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A PRELIMINARY EVALUATIONS OF A THROUGH-THE-EARTH (TTE) COMMUNICATIONS SYSTEM AT AN UNDERGROUND COAL MINE IN EASTERN KENTUCKY

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ABSTRACT

A commercially available Through-the-Earth (TTE) communications system was evaluated at an underground coal mine in eastern Kentucky. This field study was conducted as part of a larger multi-site evaluation of available TTE systems to determine their operational sensitivity. Field testing is being performed along with simulation techniques developed for geophysical surveys. The results of the field test will additionally be used to determine the applicability of these simulation techniques to TTE communications.

The mine detailed in this paper was idled at the time of the study, which provided the nearest practical representation of a post-event mine shutdown. For this study, the three following communication modes were tested: surface-to-underground, underground-to-surface and surface-to-surface. Standard deployments of the TTE system using the manufacturer's recommended procedures were able to achieve clear communications between underground and surface locations. Other arrangements of the units yielded intriguing results, some of which were predicted by computer simulations, others were unexpected. Future experimentation is planned to further evaluate the observed phenomena.

INTRODUCTION

The ability to establish effective communication between surface and underground personnel after a mine event is essential for both mine evacuation and mine rescue efforts. Current communication technology is reliant on physical infrastructure, such as antennas, cables, and repeaters, located throughout the mine. Such systems are easily disabled during a mine event because of their vulnerability to physical damage. A true emergency communications system would have the ability to function regardless of a mine's physical state. Through-the-Earth (TTE) wireless communications technology has the potential to provide such a tool.

Wireless TTE communications are exceptionally challenging because electromagnetic (EM), or radio, signals are subject to drastic attenuation as they travel through solid strata. In addition to attenuation, EM wave propagation is directly affected by the physical and petrographic characteristics, mineral compositions, metamorphic properties, and the degree of water infiltrations in the strata [1-5]. These strata characteristics are unique to each mine thus making the design of an effective, universally deployable, and reliable TTE communications system very difficult. At present, TTE technology is in the preliminary stages of practical deployment with only a few permissible TTE systems commercially available.

Although these commercial TTE systems have demonstrated the ability to communicate wirelessly through solid strata, the range and performance of the communications have been highly varied [2-4, 6-8]. A definitive explanation for these variations has not yet been developed because the manner in which TTE signals propagate through strata is not well understood. This paper presents a preliminary evaluation of a commercially available TTE magnetic communications system (MCS) at an underground room and pillar coal mine in Eastern Kentucky. Details about the site and the experimental design are also presented.

The purpose of this study was to evaluate a TTE MCS system under a variety of deployment scenarios to determine its practical operational envelope. This field experiment was conducted as part of a larger multi-site evaluation of available TTE systems. The goal of the overall study is to determine the operational sensitivity of TTE systems as an emergency communications tool. Field testing is also being performed in conjunction with simulation techniques developed for geophysical surveys. The results of the field tests will additionally be used to determine the applicability of these simulation techniques to TTE communications for both basic geophysical and TTE signal modelling.

STUDY OVERVIEW

Site Description

The field test site was conducted at an underground coal mine in the Central Appalachian region of the United States. This mine was located in Eastern Kentucky and extracts bituminous coal using the retreat room and pillar method. The seam is located at an average elevation of 120 m (400 ft) and exhibits an average seam thickness of 1 m (3 ft) with some areas exceeding 1.5 m (5 ft). The overburden thickness of this mine widely varies from 122 m (400 ft) to 305 m (1,000 ft) because of the overlying mountainous terrain. The overburden stratigraphy contains various alternating layers of sandstone and shale with thin, sporadically distributed clay beds. Water infiltrations within the overlying strata are minor.

The mine workings are fairly level with gradual changes in elevation of no more than 30 m (100 ft). The field test mine (Mine A) is also situated approximately 90 m (300 ft) below another retreat room and pillar coal mine (Mine B) that had been idled and closed prior to this study. The field test mine was open but inactive at the time of the study and was being maintained by a minimal crew of mine personnel. In this state, this mine site presented an ideal opportunity to examine MCS communication under near post-event closure conditions. A map representing the section of the mine utilized for this study is displayed in **Figure 1**.

