1st Solicitation for Single Investigator Research Grants (AFC113)

ALPHA FOUNDATION FOR THE IMPROVEMENT OF MINE SAFETY AND HEALTH

Final Technical Report

1.0 Cover Page

Project Title: Operational Sensitivity of Through-The-Earth Communication
Grant Number: AFC113-14
Organization: Virginia Center for Coal and Energy Research, Virginia Tech
Authors: Edmund C. Jong, Ph.D. and Steven J. Schafrik, Ph.D.
Principal Investigator: Steven J. Schafrik, Ph.D.
Contact Information: miningrocks@vt.edu
Period of Performance: January 1, 2014 to July 31, 2016
Acknowledgement/Disclosure: This study was sponsored by the Alpha Foundation for the Improvement of Mine Safety and Health, Inc. (ALPHA FOUNDATION). The views, opinions and recommendations expressed herein are solely those of the authors and do not imply any endorsement by the ALPHA FOUNDATION, its Directors and staff.

Table of Contents

2.0 Executive Summary

During a mine emergency, the presence of an operational communication system is critical for coordinating response and recovery efforts. Through-the-Earth (TTE) communication technology is designed to achieve wireless point-to-point communications through solid strata. This characteristic allows TTE systems to persist through structural failures that would otherwise render conventional communication platforms ineffective. However, TTE technology is currently in the preliminary stages of practical application with only a few permissible TTE systems commercially available. These systems are expected to be excellent companions to mandated underground shelters because of their robust nature.

The purpose of this project is to determine the operational sensitivity of TTE systems as an emergency mine communications tool. This evaluation addresses the problem of effective utilization of TTE systems in active mining operations through the development of implementation recommendations. These recommendations can be used by mine designers and operators to evaluate and classify the potential effectiveness of TTE deployments across a variety of scenarios. For this project, two commercially available TTE communications platforms representing the two major approaches for generating TTE communications, magnetic and electric field sensing, were tested at five field sites in four states. Field testing was performed in conjunction with simulation techniques developed for geophysical surveys to provide theoretical reinforcement to field observations.

Project goals were successfully achieved using a number of individual tests at the test sites. These mine sites suitably represented the major geologic profiles and deposit extraction methods found in underground coal and metal/non-meal mines from the Central to Eastern portion of the U.S. The Magnetic Communications System (MCS) exhibited the most consistent performance throughout the project. Transmission power impacted the MCS the most consistently. The application of increased power both extended communications range and enabled communications from very poor antenna layouts. Modifications to the MCS power system were tested and applied only in non-explosive, fresh air environments. Communications range was also extended in the presence of either rail or large contiguous sections of roof mesh. These structures allowed signals to propagate along contiguous metallic sections and communications to be received in the vicinity of the structure. Although this effect was not entirely consistent, once achieved, the range extension was significant.

The performance of the E-Field Communications System (ECS) varied across all field sites regardless of the applied antenna structure or the grounding bed connection quality. In general, ECS communications were optimized when utilizing fully grouted roof bolts, rail, and belt structure as antennas, which contrasts the manufacturer's recommendation of utilizing friction fitted copper rods. The most reliable communications were produced when either rail or belt structure was utilized in conjunction with fully grouted resin bolts. Despite the observed behavior, the portability of the ECS did give this system a mobility advantage over the MCS.

Based on these findings, mine operators and other users of TTE systems should perform individual performance evaluations similar to the tests in this project at their respective sites. Users should neither assume that TTE communication systems will perform according to the manufacturer's specifications nor expect TTE systems to function consistently even within the same mine. As an aid to users for TTE deployments, the significant findings of this project in terms of communications impacts as a function of environmental and anthropogenic conditions have been compiled into two TTE Performance Tables provided at the conclusion of this report.

Introduction

During a mine emergency, the presence of an effective, reliable communication system is critical for coordinating response and recovery efforts. Current underground communication technologies are reliant on intermediary physical infrastructure, such as antennas and repeaters, to function. As such, communications are easily disabled during a mine event because of the inherent vulnerabilities to physical damage (Damiano, 2012, National Academy of Engineers, 1970, Yenchek et al., 2012). A true emergency communications system would function regardless of a mine's physical state. Through-the-Earth (TTE) wireless communication technology is designed to achieve point-to-point communication through significant thickness of solid strata. With this capability, TTE systems have the potential to serve as a true emergency communications platform.

The main challenge in achieving underground wireless communications is the counteraction of signal attenuation when propagating through a solid medium (Barkand et al., 2006, Wadley, 1949). The long wavelengths of very low frequency (VLF) and ultra-low frequency (ULF) used by TTE systems reduces the rate of signal attenuation. Field observations and theoretical models have demonstrated this relationship between radio frequency and signal transmission (Damiano, 2012, Pittman et al., 1985, Wait, 1971, Yenchek et al., 2012, Leucci, 2008). As a result, wireless TTE technology may meet the need for a reliable, robust emergency communications system for underground mines. The main advantage afforded by TTE technology is its ability to function without the need for intermediary infrastructure.

Exploration into the use of TTE technology for this purpose dates back to the 1920s (Jakosky and Zellers, 1924, Pittman et al., 1985), but U.S. permissibility requirements stagnated its development for widespread implementation at the time (Durkin, 1980, Pittman et al., 1985). Even when operating within an optimal VLF and ULF range, TTE transmissions remain sensitive to geologic factors such as mineral compositions, metamorphic properties, water infiltrations, and other strata characteristics as well as anthropogenic features (Geyer, 1973, Geyer and Keller, 1976, Geyer et al., 1974, Jakosky and Zellers, 1924, Large et al., 1973). Because these properties are unique to each mine, investigating and understanding the impacts of these features on TTE performance is critical for an effective deployment.

At present, TTE technology is in the preliminary stages of practical application with only a few permissible TTE systems commercially available. Modern systems are descendants of five prototypes developed between 2006 and 2011 under contracts sponsored by the National Institute for Occupational Safety and Health (NIOSH) (Yenchek et al., 2012). Although these commercially developed TTE systems have demonstrated the ability to communicate wirelessly through solid strata, their performance has been highly varied (Barkand et al., 2006, Geyer and Keller, 1976, Geyer et al., 1974, Ilsley et al., 1928, Jakosky and Zellers, 1924, Yenchek et al., 2012). A definitive explanation for these variations has not yet been introduced because the factors affecting TTE signal propagation are neither well understood nor well quantified.

The purpose of this project is to determine the operational sensitivity of TTE systems as an emergency mine communications tool. In order to perform this evaluation, a variety of deployment scenarios were applied to two commercially available TTE communications platforms representing the two major approaches for generating TTE communications: magnetic and electric field communications. The Magnetic Communications System (MCS) is designed to communicate using both voice and text messages on two main frequency channels representing frequency domains in the thousands of hertz and the hundreds of hertz. The E-field

Communications Systems (ECS) is designed to communicate using only text messages transmitted on a proprietary frequency scheme. ECS text messages can only be selected through a pre-defined multiple choice list. A detailed description of both TTE systems can be found in the Research Approach chapters of this report.

The MCS and the ECS were evaluated at a number of field sites to determine the impact of natural and anthropogenic artifacts on TTE communications. Field testing was performed in conjunction with simulation techniques developed for geophysical surveys. The following report presents a comprehensive overview of the tested TTE systems, field testing procedures, and project results. Recommendations regarding optimal deployment scenarios and utilization strategies for the tested TTE systems are also provide based on field observations. A cursory theoretical background regarding impacts on TTE communications is provided in the following section of this chapter. This section provides a discussion regarding how TTE signals are expected to be impacted by field site conditions, which is useful when interpreting field test results.

Theoretical Factors

In June of 2006, the Mine Improvement and New Emergency Response Act (MINER Act) was signed into legislation, mandating the use of post-incident two-way communications in underground mines. The communications provision of the MINER Act was primarily motivated by the Sago Mine Disaster. This provision generated new interest in the development of low-frequency radio technology for underground mines and has led to a number of NIOSH sponsored projects to develop viable TTE systems (Damiano, 2012, Yenchek et al., 2012). Previous TTE development initiatives were abandoned because of the difficulties encountered with permissibility restrictions for output power. However, modern improvements in EM signal processing and encoding warranted reinvestigation of this technology (Durkin, 1980, Yenchek et al., 2012).

TTE radio systems offer several advantages over conventional communications technologies. TTE systems are physically robust because they are completely wireless and only require infrastructure to be established at the transmitting and receiving locations (Barkand et al., 2006, Damiano, 2012, Yenchek et al., 2012). As a result, TTE units are less vulnerable the pervasive physical destruction of mine workings that can occur from fires or explosions capable of rendering conventional communications systems inoperable (Damiano, 2012, Geyer et al., 1974, Large et al., 1973, Vermeulen and Blignaut, 1961, Yenchek et al., 2012). Additionally, as previously introduced, the VLF and ULF signals used by TTE systems are better suited to penetrate solid strata than the higher frequency signals implemented by conventional wireless technologies. Higher frequency broadcasts are also sensitive to routine changes in the layout of the mine environment, such as equipment relocations, structural failures, etc. (Barkand et al., 2006, Damiano, 2012, Wadley, 1949).

The recent development and field testing of new prototype TTE systems have demonstrated the potential of TTE technology to communicate in mine environments, but their performance is inconsistent. Several, interrelated factors affecting signal transmission and general system performance have been identified. Improved understanding of these impacts on available TTE systems may help achieve communications goals by allowing users to optimize system deployment based on site conditions. This knowledge is especially useful in the development of best practices for deploying TTE communications during an actual mine event.

History

In the late nineteenth century, Nicola Tesla suggested the possibility of worldwide communication using the earth as a medium for transmitting low frequency radio waves (Pittman et al., 1985, Wheeler, 1961). However, serious exploration of low frequency radio communications was not considered until the 1920s when interest was awakened by the potential for military applications. This early research later transitioned to investigate civil applications in mine settings (Pittman et al., 1985). J.J. Jakosky and researchers from the Bureau of Mines conducted meaningful studies during these early years into the parameters that affect TTE radio transmission. Identified parameters included the conductivity of geologic strata, the presence or absence of water, antenna configurations, and transmission frequencies (Jakosky and Zellers, 1924, Pittman et al., 1985). These studies identified the performance trade-off between greater signal integrity for higher frequencies and farther signal propagation (i.e., less attenuation) for low frequencies. Additionally, the impact of metallic conductors, such as trolley wire and high voltage power cables, on signal transmission was also characterized (Geyer and Keller, 1976, Geyer et al., 1974, Ilsley et al., 1928, Jakosky and Zellers, 1924, Large et al., 1973, Pittman et al., 1985).

In the 1970s, concerns of research integrity led to an important study by the Bureau of Standards to characterize electromagnetic noise in several U.S. mines (Pittman et al., 1985). The results of this study included recommended operating frequencies based on the depth of transmission, geologic conductivity, noise levels, and the ability to estimate signal-to-noise ratios based on mine conditions (Lagace et al., 1980, Pittman et al., 1985). Based on this research, the Bureau of Standards recommended operating frequencies in the range of 100 Hz to 5,000 Hz for underground mines (Lagace et al., 1980, Pittman et al., 1985). This range was fairly consistent with previous studies that attempted to identify the optimum operating frequencies (Jakosky and Zellers, 1924, Pittman et al., 1985, Joyce, 1931).

The first commercial TTE communication systems were developed for South African hard rock mines in the 1960s and 1970s. These early systems achieved transmission ranges up to 640 m (2,100 ft.) (Pittman et al., 1985, Vermeulen and Blignaut, 1961, Wadley, 1949). In the U.S., research interest in TTE communications was declining after Bureau of Mines research indicated the obstacle of achieving useful underground communications while operating at the permissible power levels defined by MSHA regulations (Durkin, 1980, Yenchek et al., 2012).

Following the Sago Mine Disaster and the passage of the MINER Act in 2006, funds were allocated to NIOSH to revisit the development of a commercially viable TTE technology as a means of emergency communication (Yenchek et al., 2012). The result was the development of five prototype systems that implemented a variety of approaches. These approaches included electric and magnetic field sensing, loop and line antennas, as well as digital and analog signal processing (Yenchek et al., 2012). Only some of these TTE units have currently been approved for used in U.S. underground mines. Detailed descriptions of these prototypes can be found in the publication *NIOSH-Sponsored Research in Through-the-Earth Communication for Mines: A Status Report* (Yenchek et al., 2012). All prototypes have shown promising field results, although goals of successful transmission over a depth range of 305 m (1,000 ft.) for voice and 610 m (2,000 ft.) for text at permissible power levels (Yenchek et al., 2012).

Performance Factors

Most of the modern TTE system prototypes share similar design features. In contrast to earlier handheld and small portable designs, modern TTE platforms consist of larger transceiving units. The underground unit is intended to be strategically located near rescue chambers, active section, or potential barricade locations (National Academy of Engineers, 1970). The surface unit is mobile and can be deployed in a variety of locations during an emergency situation (Barkand et al., 2006, Damiano, 2012, Yenchek et al., 2012). Typical operational frequencies for TTE systems are in a range of 300 Hz to 5,000 Hz with wavelengths of tens to hundreds of kilometers (Damiano, 2012, Yenchek et al., 2012, Schiffbauer and Mowrey, 2006). Frequencies are dictated to an extent by the operational capabilities implemented by a specific TTE system, which can include text, compressed voice, and/or digital real-time voice communication (Barkand et al., 2006, Damiano, 2012, Yenchek et al., 2012, National Academy of Engineers, 1970). The transmitted signal strength is proportional to the applied power (Damiano, 2012, Wadley, 1949, Yenchek et al., 2012). Underground units must be operated at limited power levels in order to comply within permissibility regulations, which limits their ultimate range. Surface units can be operated at higher power and may thus be able to transmit successfully through overburden where the underground unit cannot because of permissibility restrictions. TTE systems with the aforementioned operational characteristics have historically been sensitive to a variety of environmental and operational factors. Many of these effects remain either not well understood or debated. Several performance factors that are known to affect TTE systems are discussed in the sections that follow.

Conductivity of Earth Materials

Previous field tests have demonstrated a relationship between TTE transmission quality and the conductivity of the geologic environment. Stronger signal retention has been associated with transmission in low conductivity environments, such as those characterized by dry limestone or sandstone. High conductivity environments, including ones dominated by coal or salt, have been shown to impede signal transmission (Yenchek et al., 2012). The conductive properties of the overburden can vary by orders of magnitude at different mine sites and can potentially vary significantly at the same site (Yenchek et al., 2012).

The impact of water on TTE transmissions is disputed with the Bureau of Mines claiming that highly saturated areas had little effect on system performance while other investigators name water as a contributing or even primary factor (Damiano, 2012, Geyer and Keller, 1976, Ilsley et al., 1928, Pittman et al., 1985, Yenchek et al., 2012). This discrepancy may result from the variation in the water chemistry at different sites or over time at the same site. Local geology, mining activities, and other induced or natural factors could alter water chemistry and conductivity by introducing salts, other ions, or mobilizing metals. Characterizing the natural conductive environment defined by earth materials can be a complicated task where geology is spatially heterogeneous and mining activities may generate additional spatial-temporal heterogeneities in the strata and accumulations of water. (Yenchek et al., 2012).

Energizable Structures

Reports of anomalous radio performance in the presence of metallic conductors and energizable structures date back to at least the 1920s (Pittman et al., 1985). Most reports describe the effect as beneficial or “serendipitous,” recognizing the potential for these structure to impact EM signal range (Barkand et al., 2006, Vermeulen and Blignaut, 1961, Wadley, 1949). The presence of metallic conductors was observed to enhance radio communication signals by ten time in South African mines (Pittman et al., 1985). In the 1970s, efforts to mathematically model the effect of various conductors on electromagnetic fields and signal transmission were pursued. The simulations generally agreed with experimental data (Wait, 1960, Wait, 1971, Wait, 1972, Wait and Spies, 1972). Eventually, attempts were made to utilize this enhancing phenomenon by developing commercial communications systems that relied on propagation along conductors (Farstad, 1973, Pittman et al., 1985). However, a series of field tests noted that the presence of conductors could have the opposite effect under certain conditions. In these circumstances, signal transmission was obstructed because of signal “scattering” (Frischknecht, 1967). Understanding the circumstances under which signals are enhanced or obstructed by conductors and to what degree are important in order to anticipate system performance.

Antenna Configuration

The impact of antenna configuration and deployment on TTE system performance is relatively well understood especially for magnetic sensing-type platforms. Far fewer examinations of E-field-type antenna configurations have been performed and thus limited background information is available. As a result, only an overview of performance impacts from magnetic antenna configurations will be covered. Theoretical and field investigation results show agreement in that using horizontal loop antennas in direct vertical alignment optimizes signal transmission This configuration is optimal because the electromagnetic waveform is transmitted from the loop antenna as an oscillating magnetic dipole oriented along the axis of the loop. In a vertical orientation, the magnetically coupled alignment is best suited to receive the polarized signal (Wadley, 1949, Wait and Spies, 1972, Yenchek et al., 2012).

However, these investigations involved idealized cases that did not include unconventional layouts such as those that may be utilized in restricted mine geometries. One study did consider the scenario where a direct vertical alignment would not be possible. This study found that the signal would drop off with increasing distance from the underground loop at a rate determined by geologic characteristics (Damiano, 2012). Underground antenna configurations would be the most subject to antenna layout problems because of mine geometry constraints, artificial obstructions, etc. (Damiano, 2012, National Academy of Engineers, 1970, Pittman et al., 1985, Yenchek et al., 2012).

Electromagnetic Noise

Low-frequency electromagnetic noise directly interferes with TTE system performance by polluting the transmission environment and reducing the signal-to-noise ratio. Manmade sources of low-frequency noise include machinery, transmission lines, and VLF military stations (Pittman et al., 1985, Yenchek et al., 2012). Worldwide lightning is a major source of natural electromagnetic noise because its low-frequency signals travel with little attenuation causing persistent background interference (Pittman et al., 1985). The EM noise profile from manmade sources changes over time in relation to technological advancements, voltages requirements, and increasing numbers of sources (Yenchek et al., 2012). For some sites, regularly scheduled EM surveys to characterize the noise may be necessary. Small-scale changes in the character of the noise profile could also occur over short time scales because of shifts in equipment usage or mine activity levels. However, one study found that noise sources common to mine environments, such as high voltage equipment, are likely to be located near power cables or conductors that could potentially enhance TTE signals and overcome local noise sources (Vermeulen and Blignaut, 1961).

3.0 Problem Statement

The Mine Safety and Health Administration (MSHA) has communicated the need for a robust communications system that persists through the destruction of underground mining structures and equipment during major emergency events. The production of commercially available TTE systems capable of voice and text communications have advanced the mining industry toward this goal. Low frequency TTE technology utilizes VLF and ULF transmissions, which severely limits the amount of data that can be communicated. As a result, TTE systems are intended for use in emergencies only. Demonstrations of TTE systems have shown that this technology has great potential. However, the youthfulness of TTE technology presents implementation challenges. Although these systems have adequately performed in controlled field locations, how they will react to dynamic underground conditions is not well understood.

This project is designed to address the problem of effective TTE system implementation operations by defining its operational sensitivity. The objective of this project is to develop guidelines for using TTE technology through experimentation assisted by theoretical research. These guidelines can then be used by mine designers and operators to evaluate and classify the potential effectiveness of TTE deployments. From this information, a TTE unit may be deployed in a manner that elicits optimal system performance. Responders deploying a TTE unit above ground will also gain a similar benefit from project findings. Three aims were defined to complete this objective: the identification of performance factors, the evaluation of TTE system performance, and the definition of recommendations for TTE system utilization.

The first aim, the identification of performance factors, seeks to define the geologic and anthropogenic factors that impact TTE technology. To this end, simulation software designed for geophysical surveys, APhiD, was used to gain a greater understanding of TTE signal behavior within the Earth. A forward modeling approach was utilized to explore how transmitter location affected communications in a given environment. Once individual simulations were completed for reoccurring or unique effects observed during field testing, four geologic archetypes, Southern Appalachian, Central Appalachian, Northern Appalachian, and Illinois Basin, were developed to assess the conditions both favorable and unfavorable to TTE deployments.

The second aim, performance testing and evaluation, covers the desired outcomes for field testing. Collected data and observations were processed and summarized to identify notable impacts on TTE communications. Any significant impacts were highlighted for further examination. Repeatable effects on TTE communications were categorized according to the condition suspected of causing the anomaly. A summary of each significant effect was then created in order to help define recommendations for TTE system deployment.

The final aim, operational and planning recommendations, represents the final deliverables from this project. Using the observations and simulations produced during research, a set of recommendations for mine designers and operators were produced. These recommendations allow users to identify locations in a mine where TTE technology will likely function. Locations in which TTE systems are suspected to have reduced or no functionality are also presented. TTE systems are expected to be deployed in emergency situations involving trapped miners. In these scenarios, understanding the operation of available TTE technology is critical for both responders and miners.

4.0 Research Approach

A combination of theoretical background research, computer simulations, and field studies were implemented to perform a comprehensive evaluation of commercially available TTE systems. Five formal tasks were defined to represent the major project goals that would fulfill project objectives. These project tasks are summarized in Table 1. Three aims, Identification of Performance Factors, Performance Testing and Evaluation, and Operational and Planning Recommendations, were also defined to specify the primary deliverables from this project. A description of these aims is provided in the Problem Statement and Objective chapter and will not be discussed in this section. The following chapter provides a comprehensive overview of the field sites and the experimental procedures used to complete Tasks 3-5. Procedures are organized by TTE system (i.e., MCS procedures and ECS procedures) and are followed by a discussion of how specific environmental and anthropogenic conditions were examined.

Table 1. Project Tasks.

Task	Description
1	Theoretical Factors Report: report will include a comprehensive literature review and simulations that describe the anticipated results. This report will be the basis of the testing that will be performed.
2	Test Procedures Report: this is a complete listing of the tests that must be performed under Task 3 with descriptions of the data required for performance.
3	Performance of field work
4	Data and Initial Analysis Report: report will describe all data collected in a manner that will allow for replication.
5	Final Report: Report will detail means and methods for determining quality of TTE technology in mine designs. Training materials: Training materials aimed at miners responsible for deploying the TTE technology will take the form of presentations or handouts.

Field Sites

The majority of the TTE surveys were completed with a two-person team. Some exceptions occurred depending on the demands of the planned experiment and the limitations present at particular field sites. In addition to the two-person team, one to three mine employees were provided to accompany the researchers as dictated by mine company policies as well as by State and Federal regulations. Communication surveys were conducted at five underground mines representing three coal mines and two metal/nonmetal (M/NM) mines. An overview of these sites is presented in Table 2.

Table 2. List of field test sites.

Field Site	Type	Location	Mining Method
A	Coal	Central Appalachian Region	Retreat room and pillar
B	Coal	North Central Appalachian Region	Longwall
C	Coal	Illinois Basin	Longwall
D	Metal	South Central Appalachian Region	Stope and pillar
E	Non-Metal	South Central Appalachian Region	Stope and pillar

Field Site A is an underground retreat room and pillar coal mine in the Central Appalachian region of the U.S. This mine is located in Eastern Kentucky and extracts bituminous coal for electrical power generation. The seam is located at an average elevation above sea level 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 surface is composed of irregular hills, ridges, and mountains formed from stream erosion and a sporadic distribution of artificial structures. This terrain causes the overburden thickness to widely vary from 122 m (400 ft.) to 305 m (1,000 ft.). The overburden stratigraphy contains alternating layers of conglomerated sandstone and shale with thin, sporadically distributed clay beds. Water infiltrations within the overlying strata are minor.

The mine's accessible areas were fairly level with gradual changes in elevation of no more than 30 m (100 ft.). The field test mine was also situated approximately 90 m (300 ft.) below another retreat room and pillar coal mine, which was closed prior to field testing. No information was available regarding the state of the overlying mine's workings, such as the layouts of rail, conveyor belt, metallic structures, and electrical infrastructure. The field test mine was open but inactive at the time of the study. In this idled state, Field Site A presented an ideal opportunity to examine TTE communications under near post-event shutdown conditions. All reported elevations and stratigraphic details are based on data provided by mine personnel. Maps containing detailed topographic profiles, seam elevations, and stratigraphic compositions could not be obtained.

Field Site B is an underground longwall mine located in the North Central Appalachian region of the U.S. This mine is located in West Virginia and extracts bituminous coal for electrical power generation. The coal seam is situated at an average elevation above sea level of 170 m (550 ft.) and has a seam thickness of approximately 2 m (6 ft.). The overburden thickness above this mine varies from 150 m (500 ft.) to 300 m (1,000 ft.) because of the overlying mountainous terrain. The full extent of the mine's accessible underground workings is effectively level with only gradual changes in elevation of no more than 10 m (40 ft.). The overlying stratigraphy does not contain any significant geologic features such as major faults or water infiltrations. A large portion of this mine is, however, overlain by an inactive oil-gas field populated by densely spaced wells with intact casings.

The presence of this field provided a unique opportunity to determine the impact of numerous grounded metallic structures on TTE communications. Very few artificial structures were present over the mine because of the terrain. Surface features that may have potentially affected TTE communication included residential properties, high voltage power lines, processing facilities, and a tailings pond. Maps containing detailed topographic profiles, seam elevations, and stratigraphic compositions could not be obtained.

Field Site C is an underground longwall mine in the Illinois Basin region of the U.S. This mine is located in Southern Illinois and extracts bituminous coal for electrical power generation. The seam is located at an average elevation above sea level of 170 m (-100 ft.) and has a thickness ranging from 2-5 m (6-15 ft.). Given the magnitude of the seam thickness, the use of support mesh is prevalent throughout the mine to secure sloughage from the roof and the ribs. As a result, the majority of the active areas are installed with contiguous sections of support mesh. The surface above the mine is effectively flat with an average overburden thickness of 150 m (550 ft.). The overburden consists of either silty gray or black fissile shale interbedded with a sandstone channel. A layer of limestone is also present over some of the mine.

The full extent of this mine's accessible underground workings is effectively level with only gradual changes in elevation of no more than 10 m (50 ft.). The primary method of travel and supply haulage through the mine is accomplished using rubber-tired vehicles. As a result, no rail infrastructure is installed. The composition of the overburden does not contain any significant geologic features such as major faults or water infiltrations. Although the surface terrain above the mine was level and open with minimal natural obstructions or artificial structures, the majority of the land was privately owned and inaccessible for study. Maps containing detailed topographic profiles, seam elevations, and stratigraphic compositions could not be obtained.

Field Site D is an underground stope and pillar metal mine in the South Central Appalachian region of the U.S. This mine is located in Eastern Tennessee and extract zinc from a dome shaped deposit. The deposit is located within the early Ordovician-aged Mascot and Kingsport geologic formations, which are composed predominantly of limestone and dolomite. The mine workings consist of multiple overlapping levels that were designed to follow the dome-shaped ore deposit. This shape causes the mine workings to vary significantly in elevation from approximately 170 m (550 ft.) to -35 m (-110 ft.). Although some separate levels were present, the majority of the mine is developed along a single contiguous horizon that followed the outer edge of the deposit.

The average mining height at this field site varies from approximately 6 m (20 ft.) to 24 m (80 ft.). Pillar geometry and pillar spacing also differ because of the heterogeneous distribution of ore grades. Overburden thicknesses at this mine range from 305 m (1,000 ft.) to 520 m (1,700 ft.). The overlying stratigraphy consists mostly of alternating limestone and dolomite sections with some interspersed sedimentary beds. Numerous faults both regional and local in scale intersect the mine workings. These faults produce large planes of water that empty into the mine at various points. The surface terrain overlaying the mine is fairly level and contained a moderate amount of anthropogenic artifacts consisting mostly of sparsely spaced residential, commercial, and agricultural structures. Artificial surface features associated with the mine itself included processing facilities and a tailings pond. Maps containing detailed topographic profiles, seam elevations, and stratigraphic compositions could not be obtained.

Field Site E is an underground stope and pillar non-metal mine in the South Central Appalachian region of the U.S. This mine is located in Southern Virginia and extracts chemical-grade limestone. The deposit is located within the Ordovician-aged Five Oaks geologic formation. A series of thrust faults associated with Alleghenian orogenesis form a synform in which the mine is nested near the northwest flank. The mine workings consist of multiple overlapping levels that follow the steeply dipping limestone deposit into the mountain. Each level is developed at separate elevations and connected by a central spiral ramp system.

The mine's workings extend to a depth of 700 m (2,300 ft.). Pillar geometry and mining height are both highly variable with some caverns reaching up to 34 m (110 ft.). The mine is overlain by mountainous terrain that limits physical access and contributes to the variations in the overburden thickness. A few residential structures are present in the vicinity of the mine directly adjacent to a rail haulage thoroughfare. The overburden is composed almost entirely of the Martinsburg formation, which is a combination of shale and limestone with some sandstone beds. Certain sections of this mine contained significant water infiltrations that were diverted to a central sump for removal. Maps containing detailed topographic profiles, seam elevations, and stratigraphic compositions could not be obtained.

MCS Test Procedures

Overview

Field tests of the MCS were conducted at various underground mine sites to determine the operational sensitivity this system to anthropogenic and environmental conditions. Three modes of communications were examined at these field studies. These modes were surface to underground, underground to surface, and underground to underground. The unpredictable accessibility of survey locations and the irregular availability of mine personnel at the field sites prevented the implementation of a formal experimental design. As a result, the format of this project was an observational survey in which a formal experimental design was not required. A non-experimental design was utilized to examine the behavior of the MCS.

Given the project objectives, this non-experimental design was ideal because the majority of experimental variables could not be controlled. The basic structure of the observational TTE evaluation utilized a stationary transmitting unit and a traversing receiving unit. The traversing unit was moved to various accessible locations at which observations and pertinent data were recorded. This data was used to determine the communications performance of the MCS at each tested location. Details regarding the execution of the MCS field tests can be found in sections that follow.

Instrumentation

Two MCS surface units were utilized for this project. Although the use of surface units precluded the testing of non-permissible regions of underground coal mines, the size and the weight of the permissible MCS underground unit would have prevented the execution of any useful survey. One of the surface units were, however, modified to mimic the reduced power transmission power of a permissible MCS underground unit. The MCS surface units are composed of six primary components: a control panel, two power supplies, a laptop computer, a transmitting antenna, and a receiving antenna.

The control panel houses the infrastructure needed for power delivery and communications routing between the laptop and the antennas. This panel is housed within an impact-resistant aluminum case hardened for deployment in dusty and wet environments. The control panel does not contain any electronics that directly encode or interpret MCS communications. Instead, this task is assigned to the supplied laptop computer. The laptop provides both an interactive graphical user interface as well as executes the software responsible for transmitting and receiving communications through the control center. The MCS is able to send and interpret both voice and text communications using two main frequency channels in the VLF band: the voice and text channel (V-channel) and the text-only channel (T-channel) with average operational frequencies in thousands of hertz (Hz) and in hundreds of hertz (Hz), respectively. The higher frequency V-channel is able to send both voice and text transmissions while the lower frequency T-channel is able to send only text transmissions.

Voice communications are limited to 10 s recordings that are not communicated in real-time. A voice communication must be recorded, encoded, and then transmitted. The transmitted voice recording must then be received, interpreted, and re-played. This process requires approximately 30 s to transmit a recording in a single direction. Voice communication are thus pseudo half-duplex in nature. Under some circumstances, the interpretation software is unable to resolve an incoming message during the transmission of an outgoing communication, which results in either the loss or corruption of one of the messages. Text communications are restricted to a character limit of 22 for both available channels. Although a text message may contain more characters, the software interface will break the message at the character limit and wrap the text into a separate transmission. This wrapping occurs with no regard for natural breaks in the message content, which may create confusion.

The MCS is powered by two battery units, one 12 V lead-acid marine battery and a 24 V battery pack composed of two individual 12 V batteries. The 12 V battery supplies power to the transmitting antenna while the 24 V battery pack supplies power to both the laptop and the receiving antenna. Although functional, the design of this power system is cumbersome and difficult to transport without the aid of a customized apparatus. Fully charged power supplies are sufficient for at least three hours of continuous usage. Battery capacity is a function of communications frequency, environmental conditions, charge quality, and battery age.

The MCS antenna is composed of two separate components in the MCS system. The transmitting antenna is constructed from a flexible cord that is 120 m (400 ft) in length and approximately 3.5 mm (0.25 in) in diameter. The antenna is designed to be wrapped around a pillar in a manner that maximizes the total enclosed area of the loop. The loop can be similarly deployed on the surface in a large open area. The receiving antenna is composed of three helical ferrite rods that are oriented in the three principal axes. This antenna configuration allows the MCS to receive transmissions regardless of the arriving signal orientation. The three rods are contained within an impact resistant case hardened against and moisture. A conceptual diagram of two deployed MCS units is displayed in Figure 1. This figure represents a MCS communication scenario that may occur between surface and underground personnel.

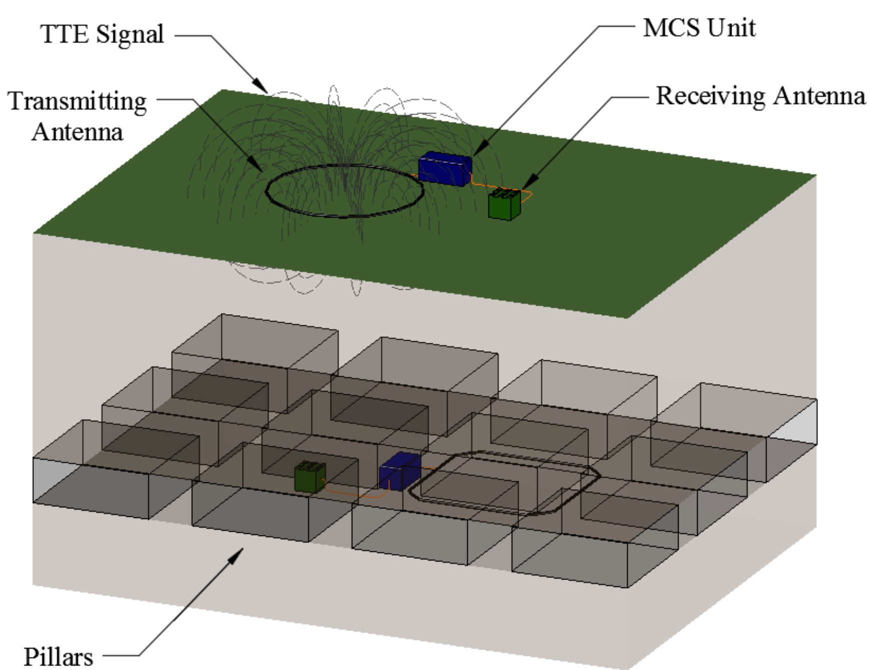


Figure 1. Conceptual diagram of an MCS deployment scenario. The underground MCS unit has its loop antenna wrapped around a pillar while the surface MCS unit has its loop antenna laid out in an open field. An outline of the toroid shaped signal emitted by the MCS is also included.

Experimental Design

The MCS field evaluations were completed using a survey of one-way communications from one transmitting location and a variety of accessible surface and underground receiving locations. As previously described, the field team consisted of two to three researchers and enough mine employees to satisfy applicable mine company policies and government regulations. No mine personnel were required to help manipulate the equipment or to assist in the data collection. The mine also provided hazard training along with any additional required training or supplies to the investigators. All field study instrumentation and research personal protective equipment (PPE) were furnished by the investigators. Other assistance needed from the mine, such as providing advice about selecting transmit locations, was kept to a minimum. The basic execution of an MCS field survey is summarized by the following steps.

1. Identify suitable test locations for the MCS
2. Set-up and initialize the stationary MCS at the selected transmit location
3. Activate automated communications script on the stationary unit
4. Set up and initialize the traversing MCS unit
5. Verify transmission and reception of automated communications
6. Commence location traverse of selected areas surrounding the transmitting unit
7. If more testing is scheduled, repeat the aforementioned procedures for the new stationary transmitting location

Multiple transmitting locations were tested on both the surface and underground to evaluate the MCS across each of the field sites. The order by which the individual locations were tested at each site was scheduled in a manner that minimized the impact on normal mine operations. The majority of the data collection was also automated to reduce the time needed at each receiving location. A detailed description of the major tasks in the MCS evaluation is presented in the following sections.

Survey Description

Location surveys were used to establish the transmission range of the MCS across a variety of locations representing various combinations of geological properties and anthropogenic artifacts. Three modes of one-way communication were used to evaluate the MCS. These modes were surface to underground, underground to surface, and underground to underground. As the modes imply, a stationary MCS unit was established at either a surface or an underground location as the surveys antenna station (Underground Antenna Station (UGAS), Surface Antenna Station (SAS)). This location was selected based on the level of major mine traffic and unobtrusiveness to mine personnel. Given the variety of terrain and mine layouts represented by the field sites, transmission locations were determined by the researchers after interacting with mine personnel and examining potential locations. Once the locations were identified, the traverses were then scheduled based on resource availability and mine traffic patterns.

At the transmitting location, one of TTE units was set up to be the stationary, standalone system for the duration of the particular test. Both the transmitting loop antenna and receiving three-axis antenna were placed at this location. The MCS system design requires the installation of both antennas to transmit messages. However, only the three-axis antenna is needed to receive messages. The automated script on the transmitting unit was then initialized so that a text message was broadcasted on a 30 s interval. The text messages also alternated between the higher frequency V-channel and the lower frequency T-channel so that both frequency domains could be evaluated. The voice aspect of the MCS was not examined throughout this project because of time restrictions at the field sites. However, both voice and text on the V-channel uses the same mode of operation and thus text quality is indicative of voice quality.

After establishing the transmitting location, the receiving unit was then brought to the opposing location depending on the test (i.e., surface or underground) to examine the reciprocal one-way communication performance. The one-way nature of the tests required only the three-axis antenna to be implemented at the receiving locations. Traverses were started by first placing the receiving unit as close as practically possible to the center vertical axis of the transmitting loop antenna. At this initial receiving location, the signal indicator value and the qualitative quality of the received text were recorded for each received message.

The signal indicator value is a quantitative descriptor of the signal quality specific to the MCS system utilized in this project. The indicator value is automatically generated and logged by the MCS for each received message. The method used to determine this value is proprietary to the manufacturer and its absolute and expected ranges are unknown. Indicator values recorded for received messages as well as their relationship to message clarity varied from site to site. Based on these observations and feedback provided by the manufacturer, the signal indicator value is computed from an internal algorithm that recalibrates its upper and lower limits as well as its numeric range each time the MCS is activated.

As such, no quantitative conjectures could be made relating the signal indicator value to message reception quality, signal reception threshold, or overall system performance. Since the indicator value is proportional to the signal strength perceived by the MCS, the qualitative trend of recorded indicator values relative to transmission distance can provide a general indication of how these properties interact. During this project, the indicator value was indirectly proportional to the point to point transmission distance in that the MCS' perceived signal strength linearly decreased with increasing transmission distance. The rate of decrease varied from survey to survey, which was conjectured to be an artifact of the field site characteristics in conjunction with the signal indicator value's calibration parameters.

Given the encapsulated and confidential nature of the MCS' software, the calibration parameter could not be isolated from the field site characteristics, which did not allow for any detailed analysis of signal strength relative to observed field site conditions. For these reasons, the signal indicator values will only be summarized for Field Site A to provide an example of how indicator thresholds may be determined for each communications test. No other summary tables will be provided in subsequent field site summaries because of the largely unknown basis for the signal indicator value.

After surveying the initial location, the receiving unit was then moved to other accessible locations around the vertical axis of the loop antenna. The signal indicator value and text quality were also recorded at each of the subsequent receiving locations. Recorded qualitative data included descriptions of pertinent physical characteristics about the area surrounding each receiving site and observations about text clarity. Deterioration in text clarity was displayed by the MCS as random typos, such as "TfEXo" instead of "TEXT," and/or the inclusion of extraneous symbols, such as %, &, and @. Any unexpected behavior observed during each survey was also noted, such as errant transmissions.

Errant transmissions were the most frequently encountered anomaly. An errant transmission in the context of this project describes a message that was received in a surveyed receiving location that was unexpected based on observed behavior. For example, during the course of a survey, the loss of the MCS signal was verified by traversing several areas located further from the point where communications were initially lost. At times, a message would be received at a location positioned beyond the initially observed point of signal loss. Any such unexpected message reception relative to observed MCS behavior was identified as an errant transmission, which could indicate the presence of an anthropogenic or natural anomaly that either created a zone of interference or allowed the signal range to be extended to a specific receiving location. If sufficient information was available regarding possible causes for the errant transmission, then a description of the circumstances was provided. However, errant transmissions could not always be attributed to characteristic of the field site. In these cases, the errant transmission was simply noted and presented for potential future analyses.

The location of each surveyed receiving location was chosen based on accessibility and available time. Traverses continued until the signal from the transmitting MCS unit could no longer be received. Another transmitting location or communication mode would then be evaluated in the same manner. As previously discussed, two-way communications were not directly tested because of time and technological constraints. In order to send reply messages from the receiving stations, the loop transmitting antenna would need to be deployed, which was not practical. Additionally, the MCS does not maintain a log of received text messages thereby removing the ability to automate a two-way communications test. Although two-way communications were not formally investigated during individual tests, the alternation between surface to underground and underground to surface modes provided a suitable analog.

MCS Unit Deployment

As previously introduced, the MCS consists of six primary components: a control panel, two power supplies, a laptop computer, a transmitting antenna, and a receiving antenna. The control panel, the 24 V power supply, and the laptop computer are housed in an integrated, impact-resistant case. The remaining three components, the transmitting antenna, the receiving antenna, and the 12 V battery, are free standing and independent from the control center. The set up procedures for the MCS unit are straightforward and do not require a significant amount of time to accomplish in most cases. However, the size of the components, especially the transmitting antenna, made physical manipulation challenging in restricted terrain.

