification procedure for the RX. Since the H-field is proportional to the amplitude of the transmitted current, the received H-field strength should be reduced to half when the TX current is reduced from full to half. For example, at a distance of 950 ft. in horizontal transmission, the z-component of H-field is 9.8515E-5 A/m at full TX current, and it decreases to 4.9374E-5 A/m at half TX current. The ratio is 1.99 compared to a theoretical value of 2.

With the TX powered with maximum current, the Rx can only detect the signal for frequencies below 1000 Hz. The higher frequencies (above 1000 Hz) were severely attenuated by the earth medium and did not pass through (Table 1). While low frequencies did achieve attenuation signal, they have a lower bit rate so it is not suitable for voice communications. An optimum operating frequency should be chosen at a specific mine to achieve the best system

performance.

Table 1. Signal strength for various frequencies at 500 ft. distance. Of all 9 transmitted frequencies, only 4 of them can be received by the RX for downlink transmission.

Frequency (Hz)	150	330	570	990	1770, 5610,	3150, 9810
Signal Strength (dBV)	-65	-65	-70	-76.67	N/A	

The measured radial component and vertical component of the B-field at frequency 330 Hz are plotted versus TX-RX horizontal separation distance in Fig. 6. The radial B-field component has a maximum value between 50-100 ft separation and drops as radial distance increases, staying about the same value in the range of 400 to 900 ft. The vertical component peaks at around 400 ft separation instead of as expected at RX directly below the TX antenna (0 ft separation). The reason behind this is not fully understood at this time. Possible explanations are that the RX starting position was not directly below the TX loop or that the inclination of the TX and RX units might not have been optimally aligned. The signal strength decreases while the Rx moves away from the TX, and it vanishes at about 1500 ft. radially away from the TX for all frequencies.

C. Underground-to-Surface (Uplink) Transmission

In an uplink transmission, the TX unit is located underground and remains static; the RX unit is static or moves on the surface. The surface unit receive signals sent by the underground unit. For uplink communication, the TX loop antenna is deployed within the mine entry. The transmitted power or current for underground TX is limited by the IS (Intrinsical Safety) requirement; hence the magnetic moment is limited too.

Similar to the downlink test, although the TX was supplied with the maximum allowable current by the NIOSH TTE system, the surface RX unit could only receive signals at frequencies below 1000 Hz. The signal strength decreases with the RX moving away from the z-axis of the TX antenna. The signal was not detected past 900 ft radially away from the TX for all frequencies, as compared to the 1500 ft radial transmission range for the downlink case. This decreased transmission range was probably due to the increased ambient noise observed at the surface as discovered in test *A*. The RX signal for 330 Hz is shown in Fig. 7. As in the downlink case, the large value of the horizontal magnetic field at zero radial distance is probably an indication that the RX is may not have been optimally aligned.
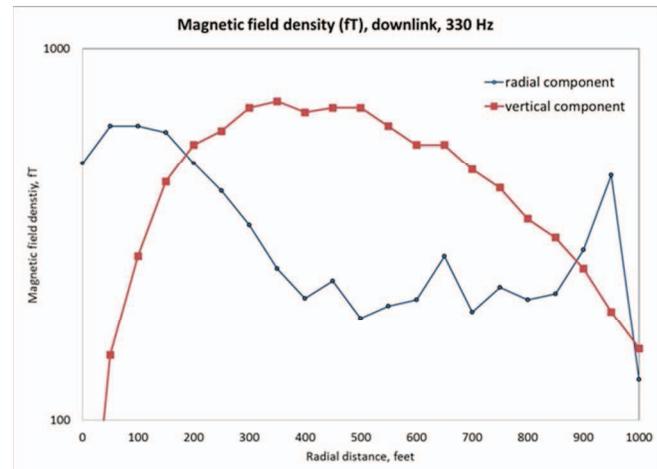

Fig. 6. Radial and vertical component of magnetic field, downlink.

D. Underground-to-Underground Transmission

Typically, the TX and RX antennas are vertically separated by the earth overburden, which is a coaxial arrangement. The TX and RX antennas can be also arranged horizontally in a mine, which allows to communicate within the mine. There are advantages to separating the TX and RX antennas horizontally (Fig. 8), hence, communicating within the mine itself. The horizontal TTE configuration offers the advantage that one unit can be in a fixed location while the other can move as the mining face progresses. The fixed position unit can then potentially be used as a relay to a surface unit, which can also be in a fixed location. Mines do not always have access rights to all areas on the surface, so the fixed position surface unit can be in an area to which the mine does have access.
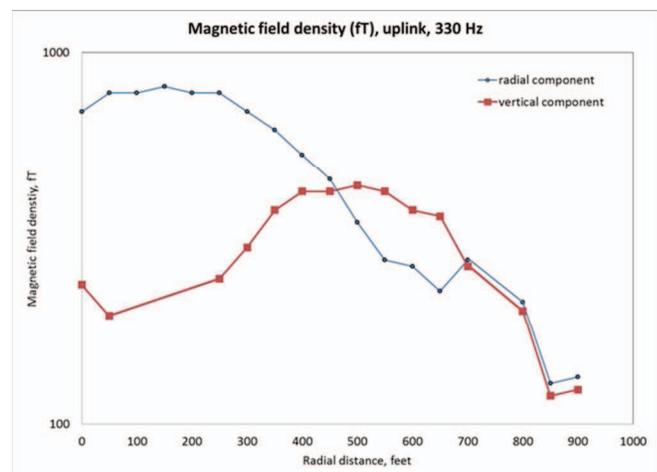

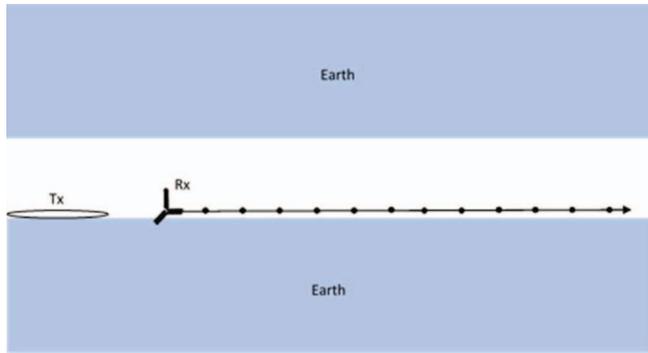Fig. 7. Radial and vertical component of magnetic field, uplink.