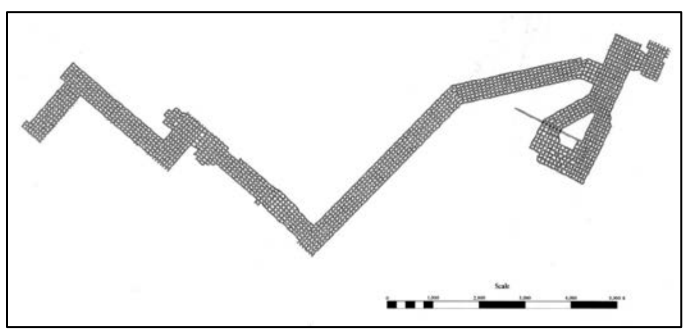

Figure 1. Mine map of the MCS field test site.

TTE Magnetic Communications System

The TTE system used in this study is designed for two-way communication using magnetic field sensing between underground and surface personnel without the need for physical infrastructure. The MCS is able to send and interpret voice and text communications to and from other compatible MCS systems. Voice and text are transmitted using two main frequency channels: the voice and text (V) channel and the text only (T) channel with average operational frequencies in thousands of hertz (Hz) and in hundreds of hertz (Hz), respectively. In order to implement this system, the deployment of both a surface unit and an underground unit is required.

Both of the underground and surface units function in almost the same manner except for certain design characteristics that were modified on the underground unit. The underground unit is designed to be stationary emergency communications system that can be located in permissible areas of underground mines. This unit is contained within an explosion-proof case and utilizes significantly less signal transmission power to comply with U.S. Federal regulations. These design characteristics cause the underground unit to be heavy and bulky. The lower transmission power also reduces the underground unit's effective transmission range.

Two surface MCS units were used in this study instead of an underground unit and a surface unit because of the limited mobility of the underground unit. As a result, only intake and neutral airways were examined during the course of the experiment. In order to closely mimic the communication capabilities of an actual underground unit, one of the surface units was modified to utilize the same, reduced transmission power as an underground unit. The surface unit will be referred to as the SU (surface unit) and the modified surface unit will be referred to as the UGU (underground unit) for this discussion.

The SU and the UGU both consist of three main components: the control center, the transmitting antenna, and the receiving antenna. The control center provides the main interface for sending and receiving the TTE communications. Power is also delivered to both the transmitting and the receiving antennas from rechargeable battery packs through the control center. The transmitting antenna is a loop antenna with a length of 120 m (400 ft). According to the manufacturer, the full length of this antenna must be deployed in a manner that maximizes the internal surface area of the loop in order to achieve the maximum transmission potential. The receiving antenna is a three-axis antenna enclosed in an impact-resistant case. This design allows for signal reception regardless of EM wave orientation in the three principal axes.

Experimental Design

Communications between the SU and the UGU were evaluated using a series of individual tests at various underground and surface locations over the course of five days. Three different communication modes were examined, which included underground to surface (UG to SUR), surface to underground (SUR to UG), and surface to surface (SUR to SUR) communications. These modes were evaluated by traversing various surface and underground locations using two surface-type MCS units in tandem. Each test required the use of two sites, a transmit site and a receive site. At the transmit site, a stationary TTE unit was set up to automatically broadcast a text message on a 30 second interval. The automated text messages alternated between the V and the T channels.

The receiving unit was first placed as close as practically possible to the vertical axis of the transmitting loop antenna. At this initial location, the signal indicator value and the qualitative quality of the received text were recorded for each of the channels. The signal indicator value is a quantitative descriptor of the signal quality unique to the communications system tested in this study. The indicator value is automatically generated by the MCS for each received message. The receiving unit was then moved to various accessible locations around the transmitting unit to record how the communications quality varied across the traverse. The signal and text quality were recorded at each of the receive locations. Any pertinent qualitative observations and properties about the surrounding area were also logged.

The traverse continued until the signal from the transmitting MCS unit could no longer be received at the accessible areas. Once the limit of the transmission range was confirmed, another communication mode or site would then be evaluated in the same manner. The locations of each surveyed receiving site, or station, was chosen based on accessibility, available time, and observed performance of the MCS. A brief outline summarizing the tests conducted at the field site is presented in **Table 1**.

Table 1. Outline of the MCS tests conducted at the field site.