Two MCS surface units were used to conduct the TTE study at each of the mine sites. One MCS was permanently assigned as the underground unit (MGU) while the other MCS was permanently assigned as the surface unit (MSU). The MGU was configured to operate using the same power output specifications as a permissible underground unit. The receiving and transmitting antennas for the MGU and the MSU remained with their assigned units and were only interchanged during troubleshooting activities. This compartmentalization of the MCS units and modification of the MGU unit to permissible power specifications closely replicated how a MCS system would be deployed during a mine event. An inventory and a brief inspection of the MCS equipment was completed prior to operation. All major components were checked for any substantial physical wear and functional abnormalities. An itemized description of MCS components are listed in Table 3.

Table 3. MCS component list and description.

Component	Description
Control Panel	This component is contained within an impact and abrasion resistant metal case. The control panel serves as the primary interface between all other MCS components.
Laptop Computer	This component provides the user interface (UI) and communications protocols for the MCS. The laptop is hardened against impact, moisture, and abrasion but remains susceptible to software and computer hardware failures.
Receiving antenna	This component is housed in an impact resistant cube-shaped case. The case has three female MIL-SPEC ports installed on the exterior.
Transmitting antenna	This component consists of a 120 m (400 ft) long cable that is wrapped around a metal reel. Each end of the antenna is terminated with a male MIL-SPEC connector.
12V Power Supply	This component consists of a standard automotive battery housed within a marine battery carrying case. The battery has plug-in power connectors already affixed to the terminals.
24V Power Supply	This component consists of two independent 12 V batteries that are wrapped together to create a single batter pack. The batteries are spliced together with a single MIL-SPEC connector.
Laptop Computer Cables	In order to interface with the control panel, the laptop requires one USB cable and one power cable. These cables are standard retail grade cables and are integrated into the control panel. Given the un-hardened nature of the cables, care should be taken when connecting the laptop.
Receiving antenna Cables	The receiving antenna communicates with the control panel through three separate cables. These three cables are terminated on both ends with two different types of connectors. One end of the cables is terminated with male MIL-SPEC connectors. This end is attached to the female ports on the transmitting antenna case. The other end of the cables is terminated with a BNC-like quarter turn connector. This end is attached to the associated BNC-like ports on the control panel.

The assembly process for the MCS required five main connections to be made. These connections were the two power supplies, the laptop, and the two antennas to the control panel. The basic set up procedure is presented in the list that follows. A detailed description of these steps is also provided.

1. Identify and determine the layout of the MCS based on available space, obstacles, hazards, sources of interference, and impact on mine operations
2. Secure and connect the laptop to the control panel if not already installed
3. Secure and connect the 24 V power supply to the control panel
4. Place and connect the 12 V power supply to the control panel ensuring that the battery is not located within the internal area of the loop antenna
5. Verify that the batteries are operating within expected parameters
6. Place the completed control center in the designated area
7. Lay connect the transmit and receiving antennas ensuring that neither the transmitting antenna nor the control center is located within the internal area of the loop antenna
8. Activate the laptop computer and verify that the MCS is operating within expected parameters

Once a transmitting location was identified, the layout of the loop antenna would then be determined. Given the 120 m (400 ft) length of this antenna, the space requirement for a full-scale deployment is significant. Under ideal circumstances, the design of the transmitting antenna requires that the entire length be arranged in a perfect circle, which encompasses approximately 1,180 m^2 (12,700 ft^2). However, an objective of this project is to also evaluate non-ideal installations of the MCS to realistically represent an emergency situation.

In order to satisfy this objective, the transmitting antenna was deployed in a manner that was both simple and quick based on the characteristics of the location. Examples of such non-ideal installations include irregularly shaped loops, short loops, suspended loops, crossed wire arrangements, etc. Ideal placements were implemented when possible to establish a basis of comparison for non-ideal placements. The receiving antenna was not set up in areas where equipment or vehicle movement may damage the antenna. The control panel, the receiving antenna, and the 12 V power source were arranged so that these components were kept dry, accessible, unobtrusive, and outside of the transmitting antenna's internal area.

Once the loop antenna layout and location were determined based on the previously discussed criteria, the MCS system was assembled. The following procedures for connecting the MCS components were used across all field sites and are presented in an order that allows the control panel to become operational and tested prior to attaching the peripheral components. However, future replications of MCS installations do not necessarily need to follow the presented connection order. As long as the MCS is fully assembled and powered before starting the laptop software, any connection sequence may be utilized. Should the opposite activation order unintentionally occur, the laptop would need to be restarted to allow for a proper connection. Special care was also taken to ensure that each connector was installed on its assigned port.

The laptop, if not already secured, was placed in the center of the control panel between the appropriate bracket and secured using the provided clamps. The laptop power and USB cord were then connected. After installing the laptop, the 24V power supply was installed using the provided straps and attached using the quarter-turn MIL-SPEC connector to the designated port.

The 12V marine battery was then connected to the control panel using the provided push-fit connector. Once the laptop and the two power supplies were installed, the two power switches on the control panel were toggled to the “ON” position. The displayed voltage on the battery charge indicators was verified to be within ±1-4 V of the rated voltages. If the voltages were beyond these tolerances, the batteries were replaced with a backup. Once the laptop and power supplies were connected, the antennas were then installed.

The ends of the transmitting antenna consist of two MIL-SPEC screw connectors that connect to the control panel. Care was taken to align the connector’s pins before the connector was secured to prevent any dislodging of the pins. This pin misalignment issue was experienced at several field sites. The receiving antenna is attached to the control panel using three independent cables. These cables are terminated at both ends by two different connectors, a MIL-SPEC screw connector and a BNC-like quarter turn connector. The three MIL-SPEC connectors were secured to the three ports on the antenna case. Each port must be connected to the corresponding input port on the control panel, which were labeled by the researchers on both the antenna and the control panel to prevent confusion. Once all of the connections were made, the control panel and the laptop were powered on.

After the laptop finished its boot process, the MCS UI would automatically load. If the software did not automatically load, the laptop was restarted. Once initialized, the software automatically executed a basic diagnostic routine to verify the MCS’s components. If no errors were displayed, the MCS was then ready for use. Both MCS units are identical in design and could be assembled and initialized using the same procedures. Based on this project’s experimental design, only the receiving antenna was attached to the traversing unit unless further troubleshooting was required. The removal of one antenna did not cause any issues with the communications software. The stationary, unattended unit was protected from harsh conditions such as direct sun, rain, sloughage, etc. using tents and tarps. After activating and verifying the operation of the transmitting unit and its automated script, the traversing unit was then inspected for reception functional before continuing.

Data Collection Procedures

The automated script used on the transmitting unit during communications surveys was programmed to send a standardized text message, which included a transmission timestamp. The fixed message content allowed any changes in message clarity, such as missing characters, to be noted. The signal indicator value was automatically recorded by the error logging protocol integrated into the communications software. Timestamps were also given to each log entry so that the indicator value could be correlated to a specific communication for troubleshooting or analysis. All other data collection was completed manually. Manual data collection primarily focused on location descriptions, observations about the surroundings, and notes on MCS communications. Exact locations were recorded using surface and underground mine maps. Surface surveys additionally implemented a basic GPS location logger for more precise tracking. Notes about MCS communications included message clarity with reception timestamps. When applicable, data regarding delays, equipment malfunctions, unexpected behaviors, and failures of the MCS were documented. Data collection occurred at the following points during each test. A detailed description of the data collection is provided in Table 4.

Data Collection Intervals:

1. Assemble, initialize, and test MCS stationary transmitting unit
2. Assemble, initialize, and test MCS traversing receiving unit
3. Move receiving unit to the first location and wait for automated messages
4. Record data pertinent to the current location
5. Move to the next location and repeat data collection process represented in Steps 3-5

Table 4. Detailed description of data collection procedures for MCS field evaluations.

Step	Description
Assemble, initialize, and test MCS units	After activating the MCS units and the automated transmission script on the transmitting unit, the communications between the transmitting and receiving units were verified. The time at which the MCSs were initialized was recorded along with any pertinent information regarding their status and any complications experienced during the startup routine. At this time, a detailed description of the area surrounding the MCS, such as the presences of power lines, transformers, structures, water bodies, etc., was completed. Details about the type of study to be conducted and the layout of the transmitting antenna were also recorded. The send and receive timestamps as well as the clarity of the test messages for both channels were then noted. Message clarity was classified as clear, with typos, scrambled, or not received. Clear messages were completely comprehensible with no need for interpretation. Messages with typos were comprehensible but required some intuition to compensate for errors in the text. Scrambled messages are completely incomprehensible.
Move receiving unit to receiving stations and record pertinent data	After startup and inspection, the traversing unit was moved to the first receiving location. The arrival time at the first station was recorded along with any pertinent observations regarding natural and anthropogenic artifacts in the vicinity of the receiving antenna, such as the presence of faults, rails, power lines, power centers, bodies of water, etc. The MCS was allowed to receive at least one automated text from each of the two transmission channels. The reception timestamps as well as text clarity were recorded for each channel. If typos were apparent in the text, more time was allotted to determine if the typos were repeated. Clear text did not require additional time. The procedures for moving and data recording was repeated for each subsequent location.

Table 5. Example manual data log entry for MCS location traverse testing.

Time	Description
1000	Surface to underground testing at the Minions Heritage mine: this mine is located in the NAD27 Nevada East state plane zone number 2701. The MSU was set up as the transmitting unit for surface to underground testing. The MSU loop antenna was placed in a large oval in front of a tree line overlooking Rt. 95. The entire length of the transmitting antenna was laid out at this location. A scattered rain storm was present that exhibited periodic downpours and lightening. Sections of the transmitting antenna were located in shallow pools of water because of the rain. The MSU automated script was activated at 1030.
1100	The UGU was brought to UGS 1. UGS 1 was located one break inby the slope near the bottom of the main intake shaft. The entire length of the MGU transmitting antenna was completely unraveled and wrapped around the pillar bordering the main rail travelway. After establishing UGAS 1 for future underground to surface testing, the MGU was placed on a cart to traverse the mine on-foot for the surface to underground survey.
1112	UGS 1: Voice and Text (VT)-11:12:14/11:12:18 (Reception Time/Transmit Time)-Clear. Text-Only (T)-11:12:40/11:12:48-Clear
1114	UGS 2 (Break 15 North Mains 2, Active belt drive and power center nearby): VT-11:14:14/11:14:18-Clear T-11:14:39/11:14:47-Typos

Once text messages could no longer be received from the transmitting unit, two to three more locations beyond the null area were surveyed to confirm signal loss. If communications were re-established at any time, the traverse continued until signal loss could be confirmed. Once a loss of communications was confirmed, several previously surveyed locations were repeated if possible to establish MCS performance precision. The next scheduled test would then be executed.

The data entry logs contained as much detail as practical to facilitate a comprehensive performance evaluation of the MCS. These notes additionally provided a means of reference to identify and correct any discrepancies reflected in the data. An example of a data log entries is provide in Table 5. A summary of the location traverse was also written to provide a brief overview of the main observations made during the study. An example of a summary excerpt is provided in the following paragraph:

Example Summary: The MSU was set up in front of the tree line overlooking Rt. 95. The entire length of the transmitting antenna was laid out in a large oval. A sporadic thunderstorm was present during the setup of the MSU. The first phase of testing was completed on-foot to determine the surface to underground transmission potential from SAS 1. Text-only communications were lost on several occasions as the MGU became further separated from the MSU. Unexpectedly, V-channel communications remained despite the loss of the T-channel. V-channel communications were lost between Breaks 20 and 21 in North Mains 2 despite being located in a zone of strong MSU signal. However, T-channel communications remained at this location. Outside of this zone, V-channel communication returned to full strength.

Common Problems and Contingencies

The MCS is designed to be simple, self-contained system with as few components as possible. The majority of hardware failures can be prevented if care is taken during set up. Software problems are, however, much more prevalent in comparison because of the reliance on a laptop computer to function as the primary UI. The MCS laptop used throughout this project was installed with a commercially available version of Windows 7. The MCS communications software was a Java based program that executed in the Windows 7 environment. As such, the operation of the MCS could be hindered from any software failure inherent to this operating system. Fortunately, many of the software issue, such as a nonresponsive UI, could be remediated by restarting the system. Table 6 outlines common issues and corrective steps. Challenges that were encountered outside of the MCS hardware, such as unforeseen administrative and logistics issues are not covered.

Table 6. Common problems and contingencies for the MCS.

Description	Causes	Solutions
Loss of signal from the transmitting unit	Under normal conditions, the MCS signal will eventually be lost when the ultimate transmission range is reached. This normal signal loss is indicated by a sudden lack of received messages during expected intervals. However, a loss of signal under other circumstances, such as within direct line-of-sight to the transmitter, usually indicates a problem. such as from a frozen UI or a hardware fault.	Check the battery status and the error log. If the battery voltages are outside acceptable tolerances, ± 3 V, replace the batteries. If the error log cannot be accessed and the UI is unresponsive, then restart the laptop. If the error log can be opened, determine if status updates occurred on expected intervals. Restart the laptop if the error log is not updating correctly. Any hardware fault displayed in the error log should indicate the location of any fault (e.g., transmitter error). In this case, check the connections of the faulted component for fit and tightness.
Antenna error	An antenna hardware fault is usually caused by a cable misconnection or disconnection.	Check hardware connections from the transmitting and receiving antennas. If the hardware connections are correctly installed, disconnected and examine the connectors for any damage.
Communications software is unresponsive	UI unresponsiveness is usually caused by a software fault, which can result from a number of problems. Most software faults are not serious.	Restart the laptop in the case of a software fault. If the restart does not solve the UI's unresponsiveness, inspect the hardware and operating system to identify the root cause.
Unexpected power system failure	A rapid loss of power may result from a faulty battery, a loose connection, or an incomplete charge.	Once the source of the power loss has been determined, replace the battery. If a new battery does not reinitialize the MCS, check all battery connections.

ECS Test Procedures

Overview

Field tests of the ECS were conducted at various underground mine sites to determine the operational sensitivity this system to anthropogenic and environmental conditions as well as to antenna configurations both following and contrasting the manufacturer's recommendations. Real-time, two-way communications were examined at these field studies. The unpredictable accessibility of survey locations and the irregular availability of mine personnel at the field sites prevented the implementation of a formal experimental design. As a result, the format of this project was an observational survey in which a formal experimental design was not required. A non-experimental design was utilized to examine the behavior of the ECS.

Given the project objectives, this non-experimental design was ideal because the majority of experimental variables could not be controlled. The basic structure of the observational TTE evaluation utilized a stationary site and a mobile receiving site. The mobile unit was moved to various accessible locations. Observations and pertinent data recorded at these locations were used to determine the communications performance of the ECS. Details regarding the execution of the ECS field tests can be found in sections that follow.

Instrumentation

Two ECS surface units were utilized for this project. The ECS is designed for two-way TTE communication during a mine emergency event. This system is able to send only text messages using a proprietary encoding scheme. The text messages are predefined and are selected from a multiple choice list using a touchscreen, which is located in the center of the control panel. The content of the text messages cannot be customized in real-time. The encapsulated nature of this system is designed to maximize operational simplicity for high stress situations. As a result, the fully automated nature of message transmission and reception prevents any system modifications other than what is available through the touch panel interface. Additionally, no user accessible quantitative data regarding message transmission or reception is produced by this system. The ECS is available in both surface and underground-permissible configurations. Both the surface and the underground units are highly mobile and can be rapidly deployed in a variety of environments.

The ECS produces an omnidirectional broadcast utilizing two separate antenna arrays composed of multiple, interconnected grounded metallic rods or similar metallic structures by inducing a current within the Earth. The antenna arrays, or grounding beds, are connected in parallel to the ECS. A conceptual diagram of an ECS utilizing two grounding beds with four grounding rods per bed is displayed in Figure 2. The manufacturer provides some broad recommendation for deployment. These guidelines simply state that each bed should be constructed from four friction fitted copper grounding rods. The inter-rod spacing within each bed and the separation distance between each bed is recommended to be at least 1.2 m (4 ft.) and 45 m (150 ft.), respectively. The antennas can either be pre-installed or constructed as-needed at any location with sufficient space to accommodate the beds. If copper grounding rods are not available, the antenna beds can be composed of other metallic structures such as roof bolts, rails, or belt structures.

Experimental Design

The ECS field evaluations were completed using a survey of two-way communications between surface and underground locations. As previously described, the field team consisted of two to three researches and enough mine employees to satisfy applicable mine company policies and government regulations. No mine personnel were required to help manipulate the equipment or to assist in the data collection. The mine provided hazard training along with any additional required training or supplies to the investigators. Access to the field site's communication systems was also furnished to allow reliable communications between the investigating teams. All field study instrumentation and researcher PPE were furnished by the investigators. Other assistance needed from the mine, such as providing advice about selecting transmit locations, was kept to a minimum. Multiple locations were tested on both the surface and the underground to evaluate ECS performance. The order by which the individual locations were tested at each site was scheduled in a manner that minimized the impact on normal mine operations. A detailed description of the major tasks in the ECS evaluation is presented in the following sections. The basic execution of an ECS field survey is summarized by the following steps.

8. Identify suitable test locations for the ECS
9. Set up and initialize the ECS units at the selected transmit location
10. Verify the functionality of the ECS units
11. Commence location traverse of selected areas
12. If more testing is scheduled, repeat the aforementioned procedures for the new locations

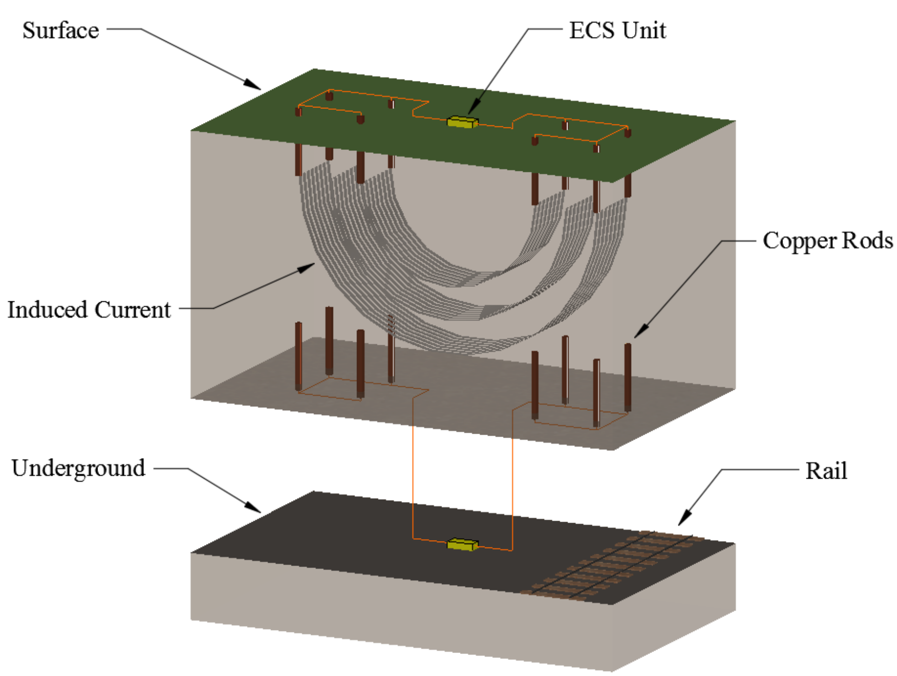


Figure 2. Conceptual diagram of an ECS deployment scenario. The underground and surface ECS units are connected to two grounding beds each composed of four copper grounding rods. An option is also available to utilize the adjacent rail as an underground grounding bed. The induced current produced by the ECS is also represented.

Survey Description

A surface unit and an underground unit were used to evaluate two-way communications. Each test qualitatively evaluated the ability of the ECS to establish communications using a variety of antenna combinations using both the manufacturer's recommendations and available grounded metallic infrastructure. ECS testing required the use of two separate teams, a mobile team and a stationary team, because of the inability to automate this system. The mobile team was responsible for moving an ECS unit to various pre-determined locations and for installing any necessary antenna infrastructure as dictated by the desired test. The stationary team remained at a single location throughout the study and was responsible for monitoring incoming messages as well as connecting the unit to different antenna configurations.

Once the teams arrived at their designated locations, any required antenna structures, such as grounding rods or friction fitted bolts, would first be identified or installed. Depending on the requirements of the scheduled test, no antenna installation may have been necessary. In this case, the ECS would be connected to the existing grounded metallic structures. Connections to the antenna beds were made through metallic clamps. These clamps also allowed the interconnection of the separate antennas within each bed to create an array. Before activating the ECS, the continuity between the antenna beds was checked to determine if a short circuit was present. If the two beds showed continuity, the problematic antenna configuration would be noted, and the ECS would be connected to the next planned antenna configuration. The same procedure was applied to both ECS units.

After establishing both ECS units, the mobile team first sent a message to the stationary team. Messages were always initiated from the mobile unit to ensure consistency. Once a message was received from the mobile unit, the stationary team was then contacted using the mine's communication system to determine if the message was either received or not received. Regardless of the message's status, a reply was sent from the stationary unit so that the directionality, one-way, two-way, or not received, and the range of the applied antenna configuration could be determined. This process was repeated with a variety of antenna configurations at both locations. The mobile unit was then moved to the next location once all practical antenna configuration combinations between the two ECS locations were exhausted. ECS testing continued in this manner until all scheduled test locations were visited.

Along with any pertinent observations about the surrounding area, such as the presence of high voltage artifacts, significant geologic formations, and antenna connection details, such as composition, separation distances, etc. The resistance outputted by the ECS was also recorded for each transmission. This value is produced from an automated diagnostic program specific to the ECS unit utilized in this project. The resistances, as previously discussed, are proprietary to this system and were used only to provide a general sense of antenna connection quality.

ECS Unit Deployment

As previously introduced, the ECS UI, power supply, and communications hardware are encapsulated in a single component. Two ECS surface model units were used to conduct the TTE field studies. One ECS was permanently assigned as the underground unit (EGU) while the other ECS was permanently assigned as the surface unit (ESU). No customizations were made to the EGU because both permissible and non-permissible ECS units utilize the same power output specifications. The only functional difference between these two units is the explosion proof case that is used to protect the internal circuitry of the permissible unit.

In order to connect the ECS units to various antenna structures, a series of metal clips interconnected by a single wire and extension wires were used. An inventory and a brief inspection of the ECS equipment was completed prior to operation. All major components were checked for any substantial physical wear and functional abnormalities. An itemized description of ECS components is provided in Table 3. The assembly process for the ECS was very simple and required three connections to be made. These connections are the clips to the two antenna grounding beds and the clip cables to the ECS control unit. A detailed description of these steps is provided as follows.

9. Identify and determine the layout of the ECS based on available space, obstacles, hazards, sources of interference, and impact on mine operations
10. Secure and connect the control center to one of the antenna beds
11. Inspect the cable connections using a multi-meter to ensure continuity between the control center and the antenna structures
12. Secure and connect the control center to one of the antenna beds
13. Inspect the cable connections using a multi-meter to ensure continuity between the control center and the antenna structures; at this time, also ensure that no continuity is present between the beds (i.e., short circuit)
14. Activate the ECS unit and send a test message
15. Verify that the ECS is operating within expected parameters and that the unit registers an adequate connection to the antenna beds

Table 7. ECS component list and descriptions.

Component	Description
Control Unit	This component is contained within an impact and abrasion resistant metal case. The control panel holds the touchscreen UI, power supply, and communications hardware. The antenna beds are connected to the control panel using a quarter-turn locking connector cable.
Antenna Cables	A series of cables that were not provided with the ECS units were used to interconnect antennas within each bed and to connect the grounding beds to the control unit. The majority of field studies utilized two 3 m (10 ft.) cables containing four metal clips attached in series with a clip to clip separation distance of 1.2 m (4 ft.) and two 15 m (50 ft.) extension cables per unit. The clips were used to interconnect suitable metallic structures to create the antenna array or grounding bed, which would in turn be attached to the ECS unit. The extension cables were used as-needed to reach certain antenna beds.

Data Collection Procedures

All data collection was completed manually and focused on location descriptions, observations about the surroundings, antenna installation details, and notes on ECS communications. Exact locations were recorded using surface and underground mine maps. Notes about ECS communications included antenna resistances, timestamps, and message directionality. When applicable, data regarding delays, equipment malfunctions, unexpected behaviors, and failures of the ECS components were documented. The data entry logs contained as much detail as practical to facilitate a comprehensive performance evaluation of the ECS. These notes also provided a means of reference to identify and correct any discrepancies reflected in the data. An example of a data log entries is provide in Table 5. A summary of the ECS survey was also written after the completion of a field study to provide a brief overview of the main observations made during a study. An example of a summary excerpt is provided in the paragraph following Table 5.

Table 8. Example data log entry for ECS communications testing.

Time	Description
1100	The EGU was set up at UGS 1, which was located one break inby the slope adjacent to the bottom of the main intake shaft. The first grounding beds were installed perpendicular to the main rail travelway with a separation distance of 30 m. Both grounding beds were composed of four, 4 ft fully grouted resin bolts with an inter-bolt separation distance of 4 ft. The EGU initially showed no connection to the grounding beds. After inspecting the cable, a break was located in one of the extensions. The damaged cable was repaired at 1130 and reconnected. The following tests were conducted with this antenna configuration. 1. 1145-Sent ping: 846.50, 1.35 W; Ping received on surface, Response from surface received 2. 1200-Sent ping: 841.75, 1.34 W Ping received on surface, Response from surface received
1220	UGS 1: EGU connected to belt structure and 4 ft fully grouted resin bolts with 80 ft of separation. Belt structure and resin bolts were perpendicular to the main rail travelway. 1. 1230-Sent ping: 249.38, 4.31 W Ping received on surface, Response from surface not received 2. 1240-Sent ping: 229.42, 4.49 W Ping received on surface, Response from surface not received
1300	UGS 1: EGU connected to 10 ft partially grouted cable bolts and 4 ft fully grouted resin bolts with 70 ft of separation. Cable bolts and resin bolts were perpendicular to the main rail travelway. 1. 1310-Sent ping: 843.25, 1.32 W Ping not received on surface, Response from surface not received 2. 1320-Sent ping: 839.00, 1.34 W Ping not received on surface, Response from surface not received

Example summary:

The main travelway between the bottom of the slope and Crosscut 84 in South Mains No. 1 was evaluated to determine the extent of ECS communication between the surface and underground from the supply yard to the north of the mine office. Various antenna configurations composed of metallic structures that were easily accessible in this area of the mine were utilized to determine their effect on ECS performance. The surface antennas were installed using two beds of 4 ft copper grounding rods. Underground antenna configurations included belt structure, 4 ft fully grouted steel rib bolts, 6 ft fully grouted steel roof bolts with mesh, and 3 ft friction fitted steel rib bolts. Communications were limited using all combinations of antenna configurations to within five breaks of the slope bottom.

Common Problems and Contingencies

The ECS is designed to be simple, self-contained system with few components. Given the encapsulated nature of the UI, software problems are expected to be rare and were in fact not encountered during the course of the ECS field tests during this project. Hardware problems, which came mostly in the form of poor electrical connections, were encountered throughout testing. However, the majority of hardware problems could be remediated through a systematic continuity test of all electrical connections. Table 9 outlines common issues and corrective steps that resolved problems encountered during ECS testing. Challenges that were encountered outside of the ECS hardware, such as unforeseen administrative and logistics issues are not included.

Table 9. Common problems and contingencies for the ECS (Continued on next page).

Description	Causes	Possible Solutions
High antenna bed resistance	The resistance of the antenna beds can be excessively high at time. This scenario was generally the result of either a poor electrical connection between the ECS and the antenna structure. However, the high resistance was also frequently observed to be an inherent property of the antenna configuration being examined.	All antenna structures were thoroughly cleaned to remove dirt, debris, rust, and any other particulate that may insulate against electrical continuity. If no improvement is reflected by the ECS resistance value, then the connection quality was noted and the next antenna configuration was implemented.

Table 9. Common problems and contingencies for the ECS.

Description	Causes	Possible Solutions
0 Ω antenna bed resistance	A 0 Ω antenna resistance reading from the ECS indicates that a poor connection exists between the ECS and one or both antenna beds. Common causes for this issue are as follows: a loose electrical connection is present, a cable is damaged, the strata in which the antennas are installed insulates against current induction between the grounding beds, the ECS system is malfunctioning, or a combination of these aforementioned causes.	First verify the functionality of the ECS using the supplied unit-to-unit test apparatus. If the malfunctioning ECS unit does not have access to another ECS unit or the test apparatus, then a systematic continuity check of the antenna connections and cables can be completed. Examine the electrical continuity between the antenna structures and the clips. If no continuity is present between the antenna and the clip, then clean the suspect antenna structures of dirt, debris, rust, and any other particulate that may insulate against electrical continuity. Once continuity between the antenna structures and the clips is either restored or verified, the electrical continuity between the cables and ECS can then be examined. In the majority of cases, a 0 Ω indicates a loose connection or damage to one of the cables. If electrical continuity between the antenna structures and the ECS through each cable is verified, then the insulation properties of the strata likely prevented an adequate electrical connection between antenna beds. In this scenario, change either one or both of the antenna beds, depending on the available antenna materials at the test location. If no subsequent antenna configuration produces an adequate connection, move the ECS to a different location in the vicinity. If the connection issue persists at the next location and the ECS unit has been inspected using the test apparatus, move the ECS to the next test location or discontinue ECS testing multiple locations have already been unsuccessfully visited.

Detailed Testing Procedures for Recurrent Site Conditions

Belt Structure, Rail, and Large Section of Support Mesh

MCS Objective

Long metallic conductors have been shown to allow the propagation of MCS communications across significant distances that exceed its rated transmission range. This phenomenon has the potential to enhance the effectiveness of the MCS during a mine event. The long metallic conductor effect is, however, not well understood. The purpose of the following series of experiments was to determine the performance of the MCS in the presence of different types and configurations of belt structure, rail, and support mesh. These tests were designed to determine the extent to which TTE transmission ranges were extended, if at all, at the examined field sites. Additionally, the effect of transmitting antenna deployment positions relative to rail on TTE communications were also evaluated. Orientation effects on belt structure and mesh were not specifically tested. The following section provides details regarding how this assessment was executed. Depending on the specific conditions and constraints present at each testing location, some of the following evaluations may have been be omitted or modified.

ECS Objective

Long metallic conductors were not expected to impact the performance of the ECS. However, the use of such structure as antennas have been shown to produce significant transmission ranges. This enhancing effect has the potential to extend the effectiveness of the ECS during a mine event. The enhancing effect of long metallic conductors on ECS transmissions is, however, not well documented. As a result, an evaluation of long metallic conductors was used to determine their effect on ECS communications. These tests were used to determine the extent to which TTE transmission ranges were extended, if at all, when utilizing belt structure, rail, or mesh as antenna beds at different field sites. Details regarding these tests are included in the Antenna Configuration section presented later in this chapter.

MCS Execution

The MCS long metallic conductor evaluation was carried out both underground and on the surface. In the context of rail examinations, two types of relative positioning were specifically examined. These positions were bisecting deployment and paralleling deployment. These antenna placements were used to determine the effect of antenna position relative to the rail on TTE transmissions. The bisecting deployment was achieved by laying the transmitting antenna in a manner that allowed the rail to divide the antenna into two separate, equal parts. An exact bisect of the loop antenna was not achievable in all cases because of field conditions. This issue was especially prevalent with underground rail because of space limitations. In these situations, the bisection of the antenna with the rail was approximated according to the conditions present. The parallel deployment was achieved by laying the transmitting antenna next to the rail such that no part of the rail was located within the internal area of the loop. These relative position tests could not be practically applied to either belt structure or mesh.

Potential transmitting locations that had proximal access to belt structure, rail, or mesh were selected. These locations were generally free from traffic, readily accessible, and contained sufficient space to accommodate the MCS loop antenna. Surface to underground and underground to surface communications were primarily examined with some instances of underground to underground tests where possible. Once the MCS was installed at the transmitting location, two types of location traverses were executed. These traverses were a general survey and a propagation survey. A general survey traversed locations away from the long metallic conductor understudy to determine the range of MCS communications around the transmitter. These tests were designed to elucidate the native broadcast radius of the MCS without propagation enhancement. A propagation survey was then carried out to determine the extent of any signal propagation enhancement along the target long metallic conductor.

The propagation survey required the use of a vehicle that could carry the receiving MCS unit to various points along the metallic conductor both underground and, if applicable, on the surface. Depending on the performance of the MCS, the receiving locations could be widely spaced to accelerate the speed of the traverse. A detailed, tightly spaced traverse was conducted when MCS transmissions were no longer received to define the outer communication boundary. At each of the selected receiving locations, the antenna was removed from the vehicle and placed on the ground for data recording. Several previous receiving locations were re-visited after the loss of MCS transmissions to determine the degree of repeatability.

The manner in which the transmitting antenna was set up, oval, reduced circumference circle, etc., was maintained for both survey types to ensure consistency. If the antenna was moved, a close approximation of the original shape was attempted. Any noticeable discrepancies between deployments were recorded. If any unusual or interesting behaviors were observed from the MCS during a test, the same transmitting location and surveys were repeated to confirm observations. Comprehensive underground and surface testing was not always possible because of site-specific circumstances, such as administrative challenges, equipment failures, changes in environmental conditions, etc.

EM Interference Sources (Charged or Conductive Features)

Objective

The MCS and the ECS, similarly to the other radio based communications systems, are subject to electromagnetic (EM) interference. TTE communications may be adversely affected by both high and low powered EM sources such as atmospheric anomalies, high voltage mining equipment, diesel powered mining equipment, power cables, transformers, breakers, and substations. The omnipresent nature of EM interference sources at mine sites could potentially reduce the effectiveness of TTE systems a mine emergency. Given the infancy of modern TTE communications technology, the exact effect of EM interference on TTE transmissions is not well understood. The purpose of the following series of experiments was to determine the performance of both the MCS and the ECS in the presence of both anthropogenic and natural EM interference sources found in and around underground mines. The following section provides details regarding how these assessments were executed. Depending on the specific conditions and constraints present at each field test location, some of the following studies may have been omitted or modified.

Execution

Atmospheric anomalies, such as electrical activity in the ionosphere and lightening, are examples of naturally occurring radio interference sources. Ambient EM interference is always present because of the electrical charge in the atmosphere. The intensity of background EM fluctuates throughout a day and also shifts from season to season. In contrast, lightening, which follows storm activity, is intermittent, unpredictable, and can greatly vary in intensity depending on conditions. Highly active electrical storms may have a significant impact on TTE communications given the usual proximity of such activity to the ground. Adverse effects from atmospheric anomalies, which normally affects only skywave transmissions, are expected to be limited for TTE communications because of their location at high altitude. However, atmospheric anomalies that appear in lower layers of the atmosphere may potentially cause some interference for TTE transmissions.

Atmospheric anomalies were not directly examined because a long term set up of the MCS and the ECS would be needed to examine their impact. The design of both TTE systems prevented the complete automation of communications testing. As a result, only significant, reportable occurrences. The impact of storms on both systems was examined opportunistically. Surveys of a field site were not specifically scheduled based on weather predictions. In the event that a storm was expected, the MCS and the ECS were set up in a manner that protected the units from moisture, wind, and debris.

High voltage anthropogenic artifacts are known to produce sufficient levels of EM activity to interfere with radio communications. The extent to which communications are effected, however, is unpredictable in the majority of cases because of the varied nature of this form of interference. Possible sources of EM interference include transformers, high voltage switches, power centers, power lines, substations, high voltage equipment, belt drives, fan motors, and hoist drives. A formal test of each interference source was not conducted given the number and the diversity of these artifacts. Instead, high voltage infrastructure was tested as it was encountered during the course of a survey.

EM interference sources were examined to varying degrees of detail depending on the observed effect from an artifact and the TTE system being utilized at the time of the test. Once encountered, testing of EM interference sources was conducted as follows. For the MCS, the receiving antenna was placed in close proximity to the artifact. Several transmitting unit message cycles would then be allowed to elapse to determine the impact of the artifact. Some EM sources, such as power lines, were located overhead. In these situations, the receiving antenna was placed directly under the EM source. If clear communications were received on both channels, one to two additional positions were tested around the artifact in the same manner. If no noticeable change in MCS communications was observed, the survey continued as planned until the next EM source was encountered.

The ECS required in-place antenna infrastructure to be available at setup locations. During certain tests, antenna structures could be installed, but even in these cases, acceptable setup locations were limited. As a result, EM artifacts were not examined in detail because of the essentially fixed nature of ECS installations. Instead, the presence and type of any EM source in the vicinity of the ECS installation was noted as well as any observed effects on ECS communications. Given the restriction of the ECS, detailed examination of EM sources was only conducted during MCS testing.

If the MCS exhibited significant changes in quality or signal strength, a detailed survey of the interference source was completed. In a detailed survey, multiple points located radially around the interfering artifact was surveyed across various depths from the source to determine the extent of the interference. Data collection proceeded according to general survey procedures with the addition of detailed observations about the interference source. These details included the type(s) and design of the artifact(s), the location of surveyed points relative to the artifact, the electrical properties of the artifact, as well as any other pertinent qualitative or quantitative characteristics. The detailed survey continued until the extent of the interference was defined.

EM sources are generally installed in clusters of many different individual systems, which created the possibility of sympathetic interference. During the course of a detailed survey around an EM source, paths towards nearby high voltage artifacts were also tested to reveal any such effects. If the interference continued to be significant toward and around adjacent artifacts, then a detailed survey was also conducted for any new EM sources. Detailed surveys continued until the outer boundary of the interference was identified.

Geologic Features

Objective

TTE communications are challenging because radio signals are subject to drastic attenuation as they travel through solid strata. Both the severity of attenuation and the path of propagation are directly impacted by the physical and petrographic characteristics, mineral compositions, metamorphic properties, and water infiltration levels of the strata. These characteristics are unique to each mine site and could potentially affect the performance of the MCS and the ECS differently depending on the combination of geologic conditions. Given the infancy of modern TTE communications technology, the exact effect of geologic features on TTE transmission is not well understood. The purpose of the following series of experiments was to determine the performance of the MCS and the ECS in the presence of notable geologic artifacts found in the overburden. The following section provides details regarding how these assessments were executed. Depending on the specific conditions and constraints present at each field test location, some of the following studies may have be omitted or modified.

Execution

TTE signals have the ability to propagate through significant thicknesses of solid strata because they utilize VLF waves. As a wavelength's size becomes significantly larger than an obstacle, its ability to both penetrate through and diffract around that obstacle are enhanced. This property gives TTE communications a greater ability to penetrate overburden than conventional radio technologies. For this reason, minor changes in stratigraphic properties will not significantly affect TTE communications. The majority of geologic formations can thus be somewhat generalized across field sites. Communications will mostly be affected by shifts in the electrical properties of the strata, such as conductivity and resistivity. Similarly, faults and igneous intrusions are not expected to drastically affect the performance of TTE communications.

The presence of water and significant voids, such as those created by sealed mine workings, may interfere with TTE communications. Areas of this type have steeper variations in electrical conductivity relative to the surrounding strata. As a result, some field tests specifically examined the effect of water and voids on MCS and ECS communications. A detailed survey of other geologic formations occurred only if either the MCS or the ECS was unexpectedly affected by a void of other similar source of interference. Otherwise, no formal testing was purposely planned for examining generic stratigraphy.

The locations of known water inundations, such as flooded voids, porous sedimentary deposits, ponds, and old mine workings, were identified with the assistance of mine personnel. Surveys of these identified locations were attempted when possible. As previously discussed, generic stratigraphy was tested opportunistically during the course of a general location survey. For the MCS, only the receiving unit was used to test the effects of these artifacts by placing the unit in the vicinity of the formation as well as at different points around, if possible, the target artifact. Detailed examinations of geologic conditions were only performed using the MCS, which is described later in this section. ECS testing, given the essentially fixed nature of the antenna installations, was conducted by orienting an artifact between the surface and subsurface unit locations when possible. During some ECS tests, one of the units could be installed in an area that contained an artifact. In this case, the presence of the feature and any obvious effects were noted. Given the semi-fixed nature of the ECS, targeted testing was only performed with the MCS.

Each geologic artifact was examined to varying degrees of detail using the MCS depending on the extent of the observed effect. The testing of water inundations, voids, and pertinent formations were generally conducted as follows. Once a source was encountered, the receiving antenna was placed near the feature. Several automated transmissions were then captured from the transmitting unit. If a clear text was received on both channels, one to three additional positions were chosen to encompass the artifact for testing. If no noticeable interference was observed, the location survey continued to the next receiving location until another geologic feature was encountered. Should the communications exhibit noticeable changes in quality or signal strength, a detailed survey of the artifact was conducted. Multiple points following a radial grid pattern around the artifact were surveyed, if possible. Data collection included the recording of additional details regarding the type of geologic feature, the location of the feature, and any other pertinent characteristics. The detailed survey continued until the extent of the interference was defined.

Metal Structures

Objective

TTE communications systems, similarly to the other radio based communications systems, are subject to interference from highly conductive objects. MCS and ECS communications may be adversely affected by large metallic structures, such as support beams and structural frames. The omnipresent nature of conductive interference sources at mine sites could potentially impact the effectiveness of TTE communications. Given the infancy of modern TTE communications technology, the exact effect of metallic structures on TTE transmission is not well understood. The purpose of the following series of experiments was to determine the performance of the MCS and the ECS in the presence of these interference sources. The following section provides details regarding how these assessments were executed. Depending on the specific conditions and constraints present at each field site, some of the following studies may have been omitted or modified.

Execution

Metallic structures are known to interfere with radio communications. The extent to which TTE communications are affected by metallic structures is, however, largely unknown. Possible sources of interference include metal framing, metal sheeting, etc. A formal, planned test of each interference source was not necessary because such structures appear frequently in and around underground mines. As a result, any significant metallic structures were tested as they were encountered during the course of a survey. Each potential interference source was examined to varying degrees of detail depending on the observed effect. Most metallic structures were not expected to affect the quality of either MCS or ECS communications. The highest interference potential would be in areas that contained tightly woven metallic structures that surrounded a MCS or an ECS unit.

