Magnetic Through-the-Earth Miner Transceiver for Emergency Communications

Final Progress Report

CDC Grant: 1R43OH010143-01
Period of Performance: 09/01/11 to 08/31/12

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November 2012

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1.0   INTRODUCTION

Mining accidents are still a regular occurrence both in the U.S. and worldwide [1,2], often resulting in the loss of dozens of lives. Many of these fatalities could have been averted had there been a reliable emergency communications system in place to provide life-saving information to search-and-rescue parties and to trapped miners. Past experience has shown that there is no practical way to harden infrastructure and ensure that the primary communications system (operating within conventional two-way radio bands) will survive any conceivable event [3]. In practice, survivability must be achieved through alternative (secondary) communications paths. However, current technology [4] requires large in-mine transmit antennas (100 ft. × 100 ft.) and is limited in range due to the Mine Safety and Health Administration (MSHA) safety restrictions on permissible current flow in a coal mine environment.

The National Institute for Occupational Safety and Health (NIOSH) supports research that leads to improvements in the safety and health of mine workers. In recent memory, a number of mine emergencies have had tragic consequences. Part of the fallout of these disasters has been the realization of the inadequacy of existing emergency mine communications. Traditional wireless radio systems are not designed for subterranean application and require a dedicated infrastructure to operate in a mine environment. This infrastructure is very likely to fail in mine emergencies such as fires, explosions, or roof cave-ins, resulting in complete loss of communication between trapped mine workers and the surface ground and rescue teams. On June 15, 2006, President George Bush signed the **Mine Improvement and New Emergency Response (MINER) Act of 2006** [5], which included the following statement: "The plan shall provide for a redundant means of communication with the surface for persons underground, such as secondary telephone or equivalent two-way communication." Current practices cover a wide range of electromagnetic bands, from UHF to ULF. Unfortunately, operating in any one of these bands has specific problems.

To address this capabilities gap, Physical Optics Corporation (POC) initiated the development in Phase I of a Magnetic Through-The-Earth Miner Transceiver for Emergency Communications (MATHEMITE) system (Figure 1). The MATHEMITE system consists of a portable in-mine zero-power transmitter (ZPT) and a handheld battery-powered in-mine receiver unit that can provide reliable two-way TTE communication to a surface transceiver. This ZPT is based on mechanical rotation of permanent magnets. As a crank-shaft is rotated by the miner, a system of gears turns a system of high-strength permanent magnets at ultra low frequencies between 5 Hz and 15 Hz, optimal for long range through-the-earth (TTE) communication in a coal (or other) mine. Individual magnets within the transmitter rotate at different frequencies, with a unique ratio serving to identify the transmitter and distinguish it from environmental interference at the receiver on the surface (outside the mine). Because electrical power is not required and the transmissions generated by the ZPT are of extremely low frequency, it meets the MSHA electrical safety regulations for coal mine environments. In order to improve the efficiency of information transfer at low bit rates, MATHEMITE incorporates a novel message-encoding method based on commonly used words or phrases—rather than ASCII text—that results in at least a fourfold improvement in message transfer rate for 99.5% of messages. MATHEMITE also includes a mine receiver (a handheld device no larger than a walkie-talkie) that receives messages from a surface transmitter and displays them as text using less than 1 W of power. Operation in the 5–15 Hz band ensures that mine-to-surface communications can be maintained in all emergency situations—unlike current leaky feeder or medium frequency (MF) radios, which require unbroken tunnels or conducting lines. The in-mine unit requires no additional infrastructure for installation or operation in the mine environment.
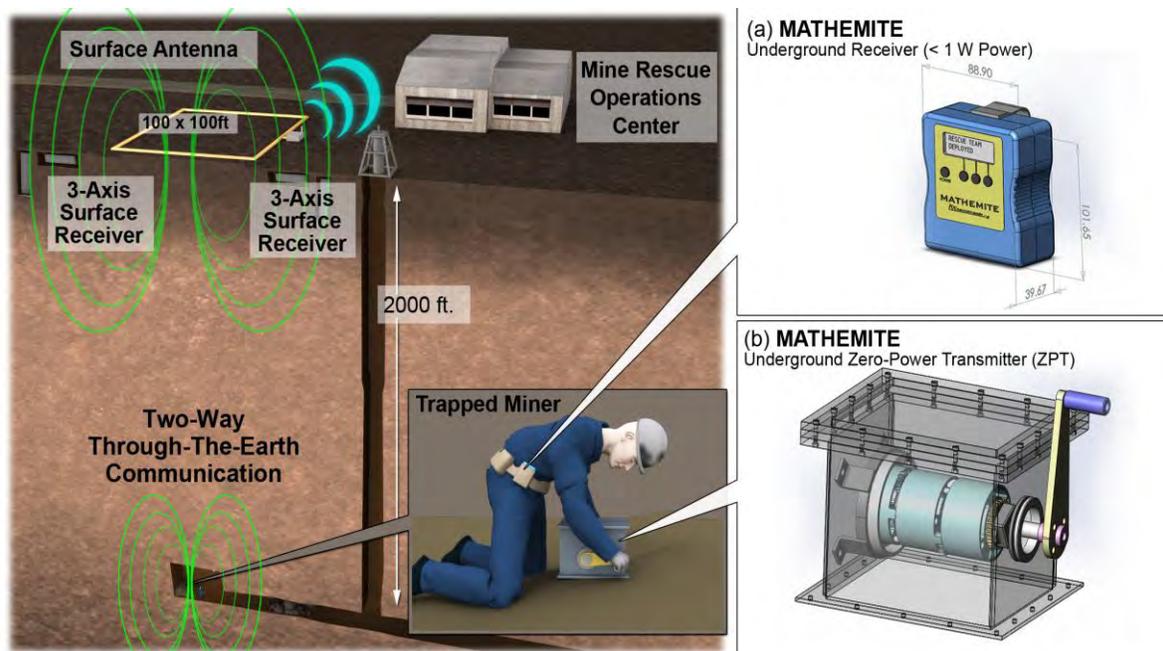
Figure 1. Left: mine roof-fall collapse scenario illustrating the two-way through-the-earth operation of MATHEMITE. Right: design of the MATHEMITE in-mine handheld battery-powered receiver (4×3½ × 1½ in.[3], weighing 8 oz, with 8 hours continuous operation) and a zero-power transmitter (ZPT) (20 × 20 × 20 in.[3], weighing 30 lb).