Day	Test Description
1	Two communications modes, SUR to UG and SUR to SUR, were tested in the vicinity of the mine portal. The same transmit site was used to test both communications modes. The surface locations were traversed using a truck and the underground locations were traversed on foot.
2	Two communications modes, UG to SUR and SUR to UG, were tested in the vicinity of the mine portal. The surface transmit site used on Day 1 was replicated. One underground transmit site and one surface transmit site were used. The surface locations were traversed using a truck and the underground locations were traversed using a mantrip along the rail. The UGU was broadcasting using the elevated surface power at this time.
3	Two communications modes, SUR to UG and UG to SUR, were tested in the vicinity of the mine portal. The UGU was modified to transmit using permissible power levels. The surface transmit site used on Day 1 was replicated. The underground transmit site intersected a rail entry. One underground transmit site and one surface transmit site were used. The surface locations were traversed using a truck and the underground locations were traversed on foot.
4	Two communications modes, UG to SUR and SUR to UG, were tested. The underground transmit site used on Day 3 was replicated. The surface transmit site was located at the portal of the overlying, idled mine. The surface locations were traversed using a truck and the UG locations were traversed using a mantrip along the rail.
5	Two communications modes, SUR to UG and UG to SUR, were tested. The surface transmit site used on Day 4 was replicated. The underground transmit site was located in the vicinity of the mine portal away from the rail entry. The surface locations were traversed using a truck and the underground locations were traversed on foot.

A detailed description of each specific test is provided in the "Results and Discussion" section. The specific portion of the underground coal mine traveled during the study is presented in **Figure 1**. **Figure 2** displays a map of the loop antenna locations both underground (UGAS – underground antenna station) and on the surface (SAS – surface antenna station). All of the traverses were conducted using these five stationary locations as the transmitting sites.

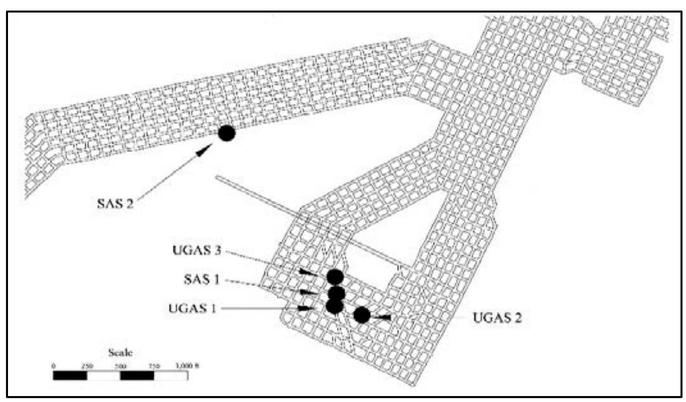

Figure 2. Map of the underground antenna stations (UGAS) and the surface antenna stations (SAS) for each TTE communication test.

RESULTS AND DISCUSSION

MCS performance data was successfully gathered about three communication modes from ten individual traverses that were used to survey five transmitting locations. Over the course of the study, both quantitative and qualitative information were gathered at each of the receiving stations. Quantitative data pertaining to signal quality was automatically recorded by the MCS only for each received message. Qualitative data included descriptions of pertinent physical characteristics about the area surrounding each receiving site and observations about message clarity. Message clarity was noted as clear, with typos, scrambled, or not received. Clear messages identified texts that were completely comprehensible with no need for additional effort to interpret. Messages with typos were texts that were comprehensible but required some effort and intuition to compensate for errors. Scrambled messages were completely incomprehensible with no discernable pattern in the text. A summary of the transmitting locations is presented in **Table 2**.

Table 2. Description of the transmitting locations.

Station Number	Antenna Layout
SAS 1	The full 120 m (400 ft) length of the loop antenna was laid out in an L-shaped oval to avoid surface obstructions on Days 1 and 2. The small diameter of the oval was approximately 1.5 m (5 ft) in length. On Day 3, the positions of the surface obstructions had changed. As a result, the entire 120 m (400 ft) length of the loop antenna was laid out in a large oval without the need for the L-modification.
SAS 2	The entire 120 m (400 ft) length of the loop antenna was laid out in a large oval at the Mine B portal. The antenna was placed in a manner that intersected the Mine B rail along the long axis of the antenna.
UGAS 1	Approximately 60 m (200 ft) of the 120 m (400 ft) loop antenna was laid out in an oval along an available underground entry. The small diameter of the oval was approximately 6 m (20 ft) in length. The long diameter of the oval was approximately 20 m (80 ft) in length.
UGAS 2	The full 120 m (400 ft) length of the loop antenna was wrapped around a pillar that intersected with a section of rail.
UGAS 3	The full 120 m (400 ft) length of the loop antenna was wrapped around a pillar located two entries outby the rail entry used for UGAS 2.

SUR to SUR and UG to SUR Transmissions

Four transmitting locations, SAS 1, UGAS 1, UGAS 2, and UGAS 3, were used to determine the ability of the MCS to communication from the surface to the surface and from underground to the surface. The extent of SUR to SUR and UG to SUR communications are displayed in **Figures 3** and **4**.