For the MCS, when a significant metallic structure was encountered, the receiving antenna was placed in the center of the structure. If clear communications were received on both channels, no further testing was required. The presence of the structure was noted for future analysis. The location survey would then continue to the next location until another metallic structure was encountered. If the received communications exhibited noticeable changes in quality or signal strength, a detailed survey of the structure would be conducted, if possible. Multiple points located within and around the suspect structure were surveyed to determine the extent of the interference. Data collection included the additional recording of details regarding the design, location, and composition of the structure. The essentially fixed nature of ECS installations prevented detailed testing of metallic structures. As a result, the presence of significant artifacts of this type were noted along with any discernable effects on ECS communications.

Antenna Configuration

Objective

The MCS and the ECS are both functionally limited by the design of their antennas. In terms of the MCS, the installation of the loop antenna was challenging because of its size. The recommended method of installation for the loop antenna is to fully lay the 120 m (400 ft) length of the antenna in a perfect circle. This deployment requirement is derived from the principle that the effectiveness of a loop antenna is linearly proportional to the magnitude of its enclosed surface area. A perfect circle maximizes the internal area of a loop antenna, which will theoretically optimize radio transmissions. Based on this principle, the second most optimal antenna deployment layout is a square followed by an equilateral triangle. Even under ideal circumstances, the installation of the MCS loop antenna using the recommended layout is difficult. In many cases, this manner of deployment may not be possible because of physical obstructions and terrain variations. The MCS antenna experiments were used to determine the effect of various loop antenna layouts on communications.

The ECS is an E-field device and thus utilizes two antenna beds electrically connected in parallel to induce a current through the Earth. The guidelines for antenna bed installation are generic and contain only broad recommendations for the size and material of the antenna conductor as well as the separation distance between the antenna beds. However, the manner in which TTE communications are generated by the ECS allows the use of any grounded metallic structure, such as roof bolts and rail, as an antenna bed. The performance of the ECS is directly related to the quality of the grounding connection and the electrical connection between beds through the strata. The ECS antenna configuration evaluations were used to determine the optimum antenna bed configuration. The following section provides details regarding how the MCS and the ECS assessments were executed. Depending on the specific conditions and constraints present at each field test location, some of the following studies may have been omitted or modified.

MCS Execution

The deployment quality of the transmitting antenna is known to affect the performance of MCS communications. The extent to which TTE communications are affected in this manner is, however, largely unknown. The design of the loop antenna allows for many layout variations, which were opportunistically tested throughout this project. When non-ideal layouts were utilized because of obstacles or other such constraints at transmitting locations, they were noted along with any unusual effects on MCS communications. Details describing the manner in which the antenna was placed, the surrounding conditions, and the reason for the non-ideal layout were also recorded. The performance of the non-ideal layouts was then compared with other loop antenna deployments to determine their impact on communications performance, if any.

Formal evaluations of loop antenna layouts were also carried out when practical. In these tests, a suitable location was identified. Underground and surface locations that were easily accessible and allowed for the vertical alignment of the transmitting and the receiving antennas between underground and surface unites were selected. These locations also had sufficient space for a full deployment of the loop antenna in a manner that conformed to the manufacture's recommendations. After the MCS units were set up, underground to surface one-way transmission were used to examine the effect of antenna layouts.

The ideal antenna layout was first examined to serve as a basis for comparing the non-ideal layouts of the loop antenna. After the baseline test was completed, the loop antenna was modified to represent various practical, non-ideal designs. These layouts included ovals, decreased diameter circles, squares, irregular polygons, squares, suspended patterns, figure eights, etc. The same receiving location used for the baseline test were repeated for each antenna layout both on the surface and underground. Surface to underground communications were not tested during formal antenna evaluations because of surface location constraints.

ECS Execution

After setting up both ECS units, a qualitative evaluation was used to determine the effect of different antenna configurations on the ability of the ECS to establish two-way communications. Two separate teams, one for each ECS unit, were employed. One team was responsible for moving the subsurface unit to various locations and for applying different antenna configurations. The remaining team remained stationary at a pre-defined location throughout the test. The stationary team was also responsible for connecting its unit to assorted antenna configurations. In addition to observational data, the teams recorded quantitative resistance and power data displayed by the ECS units for each transmission.

These quantitative values were used to evaluate the quality of each antenna configuration in a general manner as well as to identify any poor electrical connections. As previously discussed, the ECS can accept a variety of grounded metallic structures, such as roof bolts, belt structure, and rail, as antennas. All available combinations of accessible antenna materials were examined between the mobile and stationary locations. Depending on observed performance of the ECS and the conditions present at the time, some antenna configurations may have been omitted.

Messages were always initiated from the mobile ECS unit to ensure consistency. Once a message was transmitted, the stationary team would be contacted using the mine’s communication system to confirm receipt. Regardless of the message’s status, the stationary unit would then respond to determine whether the communication was one-way, two-way, or not achieved. This process would then be repeated with a variety of antenna configurations at both locations. Once all practical antenna material combinations were exhausted, the subsurface unit was moved to the next testing location.

5.0 Summary of Accomplishments

A combination of theoretical background research, computer simulations, and field studies were implemented to perform a comprehensive evaluation of commercially available TTE technologies. Five formal tasks were defined to fulfill project objectives, which are summarized in the Research Approach chapter. The following chapter provides an overview of significant accomplishments produced through the completion of these tasks and the three project aims: Identification of Performance Factors, Performance Testing and Evaluation, and Operational and Planning Recommendations. A detailed summary of project results including theoretical research, geophysical simulations, and field studies is addressed in this chapter.

Task 1 and the Theoretical Factors Report represents the majority of the theoretical research conducted during this project. This information supplied the background knowledge needed to design simulations and field studies that would effectively achieve project goals. The Theoretical Factors Report is provided in the Introduction of this report to establish a cursory background for the presented content. A number of model scenarios approximating the test sites and their geologic profiles have been generated using multiple deployment scenarios have been processed. A database of model results is accessible on anodyne.unm.edu/TTE. The database is set for future researchers to examine spatial dependence, parameter studies, etc. The geophysical simulations can be found as databases and will be made available at https://data.lib.vt.edu/, which forms the final deliverable for this task. A general description of the modeling technique, database, and results are provided at the conclusion of this section.

Task 2 and the Test Procedures Report was completed to provide a standard protocol from which field studies were executed. Although each field study contained some unique elements resulting from the dynamic nature of underground mines, the basic execution and data collection procedures remained consistent throughout the project. This report is provided in the Research Approach chapter and contains sufficient detail regarding the field testing procedures utilized in this project for future replication, if desired. Tasks 3 and 4 represent the actual field evaluation of the TTE systems and field report summaries generated for dissemination to the mining community. The results of these field studies organized by field site are summarized in the Field Study Results chapter. Task 5 defines the final deliverables from this project. A complete listing of published materials and future manuscripts is provided in the Dissemination Efforts and Highlights chapter. The TTE Performance Tables and an overall summary of project finding are provided in the Conclusions and Recommendations chapter.

Field Study Results

Field Site A

Introduction

The following section contains an overview of the MCS field conducted at an underground retreat room and pillar mine in Easter Kentucky. This study location will be referred to as Field Site A in this report. A detailed overview of this field site can be found in the Research Approach chapter. No ECS testing was conducted at Field Site A because this unit had not yet been acquired. Underground to surface and surface to underground communications were examined at Field Site A. Signal indicator values that fell between -20 and -90 could be received by the MCS at this field site. All designations utilized in this section are specific to Field Site A and do not relate to other similar or identical labels mentioned in other sections. Figure 3 displays a map of the loop antenna transmitting stations both underground and on the surface. A map of the mine overlying Field Site A is also displayed in this figure. All reported transmission distances are point to point distances and not projected distances onto a horizontal or vertical plane.

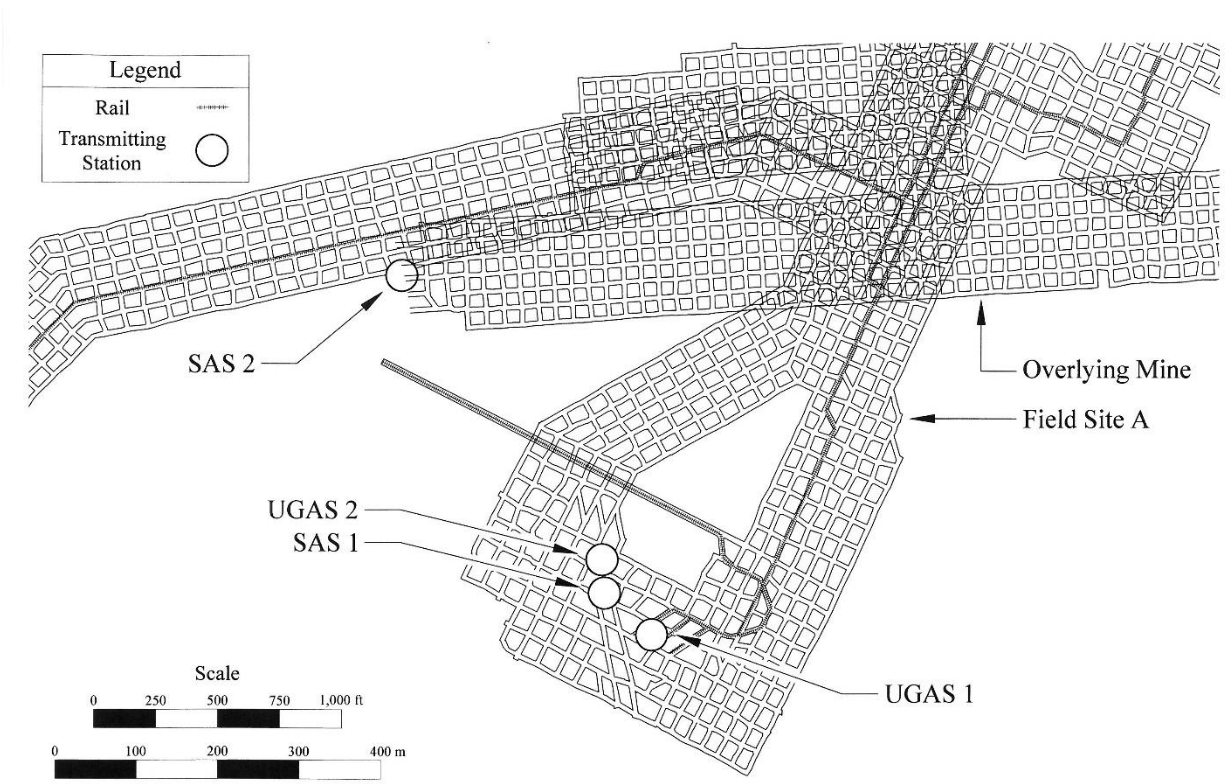


Figure 3. Map of Field Site A displaying the underground and surface transmitting stations used to evaluate MCS communications.

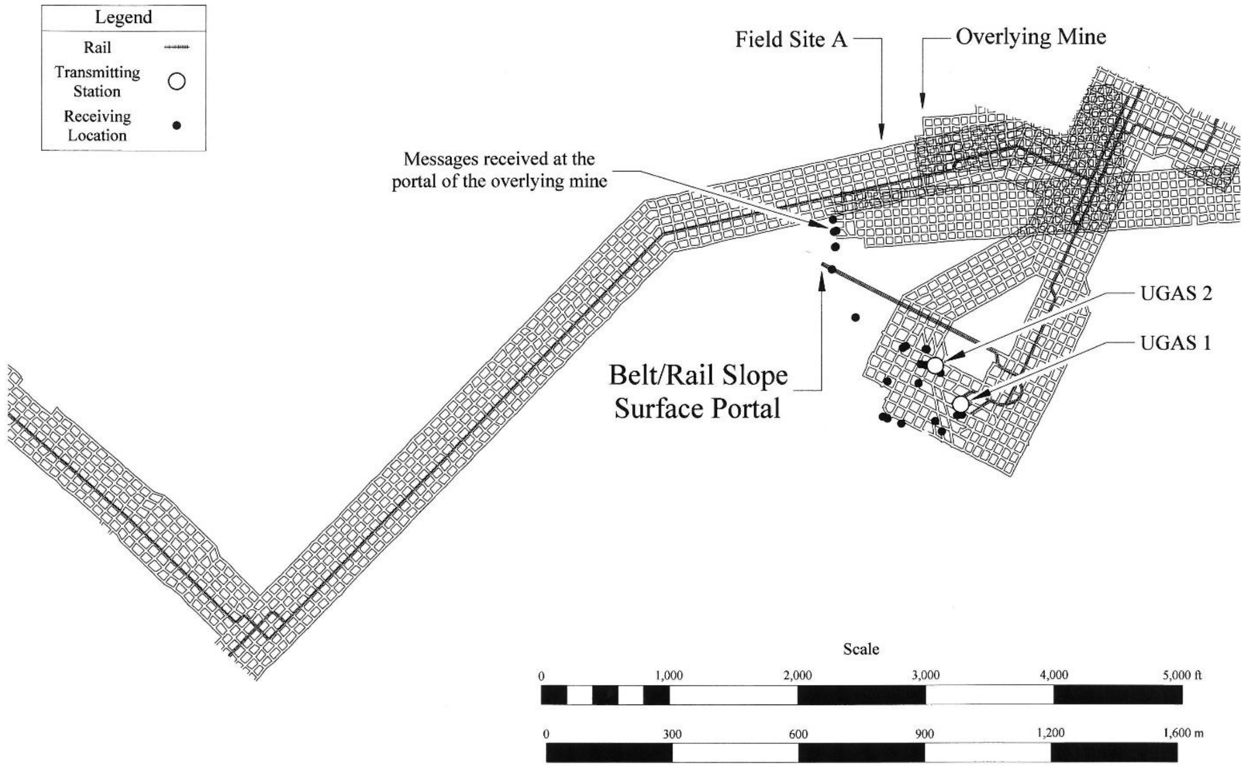


Figure 4. Map of underground to surface testing locations for UGAS 1 and 2.

Results and Discussion

Underground to Surface Transmissions

The UGAS 1 and 2 transmitting stations were used to determine the ability of the MCS to communicate from underground to the surface. The extent of underground to surface communications are displayed in Figure 4. At UGAS 1, the full 120 m (400 ft) length of the loop antenna was wrapped around a pillar adjacent to a section of rail. From this location, the MCS was observed to communicate up to 200 m (650 ft) on the V-channel and up to 130 m (440 ft) on the T-channel. Message clarity began to deteriorate for both channels at signal indicator values less than -50 and were no longer received at signal indicator values less than -60.

An anomaly, caused by some unknown variable, 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 zone regardless of the distance between the transmitting MSU and the receiving MGU. This area was situated between the main mine fan and a high voltage transformer as well as underneath several high voltage power cables. A picture of this area is displayed in Figure 5. The lack of signal was confined to the internal area of this region. Any points surveyed outside the square shaped zone produced clear messages from UGAS 1. No other interference of this nature was observed around other substations or power lines at this field site.

Figure 5. Site A anomalous region in which all MCS communications were prevented.

An unexpected transmission was received at the portal of the overlying mine located 550 m (1,800 ft) away from UGAS 1. Transmissions could be received at this portal within 15 m (50 ft) of the rail extending from the portal. Some entries in the overlying mine are driven near parallel to the rail entries in Field Site A. Although the exact rail layout of the overlying is unknown, the communications received at this portal were suspected to be the result of sympathetic TTE signal propagation between the parallel sections of rail. The ability of metallic conductors, such as rails, to affect TTE signal quality and range has been observed and documented (Barkand et al., 2006, Jakosky and Zellers, 1924, Pittman et al., 1985, Vermeulen and Blignaut, 1961) but not in this manner.

In order to determine the range of signal propagation along the rail, a surface traverse was performed to survey locations on the surface that vertically intersected Field Site A rail entries. No communications were received from UGAS 1 during this tests, which indicates that the enhancing effect is limited to the vicinity of the rail. The Field Site A re-supply slope, which has a direct rail connection to UGAS 1, was also surveyed during this test. The transmission from UGAS 1 could not be received at the top of the slope at a transmission distance of 400 m (1,300 ft). This result implies that the TTE signal was also not able to propagate up the rail slope despite the direct physical connection.

The transmitting unit was moved two entries away from the rail to UGAS 2 where the full 120 m (400 ft) length of the loop antenna was wrapped around a pillar. This location was selected to determine the underground to surface transmission range without rail amplification. Unfortunately, rail propagation was also observed during this test. The broadcast from UGAS 2 was received at the overlying mine portal despite the increased separation distance from the rail. Identically to the test from UGAS 1, the transmission was also not received at the top of the Field Site A rail slope.

The MCS was observed to communicate up to 240 m (800 ft) on the V-channel and up to 140 m (450 ft) on the T-channel from UGAS 2. Message clarity began to deteriorate for both channels at signal indicator values less than -50. Communications were no longer received at signal indicator values less than -60. The signal indicator values of the underground to surface traverse as a function of distance from the transmitting station is summarized in Figure 6. This figure shows that the signal indicator values are indirectly proportional to transmission distance except when enhanced by 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 in solid strata. Table 10 presents a summary of the underground to surface results.

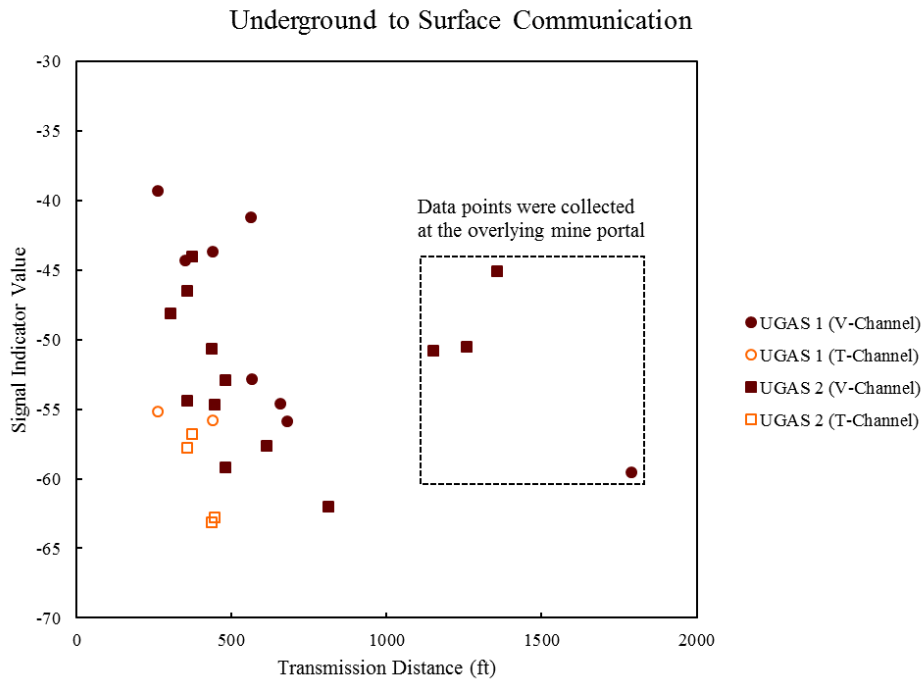


Figure 6. Signal indicator value of the underground to surface traverses as a function of transmission distance from the transmitting antenna.

Table 10. Summary of the results from the underground to surface traverses.

Antenna Station	Channel	Maximum Transmission Distance (m)(ft)	Minimum Signal Indicator Value before Signal Loss
UGAS 1 (Non-Rail)	V	200 m (650 ft)	-60
UGAS 1 (Non-Rail)	T	130 m (440 ft)	-60
UGAS 1 (Rail)	V	430 m (1,400 ft)	-60
UGAS 2 (Non-Rail)	V	240 m (800 ft)	-63
UGAS 2 (Non-Rail)	T	140 m (450 ft)	-64
UGAS 2 (Rail)	V	550 m (1,800 ft)	-53

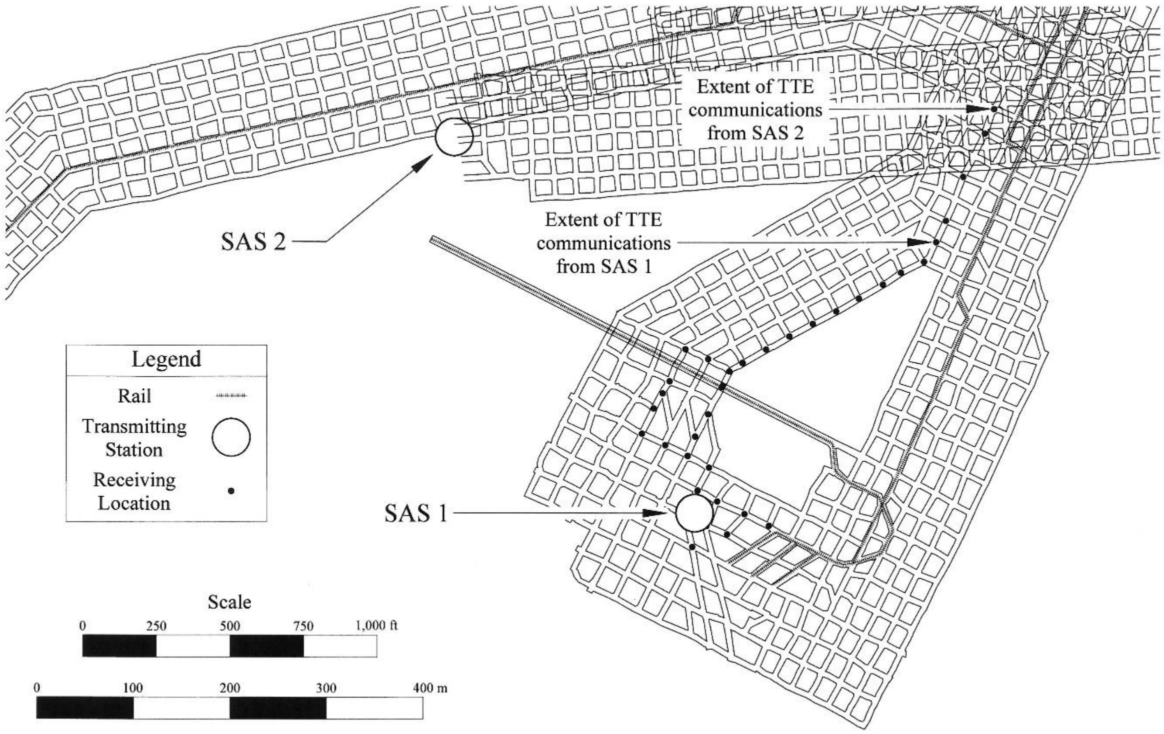


Figure 7. Map of surface to underground testing locations for SAS 1 and 2 along non-rail travelways.

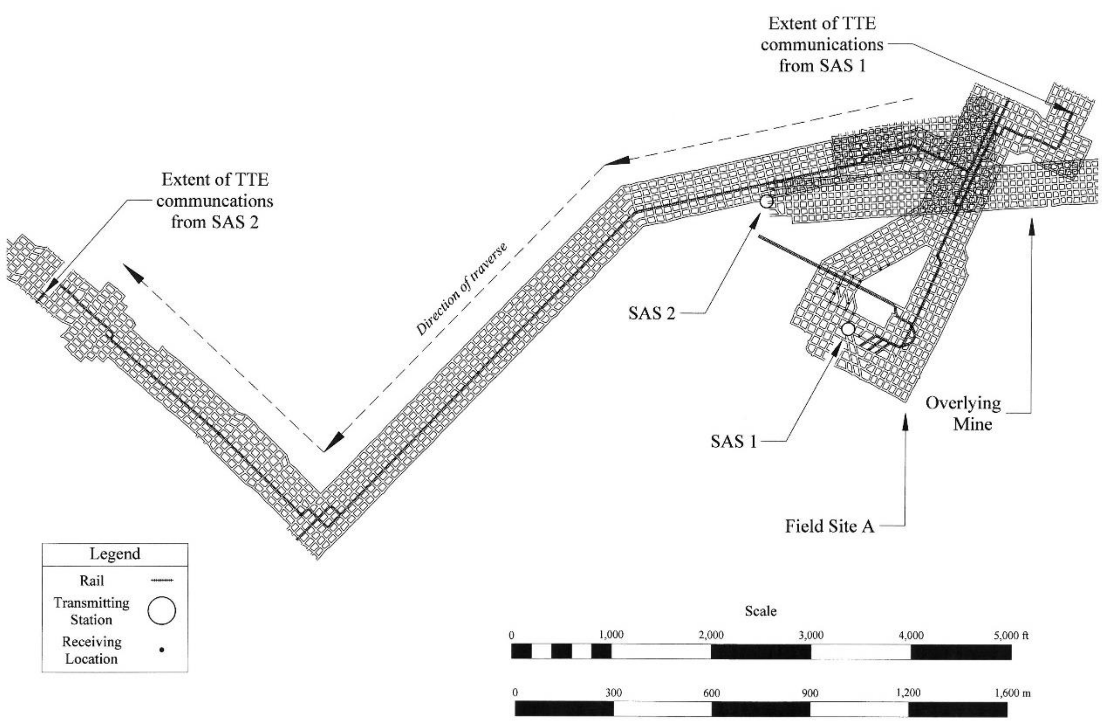


Figure 8. Map of surface to underground testing locations for SAS 1 and 2 along the rail.

Surface to Underground Testing

Two transmitting stations, SAS 1 and SAS 2, were used to determine the ability of the MCS to communicate from the surface to underground. The extent of surface to underground communications along non-rail travelways and rail travelways are displayed in Figures 7 and 8, respectively, including a map of the overlying mine. Surface to underground tests along the rail from SAS 1 were restricted to the V-channel because of a system malfunction. At SAS 1, the full 120 m (400 ft) length of the loop antenna was laid out in an elongated oval. The MCS was observed to communicate up to 400 m (1,300 ft) on the V-channel and up to 370 m (1,200 ft) on the T-channel along non-rail travelways from SAS 1. Message clarity began to deteriorate for both channels at signal indicator values less than -60. Communications were no longer received at signal indicator values less than -75 for either channel. T-channel communications were also lost at some intermediate locations. However, no significant geologic or anthropogenic artifacts could be attributed to the intermittent signal losses.

Surface to underground transmissions along the rail from SAS 1 were tested by moving the MGU in a mantrip to the northernmost section of the mine. Throughout the entire test area, the signal was not lost even through closed airlocks, under overcasts, next to high voltage cables, near power centers, and past many turns. The MCS was observed to communicate up to 950 m (3,100 ft) along the rail from SAS 1. The majority of the received messages were clear with a few showing minor typos. Clear messages were received at signal indicator values as low as -80.

The surface to underground traverse along non-rail travelways from SAS 1 was repeated during a thunderstorm with periods of heavy rain to determine the storm's impact, if any. During the non-rail thunderstorm test, the MCS was observed to communicate up to 400 m (1,300 ft) on the V-channel and up to 370 m (1,200 ft) on the T-channel. Message clarity began to deteriorate for both channels at signal indicator values less than -60. Communications were no longer received at signal indicator values less than -75 for either channel. The T-channel communications were lost on several occasions as the MGU became further separated from SAS 1 during this repeat test of non-rail travelways.

During underground to surface testing, TTE signals were received at the overlying mine portal, a picture of which is shown in Figure 9. In order to examine the reciprocal effect, the MSU was set up at this portal, which as designated SAS 2. At SAS 2, the entire 120 m (400 ft) length of the loop antenna was laid out in a large oval on top of the rail extending from the portal. The messages from SAS 2 were received at almost the furthest extent of the mine along the Field Site A rail with no deterioration in clarity despite the presence of numerous electromagnetic artifacts, direction changes, and physical obstructions. The MCS was observed to communicate up to 2,230 m (7,300 ft) on the V-channel and up to 2,200 m (7,200 ft) on the T-channel along the rail from SAS 2. Communications were no longer received from either channel at signal indicator values less than -80 and -90, respectively.

Surface to underground communications along non-rail travelways from SAS 2 were also tested. The path used for the traverse was similar to the path used for SAS 1. From SAS 2, the MCS was observed to communicate up to 550 m (1,800 ft) using both channels along non-rail travelways. Message clarity began to deteriorate 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 rails near some of the receiving locations. The transmissions were eventually lost despite being located 24 m (80 ft) from a rail entry. This behavior suggests that the signal enhancement is limited to the immediate vicinity of the rail.

Figure 9. Picture of the rail at the overlying mine portal.

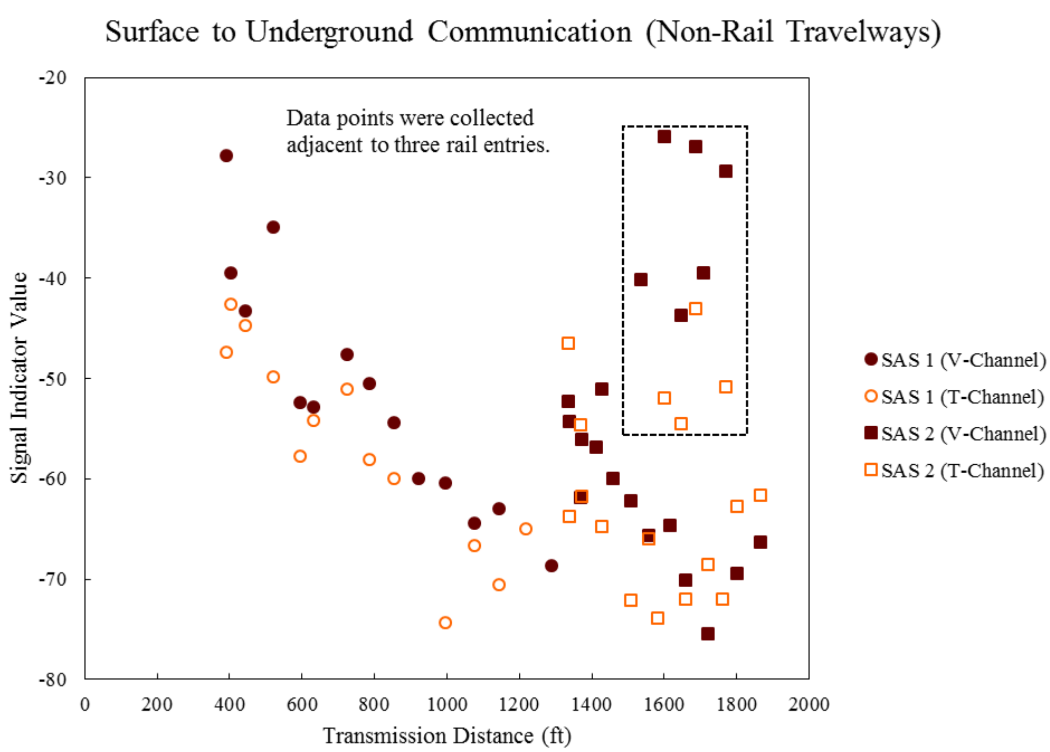


Figure 10. Signal indicator values of the surface to underground non-rail travelway traverses as a function of distance from the transmitting antenna.

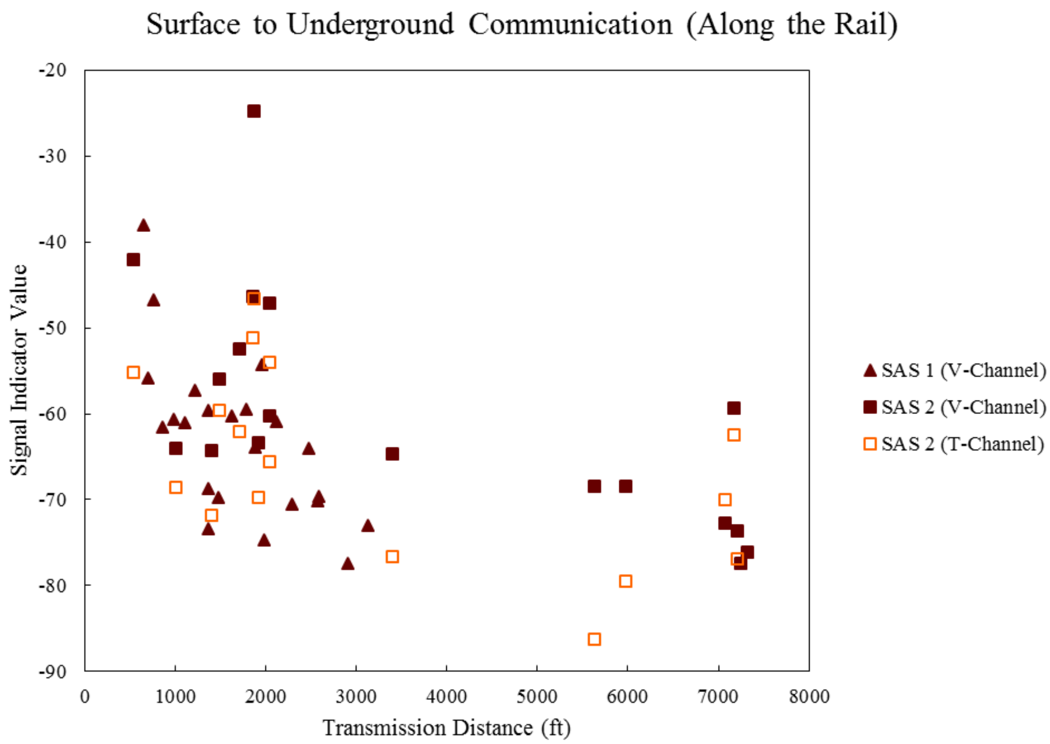


Figure 11. Signal indicator values of the surface to underground traverses along the rail as a function of distance from the transmitting antenna.

Table 11. Summary of the results from the surface to underground traverses.

Antenna Station	Channel	Maximum Transmission Distance (ft)	Minimum Signal Indicator Value before Signal Loss
SAS 1 (Non-Rail)	V	400 m (1,300 ft)	-70
SAS 1 (Non-Rail)	T	370 m (1,200 ft)	-75
SAS 1 (Rail)	V	950 m (3,100 ft)	-80
SAS 2 (Non-Rail)	V	580 m (1,900 ft)	-75
SAS 2 (Non-Rail)	T	550 m (1,800 ft)	-75
SAS 2 (Rail)	V	2,230 m (7,300 ft)	-80
SAS 2 (Rail)	T	2,200 m (7,200 ft)	-90

The signal indicator values of the surface to underground non-rail and rail traverses as a function of distance from the transmitting site are summarized in Figures 10 and 11, respectively. Figure 10 shows that the signal indicator values are indirectly proportional to transmission distance. The rate of decrease appears to have been fairly consistent throughout the testing at this field site. Figure 11 shows that the TTE signal along the rail had a shallower rate of decline than along non-rail travelways. Certain portions of the rail were able to maintain and even increase the signal indicator value in some cases. In general, the surface to underground tests supported the results from the underground to surface tests in that the lower frequency channel had a shorter transmission range than the higher frequency channel. Table 11 presents a summary of the surface to underground results.

Summary

MCS underground to surface and surface to underground communications were examined at Field Site A. Underground to surface tests observed the maximum communication range of the MCS to be approximately 240 m (800 ft) on the V-channel and showed that the higher frequency V-channel propagated further than the lower frequency T-channel. Most significantly, the underground to surface communications was observed to propagate from Field Site A to the portal of the overlying along discontinuous section of rail. However, communications were unable to propagate up a continuous section of rail at the Field Site A re-supply slope.

The maximum transmission range of the surface to underground communications along non-rail travelways was approximately 400 m (1,300 ft) on the V-channel and up to 370 m (1,200 ft) on the T-channel. Identically to underground to surface testing, the lower frequency T-channel was also not able to propagate as far as the higher frequency V-channel in non-rail travelways. The surface to underground performance of the MCS was substantially increased along rail entries, which is clearly depicted when comparing Figures 4 and 8.

Messages were clearly received along the rail at nearly the furthest extents of the mine over a range of 2,230 m (7,300 ft). The rail-enhancing effect was, however, limited to a proximal area around the rail. Higher concentrations of rail, such as the three parallel rail entries located near UGAS 2, were observed to produce higher signal indicator values even with separation distances of several hundred feet from the rail. Similar to underground to surface testing, communications from the overlying mine portal could be received underground in Field Site A but could not be received at the top of the Field Site A re-supply slope despite having a direct physical rail connection. The slope phenomenon remains unexplained especially considering that direction changes in the horizontal plane had no such effect.

The presence of high voltage artifacts did not appear to affect the ability to receive communications during either communication mode. Additionally, neither conveyor belt structures nor other large metallic artifacts were observed to affect the TTE communication in a significant manner. The non-ideal loop antenna layouts used at some of the receiving sites also did not appear to significantly affect the performance of the MCS.

Field Site B

Introduction

The following section contains an overview of the MCS and the ECS field studies conducted at an underground longwall mine in West Virginia. This site will be referred to as Field Site B in this report. A detailed overview of this field site can be found in the Research Approach chapter. For the MCS test, the ability of this system to achieve underground to surface, surface to underground, and underground to underground communications were examined. Over the course of the MCS test, messages with signal indicator values between -100 and 10 were observed. For the ECS test, the ability of this system to achieve two-way communications between underground and surface as well as between only underground locations were qualitatively evaluated using a variety of antenna configurations. A complete list of the applied ECS antenna configuration can be found in Table 15. All designations utilized in this section are specific to Field Site B and do not relate to other similar or identical labels mentioned in other sections. All reported transmission distances are point to point distances and not projected distances onto a horizontal or vertical plane.

MCS Results

Underground to Surface

UGAS 1 was located near the bottom of a newly constructed ventilation shaft. The MGU was placed in an adjacent entry that intersected the bottom of the ventilation shaft. The entire length of the loop antenna was laid in an oval that spanned two crosscuts along a single entry. Several small pools of water and an active high voltage power line were present in the vicinity of the loop antenna. A level area on the surface located approximately 300 m (1,000 ft) above UGAS 1 was surveyed. From UGAS 1, some incomprehensible messages could be received only on the V-channel with an average signal indicator value of -85. These messages were received at the locations nearest to the vertical center axis of the MGU loop antenna. The absence of any clear communications effectively signified that the MCS was unable to penetrate the overburden thickness at this location from underground.

UGAS 2 and 3 were located below an area that contained a large concentration of inactive, plugged gas-oil wells to determine their effect, if any, on MCS communications. A picture of a well casing is displayed in Figure 16. UGAS 2 was located directly under an exposed well casing in the main rail travelway. The full length of the loop antenna was wrapped around a pillar at this location. From UGAS 2, underground to surface communications could be received up to a distance of 290 m (960 ft) on both channels. An errant but clear text was also received at a distance of 400 m (1,300 ft) on only the V-channel. Text clarity began to deteriorate at signal indicator values less than -75. Messages could no longer be received at signal indicator values less than -90.

UGAS 3 was located near the bottom of another well located 160 m (530 ft) from UGAS 2. The entire length of the loop antenna was laid out around a pillar at this location. From UGAS 3, underground to surface communications could be received up to a distance of 470 m (1,500 ft) using the V-channel. Only a single T-channel message was received at a distance of 210 m (700 ft). An errant but clear text was also received at a distance of 520 m (1,700 ft) on the V-channel. Text clarity began to deteriorate at signal indicator values less than -73. Messages could no longer be received at signal indicator values less than -85. The results of these surveys are summarized in Figure 12 and in Table 12.

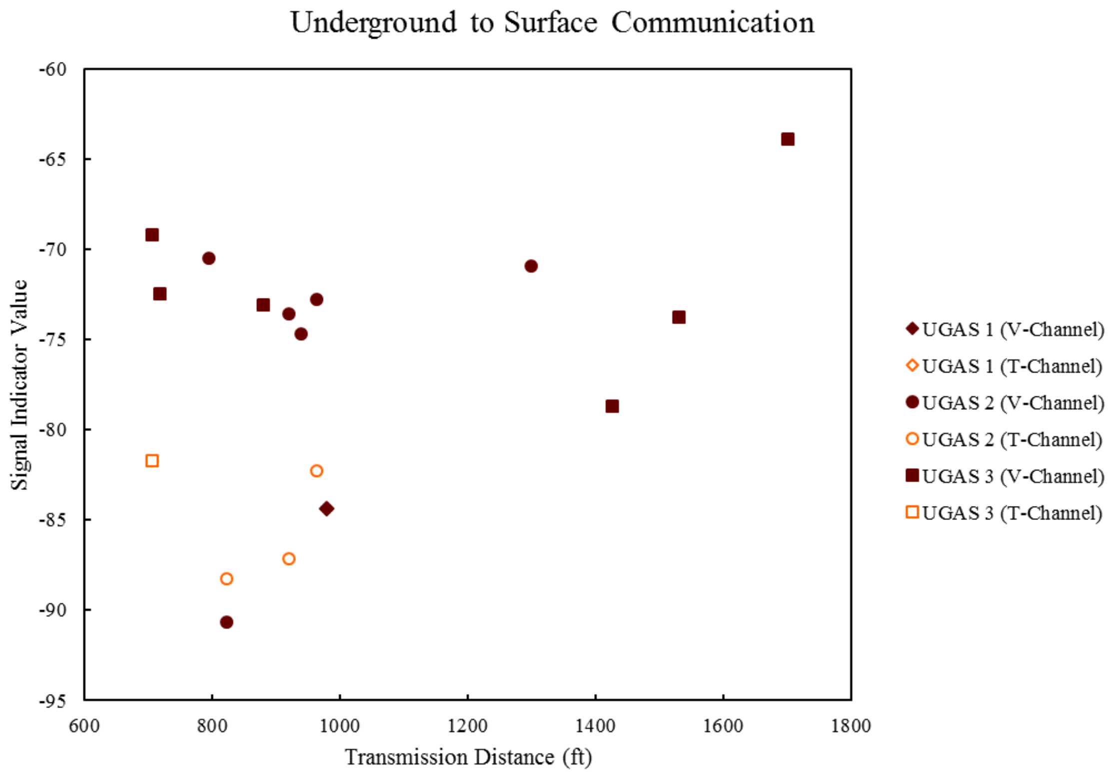


Figure 12. Signal indicator value of the underground to surface traverses as a function of transmission distance from the transmitting antenna.