In Phase I, POC achieved all of the objectives set forth for this project for requirements analysis, system design, and feasibility demonstration with prototype systems in mine environments. In Phase I, we demonstrated the feasibility of MATHEMITE through mine tests with a scaled-down MATHEMITE system conducted at the Edgar Mine (Idaho Springs, CO), where we successfully recorded transmission through 385 ft and also distinguished individual transmitters from each other and from environmental noise signals. The prototype was demonstrated to technical personnel at the NIOSH Office of Mine Safety and Health Research (OMSHR) on July 13, 2012, by transmitting an S.O.S. signal in Morse code with the MATHEMITE prototype system from within the NIOSH Experimental Mine to a surface receiver 110 ft above the mine. In addition, the experimental results showed the feasibility of our novel approach to mitigating environmental interference and reducing false positives, based on unique frequency ratios. Experimental results showed good agreement with our system model, which allowed us to develop a full-scale design to meet the 2000 ft TTE communication range recommended by NIOSH OMSHR personnel. The above advantages also make the proposed transceiver commercially attractive, since it is based on the integration of existing technologies, and potential markets include not only mine safety but also construction and energy industries [6], in addition to numerous military and security applications. As a result, POC's proposed research will significantly impact the safety of personnel involved in underground operations by providing a reliable, compact, TTE communications system.

Based on the success of the Phase I feasibility demonstration, POC developed a plan to complete the development of an MSHA-compliant MATHEMITE system and submitted a Phase II MATHEMITE proposal on August 5, 2012 based on this plan.

2.0 CURRENT STATE-OF-THE-ART TTE COMMUNICATIONS SYSTEMS

Considerable research was conducted into through-the-earth (TTE) communications in the 1960s and 1970s in the U.S. by the Bureau of Mines, including characterization of mine magnetic noise levels in the ELF and VLF bands [7]. Unfortunately, much of the original data has been lost, and it is likely that whatever remains is now becoming obsolete, as the nature of mine machinery and electrical interference sources has changed in the intervening decades. More recently [8], spurred by the presidential MINER Act of 2006 [5], a number of TTE communication developments have been funded through NIOSH OMSHR. The most successful of these developments was a TTE communications system developed by Lockheed Martin that uses a single-turn in-mine transmitter coil that encircles a 100 ft × 100 ft coal pillar [4]. The range of the Lockheed system is limited by the amount of current that can be run through the transmit coil, which is limited by MSHA safety regulations for coal mine environments. Table 1 shows an analysis POC conducted during Phase I comparing the size, weight, and power consumption of a single-turn transmit coil (such as the Lockheed system) with a permanent magnet-based system of equivalent magnetic moment (and hence range through the earth). This single-turn coil is referred to in the table as power-optimized state of the art (SOTA), or SOTA1, and a second configuration, referred to as size-optimized SOTA, or SOTA2, is based on the weight and power consumption of a coil-based transmitter of equivalent strength and size to POC's permanent magnet (MATHEMITE) system.