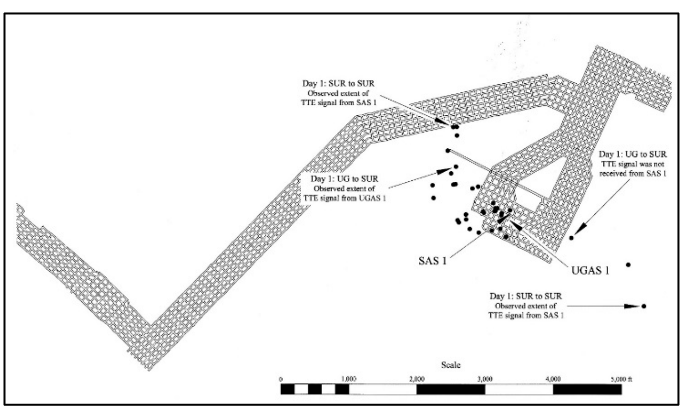

Figure 3. Map of SUR to SUR and UG to SUR testing locations from SAS 1 and UGAS 1.

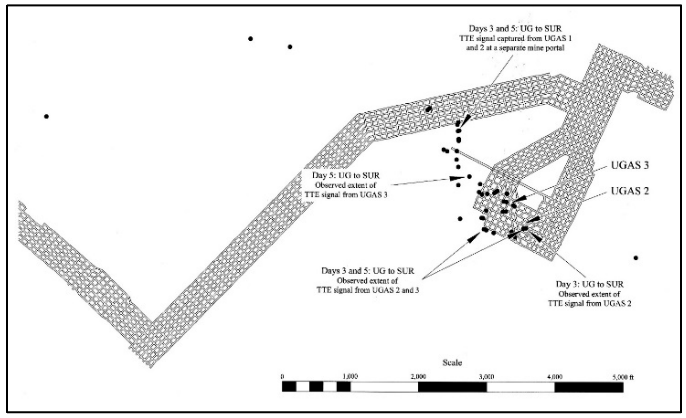

Figure 4. Map of UG to SUR testing locations from UGAS 2 and 3.

On Day 1, a SUR to SUR traverse was conducted using elevated surface transmission power. From SAS 1, the MCS was observed to communicate over distances up to 460 m (1,500 ft) from SAS 1 using a non-ideal loop antenna layout on the V-channel. Message clarity began to deteriorate at signal indicator values less than -58. From UGAS 1, a UG to SUR traverse was conducted also using elevated surface transmission power. The MCS was observed to communication over distances up to 370 m (1,200 ft) using a non-ideal antenna layout on the V-channel. Message clarity began to deteriorate at signal indicator values less than -50 and were no longer received at signal indicator values less than -68.

The signal loss appeared to be greater during the UG to SUR test with decreasing elevation as the SU approached UGAS 1. In contrast, the receiving sites located further from UGAS 1 that were at higher elevations produced stronger signals. An anomaly, due to some unknown effect, was observed within a square shaped area located approximately 60 m (200 ft) laterally along the surface from UGAS 1. The reception of any signal from UGAS 1 was prevented in this anomalous zone. This area was situated between the main mine fan and a high voltage transformer, as well as underneath several high voltage power cables. The lack of signal appeared to be confined to the internal area of this region. Any points surveyed outside the square shaped area produced clear signals from UGAS 1. No other interference of this nature was observed around other substations or power lines.

After Day 2, the MCS units were modified to broadcast using both available communication channels. The UGU was also altered to utilize the reduced underground transmission power of the permissible version of the MCS. Using these new parameters, UG to SUR testing resumed from UGAS 2 using a near-ideal loop antenna layout. The SU was traversed along the surface in a truck to establish the range of UG to SUR communication from UGAS 2. The range of the UG to SUR communication was greatly reduced using the new power level. From UGAS 2, the MCS was observed to communicate over distances up to 200 m (650 ft) using the V-channel and up to 130 m (440 ft) using the T-channel. Message clarity began to deteriorate for both the V and T channels at signal indicator values less than -50. Communications were no longer received at signal indicator values less than -60 for either channel.