Table 12. Summary of the maximum transmission distances from the underground to surface traverses.

Antenna Station	Channel	Maximum Transmission Distance
UGAS 1	V	300 m (980 ft)
UGAS 1	T	0 m (0 ft)
UGAS 2	V	400 m (1,300 ft)
UGAS 2	T	290 m (960 ft)
UGAS 3	V	520 m (1,700 ft)
UGAS 3	T	210 (700 ft)

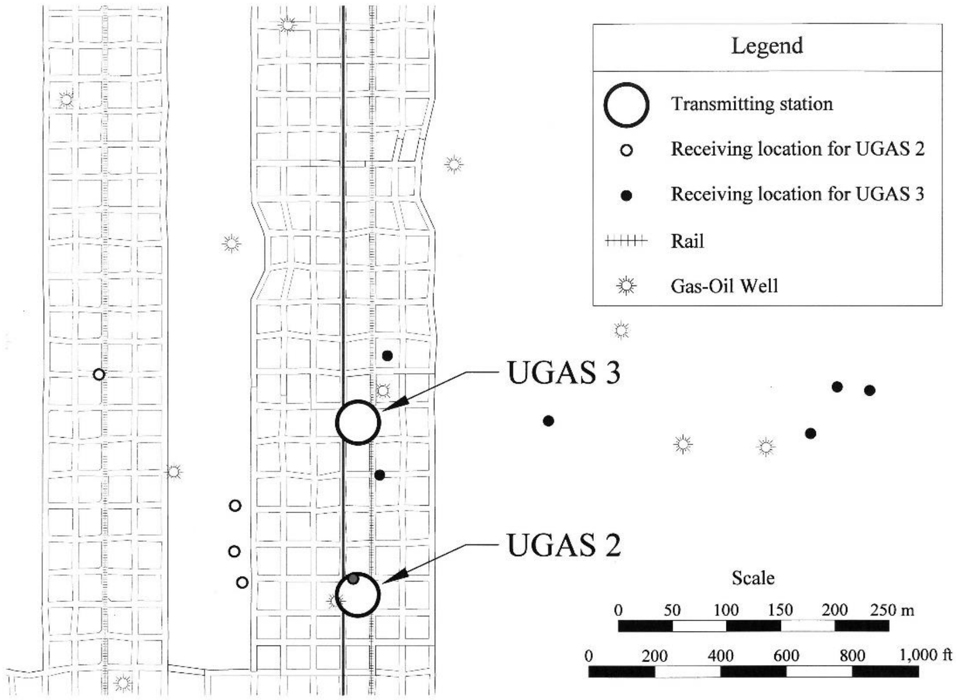


Figure 13. Map of the surface receiving locations that successfully received underground to surface MCS messages from UGAS 2 and 3.

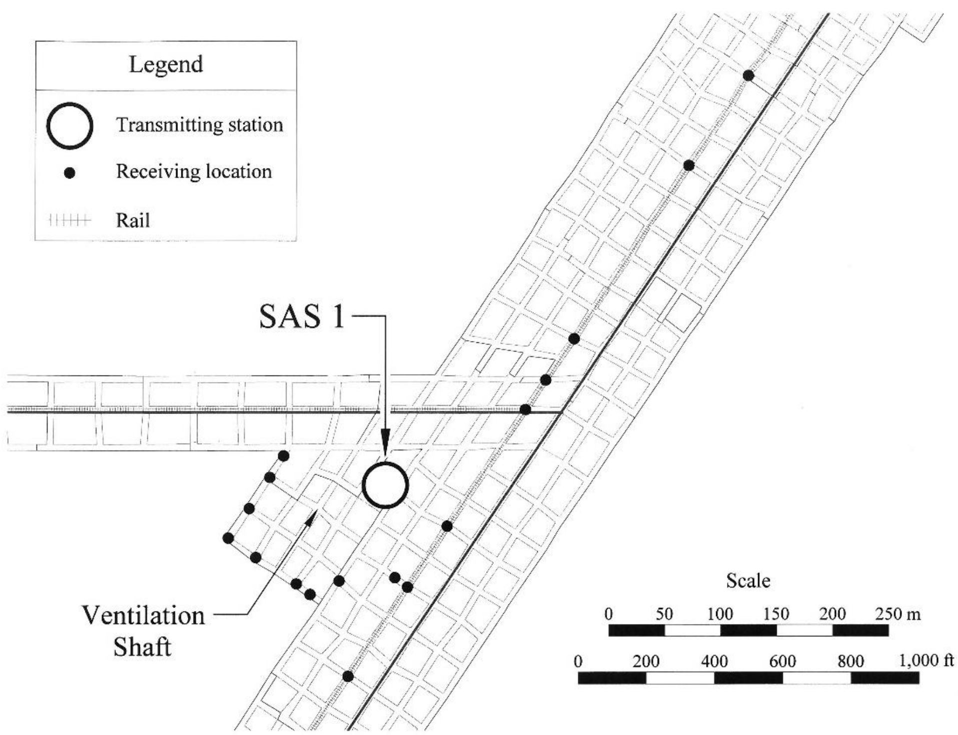


Figure 14. Map of the underground receiving stations that successfully received surface to underground MCS messages from SAS 1.

Surface to Underground

SAS 1 was located on the surface near the newly installed concrete-lined ventilation shaft. The MSU was placed on the surface above UGAS 1 located approximately 50 m (175 ft) from the top of the ventilation shaft. Three quarters of the loop antenna was laid out in a triangular shaped arrangement on the side of a small hill. Some messages were received in the vicinity of the shaft bottom. Communications rapidly degraded as the MCS was moved away from SAS 1 and toward the main rail travelway. From SAS 1, surface to underground communications could be received up to a distance of 350 m (1,200 ft) on the V-channel and 580 m (1,900 ft) on the T-channel. Text clarity on the V-channel was instead suddenly lost at signal indicator values less than -80. Text clarity on the T-channel did not deteriorate in a logical manner and instead exhibited typos in a manner that could not be correlated to the signal indicator value. For example, strong indicator values produced texts with errors while weaker indicator values produced clear texts. Based on these observations, the ventilation shaft did not impact MCS communications. The extent of successful communications from SAS 1 is displayed in Figure 14.

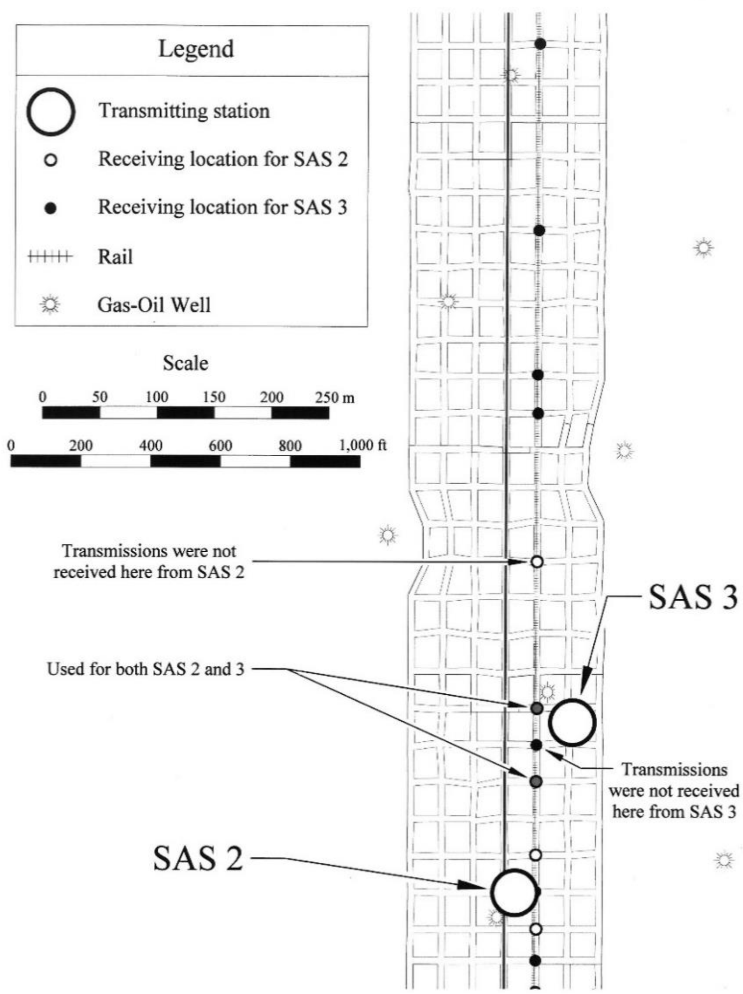


Figure 15. Map of the underground receiving stations that successfully received surface to underground MCS messages from SAS 2 and 3.

SAS 2 and 3 were located in an area above the mine that intersected a large concentration of inactive, plugged gas-oil wells to determine their effect, if any, on MCS communications. Figure 15 displays the extent of successful communications from these transmitting stations The MSU was set up adjacent to the exposed portion of the well above UGAS 2 on the surface located approximately 300 m (1,000 ft) above the mine. At this location, the full length of the loop antenna was laid out on a level clearing. From SAS 2, surface to underground transmission distances from 280 m (930 ft) to 400 m (1,300 ft) were surveyed along the rail. Communications were received clearly with no typos only at two locations positioned at 300 m (970 ft) and 320 m (1,100 ft) from SAS 2 and situated under SAS 3. All other received communication from SAS 2 were incomprehensible.

SAS 3 was located on the surface near the exposed portion of the well positioned 220 m (730 ft) above UGAS 3. The full length of the loop was laid out on a level area at the bottom of a small valley. From SAS 3, surface to underground transmissions could be received along the rail up to a distance of 350 m (1,100 ft) on the V-channel and 630 m (2,100 ft) on the T-channel. Text clarity from SAS 3 did not deteriorate on either channel. Messages were instead abruptly lost when the outer transmission range was reached at signal indicator values less than -75.

Figure 16. Intact gas-oil well casing from Field Site B.

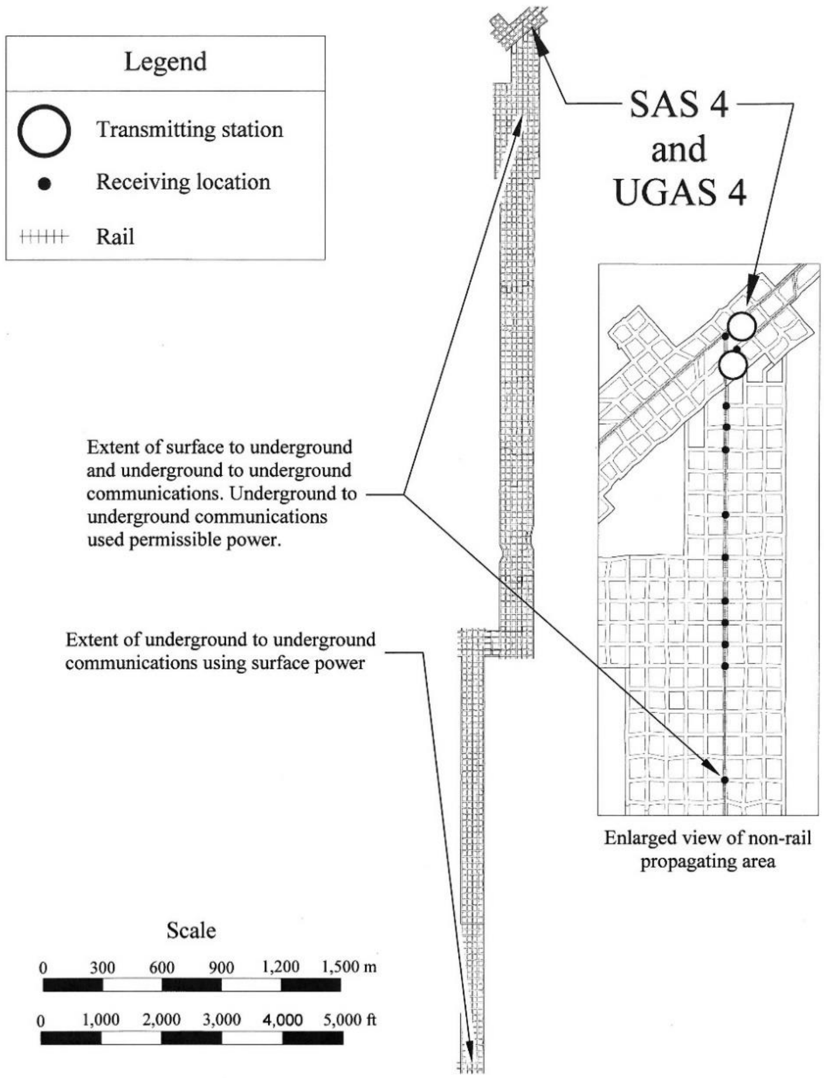


Figure 17. Map of MCS communications surveys conducted to determine the extent of rail propagation from SAS 4 and UGAS 4.

SAS 4 was used specifically to determine whether MCS transmissions could propagate along the rail at this mine. The extent of the communications observed from SAS 4 is displayed in Figure 17. This surface location was positioned 150 m (500 ft) above a mantrip departure area at this mine's northern portal. The departure area containing a large concentration of rail spurs that housed mantrips. The entire length of the loop antenna was laid out on a level, moderately vegetated surface at SAS 4.

From SAS 4, surface to underground transmissions could be received along the rail up to a distance of 230 m (760 ft) on the V-channel and 360 m (1,200 ft) on the T-channel. Text clarity did not deteriorate on either channel. Messages were abruptly lost when the extent of the transmission range was reached at signal indicator values less than -50. The results of these surface to underground surveys are summarized in Figure 18 and in Table 13. Given the lack of TTE signal propagation along the rail from the surface, an underground transmission location within the mantrip departure area was selected for underground to underground testing. This testing is covered in the next section.

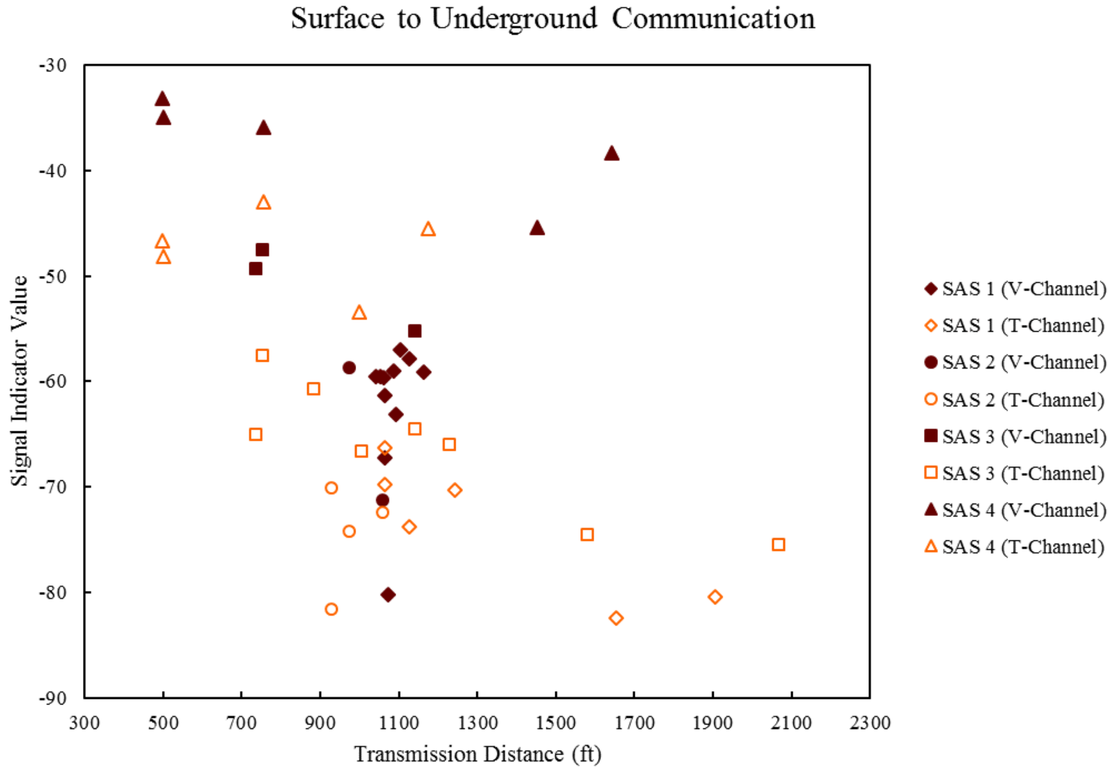


Figure 18. Signal indicator value of the surface to underground traverses as a function of transmission distance from the transmitting antenna.

Table 13. Summary of transmission distances from the surface to underground traverses.

Antenna Station	Channel	Maximum Transmission Distance
SAS 1	V	370 m (1,200 ft)
SAS 1	T	580 m (1,900 ft)
SAS 2	V and T	320 m (1,060 ft)
SAS 3	V	340 m (1,100 ft)
SAS 3	T	630 m (2,100 ft)
SAS 4	V	490 m (1,600 ft)
SAS 4	T	360 m (1,200 ft)

Underground to Underground

Underground to underground testing specifically investigated whether this communication mode would allow TTE signal propagation along the rail, which was not achieved during surface to underground testing. UGAS 4 was located at the bottom of this mine's northern portal in the mantrip departure area. The entire length of the loop antenna was wrapped around a pillar that intersected an entry containing a rail spur from the main travelway. The MGU was placed in the same entry next to the antenna. From UGAS 4, underground to underground transmissions could be received along the rail up to a distance of 330 m (1,100 ft) on the V-channel and 420 m (1,400 ft) on the T-channel. Text clarity began to deteriorate at signal indicator values less than -50. Messages could no longer be received at signal indicator values less than -80. As described in a previous section, the MGU utilized a lower transmission power than the MSU. In order to determine if transmission power was a factor in the lack of signal propagation along the rail, the MGU was replaced with the MSU.

UGAS 4 was utilized again for underground to underground testing using the elevated transmission power of the MSU. From UGAS 4, the elevated transmission power produced underground to underground transmission distances along the rail up to a distance of 5,200 m (17,000 ft) on the V-channel and 3,100 m (10,000 ft) on the T-channel. Text clarity did not deteriorate on either channel. Messages were abruptly lost when the extent of the transmission range was reached at signal indicator values less than -60. The results of these surface to underground surveys are summarized in Figure 19 and in Table 14.

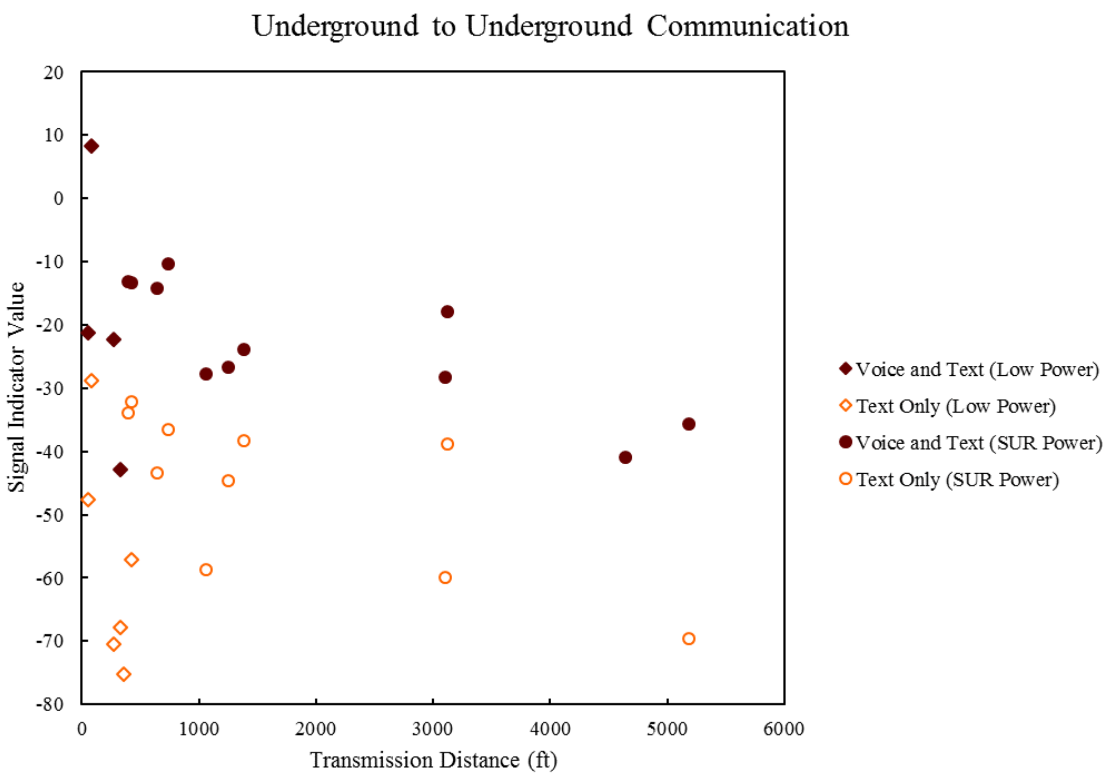


Figure 19. Signal indicator values from underground to underground traverses as a function of transmission distance from the loop antenna.

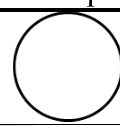
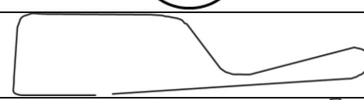
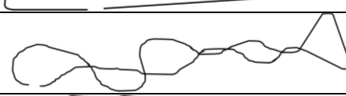
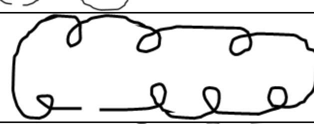
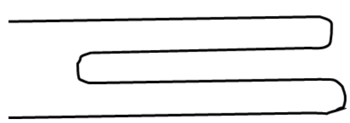
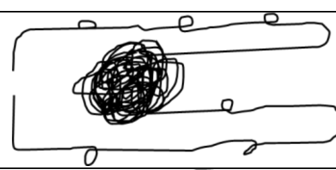
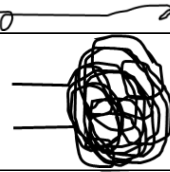
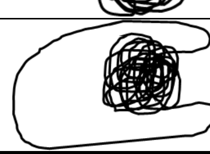
Table 14. Summary of the maximum transmission distances from underground to underground testing.

Antenna Station	Channel	Maximum Transmission Distance
UGAS 4 (Low Power)	T	420 m (1,400 ft)
UGAS 4 (High Power)	V	5,200 m (17,000 ft)

Antenna Configuration Test

The quality of the loop antenna layout relative to the manufacturer's recommendations was expected to have a significant impact on MCS transmissions. The effect of various loop antenna configurations was examined using a single underground transmitting location at Field Site B's northern portal. Nine different antenna configurations were tested using the reduced transmitting power of the MGU. Examples of the tested layouts are presented in Table 15. The MCS was able to successfully transmit messages for all of the attempted loop antenna configurations except Type VIII in which the entire length of the antenna was rolled into a ball and then thrown into an open area. As can be seen in Table 15, many of the antenna patterns severely contradicted the manufacturer's recommendations. The recorded signal indicator values for each antenna layout is displayed in Figure 20.

Table 15. Loop antenna layouts tested at Field Site B.

Antenna Layout	Example
I	
II	
III	
IV	
V	
VI	
VII	
VIII	
IX	

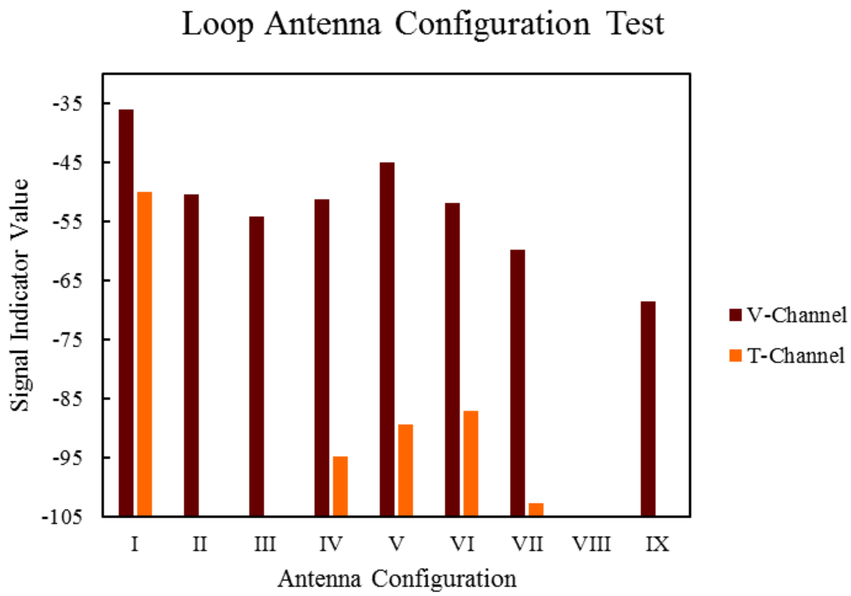


Figure 20. Signal indicator values from antenna layout testing using underground transmission power.

ECS Results

Underground and Surface Communications

Three different surface antenna configurations and six different underground antenna configurations from Table 16, Types I, II, III, V, VII, VIII, XI, XII, were used to examine ECS communications between underground and the surface. A static surface site was paired with multiple underground sites for this test. The transmitting site was located on a level area within a densely populated field of inactive-oil gas wells. One of the exposed steel casings that extended from the surface to the mine's mail rail travelway was used as a ground bed for several tests. However, this casing did not significantly affect the transmission or reception performance of the ECS. Given the insignificant impact of the well, only the results of the underground antenna configurations are overviewed in the following section.

Sites A through F represent the underground locations utilized for this ECS test. A map of these locations along with a brief summary of the results is presented in Figure 21. The sites displayed in this figure represent a number of individual test locations in the vicinity of the indicated area. The individual locations were consolidated into the defined sites for clarity. The EGU resistance as a function of ground bed separation distance for each underground antenna configuration is displayed in Figure 22. All of the underground sites were overlain by the field of inactive gas-oil wells that encompass a large portion of Field Site B.

Site A was established below the static surface site and offset approximately 60 m (200 ft) from the bottom of the well at that location. Antenna configuration Types II and III were tested at this site using ground bed separation distances ranging from 5 m (15 ft) to 10 m (35 ft). Two-way communications were successfully established at Site A regardless of antenna mode or ground bed separation distance. Based on the ground bed resistance values, the Type III antenna configuration utilizing all fully grouted roof bolts produced the lowest resistance.

Table 16. ECS antenna configurations tested at Field Site B. The bed number is used to provide a sense of separation between the two grounding beds. These numbers imply neither priority nor order.

Antenna Configuration	Description
Type I	Beds 1 and 2: Four 60 cm (2 ft) long copper grounding rods
Type II	Bed 1: Four 60 cm (2 ft) long copper grounding rods Bed 2: Four 2 m (6 ft) fully grouted roof bolts
Type III	Beds 1 and 2: Four 2 m (6 ft) long fully grouted steel roof bolts
Type IV	Beds 1 and 2: Four 2 m (6 ft) long fully grouted steel torque tension bolts
Type V	Beds 1 and 2: four 3 m (10 ft) long partially grouted cable bolts
Type VI	Bed 1: Four 2 m (6 ft) long fully grouted steel roof bolts Bed 2: Four 3 m (10 ft) long partially grouted cable bolts
Type VII	Bed 1: Four 2 m (6 ft) fully grouted steel roof bolts Bed 2: Belt structure
Type VIII	Bed 1: Four 2 m (6 ft) fully grouted steel roof bolts Bed 2: Rail
Type IX	Bed 1: Four 2 m (6 ft) fully grouted steel torque tension bolts Bed 2: Belt structure
Type X	Bed 1: Four 2 m (6 ft) fully grouted steel torque tension bolts Bed 2: Rail
Type XI	Bed 1: Four 3 m (10 ft) partially grouted cable bolts Bed 2: Belt structure
Type XII	Bed 1: Belt structure Bed 2: Rail

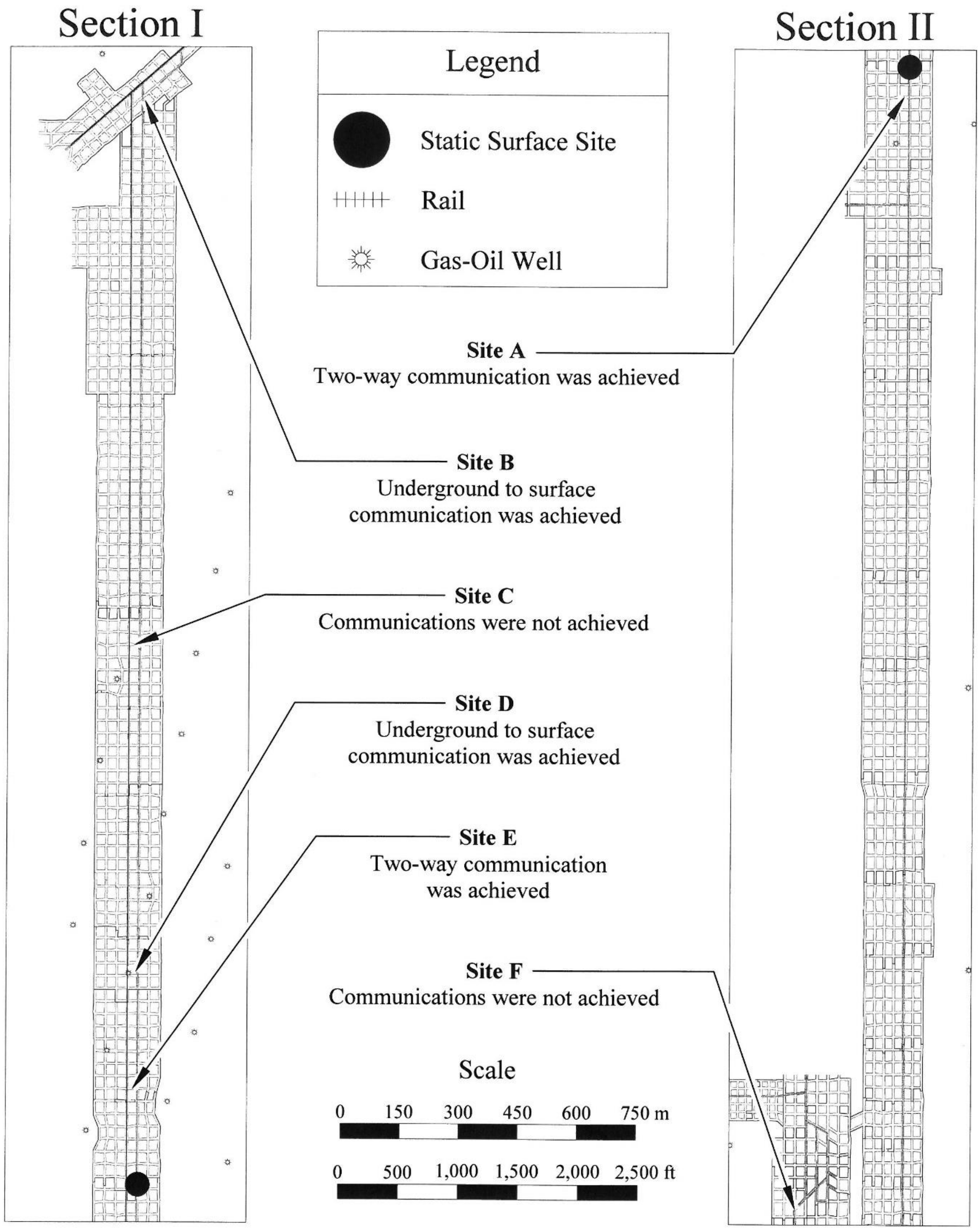


Figure 21. Map of the underground receiving sites that were used to examine ECS communications between the surface site and multiple underground sites. Sections I and II display the surveyed portions of the mine to the north and to the south of the surface site, respectively.

Site B was located at the furthest accessible northern extent of the mine situated approximately 2,800 m (9,200 ft) from the surface site. This area is the mine's northern portal, which contained a mantrip departure area and a large concentration of rail. Antenna configuration Types I, II, III, VII, and XII were tested at this site using ground bed separation distances ranging from 6 m (20 ft) to 40 m (130 ft). The Type I configuration utilizing the manufacturer's recommended installation of copper grounding rods produced the highest observed resistance at approximately 900 Ω. Given the poor performance of the copper rods at Sites A and B, the Type I configuration was not applied at the remaining sites.

Two-way communication could not be achieved at Site B. However, one-way underground to surface communication was achieved using antenna configuration Types VIII and XII. These configurations incorporated the rail with ground bed separation distances of 6 m (20 ft) to 40 m (120 ft). Resistances less than 30 Ω were also produced with the addition of the rail. Antenna configuration Type XII, utilizing both the rail and belt structure, exhibited the lowest observed resistance during this study at 5 Ω.

Site C was located approximately 1,400 m (4,600 ft) from the surface site. Antenna configuration Types III and V were tested at this site using ground bed separation distances ranging from 10 m (40 ft) to 20 m (60 ft). Neither two-way nor one-way communication could be achieved at this location. Site D was located approximately 640 m (2,100 ft) from the surface site. Antenna configuration Types III and V were tested at this site using ground bed separation distances ranging from 30 m (90 ft) to 40 m (130 ft). Only one-way underground to surface communication was at this site using both antenna configurations.

Site E was located approximately 340 m (1,100 ft) from the surface site in the vicinity of the nearby exposed well casing. Antenna configuration Types III and V were tested at this site using ground bed separation distances ranging from 15 m (50 ft) to 40 m (130 ft). Two-way communications were successfully established at this site using both antenna configurations. Site F was located approximately 2,900 m (9,500 ft) to the south of the surface site within another mantrip departure area. Antenna configuration Types V, VII, VIII, and XI were tested at this site using ground bed separation distances ranging from 6 m (20 ft) to 30 m (100 ft). Neither two-way nor one-way communication could be established regardless of the antenna configuration at Site F.

Underground Communications

Eight different antenna configurations were examined across ten separate underground locations during this study. The underground test locations are designated as Sites G through P, which are visually represented in Figures 23 and 24. The sites displayed in these figures represent a number of individual test locations in the vicinity of the indicated area. The individual locations were consolidated into the defined sites for clarity. The static underground site was paired with other underground locations along the main travelway servicing the northern portal. These mobile sites were used to determine the ultimate range of underground to underground communication at this mine from the static site.

The static ECS location was chosen as the reference location primarily because of its proximity and its ease of access to the northern mine portal. Given this positioning, that site could potentially be utilized as a staging area for rescue operations in a post-event scenario. As such, underground to underground TTE communications using the ECS would be a viable means of interaction between rescue teams and confined mine personnel. In addition to the static site's proximity to a portal, this location also minimized the study's impact on normal mine operations.

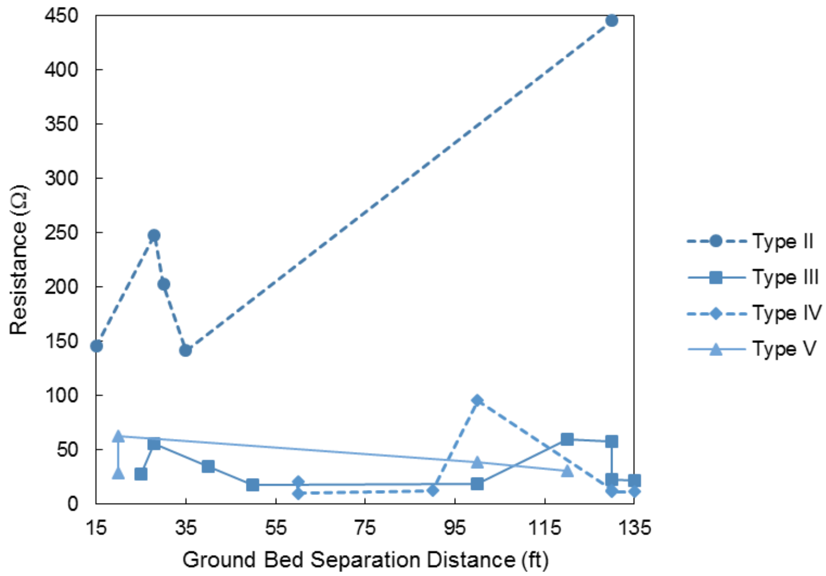


Figure 22. ECS resistance as a function of ground bed separation distance by underground antenna configuration type. Configuration types that did not successfully transmit or receive any messages are not displayed.

The ECS at the static underground site was set up adjacent to the mantrip departure area at the bottom of the northern portal. The remaining sites were located between the static site and the southern portal along the main travelway. The test sites were all surveyed in the vicinity of the rail with perpendicular separation distances between the rail and the ECS unit never exceeding 30 m (100 ft). Unless otherwise noted, all reported transmission distances are point to point distances and not projected distances onto a horizontal or vertical plane.

Antenna configurations Types III, IV, VI-X, and XII from Table 16 were examined in this test. Two maps of the ECS test sites, which include a high-level summary of the results, are presented in figures 23 and 24. The antenna configuration combinations used to communicate between the static site and the mobile underground sites are presented in Table 17 with successful two-way communication parings signified by matching subscripts. The individual antenna configurations between sites were paired using all available combinations. For example, four antenna configurations were used to test communications with Site H (i.e., III with IV, VIII with IV, III with X, and VII with X). However, only some of the configurations listed in Table 16 may have been utilized at a specific site. The antenna configurations ultimately applied at each location were selected based on the conditions that were present at the time. Antenna configurations that were unsafe, impractical, or impossible to install were not applied.

Figures 23 and 24 show that two-way communications were reliably established between the static site and nearly all of the other tested underground locations. The maximum observed underground to underground two-way transmission distance was 5,800 m (19,000 ft). The only exceptions occurred at Sites N and O. At these two sites, only one-way communications could be established regardless of the applied antenna configuration. The limited performance of the ECS at Sites I and J was unexpected given the shorter transmitting distance relative to other mobile sites at which two-way communications were achieved.

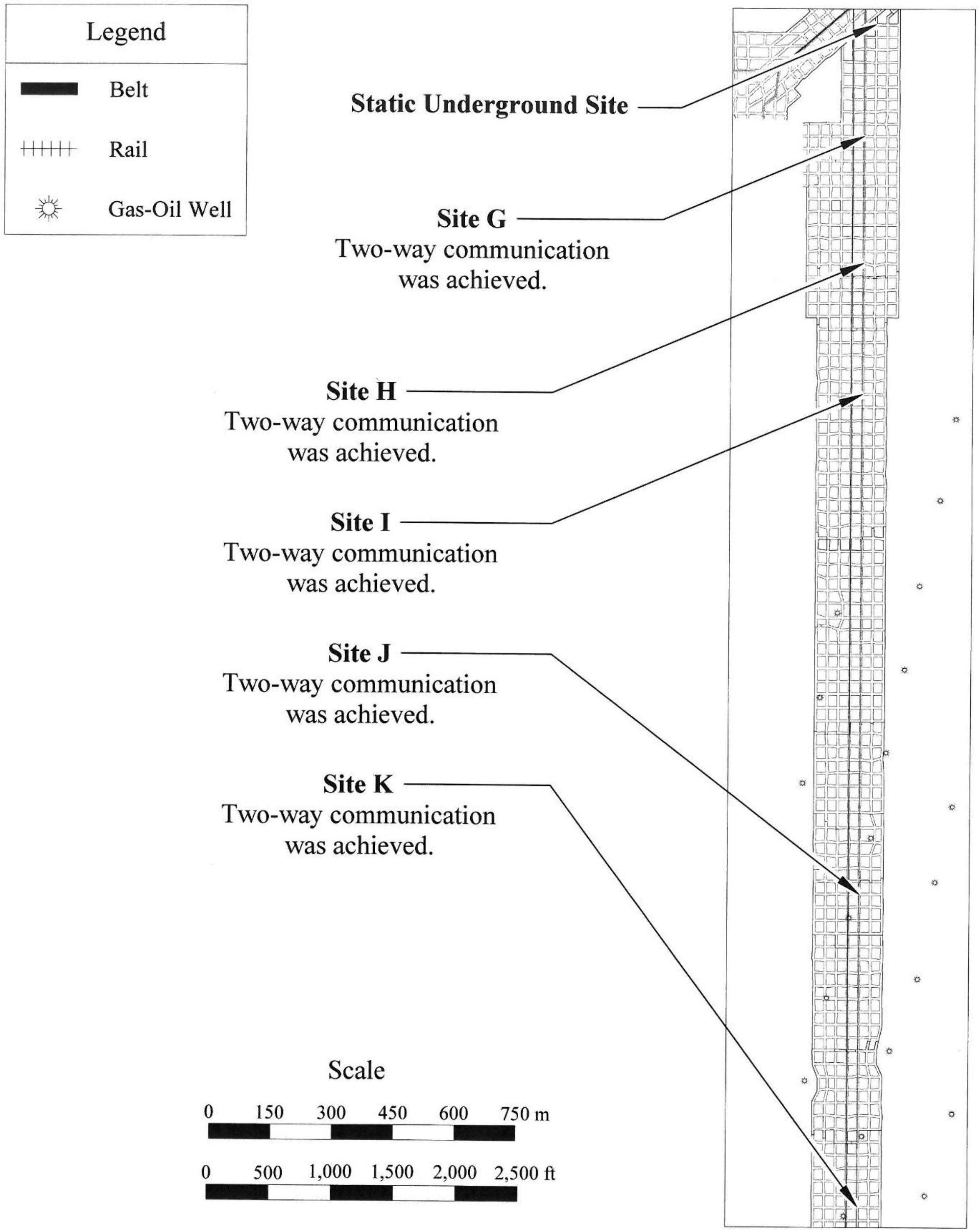


Figure 23. Map of ECS Sites A through F including a high-level overview of the type of underground to underground communications achieved at each site.