Table 1. POC's MATHEMITE vs. SOTA Through-the-Earth Communications Systems

Range	Magnetic Moment	MATHEMITE (Zero Power)			SOTA 1 (Power Optimized)				SOTA 2 (Size Optimized)			
		Magnet Size (Quantity)	Magnet Weight	Box Size	Coil Diameter	# Turns	Wire Weight	Power	Coil Diameter	# Turns	Wire Weight	Power
500 ft (150 m)	16 Am^2	3/4" (2)	0.2 lb (0.1 kg)	10" (0.25 m)	13 ft (4 m)	1	0.3 lb (0.1 kg)	0.3 W	10" (0.25 m)	283	4.8 lb (2.2 kg)	5 W
1000 ft (300 m)	130 Am^2	1 1/2" (2)	1.8 lb (0.8 kg)	20" (0.5 m)	37 ft (11 m)	1	0.8 lb (0.4 kg)	0.8 W	20" (0.5 m)	564	13 lb (6 kg)	14 W
1333 ft (400 m)	209 Am^2	2" (2)	4.3 lb (2 kg)	25" (0.63 m)	60 ft (18 m)	1	1.2 lb (0.6 kg)	1.3 W	25" (0.63 m)	754	29 lb (13 kg)	31 W
2000 ft (600 m)	1042 Am^2	3" (2)	15 lb (6.8 kg)	40" (1 m)	100 ft (33 m)	1	2.2 lb (1 kg)	2.4 W	40" (1 m)	1131	77 lb (35 kg)	80 W

3.0 PHASE I WORK AND RESULTS
3.1 Highlights of Phase I Results

In Phase I, POC achieved all of the objectives set forth for this project. The Phase I technical accomplishments include:

- Analyzed system requirements and developed the system design for the MATHEMITE system.
- Assembled multiple prototype generations.
- Developed signal processing methodologies.
- Demonstrated feasibility through prototype testing at representative mine sites.
- Identified commercial applications of the MATHEMITE system.
- Established commercial potential and product viability of the MATHEMITE system.

3.2 Phase I Technical Objectives

The overall goal of this project was to demonstrate for the first time the feasibility of a compact, low-power, through-the-earth transceiver. The following specific objectives were established to reach this goal.

Objective 1.   Design and development of a MATHEMITE system, including a tradeoff analysis of power, size, and data rate.

Objective 2.   Design of MATHEMITE components, including a photonic magnetometer receiver, compact magnetic transmitter, communication protocols, and transceiver electronics.

Objective 3.   Demonstration of feasibility of the MATHEMITE approach.

Objective 4.   Preliminary establishment of the commercial promise of MATHEMITE.

POC met all of these objectives in Phase I by designing, fabricating, assembling, testing, and demonstrating multiple MATHEMITE prototype generations. The Phase I experiments with scaled-down MATHEMITE prototypes at the Edgar Mine (Idaho Springs, CO) and NIOSH Experimental Mine (Pittsburgh, PA) demonstrated TTE communication at a range of up to 385 ft. Based on these results, we have developed a design for a full-scale prototype that will meet the targeted range of 2000 ft TTE. The above advantages also make the proposed transceiver commercially attractive, since it is based on the integration of existing technologies, and potential markets include not only mine safety but also construction and energy industries [6], in addition to numerous military and security applications. As a result, POC's proposed research will significantly impact the safety of personnel involved in underground operations by providing a reliable, compact, TTE communications system.

3.3   MATHEMITE Design

MATHEMITE Phase I Methodology and Overview. At the suggestion of Mr. Steve Inserra, the NIOSH monitor for the project, POC conducted periodic briefings on the project with technical personnel at the NIOSH Office of Mine Safety and Health Research (OMSHR), David Snyder and Joseph Waynert. They provided valuable insight and guidance, in particular regarding the current state-of-the-art in TTE mine emergency communications, where the current capability gaps exist, and what aspects of the MATHEMITE design offer the greatest potential for mine application. Specifically, they identified a zero-power mine transmitter and a handheld mine receiver as items of interest for mine use and suggested we focus on these innovative aspects of the MATHEMITE design in Phase I.

MATHEMITE System Design and Concept of Operations. The MATHEMITE system (Figure 2) is designed to provide a secondary mine communications system in the event of a mine emergency in which the primary mine communications system is disabled. To provide reliable communications in a mine emergency, MATHEMITE requires no mine infrastructure—communication is wirelessly directly TTE. Only electromagnetic signals with frequency content at 100 Hz or below can be guaranteed to propagate TTE in a coal mine environment. At higher frequencies, the conductivity of the subsurface exponentially attenuates any signal. MATHEMITE provides two-way communication between the surface and the interior of the mine, with up to 2000 ft of overburden. The most challenging communication channel has traditionally been between the mine and the surface because the transmit power as well as space to deploy large antennas within the mine is very limited and receiver detection at the surface is limited by environmental noise. This factor is addressed by the key innovation of the MATHEMITE system, the underground ZPT, which uses purely mechanical means (no electrical power or batteries required) to provide the required mine transmit signal. Other components of MATHEMITE include an in-mine handheld receiver, based on POC's magnetic receiver technology, and surface receivers and transmitters, based on commercially available components. MATHEMITE incorporates unique communication protocols and environmental noise-rejection algorithms specially designed for the novel ZPT approach.