As the UG to SUR testing was concluding, an unexpected transmission was received at a mine portal located 550 m (1,800 ft) from UGAS 2. This portal accessed a separate, idled mine (Mine B) that is located 90 m (300 ft) above the field test mine (Mine A). The transmissions could only be received at the Mine B portal within 15 m (50 ft) of the rail extending from the portal. A portion of Mine B intersects vertically with the Mine A rail entries. These communications received at the Mine B portal were posited to be the result of sympathetic TTE signal propagation along the parallel sections of rail.

In order to determine the range of signal propagation along the rail, a surface traverse was then performed to survey surface locations that intersected rail entries from Mine A. No communications were received from UGAS 2 during this test. The Mine A re-supply slope, which has a direct rail connection to UGAS 2, was also surveyed during this test. The transmission from UGAS 2 could not be received at the slope, which was located 400 m (1,300 ft) from UGAS 2. The outcome of this test implies that the TTE transmissions along the rail had insufficient power to both penetrate the overburden thicknesses at the selected locations and propagate to the Mine A re-supply slope despite having a direct physical connection.

The transmitting antenna was moved away from the rail during UG to SUR testing on Day 5. This location, UGAS 3, was selected to determine the UG to SUR transmission range without amplification from the track. The outcome of the test seemed to match the results of the previous UG to SUR traverse from UGAS 2. From UGAS 3, the MCS was observed to communicate over distances up to 240 m (800 ft) using the V-channel and up to 140 m (450 ft) using the T-channel. Message clarity began to deteriorate for both the V and T channels at signal indicator values less than -50. Communications were no longer received at signal indicator values less than -60 for either channel. During this test, the signal indicator value was observed to increase as the elevation of the surface traverse increased. The broadcast from UGAS 3, despite having been located away from the rail, did reach the Mine B portal. Identically to the previous test from UGAS 2, the transmission was also not received at the Mine A re-supply slope from UGAS 3. The signal indicator values of the SUR to SUR and the UG to SUR traverses as a function of distance from the transmitting antenna is summarized in **Figures 5** and **6**, respectively.

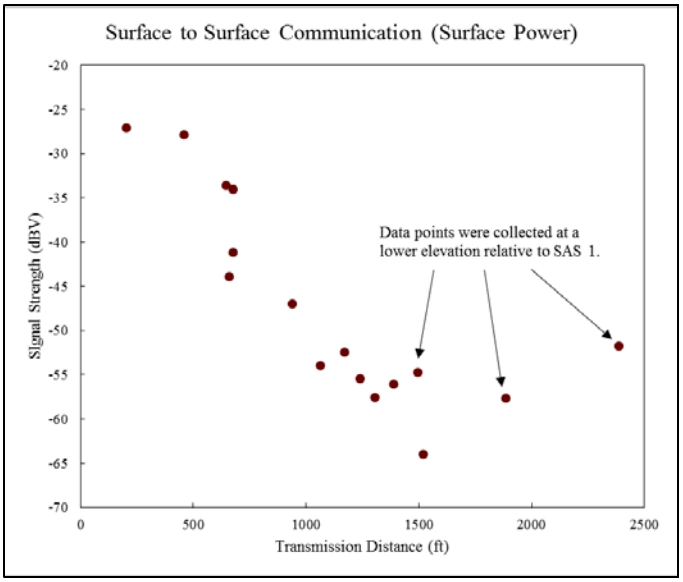

Figure 5. Signal indicator values of the SUR to SUR traverse as a function of distance from the transmitting antenna.

Figures 5 and **6** show that the received signal indicator value decreases linearly with distance with only a few exceptions caused by the signal propagation along the rail. During this field study, communications transmitted using the higher frequency V-channel exhibited a significantly greater range than the lower frequency T-channel. This behavior was unexpected because lower frequency radio waves are expected to propagate further through solid strata.

On Day 1, a SUR to UG traverse was conducted from SAS 1 along non-rail travelways using the V-channel. The MCS was observed to communicate over distances up to 260 m (860 ft) from SAS 1 using a non-ideal loop antenna layout. Message clarity began to deteriorate at signal indicator values less than -55. Communications were no longer received at signal indicator values less than -63. On Day 2, the SUR to UG transmission range along the track from SAS 1 was tested. The UGU was placed in a mantrip, which was used to carry the UGU along the main travelways to the northernmost working face. Throughout the entire test area, the signal was not lost. The MCS was observed to communicate over distances up to 980 m (3,200 ft) from SAS 1. The majority of the received messages were clear with only a few showing minor typos. Clear messages were received even at signal indicator values as low as -70. The messages could be received from SAS 1 through closed airlocks, under overcasts, next high voltage cables, near power centers, and past many turns. The range of the SUR to UG broadcast along the rail greatly exceeded the range of the non-rail travelway test conducted on Day 1.