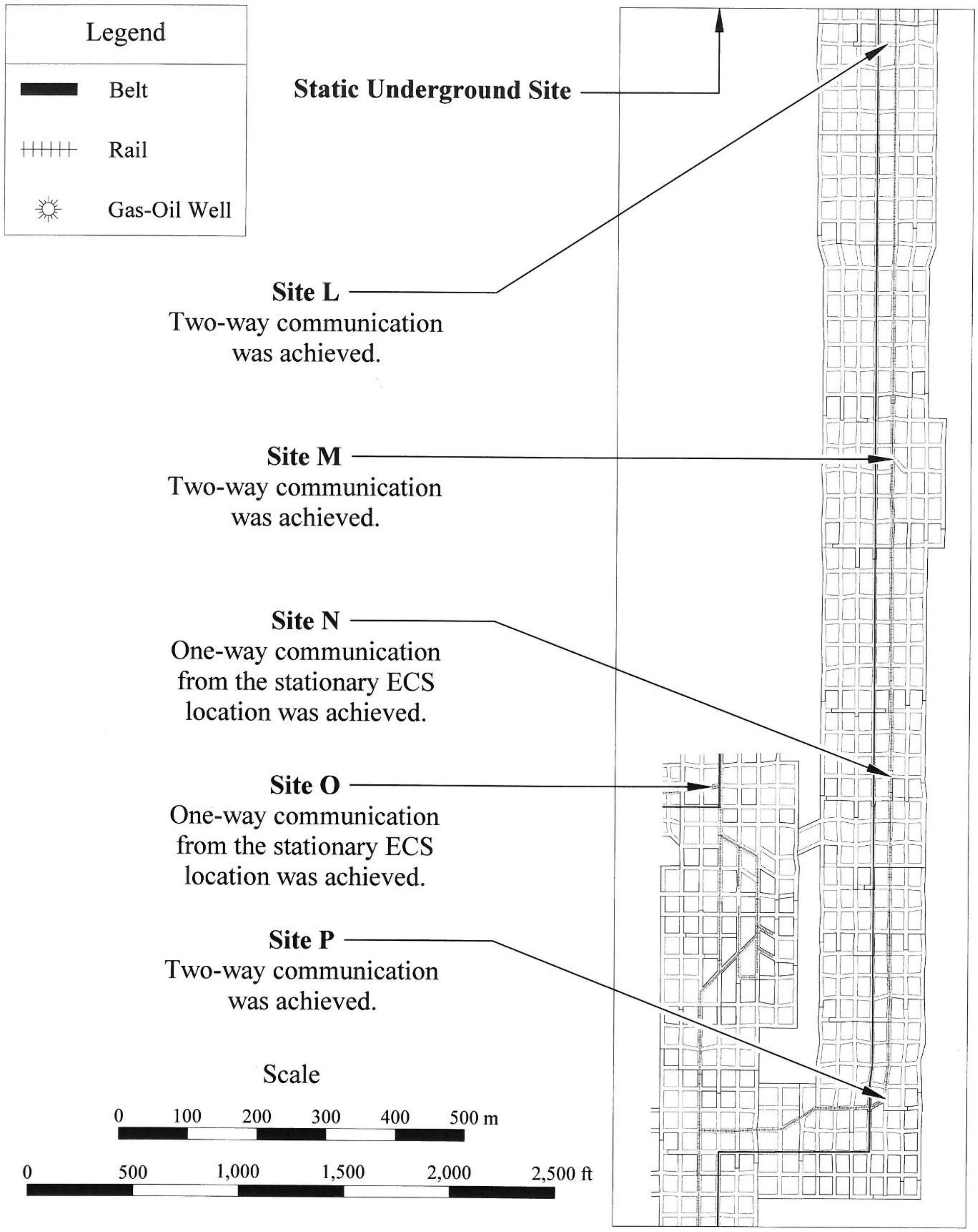


Figure 24. Map of ECS Sites G through K including a high-level overview of the type of underground to underground communications achieved at each site.

Site N was located at the bottom of a moderately dipping hill along the main travelway. Aside from the hill, this location did not exhibit any other visually significant anomalies. The ECS was set up in a rail spur offset approximately 3 m (10 ft) from the main travelway. At this location, only one-way communications from the stationary site to Site N could be achieved when connected to the rail at both sites. The roof bolt-only configuration at Site I failed to transmit or receive any messages to or from Site A, respectively. However, once the ECS was moved further from the stationary site to the next location, Site P, two-way communications could be established despite the increased distance. As such, the inability to communicate from Site N was caused by an unidentified anomaly present in this area of the mine. An identical one-way transmission restriction was also observed at Site O.

Site O was located adjacent to the mine's southern portal with a separation distance of approximately 4,700 m (15,500 ft) from the stationary site. Unlike the other underground sites, Site O was not located in the main travelway servicing the mine's northern portal. This area of the mine is offset approximately 240 m (800 ft) from the main travelway, which can be seen in Figure 24, and contained a variety of inactive conveyor belt structures. Site O, however, remained adjacent to the rail, which was contiguously connected to the main travelway rail from the northern portal.

Five different antenna configurations were examined at Site O, and three different antenna configurations were examined at the stationary site. These configurations incorporated roof bolts, belt structure, and rail at both locations, which are summarized in Table 17. No antenna configuration pairing between the two sites was able to achieve two-way communications. Different relative orientations of the antenna arrays between the two sites, such as north-south to east-west, were also attempted with no success.

Despite all efforts, only one-way communications could be established from the stationary site to Site O. Site O did not exhibit any unusual, visually significant anomalies. The mine operations that were active at the time of the study prevented the examination of other similar offset locations. Without a means of comparison, the offset nature of Site O could not be directly attributed to the lack of two-way communications. As such, the inability to communicate from Site O was caused by an unidentified anomaly.

Table 17. Antenna configuration examined between the underground stationary site and the mobile underground sites presented with the associated point to point transmission distance. Matching superscripts across rows indicate the antenna configuration pairings that were able to achieve two-way communication.

Mobile Site	Antenna Configurations used at Mobile Site	Antenna Configurations used at Site A	Transmission Distance
B	III[1]	IV[1]	270 m (900 ft)
C	III[1], VIII[2]	IV, X[1, 2]	580 m (1,900 ft)
D	III, VIII[1]	X[1]	910 m (3,000 ft)
E	III[1], VIII[2]	IV, X[1, 2]	2,130 m (7,000 ft)
F	III, VIII[1]	X[1]	2,900 m (9,500 ft)
G	III, VIII[1]	X[1]	4,270 m (14,000 ft)
H	III, VIII[1]	X[1]	4,880 m (16,000 ft)
I	III, VIII	X	5,330 m (17,500 ft)
J	IV, VI, IX, X, XII	IX, X, XII	5,330 m (17,500 ft)
K	III, VII[1], VIII[2]	IX[1, 2], X[1, 2], XII[2]	5,800 m (19,000 ft)

Two-way communications were successfully achieved between the stationary site and the remaining underground locations. Antenna configurations that included a long grounded conductor, either belt structure or rail, in combination with fully grouted roof bolts elicited the most reliable communications. As long as belt structure or rail was implemented at one site, one-way communication from the long conductor connected site to the receiving site could be achieved. The only exception was observed at Site O from which neither belt structure nor rail could be used to transmit a message to the stationary site. However, the stationary site was able to send messages to Site O when connected to a long conductor. The enhanced transmission reliability afforded by belt structure and rail was most clearly demonstrated at Sites J and P.

At these sites, roof bolt-only, belt structure, and rail configurations were applied in random order. The antenna configuration parings between the stationary site and Sites J and P cycled through all available combinations several times. Each time the transmitting ECS was connected to either belt structure or rail, one-way communication could be achieved to the receiving ECS regardless of the antenna configuration being implemented at the receiving site. Two-way communication between the aforementioned locations could be achieved only when a long conductor was applied at both ECS units.

Roof bolt-only configurations were able to achieve two-way communications at Sites G and J with transmission distances of 270 m (900 ft) and 2,130 m (7,000 ft), respectively. However, the roof bolt-only two-way communication performance could not be repeated using identical antenna configurations at either Sites H or I, which were located closer to the stationary site than Site J. No significant natural or anthropogenic artifacts were visually present at any of the four locations. The ECS roof bolt-only two-way communications achieved at Site G may be attributed to this site's relatively shorter transmission distance to the stationary site. However, the performance of the roof bolt-only configurations at Sites H through J did not adhere to a discernable pattern and could not be attributed to a physical anomaly. As a result, the cause of the inconsistent performance of the roof bolt-only antenna configurations between Sites H through J remains unidentified.

Summary

The MCS and the ECS were both examined at Field Site B. A summary of MCS performance observations will first be overviewed, which will then be followed by a summary of ECS testing results. MCS testing at this field site evaluated underground to surface, surface to underground, and underground to underground communications. The MCS was unable to reliably establish underground to surface communications across useful distances from the selected transmitting locations at this field site. This inability of the MCS to communicate from underground to the surface was likely a function of the overburden thickness combined with the presence of densely spaced cased wells that encompassed a large area of the mine. The antenna configuration test performed on the MCS loop antenna showed that poor antenna layouts did not have a detrimental effect on MCS communications. This result suggests that the MCS can function in areas that restrict the loop antenna deployment.

Figures 18 and 19 display the signal indicator values as a function of transmission distance from the surface to underground and underground to underground communications, respectively. From these figures, the signal indicator values in general can be seen decreasing linearly with increasing transmission distances. In Figure 18, the average signal indicator magnitudes in the gas-oil field and next to the ventilation shaft using a three quarter loop antenna layout are distinctively lower than the signal strength values from the other transmitting locations. A marked difference between rail propagated and un-propagated transmissions are also readily apparent in Figure 19 when comparing the underground power and surface power results. Surface to underground communications were established with slightly reduced range relative to MCS tests at other field sites. The cause of this transmission range reduction was also the likely caused by the two aforementioned properties.

The most intriguing result of the MCS study was the near complete lack of TTE signal propagation along the rail during surface to underground testing. This behavior contradicts the observed performance of the MCS observed at Field Site A. Rail enhanced communication was, however, finally achieved during underground to underground testing when utilizing the elevated transmission power of the MSU. During this test, a maximum communication range of 5,200 m (17,000 ft) was achieved on the V-channel. This result suggests that a certain power output and proximity may be required before the MCS signal is able to propagate along the rail at this mine.

The ability to communicate between underground and the surface as well as between only underground locations was evaluated during ECS testing. Reliable two-way communications could only be achieved at transmission distances of 300 m (1,000 ft) or less. Greater transmission distances restricted the ECS to one-way underground to surface communication when incorporating rail, belt structure, or both as grounding beds. One-way ECS communications was able to achieve a maximum underground to surface transmission range of 2,700 m (9,000 ft) toward the northern portal of this mine.

ECS antenna signal characteristics were optimized with fully grouted roof bolts, rail, and belt structure as grounding beds. All remaining antenna structures, such as copper grounding rods, produced inferior antenna performance. Ground bed separation distances did not significantly affect the performance of the ECS in this study. As a result, further ground bed distance evaluations were not warranted at the other field test sites.

ECS underground to underground testing achieved a maximum two-way communication distance of 5,800 m (19,000 ft). The implementation of a long grounded conductor, either belt structure or rail, produced the most reliable and furthest communications. If at least one antenna bed was composed of either belt structure or rail, one-way communication could be consistently established from the unit utilizing the long conductor to the receiving unit regardless of the antenna configuration used by the receiving ECS unit. Antenna configurations implementing only roof bolts also performed surprisingly well with the achievement of a maximum two-way communication distance of 900 m (3,000 ft). Based on the result of this test, underground to underground communications were far superior in terms of both ultimate range and full duplex capability to communications between the surface and underground.

Field Site C

Introduction

The following section contains an overview of the MCS and the ECS field studies conducted at an underground longwall mine in Illinois. This study location will be referred to as Field Site C in this report. A detailed overview of this field site can be found in the Research Approach chapter of this report. The ability of the MCS to achieve underground to surface, surface to underground, and underground to underground communications were examined. Although the surface around the mine was open and level, only a limited amount of access to these areas above the mine was available because of property boundaries. As a result, a single surface transmitting location was selected based on its ability to accommodate the MSU and its loop antenna. Similar challenges in terms of available space were also present when selecting suitable underground transmitting locations. Only a single underground location near the mine portal was identified as having both sufficient space and low enough mine traffic to accommodate the MGU and its loop antenna. This underground location was used as the transmitting location for both underground to surface and underground to underground testing. Over the course of the MCS test, messages with signal indicator values between -103 and 14 could be received. The ability of the ECS to achieve two-way communications between underground and surface were qualitatively evaluated using a variety of antenna configurations. All designations utilized in this section are specific to Field Site C and do not relate to other similar or identical labels mentioned in other sections. All reported transmission distances are point to point distances and not projected distances onto a horizontal or vertical plane.

MCS Results

Underground to Surface

The underground transmitting location was placed approximately 610 m (2,000 ft) from the bottom of the slope portal. The MGU was placed in a crosscut adjacent to the primary travelway to prevent interaction with mine traffic. Approximately 95% of the loop antenna was wrapped around a pillar because of obstructions. The surrounding area was heavily meshed on both the roof and the ribs. A significant amount of sloughage was also present along the roof and ribs creating a layer of unconsolidated material that surrounded the underground transmitting station, UGAS 1. In addition to the mesh, significant metallic infrastructure in the form of roof bolts, straps, and plates was also present including an active conveyor belt in the adjacent entry. Underground to surface communications were surveyed in the vicinity of the mine office, which included locations around the mine portal and other accessible locations on the surface roads (e.g., residential streets, state routes, etc.) overlying the mine. No surveys were conducted off mine property or away from public access roads because these remaining areas were private properties. A map of the locations at which underground to surface messages from UGAS 1 were successfully received are displayed in
Figure 25.

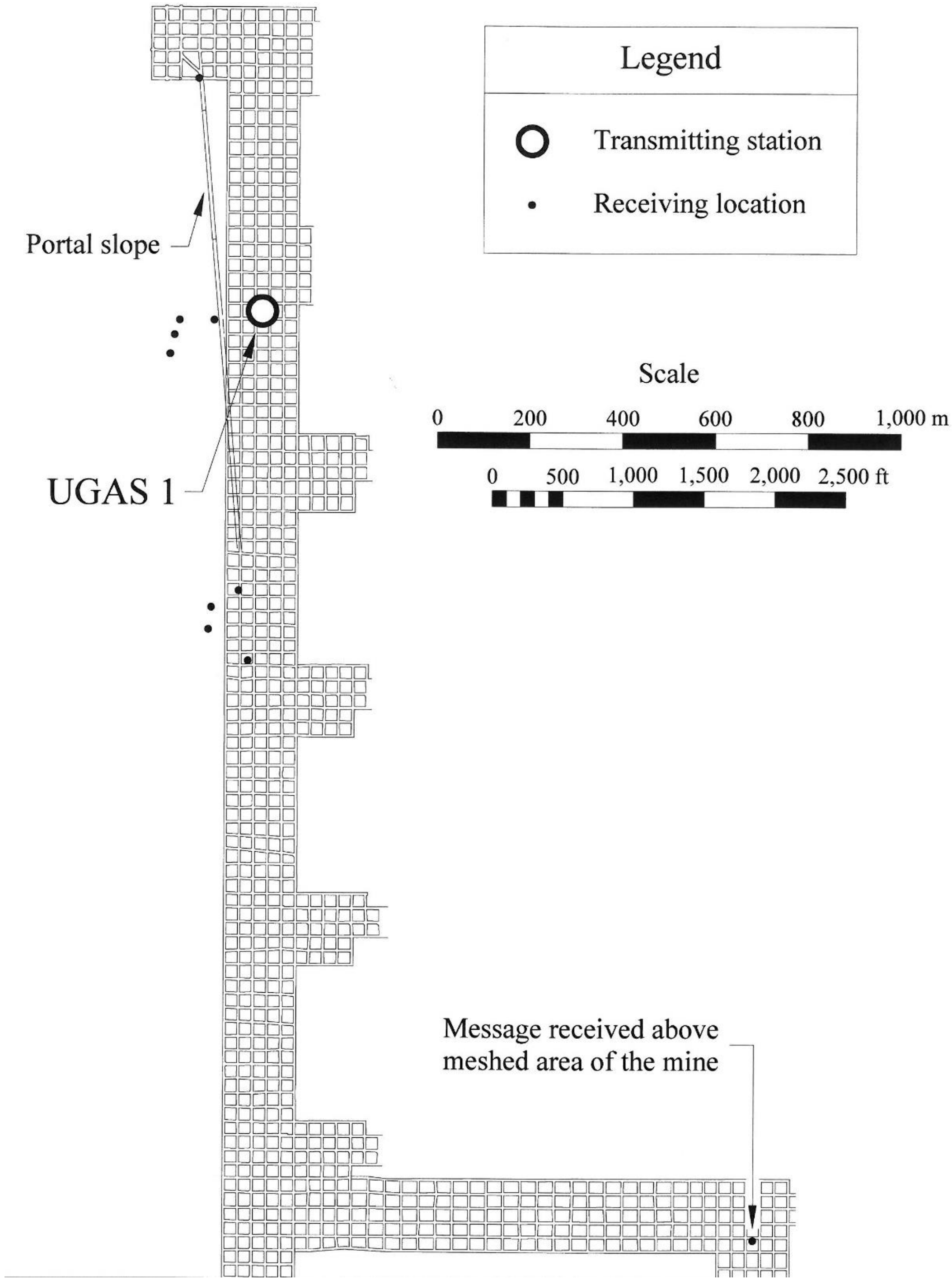


Figure 25. Map of the surface receiving locations that successfully received underground to surface MCS messages from UGAS 1.

From UGAS 1, communications could be received up to a distance of 2,280 m (7,500 ft) on the V-channel and up to 770 m (2,540 ft) on the T-channel. Text clarity began to degrade at signal indicator values less than -77 on the V-channel and less than -104 on the T-channel. Test messages were no longer received from the MGU at signal indicator values less than -102 on the V-channel and less than -105 on the T-channel. The underground to surface transmission distances at Field Site C eclipsed previous tests at other field sites. The single observable distinct attribute at Field Site C was the presence of large contiguous roof and rib mesh sections. The apparent relationship between the mesh and the increased transmission range was further reinforced when examining surface sites located a significant distance from the transmitting location.

At these surface locations, messages could only be received at areas located above active mine workings installed with mesh. Once the receiving MCS unit was moved away from active mine workings, communications from the MGU were suddenly lost. Although TTE transmissions from previous tests were able to achieve impressive transmission ranges when propagating along the rail, the mesh sections at this mine also allowed signals to propagate through 150 m (500 ft) of overburden. This degree of TTE signal enhancement from a large metallic conductor has not been observed at any other field site. Furthermore, the increased range at this mine was achieved using the reduced, permissible transmitting power of the MGU.

The transmission distances from UGAS 1 also exceeded the transmission distances observed during surface to underground testing at this field site. The low transmission power performance of the MCS contradicts the observed behavior of the MCS at the other field sites. In general, this system has always exhibited a direct relationship between transmission power and transmission distance. This contrasting performance at Field Site C suggests the presence of some unique variable at this mine, which is likely the size, configuration, and composition of the support mesh. However, since a formal test of various meshes could not be accomplished to isolate the responsible variable, this conjecture remains anecdotal.

Surface to Underground

The surface transmitting site was located in an open field adjacent to the slope portal and the rail car loading area. This field did not contain any notable natural or anthropogenic features that may have affected MCS communications. The entire length of the MSU loop antenna was laid out at this location, SAS 1, in a circle according to the manufacturer's recommendations. From this location, surface to underground communications were surveyed along the mine's primary travelway originating from the bottom of the mine portal slope. The overburden thickness along the surveyed area was effectively uniform at an average of 170 m (550 ft). A map of the locations at which surface to underground messages from SAS 1 were successfully received are displayed in
Figure 26.

From SAS 1, communications could be received up to a distance of 660 m (2,170 ft) on the V-channel and up to 860 m (2,830 ft) on the T-channel from SAS 1. Text clarity on both channels sporadically began to degrade as signal indicator values fell below -80. Text message typos would appear at random and did not deteriorate according to a logical pattern. For example, strong indicator values produced texts with errors while weaker indicator values produced clear texts at certain times with the opposite occurring during other instances. Text messages were no longer received from the MSU at signal indicator values less than -82.

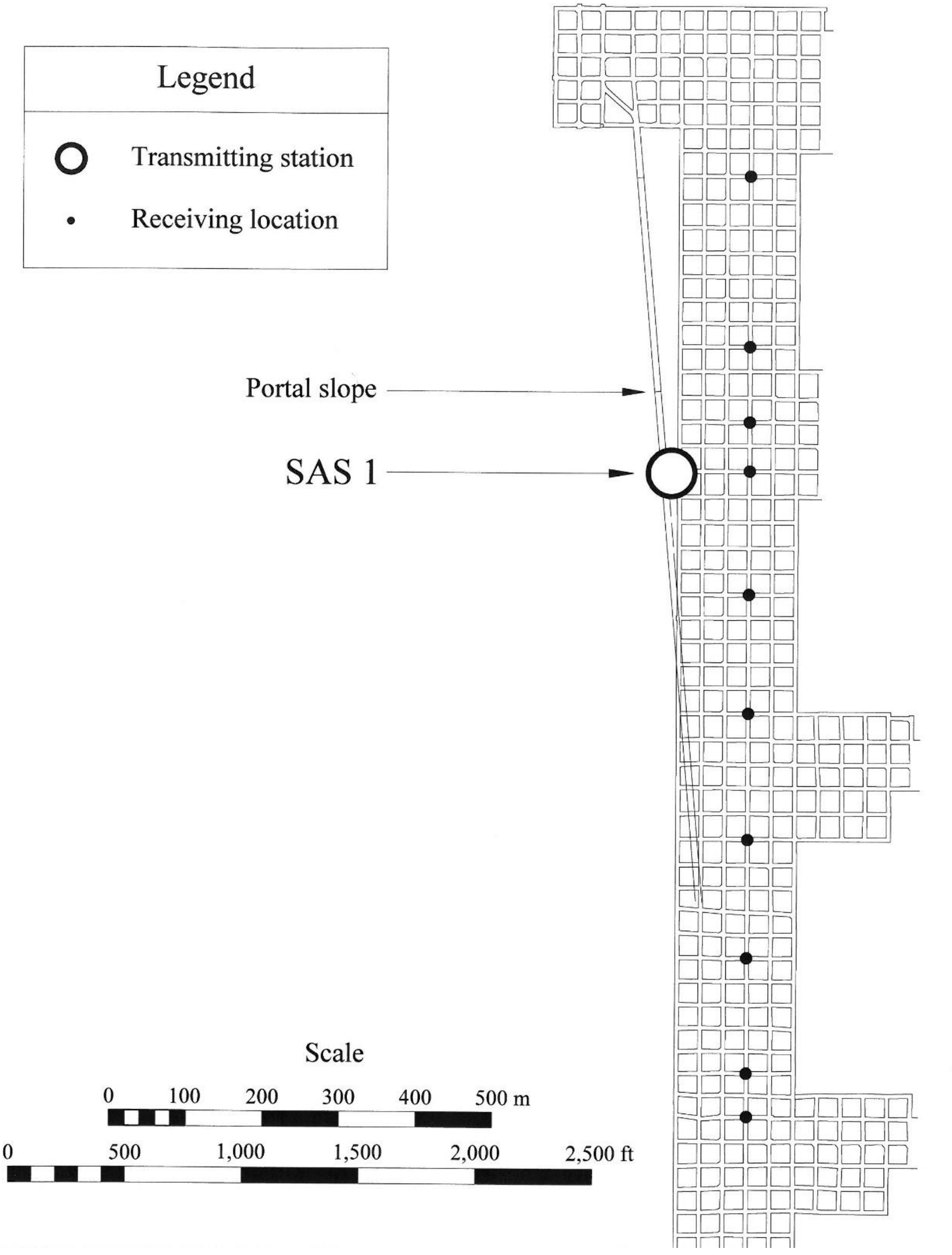


Figure 26. Map of the underground receiving locations that successfully received surface to underground MCS messages from SAS 1.

Surface to underground transmission distances at this field site were significantly higher than previous MCS tests that were not enhanced by anthropogenic features. Given the similarity of the geology and overall mine construction between the current field test and previous underground test locations, the presence of contiguous roof mesh sections is the most significant defining variable. Based on this observation, the increased the range of the surface to underground transmissions at this mine appears to have been be a function of the mesh. However, the surface to underground mesh enhancing effect was not as significant as previous enhancements to TTE signal propagation distances along underground rail. Figure 28 displays the signal indicators from the underground to surface, surface to underground, and underground to underground traverses as a function of distance from each respective transmitting station. From this figure, the signal indicator values for the surface to underground traverse in general decrease linearly with increasing transmission distances. Figure 28 displays the signal indicators from the underground to surface, surface to underground, and underground to underground traverses as a function of distance from each respective transmitting station. From this figure, the signal indicator values for the underground to surface traverse in general decrease linearly with increasing transmission distances except at locations where the mesh enhanced effect was observed.

Underground to Underground

Underground to underground testing utilized the same underground transmitting site, UGAS 1, and MGU loop antenna configuration as the underground to surface test. As such, the reduced transmitting power of the MGU would once again be applied. From UGAS 1, communications were received up to a distance of 4,560 m (15,000 ft) on the V-channel and up to 3,920 m (12,900 ft) on the T-channel. Text clarity did not degrade on the V-channel but were suddenly lost at signal indicator values less than -63. Message clarity on the T-channel began to degrade at signal indicator values less than -99. Test messages were no longer received from UGAS 1 at signal indicator values less than -63 on the V-channel and less than -100 on the T-channel. A map of the locations at which underground to underground messages from UGAS 1 were successfully received are displayed in Figure 27.

The observed underground to underground range at Field Site C far exceeded similar tests at other field sites. A large portion of the main travelway between the bottom of the mine slope and the active sections were traversed during this MCS test. From UGAS 1, TTE transmission could be received at almost the entire extent of the travelway reaching the edge of the active section. The presence of contiguous roof and rib mesh appears to have significantly extended the range, similarly to both underground to surface and surface to underground testing at this mine. A similar enhancing effect has been observed in the presence of rail at other field sites. However, the mesh enhancing effect observed at this mine is first recorded instance of this form of TTE signal augmentation. Figure 28 displays the signal indicators from the underground to surface, surface to underground, and underground to underground traverses as a function of distance from each respective transmitting station. From this figure, the signal indicator values for the underground to underground traverse in general decrease linearly with increasing transmission distances though at a much shallower rate than the other communication modes.

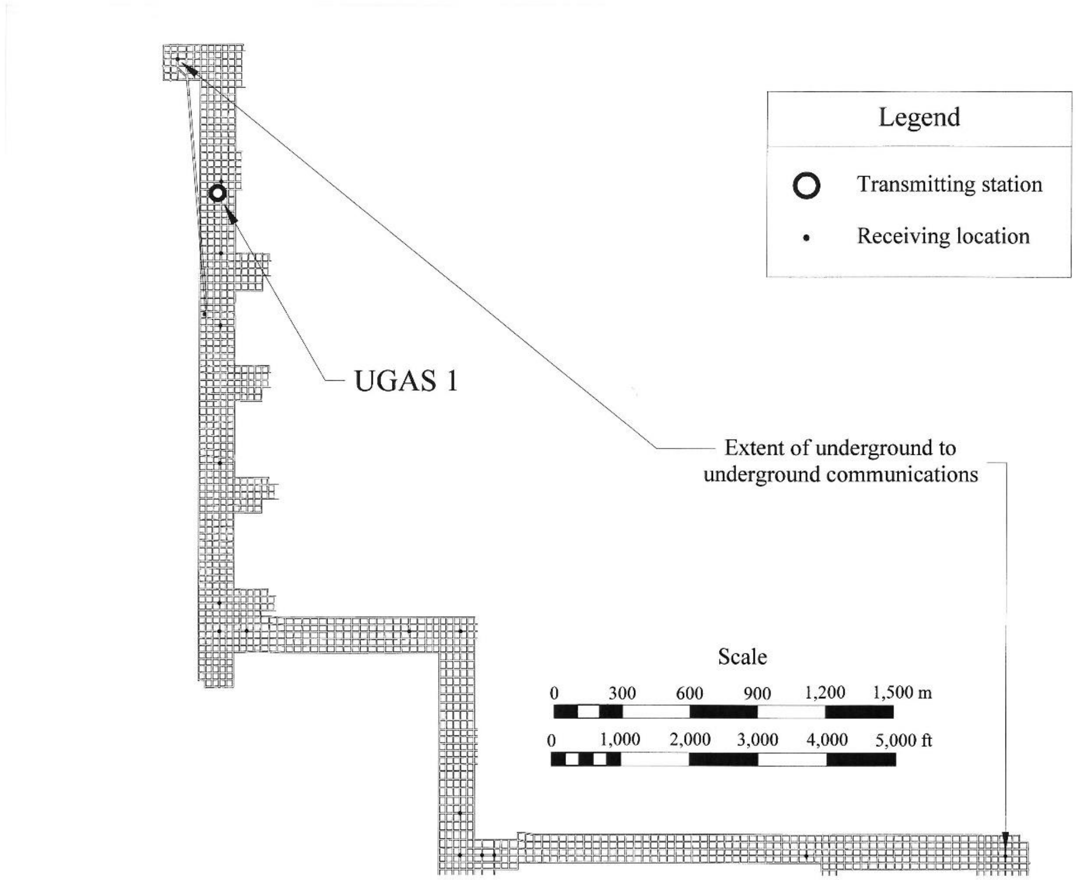


Figure 27. Map of the underground receiving locations that successfully received underground to underground MCS messages from UGAS 1.

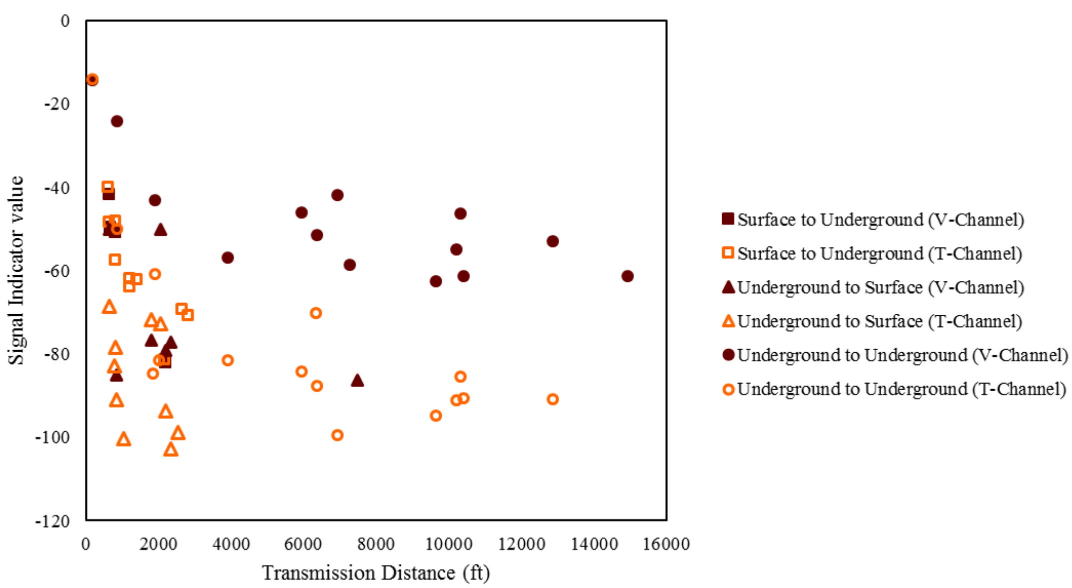


Figure 28. Signal indicator values from the MCS communication traverses as a function of transmission distance from the transmitting station.

Table 18. Summary of the maximum transmission distances from the MCS traverses (*Underground to Underground).

Antenna Station	Channel	Maximum Transmission Distance
UGAS 1	V	2,280 m (7,500 ft)
UGAS 1	T	770 m (2,540 ft)
UGAS 1*	V	4,560 m (15,000 ft)
UGAS 1*	T	3,920 m (12,900 ft)
SAS 1	V	660 m (2,170 ft)
SAS 1	T	860 m (2,830 ft)

ECS Results

Using a single surface site, the primary travelway between the bottom of the slope and the active section was evaluated to determine the extent of ECS communication between the surface and underground. Various antenna configurations composed of easily accessible metallic structures were utilized to determine their effect on ECS performance. The surface unit was deployed using two ground beds each composed of four 1.2 m (4 ft) long copper grounding rods. The ground rods were installed with a bed to bed separation distance of 60 m (200 ft). The inter-rod spacing within each bed was 1.2 m (4 ft). Each rod was almost fully driven into the ground leaving a minor above ground clearance for an electrical connection. No additional surface antenna configurations were utilized because of the lack of nearby alternate antenna structures. Underground antenna configurations included belt structure, 1.2 m (4 ft) fully grouted steel rib bolts, 2 m (6 ft) fully ground steel roof bolts with mesh, and 1.2 m (4 ft) friction fitted steel rib bolts. Examples of the antenna configurations can be found in Figures 29 through 31. A map of the examined ECS test sites is displayed in Figure 32.

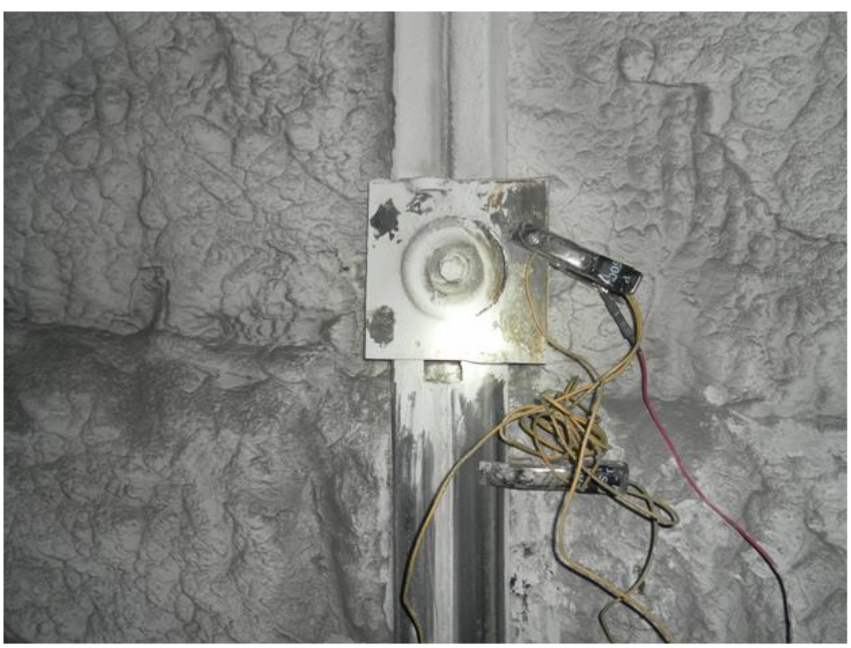


Figure 29. Underground 1.2 m (4 ft) friction fitted copper grounding rods.


Figure 30. Underground 2 m (6 ft) fully grouted resin bolts.


Figure 31. Underground 1.2 m (4 ft) friction fitted steel rib bolt.

ECS communications between the surface and underground were restricted to a 460 m (1,500 ft) horizontal area along the travelway in the vicinity of the surface ECS location. Although two-way communications were technically established, received messages were sporadic and unreliable with many individual messages lost during transmission. The inclusion of belt structure as a grounding bed was attempted at several locations but could not ultimately be tested because of continuity issues between the belt structure and the other attempted antenna structures. Roof mesh, 2 m (6 ft) fully grouted steel roof bolts, and rib bolts were, however, successfully utilized at several locations. Given the lack of rail at this field site, this antenna structure was not examined at Field Site C.

The physically contiguous nature of the mesh in conjunction with its installed size was expected to enhance ECS communications similarly to other large, grounded metallic structures examined at other field sites. However, the inclusion of mesh as a grounding bed did not noticeably improve ECS communications. This lack of ECS signal enhancement may indicate that some unknown anomaly, such as the presence of limestone in the overburden, may have nullified the large metallic conductor effect observed at other field sties when using belt structure or rail. Additionally, the configuration of the mesh itself in terms of its repeating square pattern and multi-planar coverage may have also contributed to the lack of signal enhancement. However, since a formal test of various meshes to isolate the responsible variable could not be accomplished, these conjectures remains anecdotal.

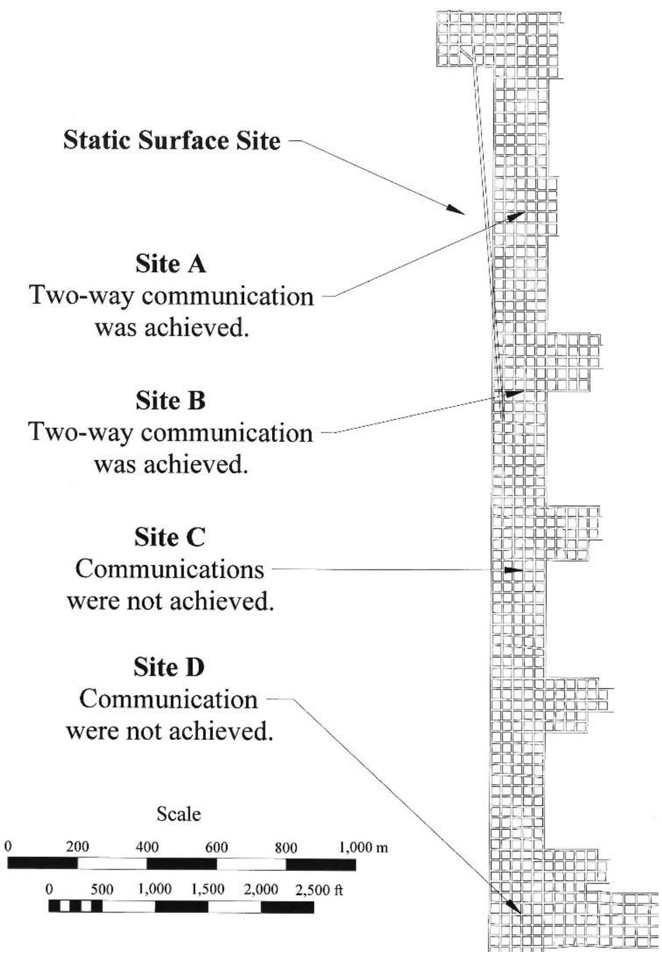


Figure 32. Map of ECS site including a high-level overview of test results

Summary

MCS underground to surface communications were received at a maximum of 2,280 m (7,500 ft) from the underground transmitting site on the V-channel. The presence of large contiguous sections of roof and rib mesh appears to have not only increased the range of MCS transmissions but also enabled these transmissions to propagate through a significant thickness of overburden. An enhancing effect to this degree from a large metallic conductor has not been observed during MCS tests at other field sites.

MCS surface to underground communication were received at a maximum of 860 m (2,830 ft) from the surface transmitting site on the T-channel. The presence of contiguous sections of roof and rib mesh along the entire extent of the surveyed underground areas also appears to have increased the range of this communication mode. However, the range extension enabled by the mesh was not as significant as the degree to which TTE signals were affected by rail in other surface to underground MCS tests.

MCS underground to underground testing at Field Site C exhibited the longest transmission range. Communications were received along almost the entire extent of the mine’s main travelway extending from the bottom of the portal to the active section. The maximum underground to underground transmission distance was 4,560 m (15,000 ft) on the V-channel. Identically to the other MCS tests at this mine, the mesh appears to have significantly extended the range of MCS communications. This transmission distance was achieved using the reduced, permissible power of the MGU.

ECS communications at Field Site C performed poorly even when utilizing the mesh as a grounding bed. In addition to the mesh, a variety of other antenna structures were utilized to determine their effect on ECS performance. Regardless of the applied antenna configuration, communications between the static surface location and underground locations were restricted to a 460 m (1,500 ft) area along the main travelway. Although two-way communications between the surface and underground were technically established at some underground locations, the messages were sporadic and unreliable. The complete lack of adequate communications may indicate that some unknown anomaly may have nullified ECS transmissions at this mine.

Field Site D

Introduction

The following section contains an overview of the MCS field study conducted at an underground stope and pillar zinc mine in eastern Tennessee. This study location will be referred to as Field Site D in this report. A detailed overview of this field site can be found in the Research Approach chapter. The installation of ECS antennas was attempted at several different locations both on the surface and underground. However, an adequate grounding bed connection could not be achieved because of the apparent low to non-existent electrical conductivity of the overburden. Given the general inability to establish a suitable electrical connection between antenna structures, no formal ECS testing was conducted at Field Site D. MCS underground to surface and surface to underground communications were examined at Field Site D. Signal indicator values that fell between -20 and -100 could be received by the MCS at this field site. A map surface and underground transmitting stations including an overlay of large-scale faults is displayed in Figure 33. All designations utilized in this section are specific to Field Site D and do not relate to other similar or identical labels mentioned in other sections. All reported transmission distances are point to point distances and not projected distances onto a horizontal or vertical plane.