MATHEMITE Underground Zero-Power Transmitter. The MATHEMITE underground ZPT Phase II prototype will be based on a scaled-up version of the Phase I prototype. The design (see Figure 2) incorporates three 3 in. cube magnets ($7.5 \times 7.5 \times 7.5$ cm^3) that rotate at different

frequencies between 5 and 15 Hz. The natural rotation frequency for a hand-cranked system is ~1–2 Hz. An overall gear system increases the magnet rotation by a factor of 5 (this was demonstrated in the Phase I Gen II ZPT prototype). Individual gear systems on each magnet ensure that each magnet rotates at a different frequency (~1–2 Hz apart) with a ratio unique to the specific hardware unit (this was demonstrated in the Phase I Gen I ZPT prototype). The magnets are commercially available neodymium magnets (identical to those used for the Phase I ZPT prototype other than a factor of two larger in linear dimension). POC will leverage its experience in manufacturing crash-survivable flight data recorders (see "Related Work by POC") to develop a mine emergency survivable packaging design. The entire packaged system (for 2000 ft TTE range) is expected to measure ~0.5 × 0.5 × 0.5 m^3 (20 × 20 × 20 in.$^{3)}$), weigh 13 kg (30 lb) and consume zero electrical power. In addition to building a full-scale prototype in Phase II, POC will explore additional design modifications to add more functionality to the ZPT, such as frequency modulation via continuously variable gears and the use of stored gravitational potential energy (height) or stored mechanical energy (springs) to rotate the magnets.
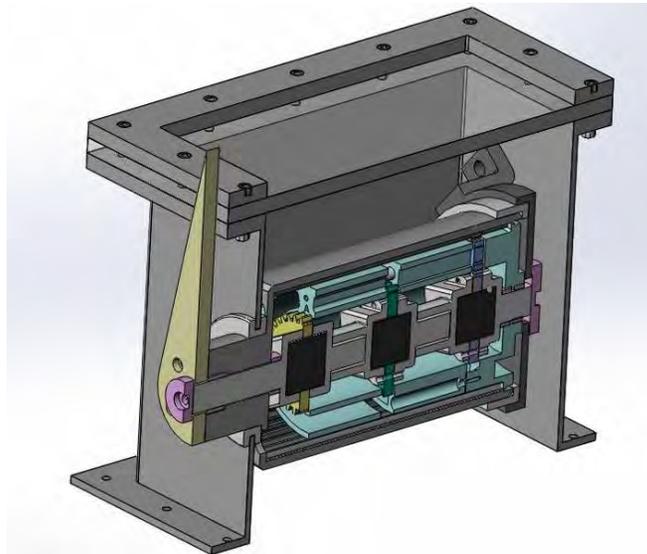

Figure 2. Cross sectional view of preliminary MATHEMITE underground ZPT (20 × 20 × 20 in.^{3}, weighing 30 lb) design for 2000 ft TTE communication range. Three identical 3 in. cube magnets rotate at different frequencies with a frequency ratio defined uniquely by a system of gears. We identified three magnets as optimal to provide a unique signature without undue size or complexity.

MATHEMITE Surface Transmitter. The surface transmitter will be developed using conventional techniques for generating large dipole moments. The dipole moment of the surface transmitter will be determined based on the surface-to-mine link budget, primarily mine receiver sensitivity, through-the-earth losses, and environmental interference levels. Our current estimate is that a dipole moment of ~100,000 Am^2 will be necessary, which could be achieved with a 100 ft. × 100 ft. loop carrying 100 amp-turns, similar to existing through-the-earth mine communications systems (see "Related Work by Others" section). The Phase II prototype will be assembled from standard multi-element cable, a power amplifier, a 16-bit 100 ksps digital-to-analog converter, and software-defined waveforms generated with the LabVIEW Modulation Toolkit. The surface transmitter setup will also be used in initial experiments to characterize the relevant mine geophysical characteristics by transmitting frequency sweeps through the earth and comparing the transmitted signal to TTE propagation models.