Fig. 8. Underground-to-underground TTE transmission. The TX transmits signal within the tunnel towards the RX, while the RX moves along the dotted line and measures signal at each position represented by the dots.

It also has been pointed out in some references that a greater transmission range can be achieved for horizontal TTE communication [3] [4] [5]. This phenomenon was observed during this test. Fig. **8** shows the setup of the underground-to-underground, or horizontal, test. The transmitter was set up in an entry. The receiver was moved along the same entry and data was acquired periodically every 50 ft. This was accomplished for a distance of 3,400 ft. Although the signal was still being detected at 3,400 ft., it had degraded significantly and the measurement was stopped. The signal can still be detected at the furthest location, which indicates that it might extend beyond this point. Fig. **9** shows a representative result at 3030 Hz for the vertical axis only and for an average of all three component axes. The units are in the receiver magnetic field (or B-field, in units of femto-Tesla or 10^{-15} Tesla) divided by the transmitter loop current in amperes.
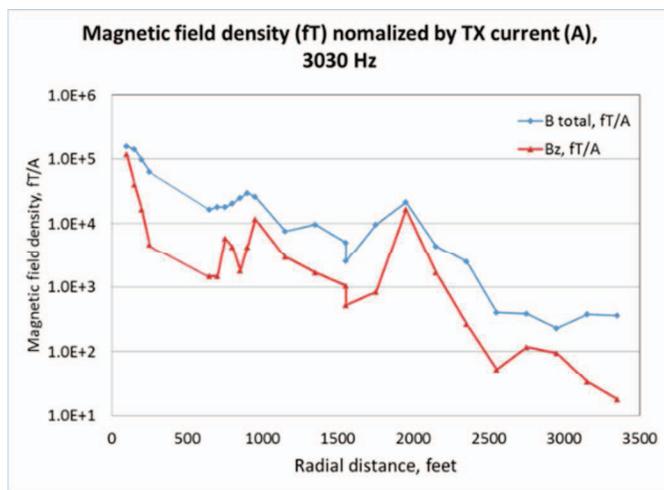

Fig. 9. Normalized B-field versus TX-RX distance.

E. Vertical Transmission vs. Horizontal Transmission

TTE wireless communication systems may get unreliable at mines with deep overburden. This is mainly because the attenuation caused by overburden highly reduces the SNR margin which is required to establish a successful communication. However, horizontal TTE communications can reach a relatively long range. To improve the reliability of TTE communications systems, one solution is to use both vertical and horizontal transmissions (Fig. 10). In this setup, the surface and underground unit can potentially communicate through a repeater underground. This repeater can have a fairly large loop antenna and can be kept fixed at a location away from any damage that would be caused by working machinery and an emergency situation. By utilizing horizontal TTE communication, this combined configuration can potentially increase the transmission range and facilitate the installation by overcoming some of the limiting factors and challenges.
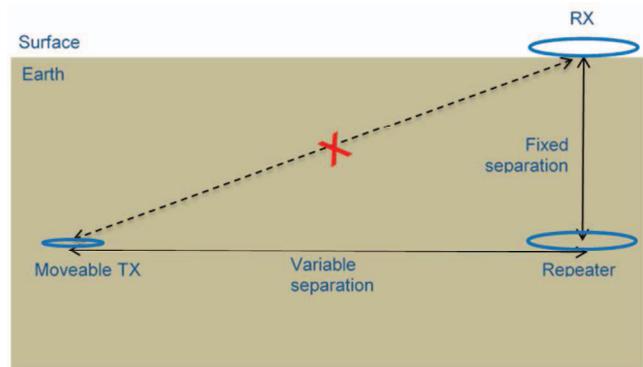

Fig. 10. A combination vertical and horizontal TTE communication, which will considerably increase the transmission range.

V. CONCLUSIONS

The NIOSH TTE system has been tested and evaluated at an operational coal mine. By using multi-turn compact size loop antenna, the NIOSH prototype TTE system is relatively easy to deploy. The VLF/ELF noise were recorded at various underground and surface locations. The FFT analysis shows that the 60-Hz harmonics appears at both underground and surface noise. By characterizing the noise environment at a mine, it is possible to specify the minimum signal source strength required for a communication system as well as the desirable receiver sensitivity. The system was used to establish vertical communications for both uplink and downlink. For uplink communication, it has shorter transmission range compared to downlink communication. This decreased transmission range was probably due to the increased ambient noise observed at the surface. A fairly large communication range was achieved for horizontal TTE transmission. While vertical TTE communication between underground and surface may be restricted by factors like deployment issue of surface TX antenna and relative small transmission range, horizontal TTE communication within the tunnel can reach relatively large transmission range and hence can establish a more reliable communication. Moreover, a combination of vertical and horizontal TTE

communication may provide a way to increase the communication range considerably.

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