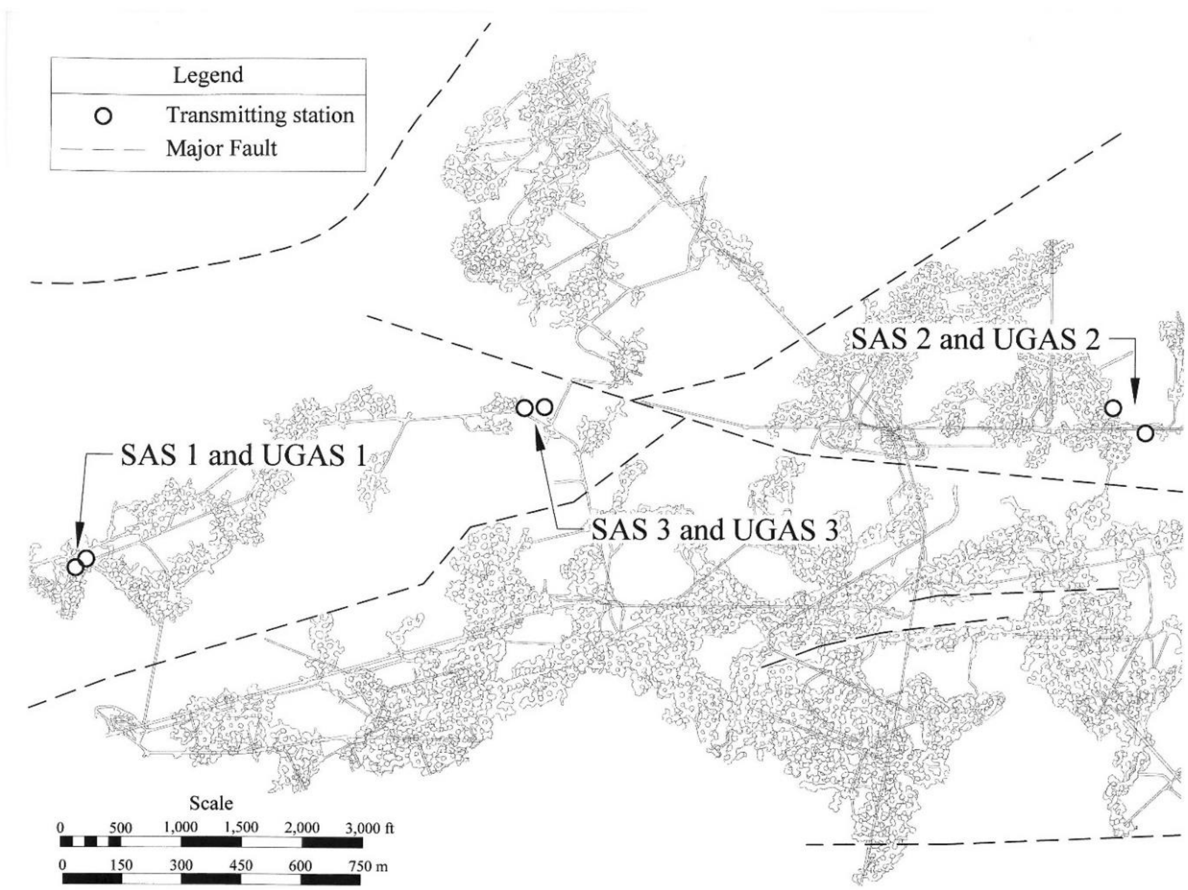


Figure 33. Map of the surface and underground transmitting stations surveyed at Field Site D.

MCS Results

Underground to Surface Transmissions

Three transmitting locations, UGAS 1, UGAS 2, and UGAS 3, were used to determine the ability of the MCS to communicate from underground to the surface. The loop antenna at UGAS 1 was fully deployed around a pillar directly below a cased borehole designed to house high voltage power cables. At the time of this field test, no electrical infrastructure had been installed in this borehole. Approximately 75% of the antenna intersected an angled surface, which dipped approximately 20° to the northwest. This area of the mine was devoid of roof control devices, such as bolts and mesh, and was geologically mundane with no notable anomalous attributes. High voltage infrastructure was also not present in the vicinity of UGAS 1. A map of surface locations that were able to receive messages from UGAS 1 is displayed in Figure 34.

From UGAS 1, clear underground to surface communications could be received up to a distance of 520 m (1,700 ft) on both the V-channel and the T-channel. The range of the transmissions was slightly greater toward the northwest, which was incidentally the direction toward which a portion of the antenna was dipping. Text clarity began to deteriorate at signal indicator values less than -65. Messages could no longer be received at signal indicator values less than -85.

The loop antenna at UGAS 2 was fully deployed around a pillar below a tailings impoundment. A shallow body of water about 0.3 m (1.0 ft) deep was present in the vicinity of UGAS 2. Approximately 50% of the antenna was located around this body of water. Portions of the antenna in the vicinity of the pond were also submerged. The remaining portion of the antenna was located on a flat, dry surface and suspended in one section to negotiate a short, steep hill. An active haul road with periodic diesel powered vehicle traffic was located approximately 30 m (100 ft) from the loop antenna. From UGAS 2, no underground to surface communications could be received around the tailings pond with attempted transmission distances ranging from 230 m (760 ft) to 690 m (2,250 ft) during the traverse.

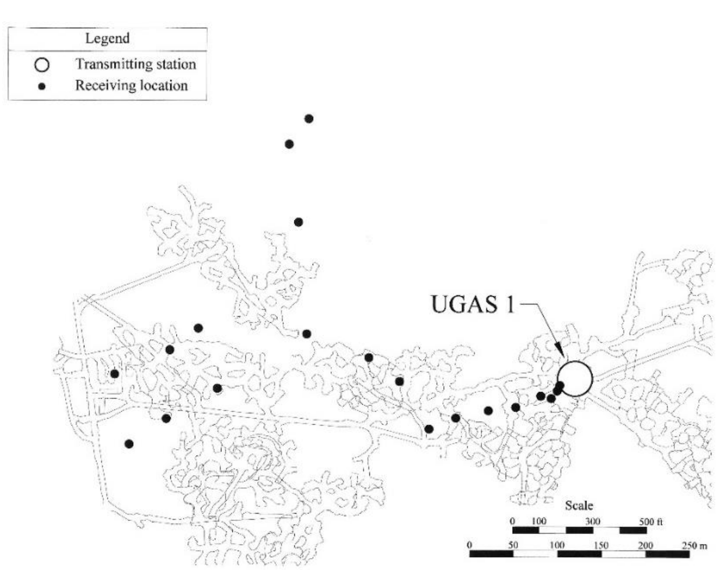


Figure 34 Map of the surface locations that received messages from UGAS 1.

The loop antenna at UGAS 3 was fully deployed in concentric circles around a refuge chamber along a main travelway. The available space at this location was limited by the traffic that would occasionally move past the refuge chamber. As a result, the loop antenna was wrapped around the refuge chamber four times to utilize the full length of the antenna. Otherwise, only 25% of the loop could be utilized at this location. Although not ideal, this antenna layout represented a deployment scenario that could potentially occur during an emergency situation with similar constraints.

From UGAS 3, underground to surface communications could not be received within the attempted transmission distances ranging from 130 m (430 ft) to 400 m (1,300 ft) during the traverse. The signal indicator values recorded from UGAS 1 as a function of distance from the transmitting antenna are presented in Figure 35. This figure shows that the received signal indicator value decreased linearly with distance with one exception represented by the T-channel data point recorded at a transmission distance of over 500 m (1,600 ft). This outlier was logged in the vicinity of a high voltage overhead power line. A summary of signal indicator values and transmission distances from the underground to surface traverses can be found in Figure 35 and Table 19, respectively.

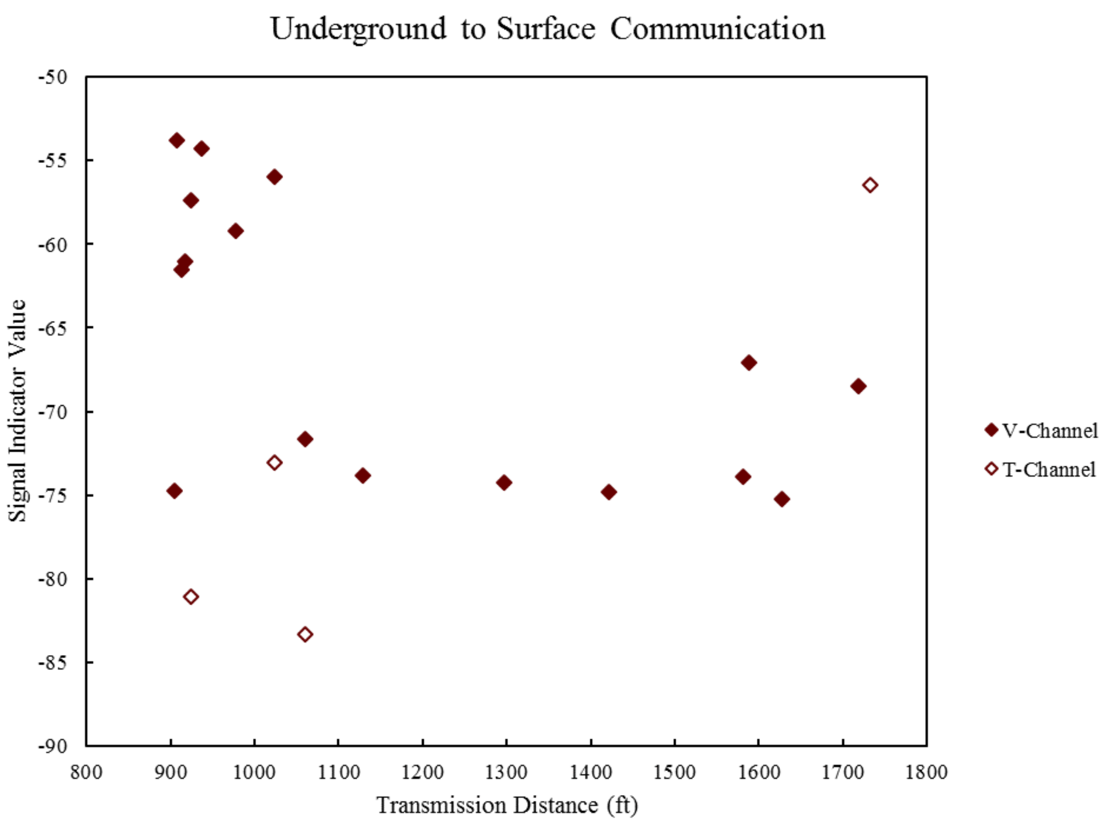


Figure 35 Signal indicator values from received messages gathered during the underground to surface survey as a function of transmission distance from UGAS 1.

Table 19. Summary of the underground to surface survey results.

Antenna Station	Channel	Maximum Transmission Distance
UGAS 1	V	520 m (1,700 ft)
UGAS 1	T	520 m (1,700 ft)
UGAS 2	V and T	0 m (0 ft)
UGAS 3	V and T	0 m (0 ft)

Surface to Underground Transmissions

Three transmitting locations, SAS 1, SAS 2, and SAS 3, were used to determine the ability of the MCS to communicate from the surface to underground. The extent of surface to underground communications are displayed in Figures 36 and 37. The loop antenna at SAS 1 was fully deployed on a level surface adjacent to the cased power borehole described in the previous section. A high voltage substation was also located nearby as well as a single high voltage power line suspended above SAS 1.

From SAS 1, clear surface to underground communications could be received up to a distance of 1,200 m (3,900 ft) on the V-channel and 550 m (1,800 ft) on the T-channel. Messages could not be received only at a limited number of underground locations. A reception anomaly occurred around a refuge chamber located in a spur along the main travelway. A series of small, densely spaced water inundated fractures were present in the rib next to this refuge chamber. When the MGU crossed this fracture, communications from SAS 1 were suddenly lost. This phenomenon was observed only during this surface to underground test at the location highlighted in Figure 36. Text clarity did not deteriorate with decreasing signal strength. Instead, messages were suddenly lost when the extent of the transmission range was reached. Messages could no longer be received at signal indicator values less than -85.

The loop antenna at SAS 2 was fully deployed on a level, elevated area of the tailings pond composed of compacted but unconsolidated material. This transmitting site overlooked a tailings impoundment and was selected to examine the ability of the MCS to communicate through unconsolidated material from the surface to underground. From SAS 2, clear surface to underground communications could be received up to a distance of 950 m (3,100 ft) on the V-channel and 630 m (2,100 ft) on the T-channel. Communications were successfully received at all of the underground locations surveyed during this test. Text clarity began to deteriorate at signal indicator values less than -80. Messages could no longer be received at signal indicator values less than -81.

The loop antenna at SAS 3 was fully deployed on a level, open field located near the mine portal. This transmitting site was positioned over a refuge chamber and between the two faults displayed in Figure 33. Communications were successfully received at all of the underground locations surveyed during this test. From SAS 3, clear surface to underground communications could be received up to a distance of 730 m (2,400 ft) on both the V-channel and the T-channel. Text clarity did not deteriorate across the traverse and were not lost during the traverse. The minimum signal indicator value recorded during this survey of SAS 3 was -80. The signal indicator values recorded from SAS 1-3 as a function of distance from the transmitting antenna are displayed in Figure 38, which shows that the signal indicator values of the received messages decreased linearly with distance. A summary of transmission distances from SAS 1-3 is presented in Table 20.

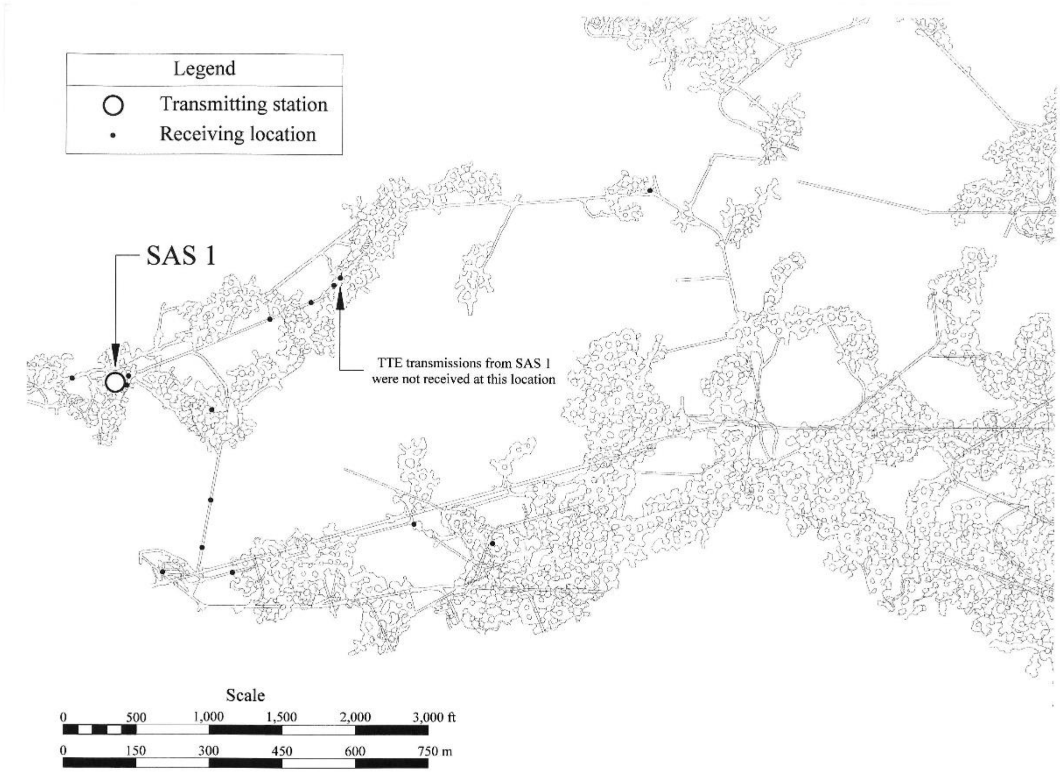


Figure 36. Map of the underground locations that received messages from SAS 1.

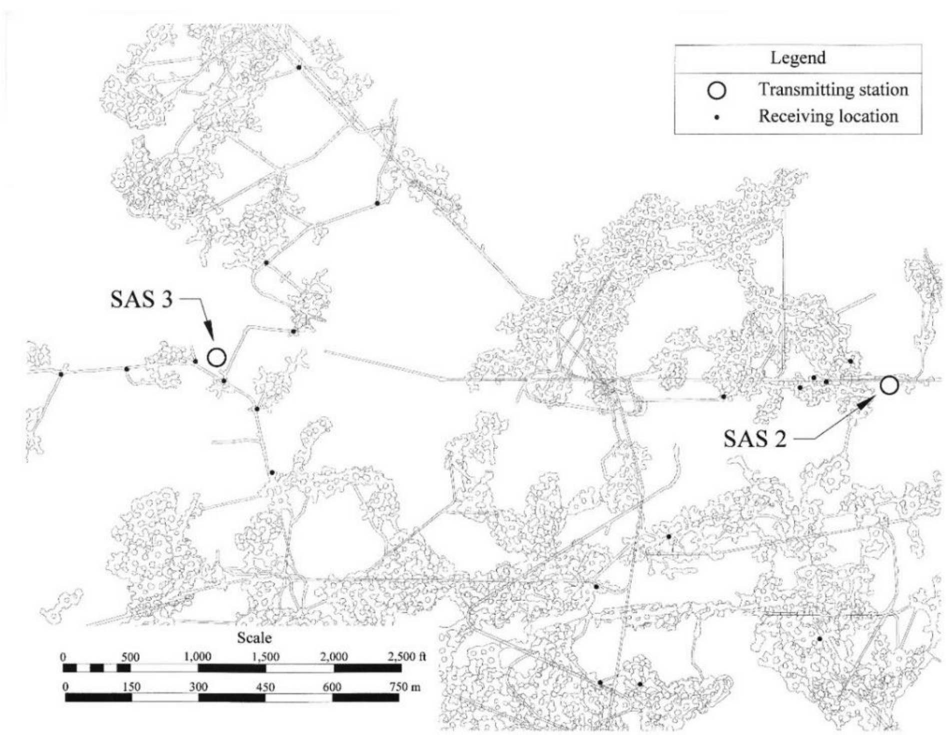


Figure 37. Map of the underground locations that received messages from SAS 2 and 3. Receiving locations for SAS 2 and 3 are grouped respectively to the right and to the left of the figure.

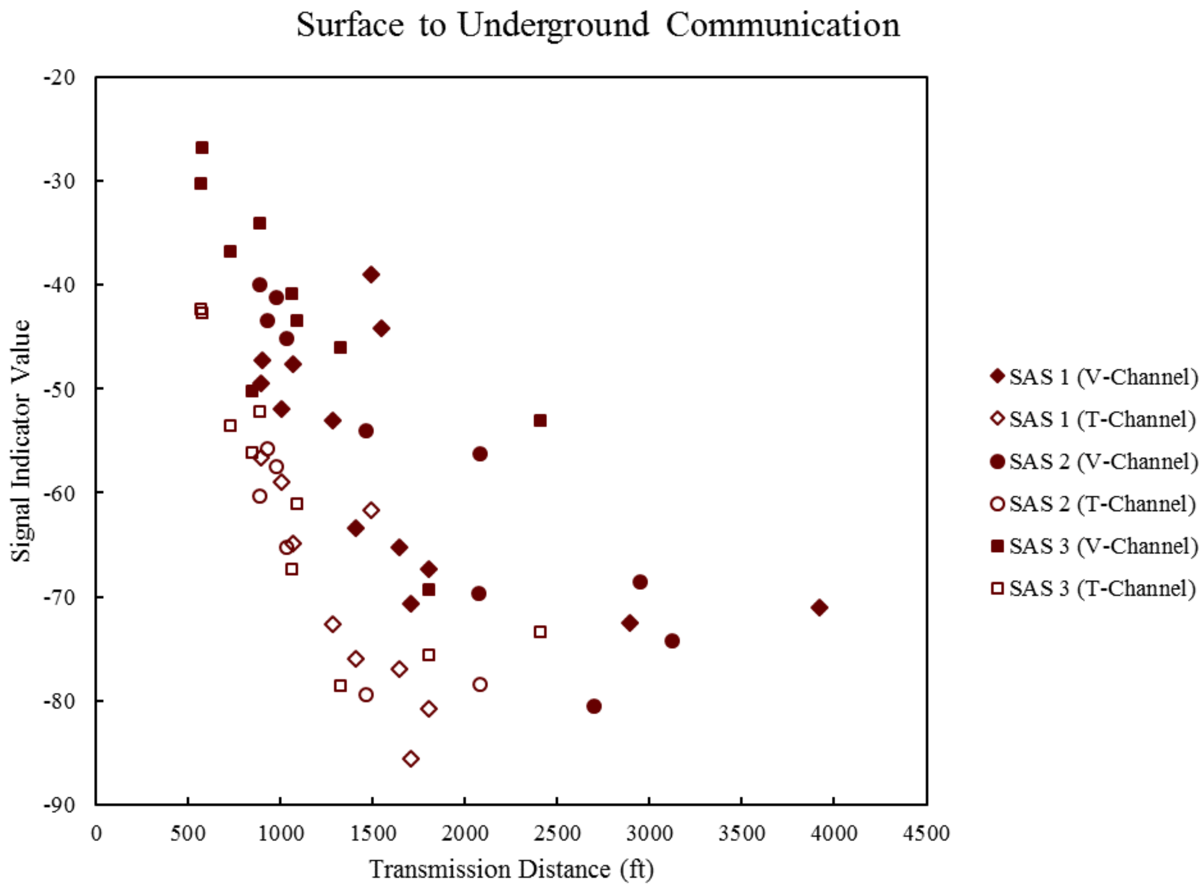


Figure 38. Signal indicator values from the surface to underground travers as a function of transmission distance from the transmitting antenna.

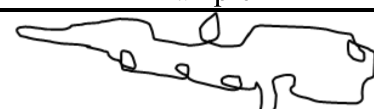
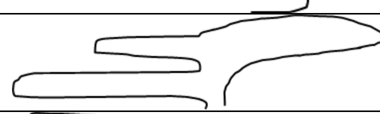
Table 20. Summary of the surface to underground survey results.

Antenna Station	Channel	Maximum Transmission Distance
SAS 1	V	1,200 m (3,900 ft)
SAS 1	T	550 m (1,800 ft)
SAS 2	V	950 m (3,100 ft)
SAS 2	T	630 m (2,100 ft)
SAS 3	V	730 m (2,400 ft)
SAS 3	T	730 m (2,400 ft)

Antenna Configuration Test

Nine different antenna configurations were tested using the elevated transmitting power of the MSU. Two V-channel messages and two T-channel messages were sent for each antenna configuration. Only the Type I antenna configuration could not successfully communicate with the MGU on the surface. The unsuccessful Type I configuration utilized the full length of the loop antenna laid out in large oval that had a short axis diameter of 30 cm (12 in). The outer edges of the oval contained several loops were the antenna was purposefully twisted such that the antenna was laid over itself. The most surprising result was produced from the Type VII antenna configuration in which the entire length of the antenna was rolled into a ball and then thrown into an open area. This configuration produced clear messages with only a ten-unit reduction in the signal indicator value. The test that utilized one quarter of the loop antenna's length performed the poorest among the nine configurations tested with a 75% reduction in the signal indicator value. All of the remaining configurations performed similarly in terms of the signal indicator value.

Loop antenna layouts tested at Field Site D.

Antenna Layout	Example
I	
II	
III	
IV	
V	
VI	
VII	
VIII	Half-length loop
IX	One-quarter length loop

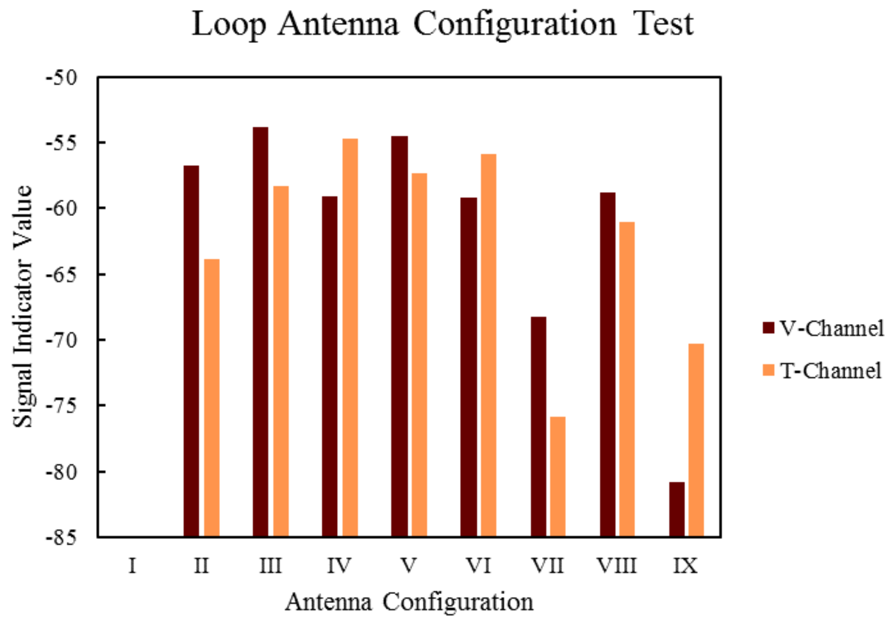


Figure 39. Signal indicator values from antenna layout testing using underground transmission power.

Summary

The MCS demonstrated the ability to establish one-way surface to underground TTE communications at a maximum range of 1,200 m (3,900 ft) on the V-channel. This transmission distance was achieved regardless of the presence of faults, anthropogenic artifacts, and unconsolidated overburden as well as without anthropogenic enhancement. The observed transmission range exceeded the rated ability of the MCS. The enhanced surface to underground transmission distance appears to have been a function of the highly consolidated nature of the overburden. The only exception occurred in a single area at Field Site D that contained water inundated fractures in which MCS communications were completely prevented. The antenna configuration test performed on the MCS loop antenna showed that poor antenna layouts did not have a detrimental effect on MCS communications. This result suggests that the MCS can function in areas that restrict the loop antenna deployment.

Underground to surface communications were largely unsuccessful at Field Site D. Only communications from UGAS 1 were able to be received on the surface. The overburden in this area of the mine has a thickness of approximately 260 m (850 ft) and contained a newly drilled power borehole. The inability of the MCS to transmit from UGAS 2 and 3 underground were potentially caused by some of the unique properties at these two locations.

UGAS 2 was located under a tailings pond composed of unconsolidated fill material and near a moderately sized shallow pond. Although these characteristics did not affect surface to underground communication, the combination of unconsolidated fill and water may have been sufficient to obstruct the transmission produced by the reduced transmitting power of the MGU. The loop antenna at UGAS 3 was deployed using multiple concentric circles to wrap refuge chamber. Although this antenna layout likely explains the loss of messages from UGAS 3, this conjecture remains subjective because an ideal layout was not tested at this location.

Field Site E

Introduction

The following section contains an overview of the MCS field study conducted at an underground stope and pillar limestone mine in southern Virginia. This study location will be referred to as Field Site E in this report. A detailed overview of this site can be found in the Research Approach chapter. The installation of ECS antennas was attempted at several different locations both on the surface and underground. However, an adequate grounding bed resistance could not be achieved at any underground location. The overburden exhibited an apparent low to non-existent electrical conductivity, which prevented a connection between grounding beds. Given the general inability to establish a suitable electrical connection between antenna structures, no formal ECS testing was conducted at Field Site E. MCS underground to surface and surface to underground communications were examined at Field Site E. Signal indicator values that fell between -20 and -100 could be received by the MCS at this field site. A map of the transmitting stations used at this field site is displayed in Figure 40. All designations utilized in this section are specific to Field Site E and do not relate to other similar or identical labels mentioned in other sections.

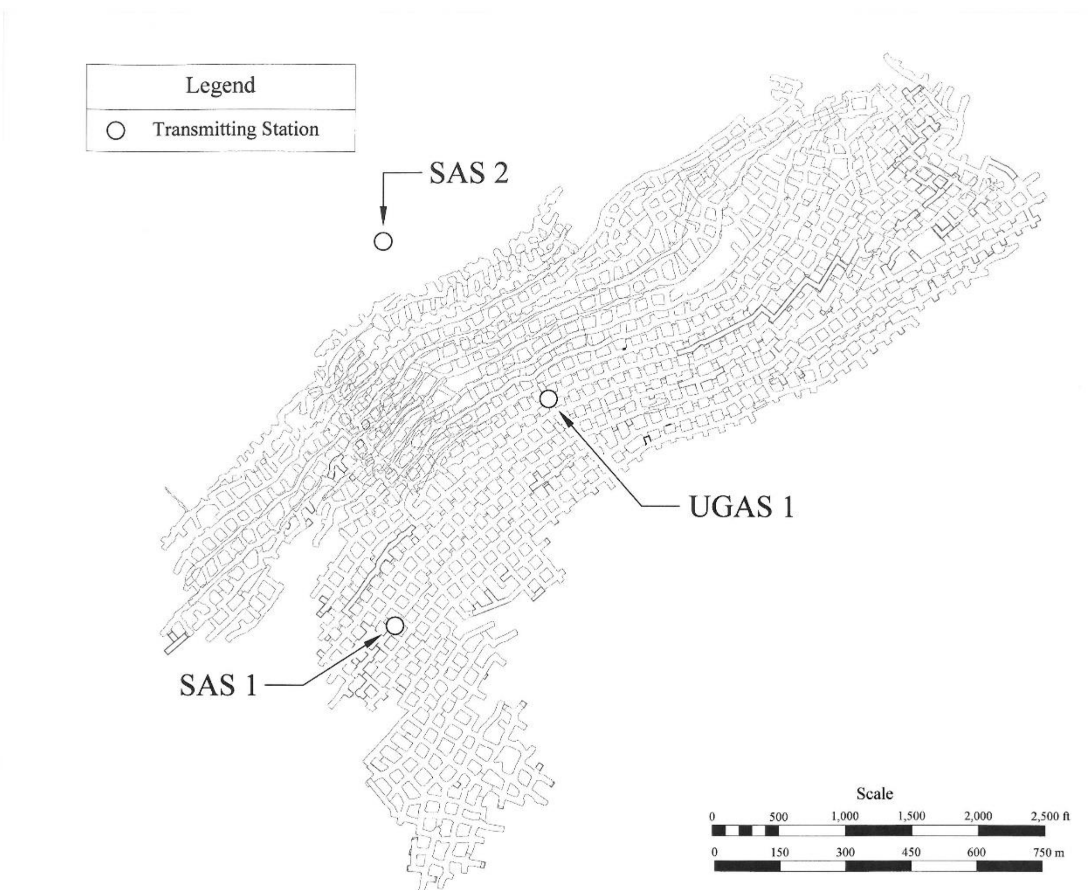


Figure 40. Map of the surface and underground transmitting locations used at Field Site E.

MCS Results

MCS performance data was gathered from two communication modes across three individual traverses. These traverses were used to survey two surface transmitting stations and one underground transmitting station displayed in Figure 40. All reported transmission distances are point to point distances and not projected distances onto a horizontal or vertical plane.

Underground to Surface Transmissions

One transmitting location at Field Site E, UGAS 1, was used to determine the ability of the MCS to communicate from underground to the surface. The loop antenna was fully deployed in an open, level entry on the 12th level of the mine. From UGAS 1, no underground to surface communications could be received on the surface. Increased surface power transmissions were also tested at several shallow and deep location with no success. Attempted transmission distances between UGAS 1 and the surveyed surface receiving locations ranged from 180 m (600 ft) to 1,200 m (3,900 ft). This area of the mine did not contain any geologic or anthropogenic artifacts that could be directly attributed to this lack of surface reception. However, the voids created by the 11 overlying mine levels located between UGAS 1 and the surface may have contributed to the complete lack underground to surface communications.

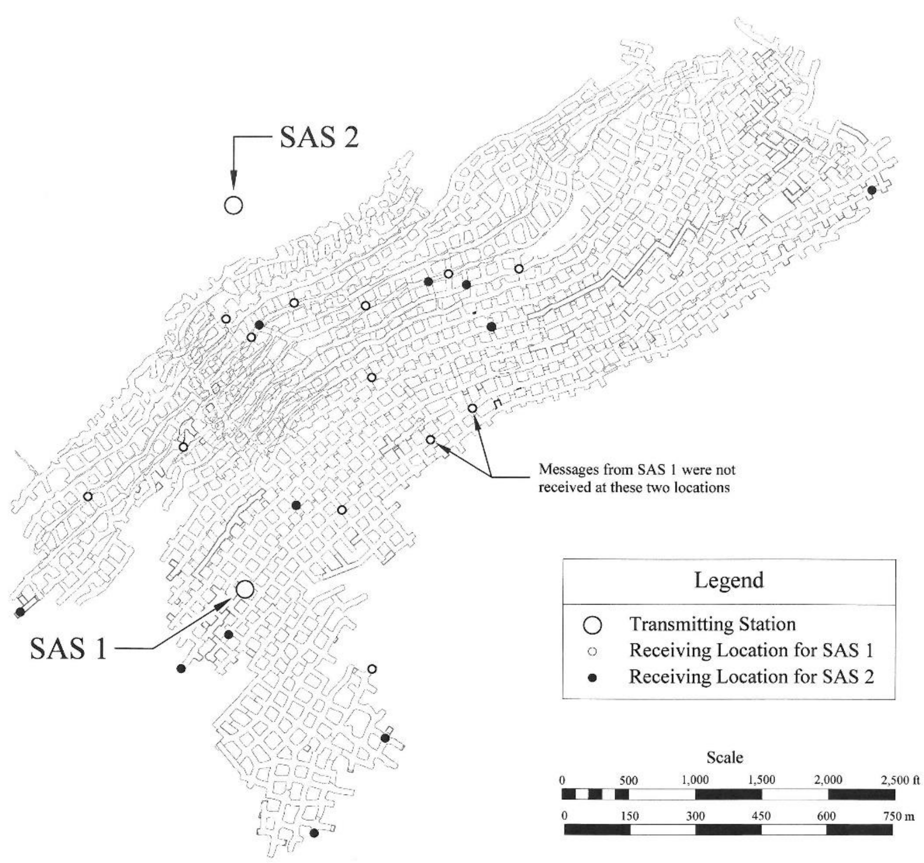


Figure 41. Map of the underground locations that received messages from SAS 1 and 2.

Surface to Underground Transmissions

Two transmitting locations, SAS 1 and SAS 2, were used at Field Site E to determine the ability of the MCS to communicate from the surface to underground. The extent of surface to underground communications are displayed in Figure 41. The loop antenna at SAS 1 was fully deployed on a level clearing located above the top hanging wall center axis of the mine. From SAS 1, clear surface to underground communications could be received up to a distance of 1,000 m (3,300 ft) on both the V-channel and the T-channel. Messages could not be received at the two locations highlighted in Figure 41. These two areas were positioned next to a series of small water inundated fractures located in the mine roof and ribs. When the MGU was moved beyond these fractures, communications from SAS 1 were suddenly restored. This phenomenon has been previously observed at Field Site D. No other occurrences of similar interference were noted during this surface to underground test of Field Site E. Text clarity began to deteriorate at signal indicator values less than -75. Messages could no longer received at signal indicator values less than -93.

The loop antenna at SAS 2 was fully deployed on a level, elevated surface composed of post-reclamation tailings material on top of a closed tailings impoundment. This transmitting location was selected to examine the ability of the MCS to communicate through unconsolidated material from the surface to underground. From SAS 2, clear surface to underground communications could be received up to a distance of 1,500 m (5,000 ft) on both the V-channel and the T-channel. Communications were successfully received at all of the locations surveyed during this test. Text clarity began to deteriorate at signal indicator values less than -80. The lowest signal indicator value recorded during the SAS 2 survey was -95. The signal indicator values recorded from SAS 2 and 3 as a function of distance from the transmitting antenna are presented in Figure 42. This figure shows that the signal indicator values of the received messages decreased linearly with distance. Table 21 presents a summary of the surface to underground transmission distances.

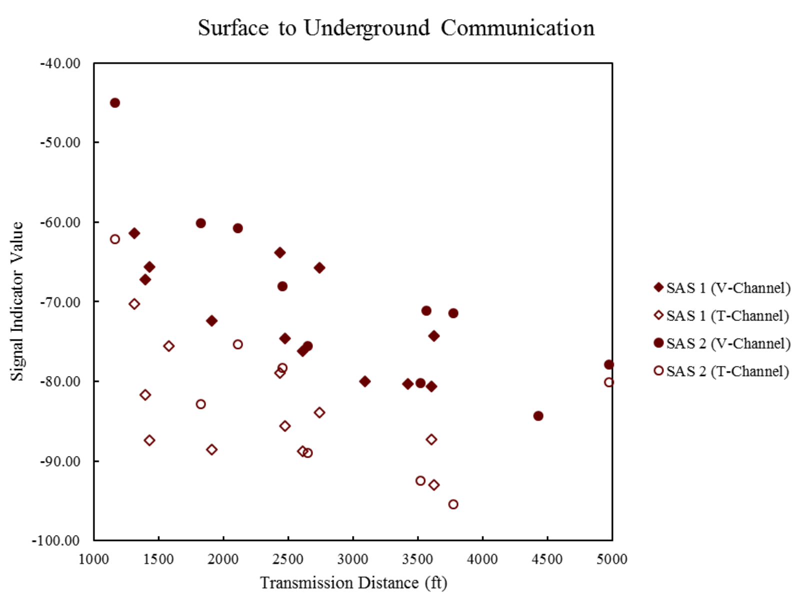


Figure 42. Signal indicator values from the surface to underground surveys as a function of transmission distance from the transmitting station.

Table 21. Summary of the surface to underground test results.

Antenna Station	Channel	Maximum Transmission Distance
SAS 1	V	1,000 m (3,300 ft)
SAS 1	T	1,000 m (3,300 ft)
SAS 2	V	1,500 m (5,000 ft)
SAS 2	T	1,500 m (5,000 ft)

Summary

The MCS demonstrated the ability to establish one-way surface to underground communications at a maximum range of 1,500 m (5,000 ft) on both the V-channel and the T-channel. This transmission distance was achieved regardless of the presence of faults, anthropogenic artifacts, and unconsolidated overburden. No anthropogenic enhancement, such as signal propagation along a metallic conduction, was observed that may have extended the range of the MCS. The observed transmission range exceeded the rated ability of the MCS. The enhanced surface to underground transmission distance appears to have been a function of the highly consolidated nature of the overburden at Field Site E. Underground to surface communications were unsuccessful at this field site. Transmission distances ranging from 180 m (600 ft) to 1,200 m (3,900 ft) were attempted at all accessible locations of this mine. The use of surface power transmissions was also examined without success. Field site E was the first and only multi-level underground mine that was surveyed during this project. Although the presence of 12 large, consecutive open voids may have been sufficient to interfere with lower power MCS transmissions, no formal conclusion can be made with the lack of a suitable analog test.

Geophysical Simulations of TTE Communications

Section Author: Chester J. Weiss, Ph. D., Sandia National Laboratories (cjweiss@sandia.gov)

APhiD TTE Antenna Propagation Simulation Method

Numerical simulations of TTE antenna propagation were computed by the method of finite differences on a 3D rectilinear grid. The grid cells were assigned realistic values of Earth conductivity. The simulation method that was applied can be summarized as follows. The electric and magnetic fields of the governing Maxwell equations are recast in terms of the frequency-domain magnetic vector and electric scalar potentials, and the "full physics" of both high-frequency wave and low-frequency diffusion propagation are retained. For a given TTE antenna configuration, the potentials are determined using a Lorenz gauge condition by solving the large, complex-valued linear system of equations resulting from discretizing the potentials and the underlying Earth conductivity model on a 3D Cartesian grid for a fixed frequency.

Once the potentials are computed, the electric and magnetic fields can be derived from straightforward numerical differentiation of the potentials. Output of the fields and conductivity models from the simulations is given in VTK data format, which is readable by most modern 3D data visualization tools such as Paraview or VisIt. Magnetic field components normal to the x, y, and z directed cell faces in the grid are contained in the Bx.vtk, By.vtk and Bz.vtk files. Electric field components along cell edges are contained in the Ex.vtk, Ey.vtk and Ez.vtk files. A composite vtk file (EM_cell.vtk) contains vector-valued interpolations of the electric and magnetic fields at cell centers. File sigma.vtk contains values of the specific conductivity model. All quantities are reported in SI units. Hence, the simulation output is a 3D data volume of the complete electromagnetic environment and its causative conductivity model.

Other details to note about the modeling approach are provided as follows: Variations in magnetic permeability are not considered. The TTE source antenna is co-located along cell edges internal to the 3D grid and is thus restricted to layout geometries that are either rectangular or "stair-cased" to approximate a curved path. Furthermore, the physical extent of the grid was chosen by trial-and-error to be a distance sufficiently far away from a region of interest within the grid (e.g., the area above a TTE deployment) where numerical errors from spurious grid-boundary reflections are relatively insignificant.

Description of TTE Scenario Databases.

A comprehensive database of numerical simulations was developed to represent a broad range of TTE scenarios in various mining environments shown in Figure 43. In each simulation, the numerical grid is composed of 202 x 202 x 139 nodes in the x, y and z planes, respectively, over the physical domain $|x|, |y| < 1$ km in lateral dimensions and depth $0 < z < 1$ km. Additionally, to accommodate air-propagation of the TTE signal, each mesh is overlain by a 400 m thick layer of resistive "air" with a conductivity 1E-8 S/m. The TTE loop antenna is taken to be a 30 x 30 m square loop operating at 3.2 kHz and deployed at depth within the "earth region" of the model and offset 160 m in the positive x and y directions.

For the faulted earth models, Figure 43, the Earth part of the mesh is decomposed into four quadrants shown in Figure 44, each with a uniform conductivity at discrete values of 1, 3.2, 10, 32 and 100 mS/m spanning a realistic range of geologic values presented in Figure 45. All permutations of the four quadrants at five conductivity values leads to a total of $5^4 = 625$ forward simulations. Within these permutations lie simple double half-space models such as those shown in the limestone scenario. Even simpler whole-space models of uniform conductivity where no fault is present and more complex zinc models where each of the quadrants can be different or even paired up for an effective three parameter model are presented. Complete model definitions, conductivity models in VTK format, model generation codes in Python and FORTRAN, and simulation outputs are available at "anodyne.unm.edu/TTE" for further analysis. Directory "Deep_Zinc" contains results for a 300 m TTE antenna depth whereas directory "Shallow_Zinc" contains analogous results for a shallow, 100 m TTE antenna depth.