MATHEMITE Underground Handheld Receiver. The MATHEMITE underground receiver (see Figure 3) is designed for portability and low-power consumption. It consists of a miniature, high-sensitivity, 3-axis magnetometer, signal processing electronics, a text display, and a battery pack. For the 3-axis magnetometer we plan to use a miniature fluxgate, such as the Billingsley model TFM100G2 (20 pT/√Hz at 1 Hz magnetic sensitivity) used in the Phase I experiments. POC is also developing novel miniature magnetometers (see "Related Work by POC" section) which are projected by 2014 to achieve comparable sensing performance with lower power consumption. The receiver electronics module, which is based on POC's existing hardware (see "Related Work by POC" section) is compatible with both COTS and in-house magnetometers, allowing POC to select the best technology option at the time of prototype assembly (see Table 2). The packaged self-contained receiver measures ~10 × 9 × 4 cm^3 (4 × 3½ × 1½ in.^{3}), weighs ~225 g (8 oz.), and consumes ~940 mW (for >8 hr of continuous operation on two standard 9 V batteries), as summarized in the power budget in Table 3. It has a clip on the back that allows it to be attached to a standard miner belt.
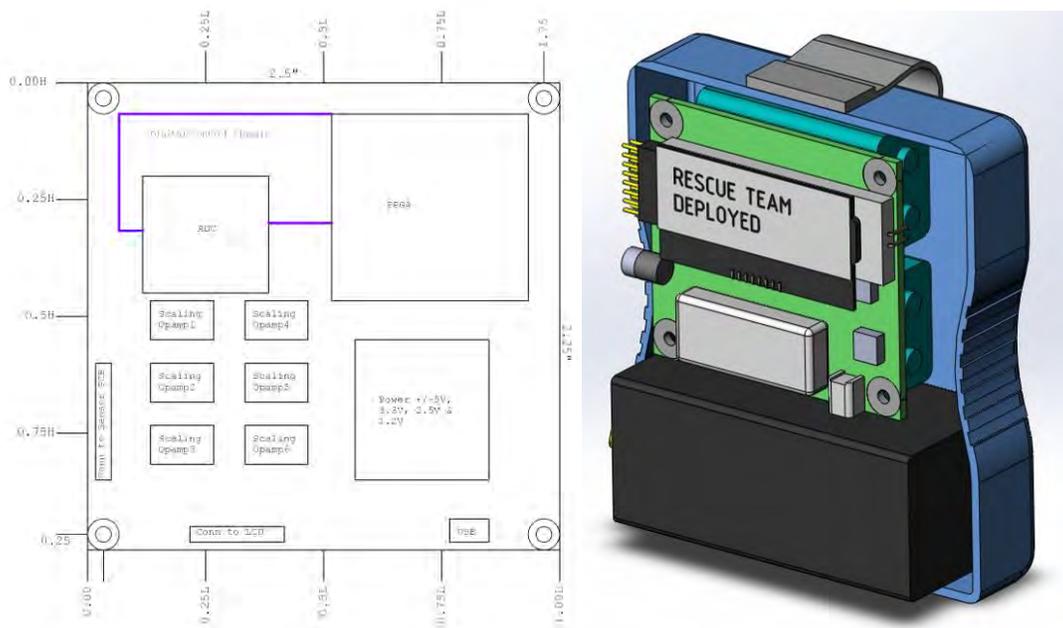

Figure 3. Electrical design (top) and mechanical design (bottom) of the MATHEMITE handheld underground receiver (4×3½×1½ in.^{3}, weighing 8 oz.), which is based on low power digital processing electronics developed at POC for monitoring power line signals from small unmanned vehicles.

Table 2. Magnetometer Specifications Comparison for MATHEMITE Handheld Receiver

Specification	COTS Fluxgate with POC Data Acquisition and Processing Electronics	POC Photonic Magnetometer (Current Generation, Measured)	POC Photonic Magnetometer (Next Generation, Estimated)
Magnetic Noise Floor	20 pT/√Hz		20 pT/√Hz
Number of Axes	3	1	3
Size	10×9×4 cm^3	7×4×2 cm^3	10×7×3 cm^3
Weight	225 g	75 g	175 g
Power Consumption	0.94 W	3 W	3 W

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Table 3. Power Budget for MATHEMITE Handheld Underground Receiver

Component	FPGA	ADC	OpAmps	LCD	Regulator	Fluxgate	Total
Power (mW)	204	50	24	32	184	446	**940**

MATHEMITE Surface Receiver. Based on our Phase I experiments, we determined that the surface receiver should have sub-pT/√Hz sensitivity in the 1 Hz–100 Hz range to detect the signals generated by the ZPT with sufficient signal-to-noise ratio. In addition, we found that at least two measurement axes (vertical and horizontal) will be needed to avoid a null of the transmit signal for specific transmitter/receiver placements. More than one receiver can also provide additional benefits in noise rejection analysis and signal processing. The geophysical instrument we used for the Phase I experiments (LEMI-120, KMS Technologies, Houston, TX) performed well in this respect, with a calibrated, pre-amplified, analog output signal, and better than 1 pT√Hz sensitivity between 0.1 Hz and 10 kHz. For Phase II experiments and demonstration, we intend to add more (identical) receivers, improve the receiver field installation to minimize vibrations, and define optimal receiver placements for an objective system. The surface data acquisition setup will also include the National Instruments 24-bit, 50 ksps, 4-channel, USB data acquisition module, connected to a laptop computer containing data acquisition and signal processing algorithms coded with the LabVIEW Signal Processing Toolkit.