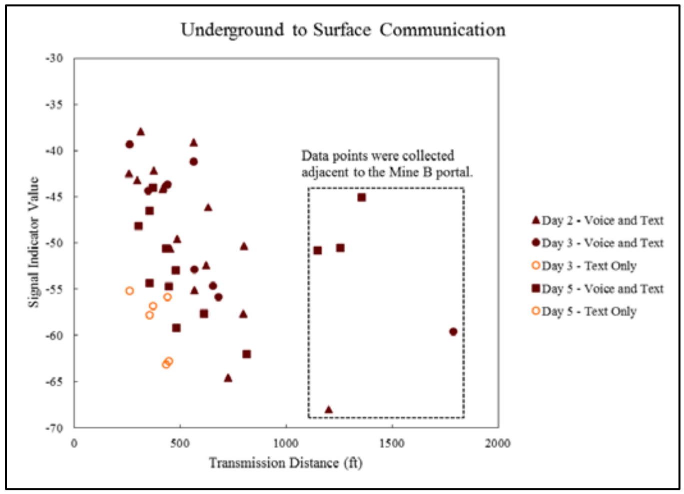

Figure 6. Signal indicator value of the UG to SUR traverses as a function of distance from the transmitting antenna

SUR to UG Testing

Two transmitting locations, SAS 1 and SAS 2, were used to determine the ability of the MCS to communication from the surface to underground. The extent of SUR to UG communications along non-rail travelways and along the rail in **Figures 7** and **8**, respectively.

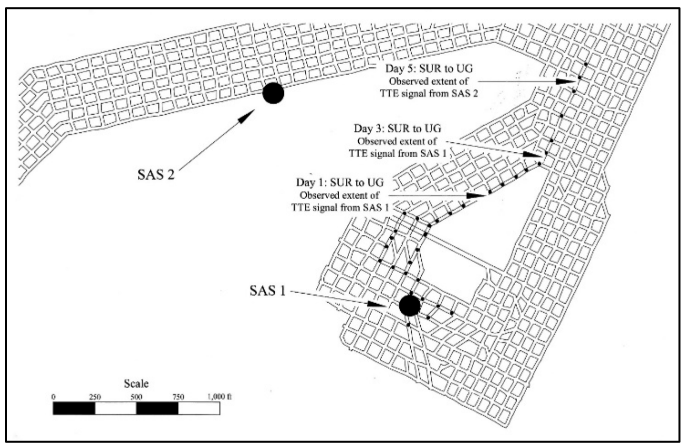

Figure 7. Map of SUR to UG testing locations from SAS 1 and 2 along non-rail travelways.

For the subsequent SUR to UG tests after Day 2, the MCS units were modified to broadcast using both available communication channels. On Day 3, the non-rail travelway SUR to UG traverse conducted on Day 1 was repeated using a new loop antenna layout, which is described in **Table 2**. During the test, a sporadic thunderstorm with periods of heavy rain was present. From SAS 1, the transmission range appeared to have been slightly extended with the new antenna layout. The MCS was observed to communicate over distances up to 400 m (1,300 ft) using the V-channel and up to 370 m (1,200 ft) using the T-channel. Message clarity began to deteriorate for both the V and T channels at signal indicator values less than -60. Communications were no longer received at signal indicator values less than -70 for either channel. The T-channel communication from SAS 1 was lost on several occasions as the UGU became further separated from SAS 1. The V-channel communication range was observed to be greater than the T-channel.

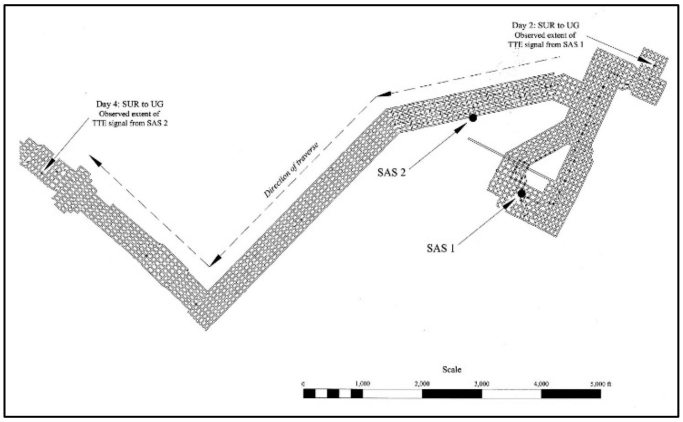

Figure 8. Map of SUR to UG testing locations from SAS 1 and 2 along the rail.