For the remaining modeling scenarios, "Appalachia" and "Illinois Basin," a similar four parameter suite of models was constructed with each parameter taking on one of five values. In contrast to the quadrant models just described, these mining scenarios are dominated by layered geology with a potentially dipping overburden. Hence, instead of quadrant conductivity, the four model parameters for these models are layer conductivities (sigma_1 and sigma_2), the overburden thickness, and the dip of the overburden. Layer thickness is taken to be constant for all models at 10 m. Dips range from 0, 22.5, 45.0, 67.5 and 90.0 degrees. Overburden thicknesses range from 0, 25, 50, 75 and 100 m, and layer conductivities, as before, range from 1, 3.2, 10, 32 and 100 mS/m.

TTE source antenna depth is 300 m. The Appalachian model is a degenerate case of the Illinois Basin model for an overburden of zero-dip. As before, a total of 625 model simulations were computed. Input files, results, and model descriptions are contained in directory TTE_IL_Basin on anodyne.unm.edu/TTE. Naming conventions in the database for each of 625 models from the two model classes "Zinc" and "Illinois Basin" are described in Figures 46 and 47, respectively. Representative conductivity models from each of the classes, along with the accompanying database nomenclature, are shown in Figure 48.

To demonstrate the potential of the database just described for TTE propagation analysis, a sample of results from parametric studies on the effect of overburden dip and conductivity contrast between "Appalachian" and "Illinois Basin" models and the effect of conductivity contrast between neighboring fault blocks "Zinc" and "Limestone" models are summarized. For example, the models show that overburden dip strongly distorts the radiation pattern of the TTE field in Figure 49, an effect most likely modulated by the conductivity contrast of the inter-beds within the model in Figure 50. In the case of horizontal inter-beds (Appalachia), the effect of resistive inter-beds is to generally boost the strength of the TTE signal by a factor of ten or more without distorting its radiation pattern in Figure 51. Similarly, the effect of conductivity contrast on "Limestone" and "Zinc" mining scenarios can be extreme, resulting in a peak TTE signal that is hundreds of meters away laterally from the location directly over the TTE antenna in Figures 52 and 53.

Although specific mining scenarios involving TTE/rail coupling are absent, the database of results represents a "learning set" for future TTE analyses, which does not depend on specific expertise in numerical modeling of Maxwell's equations in 3D. Such a database of results is not available in the mining or exploration geophysics communities. Extracting specific answers to particular TTE scenario questions (e.g., What is the effect of a wet vs. a moist hanging block on signal propagation?) is simplified with the existence of this resource. A database search can be executed rather than the tedious task of mesh-design and algorithm verification. Input scripts and model-definition codes are provided with the database so that the simulations may be supplemented with additional results in the future.

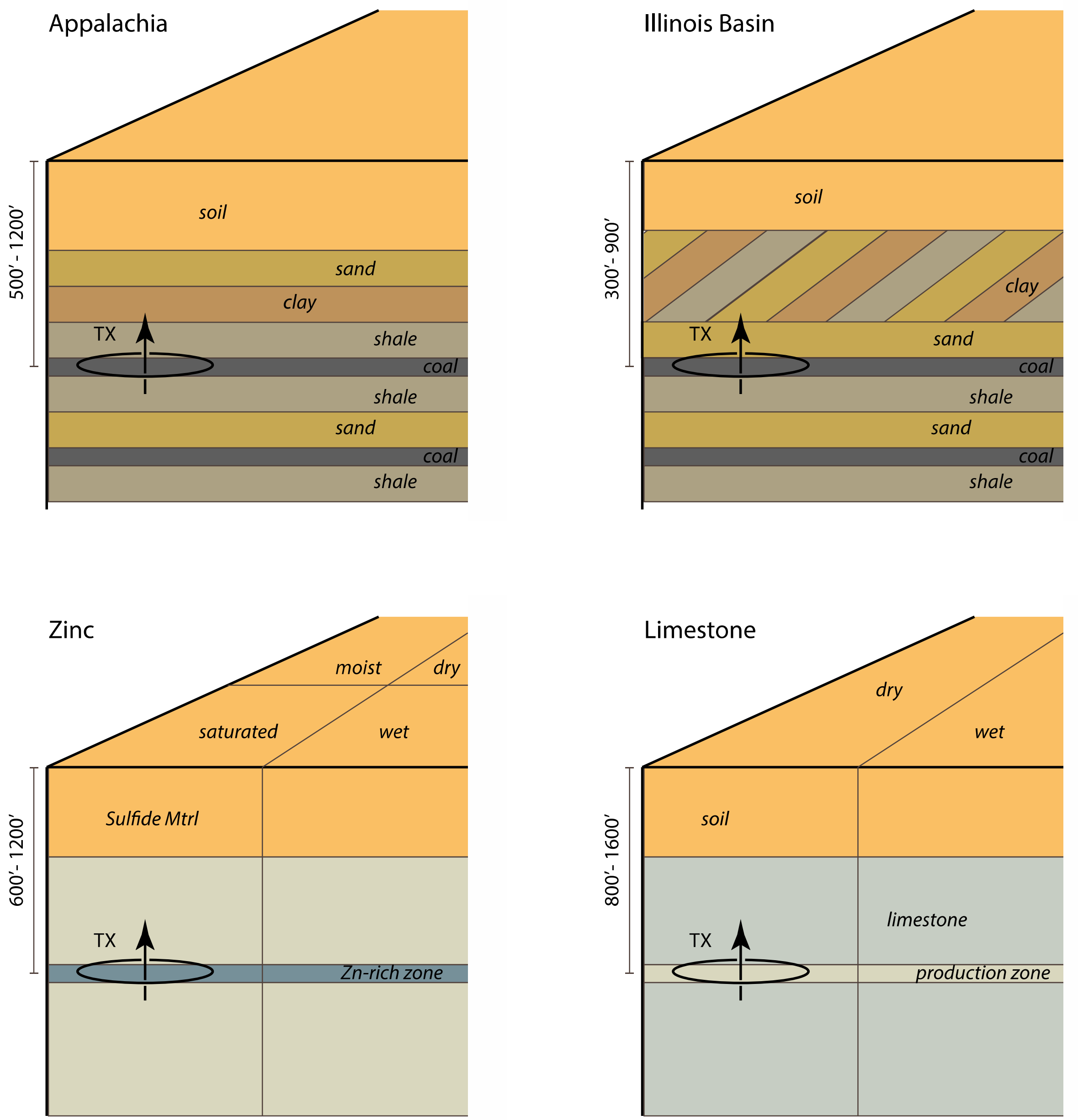


Figure 43. Representative mining environments for TTE deployment. Structurally, the single-fault Limestone geometry is a subset of the more general double-fault Zinc geometry. Similarly, the horizontal layering in the near surface of the Appalachia geometry is a subset of the more general Illinois basin geometry where the near-surface can take on variable stratigraphic dip.

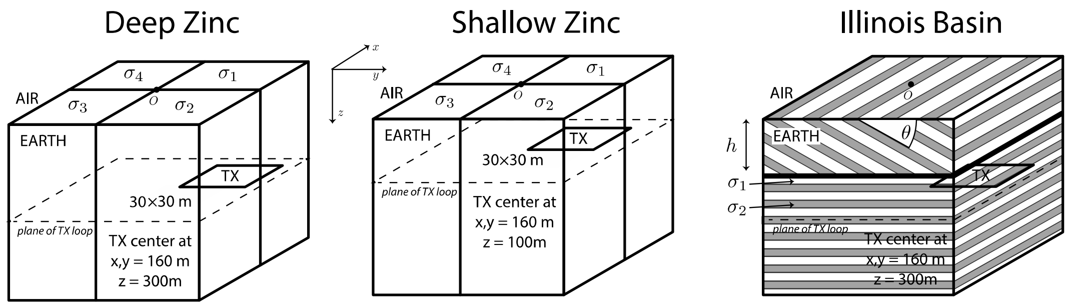


Figure 44. Sketch of the two model classes contained in the database. In each class, Zinc or Illinois Basin, are four model parameters to be considered. For the Zinc class, the model parameters are the conductivity values for each quadrant of the model. Degenerate cases where neighboring quadrants share the same conductivity value are therefore representative of the Limestone, single-fault geometry in Figure 43. For the Illinois Basin class, the model parameters are overburden depth, stratigraphic dip of the overburden, and the conductivity values for a binary sequence of alternating thin beds in both the overburden and below.

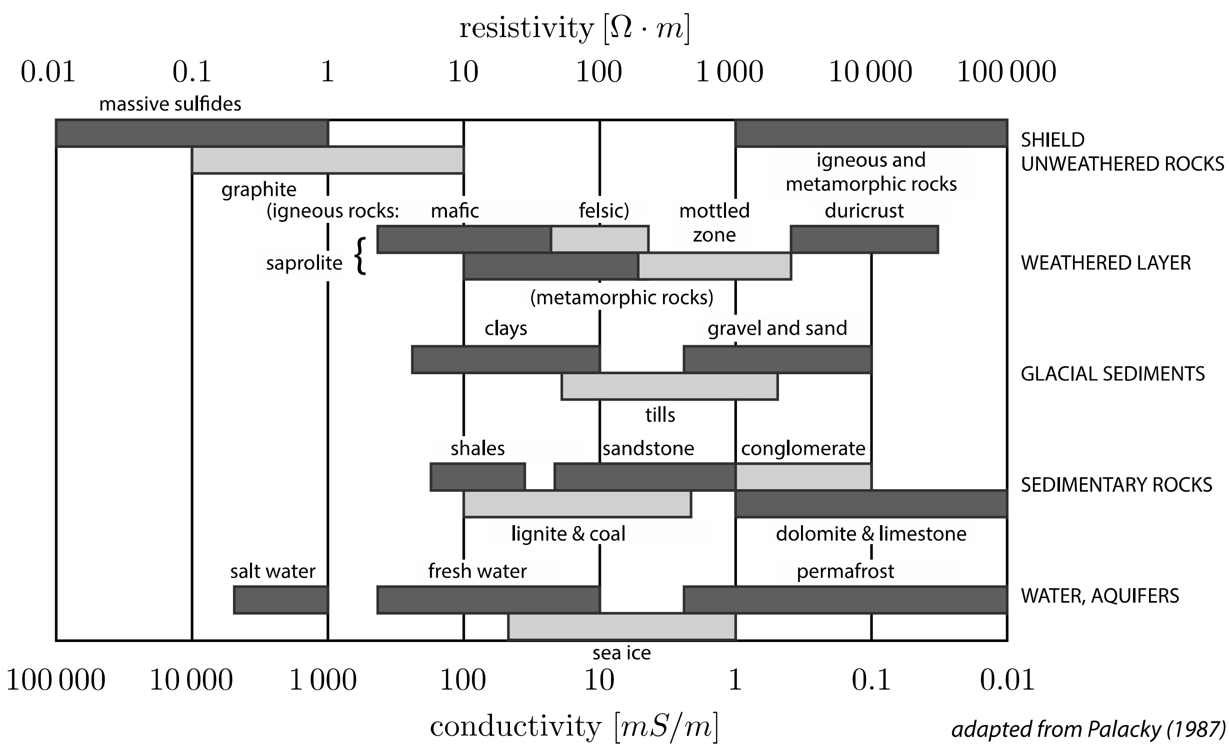
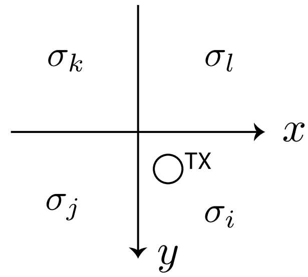


Figure 45. Conductivity values for common geo-materials. Values between 10 and 1,000 Ohm-m are used in the models shown in Figure 44.

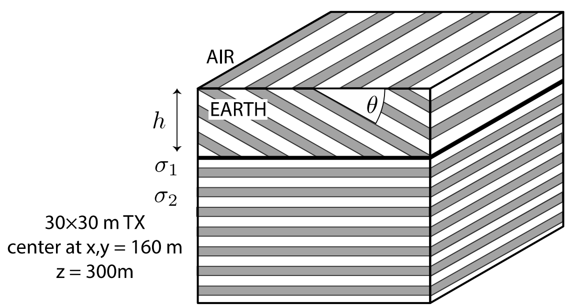
directory: model_*ijkl*



i,j,k,l	σ_i	σ_j	σ_k	σ_l
1	0.001	0.001	0.001	0.001
2	0.0032	0.0032	0.0032	0.0032
3	0.01	0.01	0.01	0.01
4	0.032	0.032	0.032	0.032
5	0.1	0.1	0.1	0.1

Figure 46. Database nomenclature for Zinc class models. Directory “model_ijl” contains a full numerical solution and model definition in VTK format for the conductivity model specified by the chart. For example, when i = j = k = l, the resulting conductivity model is a uniform whole-space. Similarly, when i = j ≠ j = k, the resulting model is a double half-space as shown in the Limestone geometry in Figure 43.

directory: model_*ijkl*



i,j,k,l	h_i	θ_j	σ_k	σ_l
1	0	0	0.001	0.001
2	25	22.5	0.0032	0.0032
3	50	45	0.01	0.01
4	75	67.5	0.032	0.032
5	100	90	0.1	0.1

Figure 47. Database nomenclature for Illinois Basin class of models. Directory “model_ijl” contains full numerical solution and model definition in VTK format for the conductivity model specified by the chart. For example, when j = 1, the resulting conductivity model has an overburden with zero-dip, and thus representative of the Appalachia model in Figure 43.

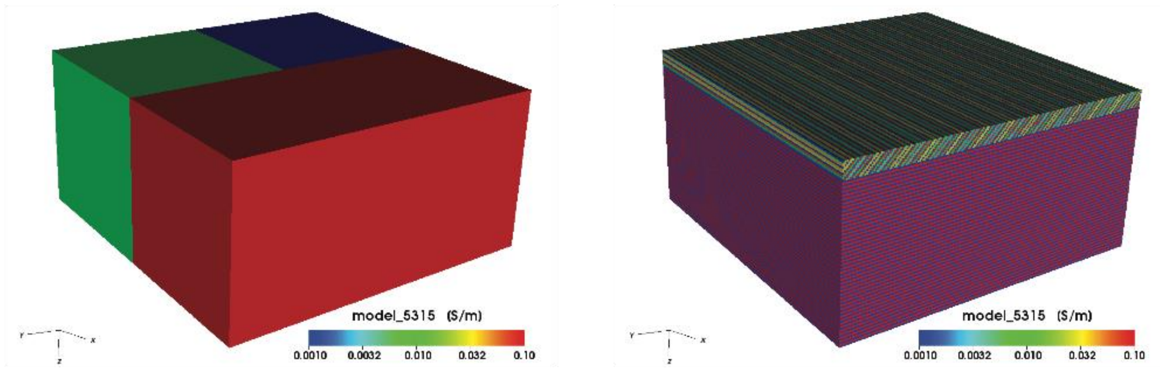


Figure 48. Example conductivity models for the Zinc (left) and Illinois Basin (right) classes of models. Database indexing for each of these models is (i, j, k, l) = (5, 3, 1, 5) in their respective master directories, following the tabulated values in Figures 46 and 47. Note that for the Zinc model, i = k = 5, resulting conductive fault block intersecting two smaller, resistive fault blocks. For the same indexing, the Illinois Basin model shows high conductivity contrast inter-bedding (k = 1, l = 5) and a thick (I = 5) and 45 degree (j = 3) dipping overburden. Green colors in the overburden represent conductivity values intermediate between the extremes of the conductivity contrast, 0.001 and 0.1 S/m, arise from numerical interpolation of the idealized conductivity model shown in Figures 44 and 47 onto the Cartesian, rectilinear grid used for numerical modeling.

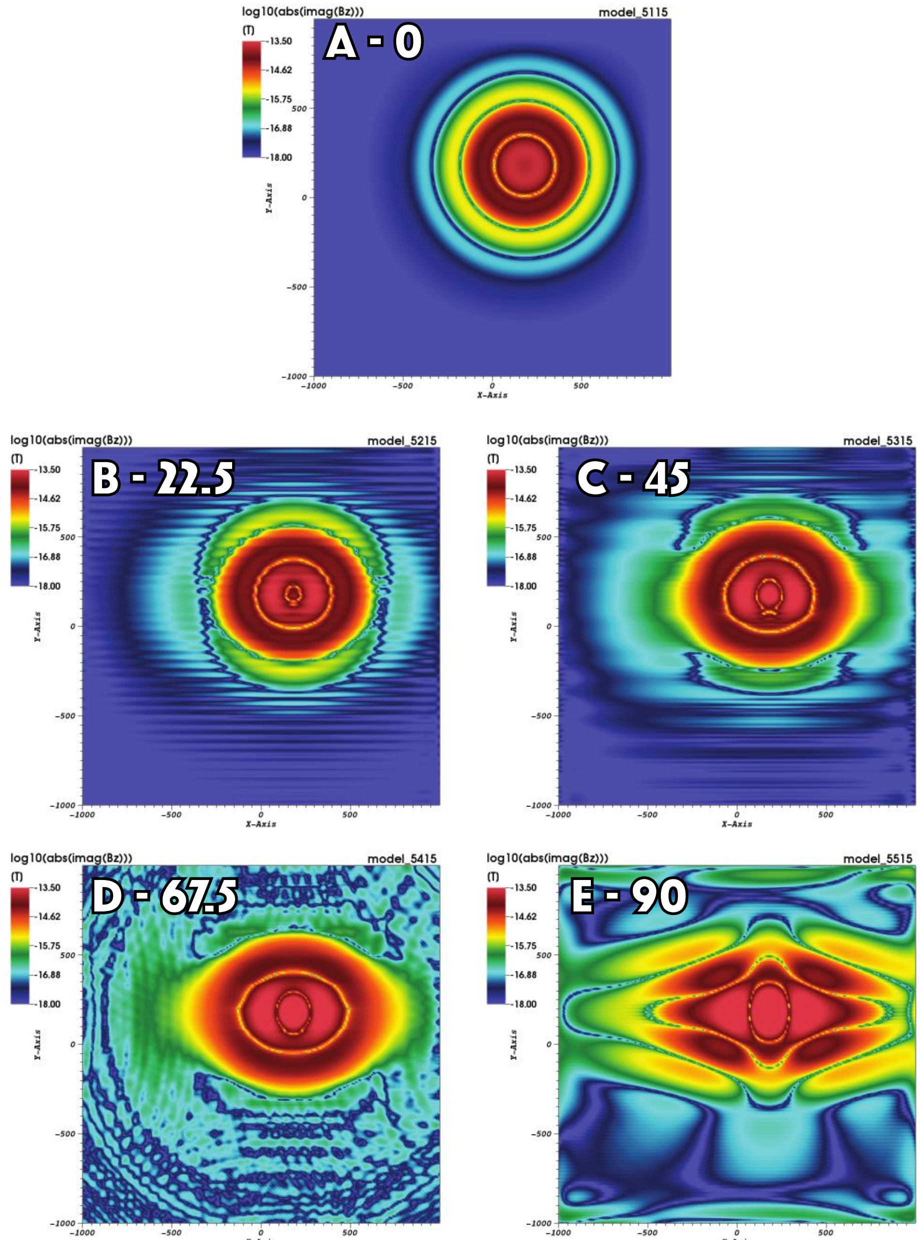


Figure 49. Parametric analysis on the effect of overburden dip for high contrast interbeds in the Illinois Basin class of models. Shown in color scale is the log10 magnitude of the quadrature phase of vertical magnetic field on the surface of the Earth for five different values of overburden dip (A-E, 0, 22.5, 45, 67.5 and 90 degrees, respectively). Interbed conductivity values are 0.1 and 0.001 S/m and overburden thickness is 100m. For the case of zero dip (a degenerate case of the Illinois Basin model which reduces to the Appalachia model), the TTE antenna at 300 m depth generates circularly symmetric radiation pattern on Earth's surface, as expected. However, as overburden dip increases, not only are individual beds resolvable in magnetic field response, but also the general shape of the radiation pattern changes strongly from the circularly symmetric case (A). Also apparent in the extreme case of vertical dip (E) is are isolated pockets of strong vertical B but with alternating sign. Dimensions in x and y are given in meters.

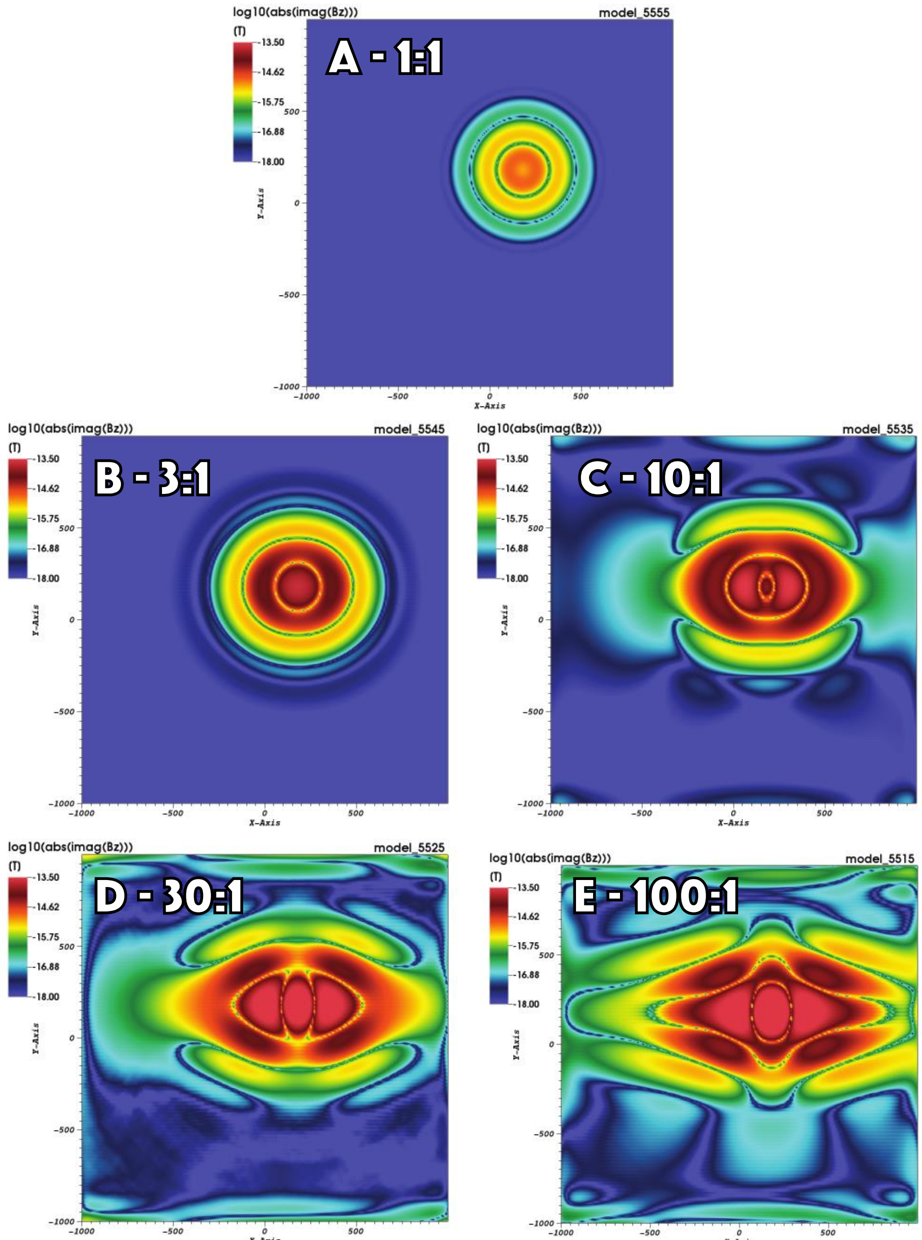


Figure 50. Parametric analysis on the effect of interbed conductivity contrast in the Illinois Basin class of models for the endmember case of vertically dipping layers. Shown in color scale is the log10 magnitude of the quadrature phase of vertical magnetic field on the surface of the Earth for five different contrasts in conductivity contrast (keeping one layer constant at 0.1 S/m, panels A-E show the effect when the other layers is 0.1, 0.032, 0.01, 0.0032 and 0.001 S/m, respectively). Overburden thickness thickness is 100m. For the degenerate case of a 1:1 contrast (panel A) the response is simply that of a uniform halfspace. Panel E, the high contrast case, is equivalent to panel E in figure 7. Dimensions in x and y are given in meters.

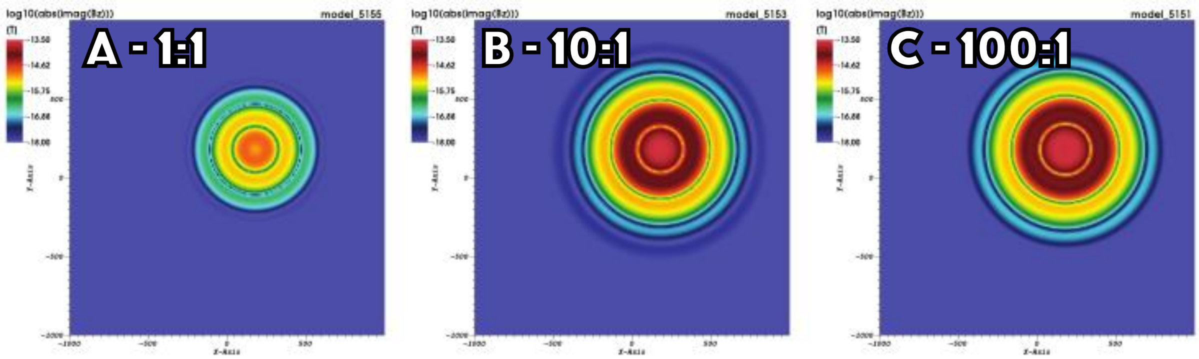


Figure 51. Parametric analysis on the effect of inter-bed conductivity contrast in the Appalachia class of models. Shown in color scale is the log10 magnitude of the quadrature phase of vertical magnetic field on the surface of the Earth for three different contrasts in conductivity contrast (keeping one layer constant at 0.1 S/m, panels A-C show the effect when the other layers is 0.1, 0.01, and 0.001 S/m, respectively). Overburden thickness is 100m. For the degenerate case of a 1:1 contrast (panel A) the response is simply that of a uniform half-space. Panel A, half-space case, is equivalent to panel A in Figure 50. Dimensions in x and y are given in meters.

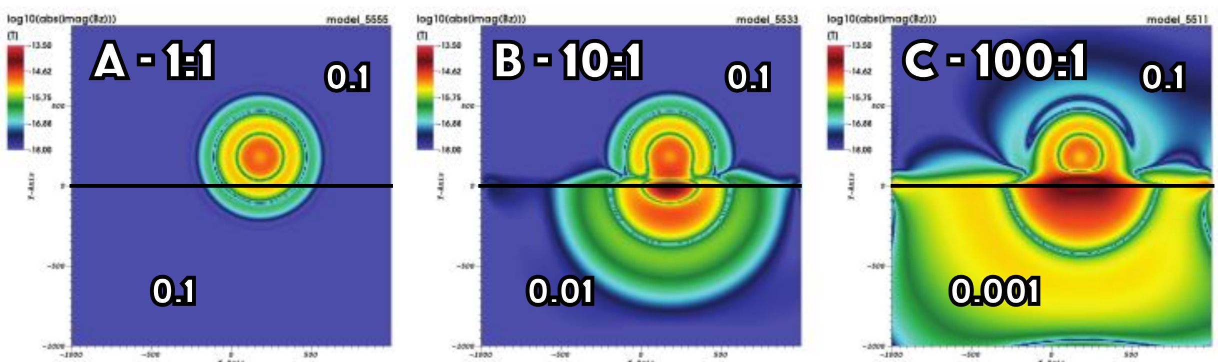


Figure 52. Parametric analysis on the effect of fault block conductivity contrast in Limestone class of models with a 300 m TTE antenna depth. Shown in color scale is the log10 magnitude of the quadrature phase of vertical magnetic field on the surface of the Earth for three different contrasts in conductivity contrast (keeping the y > 0 block constant at 0.1 S/m, panels A-C show the effect when the y < 0 block is 0.1, 0.01, and 0.001 S/m, respectively). Fault block conductivities in S/m are annotated in each of the panels A-C. For the degenerate case of a 1:1 contrast (panel A) the response is simply that of a uniform half-space. Panel A, the half-space case, is equivalent to panel A in Figure 51. Dimensions in x and y are given in meters.

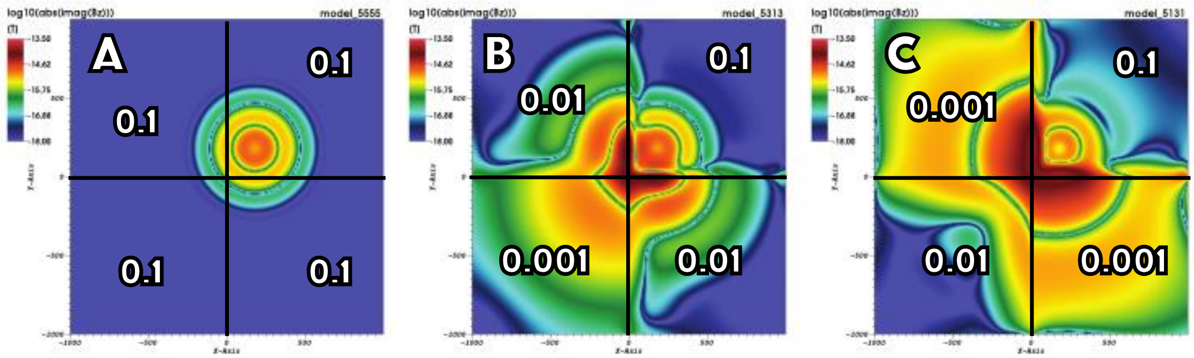


Figure 53. Parametric analysis on the effect of fault block conductivity contrast in Zinc class of models with a 300 m TTE antenna depth. Shown in color scale is the log10 magnitude of the quadrature phase of vertical magnetic field on the surface of the Earth for three double-fault models. Quadrant conductivities in S/m are annotated in each of the panels A-C. For the degenerate case of a 1:1 contrast (panel A) the response is simply that of a uniform half-space. Panel A, the half-space case, is equivalent to panel A in Figure 52. Dimensions in x and y are given in meters.

6.0 Dissemination Efforts and Highlights

Significant findings were distributed throughout the course of this project to the mining community through presentations and peer-reviewed publications. Presentations were given at a variety of national and international venues including the 2015 SME Annual Conference and Expo in Denver, CO, 2015 Third International Future Mining Conference, Melbourne, Australia, 2015 Society of Mining Professors 26th Annual General Meeting and Conference in Freiberg, Saxony, Germany, and the 2016 SME Annual Conference and Expo in Phoenix, AZ. In addition to the aforementioned professional meetings, two targeted seminars were held to present and discuss project findings to stakeholders.

The first seminar was an informal workshop held in Pittsburgh, PA. This workshop was attended by researchers and administrators from Office of Mine Safety and Health Research (OMSHR) and MSHA. The purpose of this workshop was to overview field test results to-date and to gain constructive criticism regarding the designs of future studies. The second seminar was requested by Global Ties-U.S., an international non-profit organization, for a visiting delegation of Chinese administrators from Hubei, China. The attendees ranged in position from Director to Senior Engineer representing various land resource, geological, and environmental enforcement organizations in the People's Republic of China (PRC). This presentation provided a high-level overview of project objectives, TTE technologies, and field test results with the goal of sharing pertinent information for the improvement of mine worker health and safety.

Invited seminars on the topic of TTE technologies, test results and underground communications were delivered to the Sustainable Minerals Institute (SMI) at the University of Queensland in Brisbane, Australia and at the Sandia National Laboratories in Albuquerque, New Mexico. As previously introduced, a number of publications have been generated during this project. Two publications, one reporting an MCS field study at an underground longwall mine in the Illinois Basin and the other overviewing the TTE Performance Tables produced at the conclusion of this project. Publications that are currently available are identified in the following list:

1. Jong, E. C., & Schafrik, S. J. *Evaluation of an E-field Through-The-Earth (TTE) communications system at an underground longwall mine in West Virginia*. Mining Engineering, 68(9). 2016.

2. Jong, E. C., Schafrik, S. J., & Gilliland, E. S. *A preliminary evaluation of a Through-The-Earth (TTE) communications system at an underground coal mine in eastern Kentucky*. Mining Engineering, 68(4), 52-57. 2016.

3. Jong, E. C., Schafrik, S. J., Gilliland, E. S., Weiss, C. W., & Waynert, J. A. *Pairing magnetic and E-field Through-The-Earth communication systems based on mine site conditions*. In Proceedings Third International Future Mining Conference, Melbourne, Australia. 2015.

4. Jong, E. C., Schafrik, S. J., Gilliland, E. S., & Weiss, C. W. *The performance of a Through-the-Earth (TTE) Magnetic Communications System (MCS) at two metal/non-metal mines in the United States*. Paper presented at the Society of Mining Professors - 26th Annual General Meeting and Conference, Freiberg, Saxony, Germany. 2015.

A dataset of all geophysical simulation results can be acquired from https://data.lib.vt.edu . This dataset can be utilized to save researchers the compute time necessary. Data available form this resource will be permanently available and utilized the Data Object Identifier (DOI) system so that the data itself can be properly referenced by researchers. A manuscript overviewing the TTE simulation database, results, and the electromagnetic modeling method is presently being prepared for the journal "Geophysics." If the manuscript is accepted, the TTE simulation database will be uploaded to the SEG Open Data Wiki (wiki.seg.org/wiki/Open_data), which is a high-visibility repository for large-scale data sets and modeling results for the exploration geophysics community.

7.0 Conclusions and Impact Assessment

The project presented in this report sought to determine the operational envelope of commercially available TTE systems in a variety of underground mining environments. This goal was achieved through the evaluation of two TTE systems, the MCS and the ECS, at five field sites. The acquired systems represented the two chief technologies used to generate TTE communications at the present day. The field sites not only encompassed the primary extraction approaches applied in underground mines but also represented the major geologic regions in the Central and Eastern U.S. A detailed description of the tested TTE systems as well as the field sites can be found in Research Approach section of this report.

Prior to this project, only a minimal amount of operating knowledge for these TTE systems was available. In general, manufacturers provided a simple set of guidelines regarding how to set up each system and a list of vague performance specifications, such as ultimate range. Based on this information, a mine operator would assume that once deployed, a TTE system would then achieve its rated performance. However, communications systems by nature, especially considering the complexities of TTE propagation, are rarely simple. This conjecture was confirmed by the results of this project. Field testing and computer simulations revealed that a number of environmental and anthropogenic variables impact TTE signals. Additionally, the field performance of the tested TTE systems varied depending on deployment conditions.

The MCS exhibited the most reliable performance throughout the project. Among the different variables tested, transmission power impacted MCS communications the most consistently. The use of elevated, non-permissible power not only significantly extended MCS communications range but also allowed transmissions from very poor loop antenna layouts. Although transmissions were unsuccessful under certain conditions, this system was able to achieve communications in the majority of cases. However, the range of communication did vary substantially across the field sites as well as within individual locations at each field site.

The performance of the ECS was somewhat inconsistent across the field sites. A logical pattern that related communications performance to antenna structures or grounding bed connection quality could not be discerned. For example, one antenna configuration that functioned well at one field site performed to a mediocre degree at another field site. In general, ECS communication were optimized when utilizing fully grouted roof bolts, rail, and belt structure as grounding beds. The most reliable communications were produced when either rail or belt structure was utilized in conjunction with fully grouted resin bolts at least 2 m (6 ft) in length, which contrasts the manufacturer’s recommendations. However, even this optimal configuration varied in effectiveness at times. Despite the observed behavior, the portability and robustness of the ECS did give this system an advantage over the MCS in these respects. Given the limited opportunities for ECS testing, only the MCS will be further discussed.

The observed performance of the MCS can be classified into three categories. These categories are coal geology, consolidated geology, and anthropogenically influenced. The two geologic performance categories assume a stratigraphically mundane area void of significant conductive elements. Through overburden compositions common in areas containing coal deposits, the MCS could reliably achieve two-way communications up to a point to point distance of 200 m (650 ft). The MCS was limited by its underground to surface communications capabilities in coal geology. One-way surface to underground communications exhibited a greater reliable transmission range of up to 400 m (1,300 ft).

The highly consolidated geology found in many metal and non-metal mines greatly extended the communication range of the MCS. Through areas in this category, the MCS could achieve two-way communications distances of up to 520 m (1,700 ft), although not reliably. Underground to surface communications were the limiting factor as they were unsuccessful in many areas of Field Sites D and E. The reason for this anomalous lack of one-way underground to surface communications even when using an elevated transmission power remains unknown. In contrast, MCS surface to underground communications in consolidated geology exhibited a one-way communication range of up to 1,500 m (5,000 ft). The primary difference between underground to surface and surface to underground communications was transmission power. These observations suggest that mines with similar consolidated geology may have a transmission power threshold that will need to be met before communications can be achieved.

Anthropogenically enhanced communications included MCS communications that were able to propagate along long metallic structures. The two structures that enhanced MCS communications were rail and large contiguous sections of support mesh. Along the rail, the MCS achieved a maximum underground to underground communications distance of 3,000 m (10,000 ft). The ability of rail-enhanced communication to penetrate solid strata was extremely limited. In fact, communications could only be received around a proximal area around the rail when the un-propagated MCS range was exceeded. Along support mesh, the MCS achieved underground to surface communications distances up to 2,300 m (7,500 ft) and underground to underground communication distances up to 4,600 m (15,000 ft). Locations that clearly exceeded the native transmission range of the MCS could receive surface to underground messages if the surveyed site overlaid a meshed area of the mine. Thus, the mesh allowed MCS transmission to propagate through approximately 150 m (500 ft) overburden in these locations, which contrasts the performance of the rail described earlier in similar situations.

The presence of high voltage artifacts did not appear to affect the ability of the MCS to receive communications in either communication mode. Neither conveyor belt structures nor other large metallic artifacts were observed to affect the TTE communication in a manner resembling the rail-effect. Based on theoretical research, the layout of the loop antenna was expected to significantly impact MCS communications. However, attempted non-ideal loop antenna layouts did not appear to notably impact the performance of the MCS especially if a greater transmission power was utilized. Intriguingly, the higher frequency V-channel propagated further than the lower frequency T-channel, which contrasts norms for radio signal behavior. The exact reason for this performance remains unknown.

Based on these results, mine operators and users of TTE systems should perform individual evaluations at their respective sites. Users should neither assume that TTE systems will perform according to the manufacturer's specifications nor expect TTE systems to function consistently even within the same mine. Site evaluations should be constrained to projected utilization scenarios that represent likely emergency scenarios. Once these evaluations are completed, the TTE system should be tested at regular intervals to ensure that all components are functioning within expected parameters. In addition to regular preventative maintenance, examination intervals should also be used to reinforce user training in the deployment and operation of the TTE system. Familiarity with performance patterns, operational procedures, and troubleshooting techniques are crucial for successfully utilizing TTE systems in an emergency. In order to assist mine operators and other users in planning for TTE system deployments, the significant findings of this project in terms of TTE impacts as a function of environmental and anthropogenic conditions have been compiled into two TTE Performance Tables.

TTE Performance Tables

The information presented in this report is designed to provide a comprehensive overview of this research project. The degree of detail included in previous sections not only present a complete overview of project procedures, results, and observations but can also serve as a reference for future TTE system studies. However, the sheer amount of information may appear cumbersome to users who are seeking only guidelines for deployment of the TTE platforms evaluated in this project. As a result, two TTE Performance Tables were developed for both the MCS and the ECS that concisely summarizes the observed performance of the MCS and the ECS systems in a variety of conditions.

The objective of the TTE Performance Tables is to provide users with the ability to rapidly identify conditions that positively or negatively affect TTE communications. The means to locate a detailed description of the effect for further clarification is also provided. In order to accomplish this objective, the information presented by the TTE Performance Tables progresses systematically from concise to comprehensive. The user is first introduced an itemized list of significant environmental and anthropogenic artifacts observed at the field sites organized by TTE system, either MCS or ECS. Environmental and anthropogenic conditions are presented in Tables 23 and 24, respectively. The artifacts are classified according to their degree of positive or negative impact on TTE communications. Five classifications are applied representing two levels of positive impact, two levels of negative impact, and one level signifying neutral impact. These impact classification categories in the order of most positive to most negative impact are strongly enhances, moderately benefits, no significant effect, adversely affects, and detrimental. A color coded legend is provided in Table 22 to visually clarify the assigned impact category.

Each artifact-classification pair is then related by an index code (e.g., ME 1) located under the TTE system (i.e., MCS or ECS) to a brief description of the exact form of the condition, such as an igneous intrusion intersecting a tested travelway, and the observed impact. The impact description is located in the MCS Performance Impacts and the ECS Performance Impacts sections. These sections include a brief summary, organized by environmental and anthropogenic conditions, about how each artifact affected TTE communications, the field site where the effect was observed, and any applicable literature published from this research project. The number used to identify pertinent publications refers to the references list located in the Dissemination Efforts and Highlights chapter of this report. If further clarification is needed, the user can then use the field site and literature references to locate information both included in this report as well as in external sources, if available. This progressive layout allows users to pursue a level of detail appropriate for the desired application. Although the conditions and impacts presented in the TTE Performance Table accurately represent observations recorded during this project, the historic variability of TTE communications performance warrants additional site specific tests of any acquired TTE system. As a result, the TTE Performance Table provided in the following section should only be used as a guideline and not the sole source of information for the deployment of similar TTE platforms. The results of this project strongly indicate that any TTE system should be activated and tested at potential deployment locations and under representative utilization conditions to evaluate its viability at a mine site.

Table 22. Color legend for TTE Performance Tables

Legend	
Strongly enhances	
Moderately benefits	
No significant effect	
Adversely affects	
Detrimental	
Not applicable/Not tested	

Table 23. Environmental conditions observed during field testing of the MCS and the ECS.