Mine Emergency Communications Link Budget. In the low frequency limit (the worst case, <10 Hz, for a coal conductivity of 0.25 S/m, is shown in Figure 4), the TTE link depends on the magnetic moment m of the transmitter and minimum detectable magnetic field B via the dipole equation: $B = (\mu_0/4\pi)(m/r^3)$, where r is the range and μ_0 is the magnetic permeability. For permanent magnets $m = d^3 B_r/\mu_0$, if we assume a cubic magnet with linear size d. The magnetic remanence B_r for commercial N52 grade neodymium magnets is 1.48 T [9]. From our Phase I measurements, we found a minimum detectable magnetic field of 1 pT, which results in a range (in feet) of $r = 408d$, where d is the magnet size in inches. A single 3 in. magnet would therefore provide a range of >1200 ft. Using three such magnets (as in the ZPT design above) increases the magnetic moment by a factor of 3, resulting in a range of 1800 ft, which with further improvements in noise reduction can be extended to 2000 ft. Full analytical models [10] and finite element models of TTE transmission were also developed as part of the Phase I analysis.
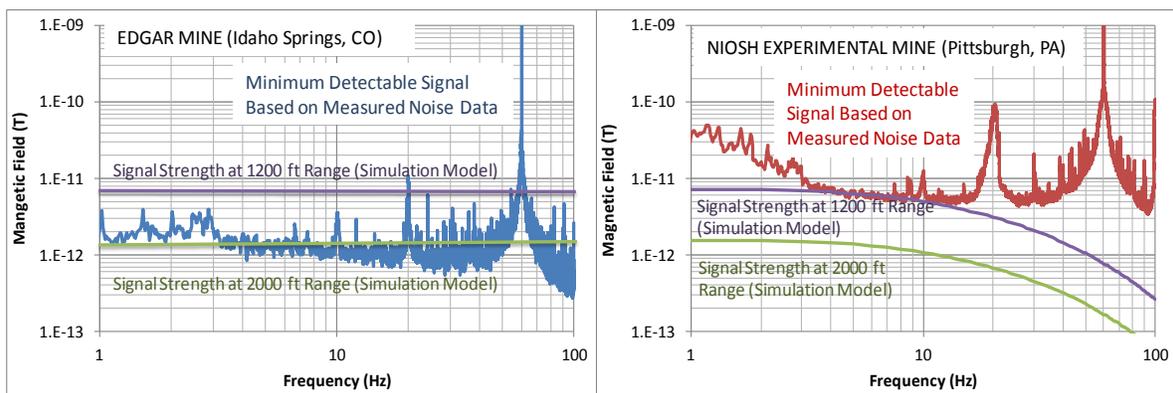

Figure 4. MATHEMITE surface receiver minimum detectable signal compared with the signal strength from the MATHEMITE underground transmitter at 1200 ft and 2000 ft (SNR=3 and 0.1 Hz bandwidth were assumed for the minimum detectable signal)