After having observed the ability of TTE signals to sympathetically propagate along the rail from Mine A to Mine B, the SU was set up at SAS 2 for SUR to UG testing. This experiment was designed to determine the potential communication range of the MCS when utilizing two separate rail systems located at different elevations. The messages from SAS 2 were received with complete clarity at almost the furthest extent of the mine. The MCS was observed to communicate over distances up to 2,230 m (7,300 ft) using the V-channel and up to 2,200 m (7,200 ft) using the T-channel. Along nearly the entire UG traverse, communications from SAS 2 were received clearly despite the presences of turns, power centers, high voltage cables, elevation changes, and metallic structures. Communications were no longer received using the V-channel and the T-channel at signal indicator values less than -80 and -90, respectively.

On Day 5, The SUR to UG communication range from SAS 2 along non-rail travelways was tested. The path used for the traverse was similar to the paths used on Days 1 and 3. The MCS performed similarly to these other experiments when broadcasting from SAS 1. From SAS 2, the MCS was observed to communicate over distances up to 550 m (1,800 ft) using both communication channels. Message clarity began to deteriorate for both the V and T channels at signal indicator values less than -65. Communications were no longer received at signal indicator values less than -75. The unusual signal indicator value and transmission distance observed during this non-rail travelway test may have resulted from the dense concentration of rail near the receiving stations or from the increased relative elevation of the SAS. The transmissions were eventually lost despite being separated from a parallel rail entry by 80 ft. This lack of signal suggests that the signal enhancement provided by the rail is limited to the presences of a dense rail array. The signal indicator values of the UG to SUR non-rain and rail traverses as a function of distance from the transmitting antenna is summarized in **Figures 9** and **10**, respectively.

Figure 9 shows that the received signal indicator value decreases linearly with distance. The rate of decrease appears to have been mostly consistent even during the SUR to UG test from SAS 2. **Figure 10** shows that the TTE signal along the rain had a shallower rate of decline in the signal indicator value. Certain portions of the rail were able to maintain, and in some cases increase the signal indicator value even though the separation distance had increased. In general, the SUR to UG tests also supported the observation from the UG to SUR tests that the lower frequency channel could not be received as far as the higher frequency channel.

CONCLUSIONS

The previously discussed field study successfully examined the operational envelope of the TTE MCS system under a variety of communication scenarios. The test was conducted at an idled underground room and pillar coal mine in Eastern Kentucky. The idled status of the mine represented near post-event conditions. Three communication modes were examined during this study: SUR to SUR, UG to SUR, and SUR to UG. The SUR to UG tests observed the maximum communication of the MCS to be approximately 240 m (800 ft) using the V-channel and 140 m (450 ft) using the T-channel from the four transmitting locations using permissible transmitting power limits. The ability to use the elevated surface transmitting power for the SUR to SUR and one of the UG to SUR tests significantly extended the communication range. The UG to SUR traverse found that the lower frequency T-channel was not able to propagate as far as the higher frequency V-channel and that a certain combination of high voltage artifacts severely interfered with TTE signal reception. Most significantly, the UG to SUR communications was observed to sympathetically propagate from Mine A to the portal of Mine B located 400 m (1,300 ft) from the transmitting location.

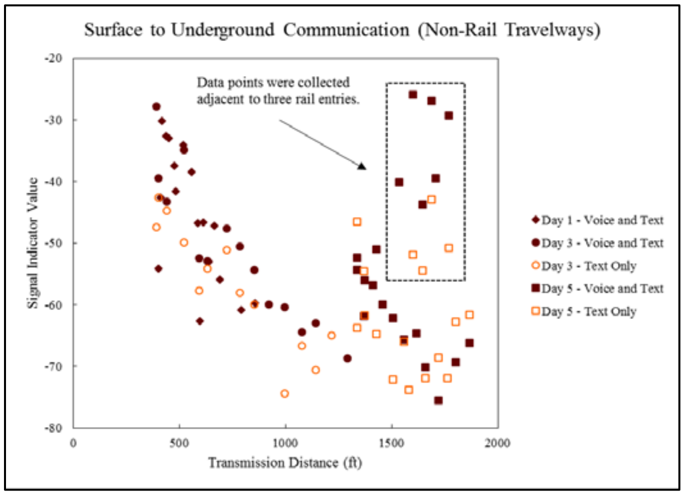

Figure 9. Signal indicator values of the SUR to UG non-rail travelway traverses as a function of distance from the transmitting antenna.