Environmental Condition	**MCS**	**ECS**
Compacted, highly consolidated overburden	ME 1	EE 1
Complex geology with varying stratigraphy (may include faults, synforms, and antiforms)	ME 2	EE 2
Depth of cover exceeding 300 m (1,000 ft) in coal mines	ME 3	EE 3
Dry fault with an insignificant level of conductivity	ME 4	EE 4
Humidity	ME 5	EE 5
Large, voids present between transmitting and receiving locations	ME 6	EE 6
Numerous fractures in the roof or ribs inundated with highly conductive mineralized water	ME 7	EE 7
Thunderstorms	ME 8	
Time of day	ME 9	EE 9
Unconsolidated overburden or loose fill material	ME 10	EE 10
Visible bodies of water in underground workings	ME 11	
Visible bodies of water on the surface	ME 12	
Wet fault with highly conductive, mineralized water	ME 13	
Light freezing rain		EE 14
Limestone deposit/overburden		EE 15
Loosely pack soil with moderate water content/mud		EE 16

Table 24. Anthropogenic conditions observed during field testing of the MCS and the ECS.

Anthropogenic Condition	MCS	ECS
Active belt drives	MA 1	EA 1
Active diesel powered equipment	MA 2	EA 2
Active high voltage mining equipment	MA 3	EA 3
Belt structure	MA 4	
Densely spaced inactive, cased gas or oil wells	MA 5	EA 5
High voltage surface power lines	MA 6	EA 6
High voltage transformers	MA 7	
High voltage underground power lines and equipment trailing cables	MA 8	EA 8
Increasing transmission power	MA 9	
Large surfaces installed with contiguous sections of support mesh	MA 10	EA 10
Large underground water lines	MA 11	EA 11
Metallic structures (e.g. overcasts, beams, mandoors, etc.)	MA 12	EA 12
Poor loop antenna layout	MA 13	
Rail	MA 14	
Roof bolts and mesh	MA 15	
Sealed mine workings containing an unknown amount and configuration of conductive artifacts	MA 16	EA 16
Underground power centers	MA 17	EA 17
Composition of antenna structures		EA 18
Ground bed separation distances		EA 19
Quality of the connection between the ground and the antenna beds		EA 20
Relative orientation of antenna beds		EA 21
Relative horizontal orientation of antenna beds		EA 22

MCS Performance Impact Conditions

Table 25. Environmental conditions that were examined using the MCS and their impacts.

Index	Condition	Description of Condition
ME 4	Dry fault with an insignificant level of conductivity	Major and minor faults that did not have significant water infiltration were located between a surface MCS unit and an underground MCS unit. No significant impacts on MCS communication were observed from the faults. This condition was examined at an underground stope and pillar zinc mine in Strawberry Plains, TN. Publication(s): 4
ME 13	Wet fault with highly conductive, mineralized water	Major and minor faults with significant infiltrations of highly mineralized water were located in the vicinity of an underground MCS unit. At these locations, both mineralized water and mud were intruding into the mine through the fault planes that intersected the active workings. These water inundated faulted areas were observed to adversely affect MCS communications. This condition was examined at an underground stope and pillar zinc mine in Strawberry Plains, TN at several underground locations. Publication(s): 4
ME 1	Compacted, highly consolidated overburden	Uniform strata containing non-interbedded overburden composed primarily of limestone and dolomite formed by sedimentation were observed to increase the transmission range of the MCS. This condition was examined at an underground stope and pillar limestone mine in Ripplemead, VA and at an underground stope and pillar zinc mine in Strawberry Plains, TN. Publication(s): 4
ME 10	Unconsolidated overburden or loose fill material	Both high and moderately compacted fill material that compose impoundments were observed to adversely affect MCS communications. This condition was examined at an underground stope and pillar limestone mine in Ripplemead, VA and an underground stope and pillar zinc mine in Strawberry Plains, TN. Publication(s): 4

Index	Condition	Brief Description/Reference for Observed Effect
ME 6	Large, voids present between transmitting and receiving locations	No significant effect on communications from caving horizons and sealed mine workings located around the MCS units was observed. The amount of water infiltration into these voids was unknown when this effect was observed. This condition was examined at an underground longwall mine in Eskdale, WV and at an underground retreat room and pillar mine in Pikeville, KY. Publication(s): 2, 3
ME 2	Complex geology with varying stratigraphy that may or may or may not include faults, synforms, and antiforms	No significant effect on MCS communications from highly stratified overburden composed of frequent alternations between shale, sandstone, and other types of sedimentary rock such as limestone/dolomite in the bedding planes was observed. The stratigraphy at the coal mines in which this condition was observed also included thinly bedded layers of coal as well as areas with multiple overlaying coals seams greater than 1 m (3 ft) in thickness. This condition was examined at an underground stope and pillar limestone mine in Ripplemead, VA and at an underground stope and pillar zinc mine in Knoxville, TN. Publication(s): 4
ME 12	Visible bodies of water on the surface	Both small settling ponds designed to capture runoff from mine property and impoundments with a visible layer of water were located in the vicinity of a surface MCS unit. The composition of the water varied from clear rain runoff to highly mineralized processing plant discharge. No significant effect on MCS communications around these surface ponds was observed. This condition was examined at an underground longwall mine in Marion, IL, at an underground retreat room and pillar mine in Pikeville, KY, and at an underground stope and pillar mine in Strawberry Plains, TN. Publication(s): 2, 3 ,4

Index	Condition	Brief Description/Reference for Observed Effect
ME 11	Visible bodies of water in underground workings	No significant effect on MCS communications from small, shallow ponds located in wet areas of underground workings and large pools located in flooded, low elevation areas were observed. The flooded areas in which this condition was also intersected faults and/or major fractures. The composition of the water varied from clear river water to highly mineralized, fracture diffused surface runoff. This condition was examined at an underground longwall mine in Eskdale, WV and at two underground stope and pillar mines in Strawberry Plains, TN and Ripplemead, VA. Publication(s): 3, 4
ME 8	Thunderstorms	Storms that ranged from extended, lightning storms to high intensity, heavy downpours without lightning occurred during several tests. No significant effect was observed from these storms on MCS communications. This condition was examined on the surface at two underground room and pillar coal mines in Eskdale, WV and in Pikeville, KY. Publication(s): 2, 3
ME 3	Depth of cover exceeding 300 m (1,000 ft)	Overburden thicknesses at multiple locations equal to or greater than 1,000 ft were consistently observed to adversely affect MCS communication at coal mines. Communication disruptions between the surface and underground were likely caused by the increased transmission distances through substantial overburden thicknesses. This condition was examined at two underground coal mines in Pikeville, KY and Eskdale, WV. Large overburden thicknesses had a significantly lower impact on MCS communication when the strata were composed of highly consolidated overburden. This scenario was present at the two metal/non-metal mines surveyed during field studies. Publication(s): 2, 3, 4

Index	Condition	Brief Description/Reference for Observed Effect
ME 7	Numerous fractures in the roof or ribs inundated with highly conductive mineralized water	Densely spaced fractures with visible, highly mineralized water infiltrations effectively surrounded the receiving antenna in the investigated underground locations. These densely spaced, water inundated fractures prevented the reception of any messages by the underground MCS unit. This condition was examined at a single location in an underground stope and pillar zinc mine in Strawberry Plains, TN and at a single location location in an underground stope and pillar limestone mine in Ripplemead, VA. Publication(s): 4
ME 5	Humidity	The humidity varied from 30% to 80% at all field sites. No significant impacts on MCS communications were observed as a function of humidity variations.
ME 9	Time of day	All field tests of the MCS were largely conducted between the hours of 0800 to 1700 during weekdays. No significant impacts on MCS performance were observed based on the time of day during field tests.

Table 26. Anthropogenic conditions that were examined using the MCS and their impacts.

Index	Condition	Brief Description/Reference for Observed Effect
MA 7	High voltage transformers	The MCS was placed within 1 m (3 ft) of a large surface high voltage transformer at two different field sites. The first high voltage transformer effect was examined at an underground retreat room and pillar mine in Pikeville, KY. At this site, the reception of any signal from the MCS was prevented in an area situated between the main mine fan motor and the high voltage transformer. This zone was also located underneath several high voltage power cables. The lack of signal reception was confined to the internal area of this region. Any points surveyed outside the square shaped area were suddenly enabled and uninterrupted by the high voltage artifacts. The second high voltage transformer examined at an underground stope and pillar mine in Strawberry Plains, TN had no effect on MCS communications. As can be seen by these observations, the effect of high voltage transformers on MCS communications appears to be situation specific. Publication(s): 2, 3 ,4
MA 17	Underground power centers	The MCS was placed adjacent to various underground power centers in three different mines representing three different mining methods. The MCS was not affected regardless of the proximity to or the configuration of the power center This condition was examined at an underground stope and pillar zinc mine in Strawberry Plains, TN, at one location in an underground stope and pillar limestone mine in Ripplemead, VA, at an underground retreat room and pillar coal mines in Pikeville, KY, and at an underground longwall mine in Eskdale, WV. Publication(s): 2, 3
MA 3	Active high voltage mining equipment	Several types of active underground mining equipment were present in the vicinity of the MCS during communications testing. The equipment included roof bolters, continuous miners, mantrips, shuttle cars, and longwall shields/shearers. None of the equipment affected MCS transmissions in a significant manner. This condition was observed at an underground retreat room and pillar coal mines in Pikeville, KY and at an underground longwall mine in Eskdale, WV. Publication(s): 2, 3

Index	Condition	Brief Description/Reference for Observed Effect
MA 8	High voltage underground power lines and equipment trailing cables	The MCS was placed adjacent to various underground power lines both suspended from the mine roof and secured to the mine floor. Trailing cables from high voltage mining equipment were also present at many underground locations. MCS communications were not affected regardless of the proximity, density, or configuration of the power lines. This condition was examined at an underground stope and pillar zinc mine in Strawberry Plains, TN, at an underground retreat room and pillar coal mines in Pikeville, KY, and at an underground longwall mine in Eskdale, WV. Publication(s): 2, 3, 4
MA 14	Rail	The MCS communication range was substantially increased when the system was placed near the rail. Transmissions were able to propagate along the rail, which facilitated clear reception at nearly the furthest extents of travelways that contained contiguous sections of rail. The enhancing effect was, however, limited to a proximal area around the rail. Higher concentrations of rail, such as multiple parallel rail entries, were observed to increase the proximal transmission area around the rail to tens of meters (several hundred feet). This effect was enables regardless of utilized transmission power. This condition was examined at an underground retreat room and pillar mine in Pikeville, KY. Another version of the rail enhancing effect was observed at an underground longwall mine in Eskdale, WV. At this mine, only an elevated transmission power with the underground MCS loop antenna placed in close proximity to the rail was able to produce the enhancing effect. Publication(s): 2, 3

Index	Condition	Brief Description/Reference for Observed Effect
MA 5	Densely spaced inactive, cased gas or oil wells	Densely spaced, steel casings from inactive oil/gas wells surrounded a surface MCS unit. These wells were located above the mine's main travelway in a mountainous area with an average overburden thickness of 150-180 m (500-600 ft). The wells had originally been constructed as oil wells in the 1900s and were later converted to natural gas wells before their eventual sealing in the 1980s. Some of the casings directly intersected the main travelway in several locations. MCS communication, although achievable, were adversely affected in terms of ultimate range in this area of the mine. This condition was examined at an underground longwall mine in Eskdale, WV. Publication(s): 3
MA 6	High voltage surface power lines	The MCS was placed adjacent to various suspended surface power lines. In the examined cases, MCS communications were not affected regardless of the proximity, density, or configuration of the power lines. This condition was examined at an underground stope and pillar zinc mine in Strawberry Plains, TN, at an underground stope and pillar limestone mine in Ripplemead, VA, at an underground retreat room and pillar coal mines in Pikeville, KY, at an underground longwall mine in Marion, IL, and at an underground longwall mine in Eskdale, WV. Publication(s): 2, 3, 4
MA 11	Large underground water lines	The MCS was placed adjacent to various underground water lines that were both suspended from the roof as well as secured to the floor. MCS communications were not affected regardless of the proximity, size, or configuration of the water lines. This condition was examined at an underground stope and pillar zinc mine in Strawberry Plains, TN, at an underground stope and pillar limestone mine in Ripplemead, VA, at an underground retreat room and pillar coal mines in Pikeville, KY, and at an underground longwall mine in Eskdale, WV.

Index	Condition	Brief Description/Reference for Observed Effect
MA 4	Belt structure	The underground MCS unit was placed adjacent to numerous belt structures both along main travelways, in low traffic outby workings, and in production areas. MCS communications were not affected regardless of the proximity to or the configuration of the belt structures. Although, no negative effects on communications were observed, the enhancing effect observed in the presences of rail and large contiguous sections of mesh was also not apparent. This condition was examined at an underground stope and pillar limestone mine in Ripplemead, VA, at an underground retreat room and pillar coal mines in Pikeville, KY, at an underground longwall mine in Marian, IL, and at an underground longwall mine in Eskdale, WV. Publication(s): 2, 3, 4
MA 1	Active belt drives	The underground MCS unit was placed adjacent to several active belt drives. MCS communications were not significantly affected regardless of the proximity to or the size of the drive. This condition was examined at an underground stope and pillar limestone mine in Ripplemead, VA and at an underground longwall mine in Eskdale, WV. Publication(s): 2, 3, 4
MA 15	Roof bolts and mesh	Various roof bolt types, installation configurations, and structural reinforcements such as mesh were investigated. Roof bolts included fully grouted resin bolts, partially grouted mechanical bolts, partially grouted cable bolts, and friction fitted bolts ranging in length from 1-3 m (4-10 ft). Both roof and rib meshes installed on an as-needed basis (i.e., moderate coverage with discontinuous mesh sections in locations where sloughage was an issue) were investigated. MCS communications were not affected by any design, combination, or configuration of roof bolts or meshes. This condition was examined at an underground stope and pillar zinc mine in Strawberry Plains, TN, at an underground stope and pillar limestone mine in Ripplemead, VA, at an underground retreat room and pillar coal mines in Pikeville, KY, and at an underground longwall mine in Eskdale, WV. Publication(s): 2, 3, 4

Index	Condition	Brief Description/Reference for Observed Effect
MA 12	Metallic structures (e.g. overcasts, beams, mandoors, etc.)	The MCS underground unit was placed adjacent to metallic structures that represented a variety of scales from a single support to sheet metal covered, I-beam reinforced overcasts. MCS communications were not affected regardless of the proximity, size, or configuration of these structures. This condition was examined at an underground stope and pillar zinc mine in Strawberry Plains, TN, at an underground stope and pillar limestone mine in Ripplemead, VA, at an underground retreat room and pillar coal mines in Pikeville, KY, at an underground longwall mine in Marion, IL, and at an underground longwall mine in Eskdale, WV. Publication(s): 2, 3, 4
MA 13	Poor loop antenna layout	Loop antenna configurations ranging from optimal (i.e., manufacturer recommended) to extremely poor were examined. The optimal and near optimal deployment layouts where the full length of the antenna was utilized in a manner that maximized the internal surface area of the loop elicited the best communications performance. Antenna shapes there were near optimal, which included elongated ovals, squares, and triangles, performed similarly to perfect circles. MCS communications became significantly affected when either shorter lengths of the antenna were utilized or the antenna was crossed over itself several times. Although communications were affected, they were not prevented, which suggests that poor configurations may be viable in a limited capacity if no alternatives are available. This condition was examined at an underground stope and pillar zinc mine in Strawberry Plains, TN, at an underground stope and pillar limestone mine in Ripplemead, VA, at an underground retreat room and pillar coal mines in Pikeville, KY, and at an underground longwall mine in Eskdale, WV. Publication(s): 2, 3, 4

Index	Condition	Brief Description/Reference for Observed Effect
MA 9	Increasing transmission power	Signal transmission range and strata propagation efficacy increased with transmission power in almost all examined cases. Transmission power increases were found to consistently enhance MCS communications. In some cases, the range was enhanced to a degree that allowed the reception of communications throughout the entire extent of the mine from a single transmitting point. During the remaining test, the communication range was extended but only slightly (i.e., approximately 100-200 ft). This condition was examined at an underground stope and pillar zinc mine in Strawberry Plains, TN, at an underground stope and pillar limestone mine in Ripplemead, VA, and at an underground longwall mine in Eskdale, WV. Publication(s): 3, 4
MA 2	Active diesel powered equipment	Several types of active diesel powered equipment both underground and on the surface were present in the vicinity of the MCS units. The equipment included haul trucks, mantrips, and personal trucks. MCS transmissions encountered interference over numerous instances when active diesel powered equipment was either present in the vicinity or driving by the receiving antenna. However, the disruption to communications did not occur in all instances. This condition was observed at an underground longwall mine in Marion, IL, at an underground stope and pillar zinc mine in Strawberry Plains, TN, at an underground stope and pillar limestone mine in Ripplemead, VA. Publication(s): 3, 4
MA 16	Sealed mine workings containing an unknown amount and configuration of conductive artifacts	No significant effect on MCS communication from sealed longwall panels, sealed main travelway, and large sealed mine working spaced were observed. The tested sealed areas were oriented in a manner that intersect MCS communications. In all cases, the voids did not affect communications. These conditions were examined an underground retreat room and pillar coal mines in Pikeville, KY and at an underground longwall mine in Eskdale, WV. Publication(s): 2, 3

Index	Condition	Brief Description/Reference for Observed Effect
MA 10	Large surfaces installed with contiguous sections of support mesh	Active mine workings were installed with contiguous sections of roof and rib mesh. The mesh covered the majority of exposed surfaces throughout the mine to secure significant sloughage of the roof and ribs. Very few surfaces other than the floor were not covered by support mesh. The presence of mesh significantly increased the range of MCS transmissions. The enhancing effect of the mesh when using reduced power on underground to surface and underground to underground communications was especially significant. The mesh during these communication modes enabled not only longer ranges but also greater propagation through overburden. Although the transmission range of surface to underground communications using the surface MCS unit was longer relative to past tests, the increased transmission power from the surface unit did not perform as well as the reduced power underground unit. This condition was examined at an underground longwall mine in Marion, IL.

ECS Performance Impact Conditions

Table 27. Environmental conditions that were examined using the ECS and their impacts.

Index	Condition	Brief Description/Reference for Observed Effect
EE 4	Dry fault with an insignificant level of conductivity	Densely faulted overburden composed of both local and regional scale fractures intersected the underground workings in multiple locations. No significant effect on ECS communications was observed from these faults. This condition was examined at an underground stope and pillar limestone mine in Ripplemead, VA and an underground stope and pillar zinc mine in Strawberry Plains, TN.
EE 1	Compacted, highly consolidated overburden	Overburden composed primarily of limestone and dolomite was examined. The deposit as well as its encompassing rock was formed by sedimentation without inter-bedding, which created uniform strata without complex layering. Although communications between ECS units could not be established in certain locations of the examined field site, other confounding variables were more likely to have caused the lack of communication. As a result, no significant effect on ECS communications was observed from this type of overburden. This condition was examined at an underground stope and pillar zinc mine in Strawberry Plains, TN.
EE 10	Unconsolidated overburden or loose fill material	The observed condition included both highly compacted and moderately compacted fill material on impoundments. No significant effect on ECS communications was observed from this type of overburden. This condition was examined at an underground stope and pillar limestone mine in Ripplemead, VA. Publication(s): 1, 3

Index	Condition	Brief Description/Reference for Observed Effect
EE 6	Large voids present between transmitting and receiving locations	Caving horizons, open mine workings, and sealed mine workings located between two ECS units were present in several locations. The amount of water infiltration into the voids was unknown. Although communications between ECS units could not be established in certain locations with voids in the vicinity, other confounding variables were more likely to have caused the lack of communication. As a result, no significant effect on ECS communications was observed from these voids. This condition was examined at an underground longwall mine in Eskdale, WV, at an underground longwall mine in Marion, IL, at an underground stope and pillar limestone mine in Ripplemead, VA, and at an underground stope and pillar zinc mine in Strawberry Plains, TN. Publication(s): 1, 3
EE 2	Complex geology with highly varying stratigraphy that may or may not include faults, synforms, and antiforms	Highly stratified overburden with frequent alternations of shale, sandstone, and other types of sedimentary rock such as limestone/dolomite were investigated. The stratigraphy at the surveyed coal mines also included thinly bedded layers of coal as well as areas with multiple overlying coal seams greater than 1 m (3 ft) in thickness. No significant effect on ECS communications was observed from this type of geology. These conditions were examined at both coal and M/NM field sites form Ripplemead, VA to Knoxville, TN. Publication(s): 1, 3
EE 3	Depth of cover exceeding 300 m (1,000 ft)	Several sites with large overburden thicknesses created by both mountainous terrain and depth of the deposit was examined. Although communications between ECS units could not be established in some locations with this condition, other confounding variables were more likely to have caused the lack of communication. As a result, no significant effect on ECS communications was observed from the depth of cover. This condition was examined at an underground stope and pillar limestone mine in Ripplemead, VA and an underground stope and pillar zinc mine in Strawberry Plains, TN. Publication(s): 1, 3

Index	Condition	Brief Description/Reference for Observed Effect
EE 7	Numerous fractures in the roof or ribs inundated with highly conductive mineralized water	Water inundated fractures were present in the roof and the ribs around the ECS unit underground. Although communications between ECS units could not be established in some locations with this condition, other confounding variables were more likely to have caused the lack of communication. As a result, no significant effect on ECS communications was observed from these fractures. This condition was examined at an underground stope and pillar limestone mine in Ripplemead, VA and an underground stope and pillar zinc mine in Strawberry Plains, TN.
EE 14	Light Freezing Rain	Continuous light freezing rain was present during one investigation of ECS communications. Although communications between ECS units could not be established in some locations while this condition was occurring, other confounding variables were more likely to have caused the lack of communication. As a result, no significant effect on ECS communications was observed from light freezing rain. This condition was examined at an underground stope and pillar limestone mine in Ripplemead, VA.
EE 5	Humidity	The humidity varied from 30% to 80% at all field sites. No significant impacts on ECS communications were observed as a function of humidity variations.
EE 9	Time of day	All field tests of the ECS were largely conducted during the hours of 0800 to 1700 during weekdays. No significant impacts on ECS performance were observed based on the time of day during the field tests.
EE 15	Limestone	During investigations in which the strata was either partially or entirely composed of limestone, ECS communications were either entirely prevented or severely restricted in communications range. The complete prevention of communications was caused by the inability of the ECS to create an adequate connection between antenna beds in which the grounding medium was completely composed of limestone. In locations where limestone occupied only a portion of the overburden, an adequate connection between antenna beds could be achieved, but the communications were severely limited in range. Preparatory testing of the ECS in likely usage locations, mediums, and scenarios is highly recommended. These conditions were examined at both coal and M/NM field sites in Marion, IL and Ripplemead, VA, respectively.

Index	Condition	Brief Description/Reference for Observed Effect
EE 16	Loosely pack soil with moderate water content/mud	The ECS unit was installed in an area where the soil was both moist and soft but not muddy and muddy but could still be traveled over on-foot with minor difficulty. The antennas could be either easily pushed into place by-hand or hammered into the ground with limited difficulty. The elevated soil conductance caused by the higher than normal moisture content was observed to have benefited the connection quality between the ECS antenna beds. However, the ultimate effect of the high moisture soil in terms of communications performance could not be directly tested because the remaining ECS unit was prevented from establishing an adequate antenna connection underground. This condition was examined at an underground limestone mine in Ripplemead, VA and at an underground coal mine in Marion, IL.

Table 28. Anthropogenic conditions that were examined using the ECS and their impacts.

Index	Condition	Brief Description/Reference for Observed Effect
EA 17	Underground power centers	The ECS was placed adjacent to various underground power centers. ECS communications were not affected regardless of the proximity to or configuration of the power center. This condition was examined at an underground stope and pillar zinc mine in Strawberry Plains, TN, at one location in an underground stope and pillar limestone mine in Ripplemead, VA, and at an underground longwall mine in Eskdale, WV. Publication(s): 1, 3
EA 3	Active high voltage mining equipment	Several types of active mining equipment were present in the vicinity of the ECS during communications testing. This equipment included mantrips and scoops. None of the equipment was observed to significantly affect ECS communications. This condition was observed at an underground longwall mine in Eskdale, WV. Publication(s): 1, 3
EA 8	High voltage underground power lines	The ECS was placed adjacent to various suspended power lines. No significant effect on ECS communications was observed from the power lines regardless of their proximity, density, or configuration. This condition was examined at an underground stope and pillar zinc mine in Strawberry Plains, TN, at an underground stope and pillar limestone mine in Ripplemead, VA and at an underground longwall mine in Eskdale, WV. Publication(s): 1, 3
EA 5	Densely spaced inactive, cased gas or oil wells	Densely spaced, inactive steel cased wells located above the mine's main travelway in a mountainous area surrounded both ECS units. These wells had originally been constructed as oil wells in the 1900s and were later converted to natural gas wells before their eventual sealing in the 1980s. Some of the casings directly intersected the main travelway in several locations. No significant effect on ECS communications was observed from the inactive casings. This condition was examined at an underground longwall mine in Eskdale, WV. Publication(s): 1, 3

Index	Condition	Brief Description/Reference for Observed Effect
EA 6	High voltage surface power lines	The ECS was placed adjacent to various suspended surface power lines. The ECS was not affected regardless of the proximity, density, or configuration of the power lines. This condition was examined at an underground stope and pillar zinc mine in Strawberry Plains, TN, at an underground stope and pillar limestone mine in Ripplemead, VA, and at an underground longwall mine in Eskdale, WV. Publication(s): 1, 3
EA 11	Large underground water lines	The ECS was placed adjacent to various underground water lines that were both suspended from the ceiling and secured to the floor. ECS communications were not affected regardless of the proximity, size, or configuration of the water lines. This condition was examined at an underground stope and pillar zinc mine in Strawberry Plains, TN, at an underground stope and pillar limestone mine in Ripplemead, VA, and at an underground longwall mine in Eskdale, WV. Publication(s): 1, 3
EA 1	Active belt drives	The ECS was placed adjacent to several active belt drives. No significant effect on ECS communications from the belt drives as observed. This condition was examined at an underground longwall mine in Eskdale, WV and at an underground longwall mine in Marion, IL. Publication(s): 1, 3
EA 10	Large surfaces installed with contiguous sections of support mesh	Roof and rib mesh was present around the ECS in various sizes and concentrations. No significant effect on ECS communications was observed by any design, combination, or configuration of the mesh. The ECS also utilized a large, contiguous mesh that covered the majority of the mine as an antenna bed at one field site with no apparent benefit. This condition was examined at an underground stope and pillar zinc mine in Strawberry Plains, TN, at an underground stope and pillar limestone mine in Ripplemead, VA, at an underground longwall mine in Eskdale, WV, at an underground longwall mine in Marion, IL. Publication(s): 1, 3

Index	Condition	Brief Description/Reference for Observed Effect
EA 12	Metallic structures (e.g. overcasts, beams, mandoors, etc.)	The ECS was placed adjacent to number metallic structures across various scales from a single column to an I-beam supported overcast. No significant effect on ECS communications was observed regardless of the proximity, size, or configuration of the metallic structures. This condition was examined at an underground stope and pillar zinc mine in Strawberry Plains, TN, at an underground stope and pillar limestone mine in Ripplemead, VA, at an underground longwall mine in Marion, IL, and at an underground longwall mine in Eskdale, WV. Publication(s): 1, 3
EA 2	Active diesel powered equipment	Several types of active diesel powered mining equipment frequently passed within the vicinity of the ECS. The equipment included haul trucks, mantrips, and personal trucks. No significant effect on ECS communications was observed from diesel equipment. This condition was examined at an underground stope and pillar zinc mine in Strawberry Plains, TN, at an underground stope and pillar limestone mine in Ripplemead, VA, and at an underground longwall mine in Marion, IL.
EA 16	Sealed mine workings containing an unknown amount and configuration of conductive artifacts	Sealed longwall panels and sealed mine working were oriented in a manner that intersected ECS communication transmission paths. No significant effect on ECS communication was observed from these sealed areas. These conditions were examined an underground longwall mine in Eskdale, WV. Publication(s): 1, 3
EA 19	Ground bed separation distances	Ground bed separation distances less than the manufacturer's recommendations adversely affected ECS communications when the antenna beds were composed of either steel or copper rods. The inter-antenna and inter-bed separation distances did not significantly impact antennas composed of long metallic conductors, such as rail or belt structure, or antennas composed of fully grouted bolts greater than 1.5 m (5 ft) in length. Preparatory testing of the ECS in likely usage locations and scenarios is highly recommended. This condition was examined an underground longwall mine in Eskdale, WV. Publication(s): 1, 3

Index	Condition	Brief Description/Reference for Observed Effect
EA 21	Relative orientation of antenna beds	ECS antenna beds were oriented parallel and perpendicular relative to each other between ECS installation sites. Alternating the orientations produced no significant observable effects on ECS communications. This condition was examined at an underground longwall mine in Eskdale, WV, at an underground longwall mine in Marion, IL, and at an underground stope and pillar zinc mine in Strawberry Plains, TN. Publication(s): 1, 3
EA 18	Composition of antenna structures	The composition of the antenna arrays greatly affected ECS performance. ECS communications were optimized when utilizing fully grouted roof bolts, rail, or belt structure as antenna arrays. The implementation of a long grounded conductor, either belt structure or rail, produced the most reliable and furthest communications. If at least one antenna bed was composed of either belt structure or rail, one-way communication could be consistently established. However, utilizing contiguous sections of mesh as an antenna bed were unable to replicate the performance of rail or belt structure. The poorest communication performance was produced by the manufacturer's recommended installation of friction fitted copper grounding rods. Preparatory testing of the ECS in likely usage locations and scenarios is highly recommended. The effect of antenna configurations on ECS performance was examined at an underground longwall mine in Eskdale, WV, at an underground longwall mine in Marion, IL, at an underground stope and pillar limestone mine in Ripplemead, VA, and at an underground stope and pillar zinc mine in Strawberry Plains, TN. Publication(s): 1, 3

Index	Condition	Brief Description/Reference for Observed Effect
EA 22	Relative horizontal orientation of antenna beds	Underground to underground communications surpassed both surface to underground and underground to surface communications in terms of both range and reliability. The ECS achieved two-way underground to underground communications up to 5,800 m (19,000 ft) when a long grounded conductor, either belt structure or rail, was implemented as one of the antenna beds. This result suggests that ECS communications are optimized when the communicating ECS units are located on the same vertical plane. This condition was observed at an underground longwall mine in Eskdale, WV. Publication(s): 1, 3
EA 20	Quality of the connection between the ground and the antenna beds	Antenna connections that exhibited ground bed resistances within the manufacturer's suggested range elicited the most consistent performance when using antenna structures with a length less than 3 m (10 ft). The implementation of a long conductor as one of the antenna beds significantly enhanced ECS performance even though resistances were outside of the recommended range. In some cases, antenna configurations that produced ground bed resistances within recommended range performed poorly. Based on the observed performance of the ECS, the manufacture's recommended resistances may be used as a guideline, but the actual communication performance may not be represented of the perceived connection quality. Preparatory testing of the ECS in likely usage locations and scenarios is highly recommended. This condition was examined at an underground longwall mine Eskdale, WV, at an underground longwall mine in Marion, IL, at an underground stope and pillar limestone mine in Ripplemead, VA, and at an underground stope and pillar zinc mine in Strawberry Plains, TN. Publication(s): 1, 3

8.0 Recommendations for Future Work

The findings from this project have contributed a substantial amount of knowledge regarding the operational sensitivity of two commercially available TTE systems. Mine operators and other users of TTE technology for the purpose of emergency communications can reference the results of this project to better implement their chosen TTE platform. Although helpful, the recommendations provided in this report may not be applicable in all instances because of the unpredictable nature of TTE systems. This project showed that TTE technology in its current state is functional with sufficient advance planning and testing but also limited. These limitations are present in the areas of communication through significant overburden thicknesses, user operability, and physical deployment. Based on these deficiencies, three research topics can be defined as the next logical progressions of this research project for the improvement of mine worker safety. These topics are optimizing transmission power and antenna design for the purpose of increasing communication range in permissible environments, expanding the functionality of TTE systems through interoperability with existing communication systems, and defining practical regulatory policies for TTE system implementation.

Transmission Power Optimization for Emergency TTE Communications

Project testing showed that power is the primary variable that limits TTE signal range through solid strata. Radio design principles seek to optimize antenna design for the purpose of maximizing power efficiency. As a result, the relationship between wavelength and antenna size becomes a principal design consideration for transmitters and receivers. The efficiency of an antenna increases as its perimeter or length approaches the magnitude of the applied transmission wavelength. To achieve this efficiency benchmark, systems similar to the MCS implement the largest antenna size that is acceptable in a restrictive underground mining environment. Although such antennas are deployable, they are cumbersome and limited in effectiveness. Given the substantial impact of power on transmission range observed in this project's field studies, a research initiative to determine the feasibility of TTE system designs that utilize high transmission power in permissible environments is a logical extension of this project.

Permissibility requirements for device power output in underground coal mines severely limits the communications potential of TTE systems like the MCS. Using less efficient transmitter designs would allow the antennas and associated electrical infrastructure to be entirely contained in an explosion-proof enclosure. Thus, the application of higher transmission power levels would be allowed under current U.S. Federal and State regulations. Although antenna efficiency would be reduced, power consumption is minimally important in an emergency situation. The potential for an effective TTE communications system with these specifications was demonstrated by the ability of the MCS to penetrate significant overburden thickness utilizing increased power even when applying unconventional loop antenna layouts.

Future research would elucidate the optimal balance between transmission power and antenna design for the purpose of increasing communication range in permissible environments. This research would not only be used to determine the power level and antenna combination that would achieve this goal but would also investigate any unexpected effects on TTE communications resulting from such a modification. Any improvement to TTE transmission range from underground to the surface would significantly enhance the applicability of TTE technology and sub statically improve miner safety.

Relaying Information from Existing Communications Systems using TTE Communication Approaches

The limited bandwidth available to TTE communications systems restricts functionality to pseudo half-duplex text messages and voice recordings. Although the features of each TTE system vary, the basic utilization of character limited text messages is common. In an emergency situation, the ability to communicate with responders is essential. Even the limited communications capabilities afforded by modern TTE systems would be beneficial in a situation where conventional communications were completely disabled. As shown by this research project, the examined TTE systems do exhibit significant drawbacks in both deployment and performance under certain conditions. Additionally, the user interface is vulnerable to damage and malfunction, which would completely disable system functionality. The ability of TTE systems to serve an emergency communications platform could be greatly enhanced with the addition of automated interoperability capabilities.

At present, TTE systems require a user to fully deploy all components and actively manipulate the interface to send messages. However, project findings have revealed that TTE systems are restricted in their ability to penetrate overburden. This unpredictable behavior creates the potential for confined underground miners to squander valuable time deploying a system that may not function. Field tests have shown that TTE systems have an impressive ability to achieve underground to underground communications. Leveraging this observed characteristic, future research designed to investigate the addition of an always-active communications relay function would be a logical extension to this project.

More specifically, this function would serve as a redundant amplifier for the conventional communications system, such as mesh-node, already being employed by the mine. A separate, smaller antenna designed specifically for underground to underground communications would be developed and added to an existing TTE system. If a failure of the conventional system occurred between two junctures, the TTE backup would then serve as a relay between the severed portions of the communications system relaying both simple messages, and more importantly, tracking data. Since this ability would be automatically activated, no direct manipulation of the TTE system would be needed. If damage to the primary communications systems was too severe, then users would still have the option of deploying the TTE system as originally designed. This additional capability would significantly enhance miner safety by simplifying user manipulation and adding a level of redundancy to conventional mine communication systems.

TTE communications Policy

The findings of this research project revealed that the effective implementation of a TTE system is challenging because of its sensitivity to site-specific conditions. Any regulation requiring the acquisition of a TTE system must be written in a manner that accounts for these limitations while providing useful constraints for effective deployment. Policies that simply require a mine operator to maintain a certain configuration or number of TTE devices would likely degrade miner safety by not providing specific, realistic requirements within the operational envelope of available TTE platforms. At present, no specific policy has been stipulated for TTE communications systems in underground mines, which leaves an opportunity for future research.

The prescriptive nature of U.S. mine regulations requires the definition of specific requirements. However, truly effective policy will also account for limitations in technology while leaving sufficient flexibility for adaptations to dynamic conditions. Creating policy that adheres to these principles is exceptionally challenging. Given the complexity of TTE system performance, this challenge is further amplified. As a result, future research that combines the findings of this project with the expertise of public policy researchers would be useful in defining a set of recommendations for regulators regarding any future TTE regulation. These recommendations would be written in a manner that allows the creation of requirements, such as deployment techniques, maintenance schedules, etc., that would optimize TTE performance while accounting for system limitations and other such practical considerations. The ultimate goal would be to reduce the burden to mine operators by preventing the implementation of generic, impractical requirements while improving underground miner safety.

9.0 References

Barkand, T. D., Damiano, N. W. & Shumaker, W. A. 2006. Through-the-earth, two-way, mine emergency, voice communication systems. *41st Industry Application Society Annual Meeting.* Tampa, FL.

Damiano, N. W. 2012. Through-the-earth, post-accident communication—an emerging technology. *DHHS (NIOSH) Technology News,* 551.

Durkin, J. 1980. Assessment of present electromagnetic techniques for the location of trapped miners. *Proceedings of the 5th WVU Conference on Coal Mine Electrotechnology.* Morgantown, WV: Bureau of Mines.

Farstad, A. J. 1973. Performance of manpack electromagnetic location equipment in trapped miner location tests. Thru-the-earth electromagnetics workshop, 1973. 62-72.

Frischknecht, F. C. 1967. Fields about an oscillating magnetic dipole over a two-layer Earth and application to ground and airborne electromagnetic surveys. *Colorado School of Mines Quarterly,* 62**,** 326.

Geyer, R. G. USBM Contract Final Report (G133023). *In:* Geyer, R. G., ed. Thru-The-Earth Electromagnetics Workshop, 15-17 AUG 1973 Golden, CO. Department of the Interior.

Geyer, R. G. & Keller, G. V. 1976. Constraints affecting through-the-earth electromagnetic signalling and location techniques. *Radio Science,* 11**,** 323-342.

Geyer, R. G., Keller, G. V. & Ohya, T. 1974. Research on the transmission of electromagnetic signals between mine workings and the surface. Golden, CO: Colorado School of Mines.

Ilsley, L. C., Freeman, H. B. & Zellers, D. H. 1928. Experiments in underground communication through earth strata. *In:* U.S. Department of Commerce (ed.). Washington, D.C.: U.S. Government Printing Office.

Jakosky, J. J. & Zellers, D. H. 1924. Factors retarding transmission of radio signals underground, and some further experiments and conclusions. Washington, D.C.: U.S. Bureau of Mines.

Joyce, J. W. 1931. Electromagnetic absorption by rocks with some experimental observations taken at Mammoth Cave in Kentucky. *Bureau of Mines Technical Paper*.

Lagace, R. L., Dobbie, J. M., Doerfler, T. E., Hawes, W. S. & Spencer, R. H. 1980. Detection of trapped miner electromagnetic signals above coal mines. Cambridge, MA.

Large, D. B., Ball, L. & Farstad, A. J. 1973. Radio transmission to and from underground coal mines - theory and measurement. *IEEE Transactions on Communications,* COM-21**,** 194-202.

Leucci, G. 2008. Ground penetrating radar: the electromagnetic signal attenuation and maximum penetration depth. *Scholarly Research Exchange,* 2008**,** 1-7.

National Academy of Engineers 1970. Mine rescue and survival: final report. *Committee on Mine Rescue and Survival Technologies.*

Pittman, W. E., Jr., Church, R. H. & McLendon, J. T. 1985. Through-the-earth electromagnetic trapped miner location systems: an overview. Tuscaloosa, AL: Tuscaloosa Research Center.

Schiffbauer, W. H. & Mowrey, G. L. 2006. Preliminary assessment of communication systems for underground mines for normal and emergency operations. *NIOSH Draft Report.* National Institute of Occupational Safety and Health.

Vermeulen, D. J. & Blignaut, P. J. 1961. Underground radio communication and its application for use in mine emergencies. *Transactions of the South African Institute of Electrical Engineers,* 52.

Wadley, T. L. 1949. Radio communication through rock on the Witwatersrand mines. *CSIR Report*.

Wait, J. R. 1960. Propagation of electromagnetic pulses in a homogeneous conducting earth. *Applied Scientific Research, Section B,* 8**,** 213-253.

Wait, J. R. 1971. Criteria for locating an oscillating magnetic dipole buried in the earth. *Proceedings of the Institute of Electrical and Electronics Engineers (IEEE)*.

Wait, J. R. 1972. On the theory of transient electromagnetic sounding over a stratified earth. *Canadian Journal of Physics,* 50**,** 1055-1061.

Wait, J. R. & Spies, K. P. 1972. Subsurface electromagnetic fields of a circular loop of current above ground. *IEEE Transactions on Antennas and Propagation,* 20**,** 520-522.

Wheeler, H. A. 1961. Radio-wave propagation in the Earth's crust. *Journal of Reserach of the National Bureau of Standards-D. Radio Propagation,* 65D**,** 189-196.

Yenchek, M. R., Homce, G. T., Damiano, N. & Srednicki, J. 2012. NIOSH sponsored research in through-the-earth communications for mines: a status report. *IEEE Transactions on Industry Applications,* 48**,** 1700-1707.

10.0 Acknowledgements/Disclaimer

The authors wish to thank the operators of the field test sites for their time, assistance, and generosity. The successful completion of this project would not have been made possible without their enthusiasm and guidance. This publication was developed under a grant awarded from the Alpha Foundation for the Improvement of Mine Safety and Health, Inc. (ALPHA FOUNDATION). The findings and conclusions in this report are those of the authors and do not reflect the official policies of the ALPHA FOUNDATION. Additionally, the mention of trade names, commercial practices, or organizations does not imply endorsement by the ALPHA FOUNDATION.