MATHEMITE Communications Protocol. The choice of communication protocol is tightly correlated with the signal detection and recognition process and as such has a direct impact on the communication range and quality of the communication link. Hardware considerations limit the bit rate and modulation methods, and therefore POC will investigate novel message encoding approaches. One particular approach we identified in Phase I is to encode words or phrases, rather than use ASCII text [11]. The advantage can be seen by using Chinese characters as an example. About 99.5% of information can be conveyed using the 3500 most common characters (<12 bits c.f., 8 bits per ASCII character). A 15-word (100 ASCII character) sentence could be conveyed with 180 bits vs 800 for ASCII text, which represents a more than fourfold increase in the information transfer rate (Figure 5).
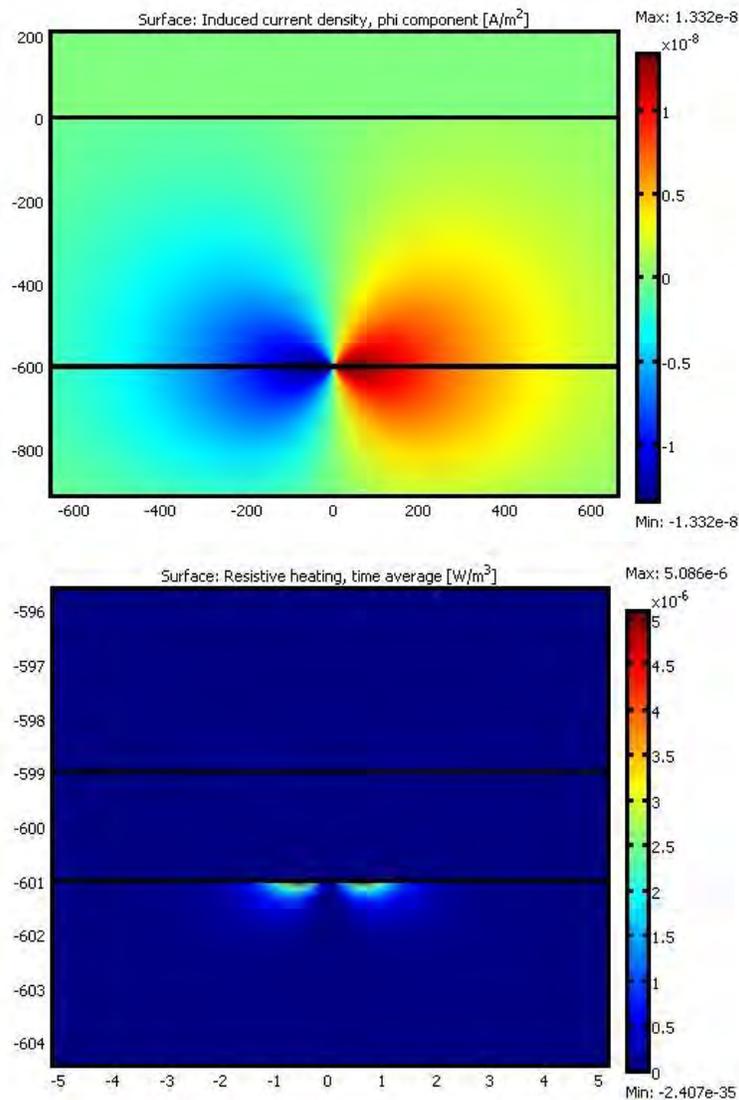
Figure 5. Finite element simulation of the MATHEMITE ZPT in-mine operation. Top: current density (max. 13 nA/m^2) induced by the MATHEMITE ZPT, at least 10 orders of magnitude below the MSHA safety standard [12]. Bottom: associated power density (max. 5 µW/m^3). At least 1 mW of power in a confined region (<1 cm^3) is required to ignite a methane air mixture [13], which is at least 10 orders of magnitude higher than the power induced by the MATHEMITE ZPT in the mine environment.

3.4 MATHEMITE Feasibility Demonstration

Over the course of Phase I, POC developed two generations of MATHEMITE prototypes and tested them in metal/nonmetal and coal mine environments. Novel communication protocols and algorithms for recognizing the transmitted signal amid environmental mine noise were also developed and evaluated in the mine tests as part of the Phase I effort. The longest range at which a signal was detected in mine testing of the MATHEMITE Phase I prototype was 385 ft., in which an S.O.S. signal was transmitted in Morse code (see Figure 6).

Raw Data Spectrogram from Edgar Mine Test Showing Detection of MATHEMITE Signals at 385 ft Range