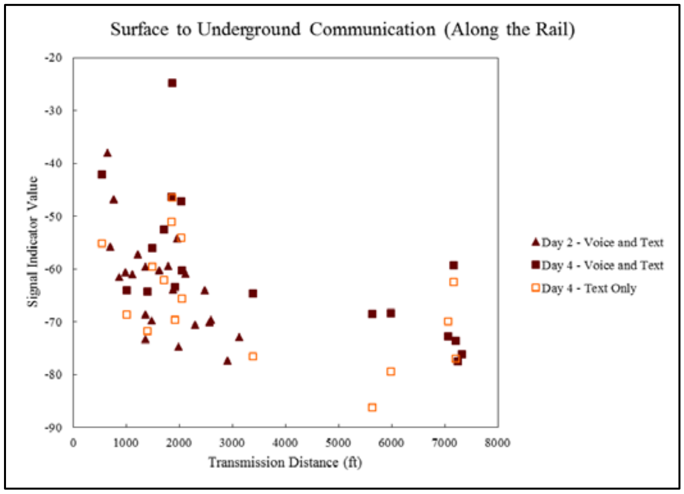

Figure 10. Signal indicator values of the SUR to UG traverses along the rail as a function of distance from the transmitting antenna.

The UG to SUR tests observed two distinct performance modes: along non-rail travelways and along the track. The traverse along non-rail travelways performed similarly to the UG to SUR tests with signal indicator values decreasing linearly with distance. The presence of high voltage artifacts did not appear to affect the ability to receive communications while underground. Interestingly, the lower frequency T-channel was also not able to propagate as far as the higher frequency V-channel, which agreed with the observed behavior of the MCS during UG to SUR testing. The maximum transmission range of the SUR to UG communication without the rail was approximately 400 m (1,300 ft) using the V-channel and up to 370 m (1,200 ft) using the T-channel. The performance of the MCS was substantially enhanced along the rail.

The SUR to UG message were clearly received at nearly the furthest extents of the mine located 2,230 m (7,300 ft) from the transmitting site. The rail-enhancing effect was limited to a proximal area around the rail. Higher concentrations of rail structures were observed to produce higher signal indicator values even with separation distances of several hundred feet from the rail. Most notably, the improved transmission range of the MCS was observed even when the SAS was located at Mine B, which had no physical rail connection to Mine A. However, the lack of signal propagation to the Mine A re-supply slope despite the presence of a physical connection remains inexplicable. The loop antenna layout was originally expected to affect the performance of the MCS. During this test, the performance the UG to SUR or the SUR to UG tests did not support this conjecture. Future testing will be conducted at other sites to further examine the behavior of the TTE system examined in this field study

REFERENCES

[1] R. G. Geyer, "USBM Contract Final Report (G133023)," in *Thru-The-Earth Electromagnetics Workshop*, Golden, CO, 1973.

[2] R. G. Geyer and G. V. Keller, "Constraints affecting through-the-earth electromagnetic signalling and location techniques," *Radio Science,* vol. 11, pp. 323-342, APR 1976.

[3] R. G. Geyer, G. V. Keller, and T. Ohya, "Research on the transmission of electromagnetic signals between mine workings and the surface," Colorado School of Mines, Golden, CO H0101691, 10 JAN 1974.

[4] J. J. Jakosky and D. H. Zellers, "Factors retarding transmission of radio signals underground, and some further experiments and conclusions," U.S. Bureau of Mines, Washington, D.C. 2651, 1924.

[5] D. B. Large, L. Ball, and A. J. Farstad, "Radio transmission to and from underground coal mines - theory and measurement," *IEEE Transactions on Communications,* vol. COM-21, pp. 194-202, MAR 1973.

[6] T. D. Barkand, N. W. Damiano, and W. A. Shumaker, "Through-the-earth, two-way, mine emergency, voice communication systems," presented at the 41st Industry Application Society Annual Meeting, Tampa, FL, 2006.

[7] L. C. Ilsley, H. B. Freeman, and D. H. Zellers, "Experiments in underground communication through earth strata," D. o. Commerce, Ed., ed. Washington, D.C.: U.S. Government Printing Office, 1928, pp. 1-60.

[8] M. R. Yenchek, G. T. Homce, N. Damiano, and J. Srednicki, "NIOSH sponsored research in through-the-earth communications for mines: a status report," presented at the Applications Society Annual Meeting (IAS), Orlando, FL, 2011.