Processed Data from Edgar Mine Test Showing Detection of MATHEMITE Morse Code S.O.S Signal at 385 ft Range
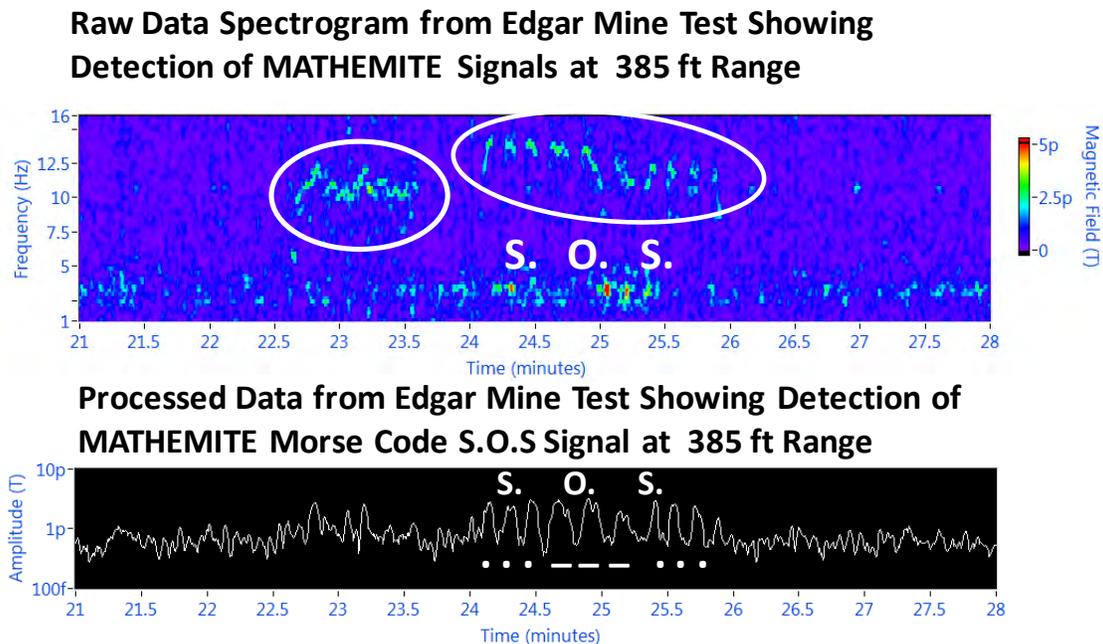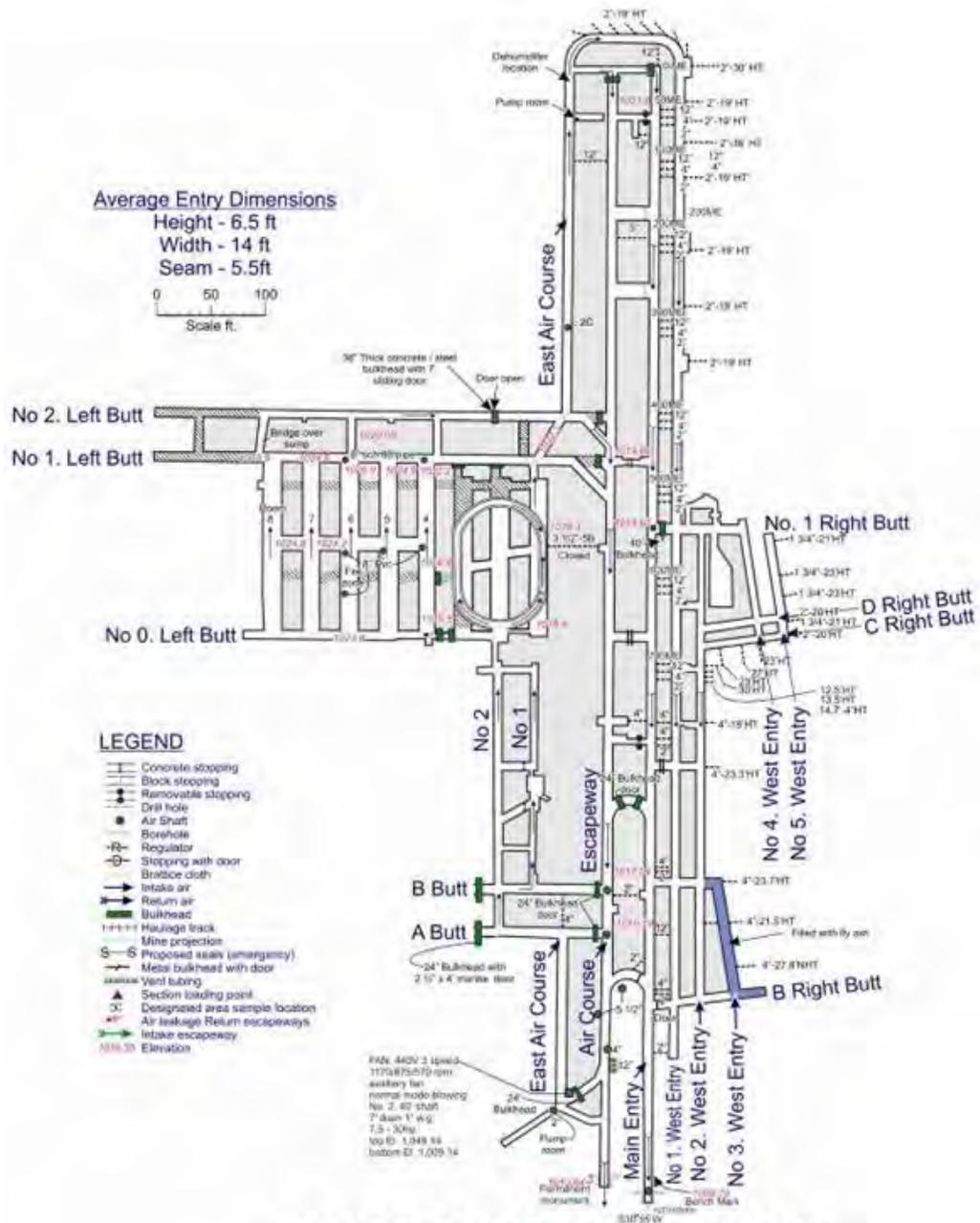
Figure 6. MATHEMITE Phase I prototype test results from the Edgar Mine (Idaho Springs, CO) showing detection of a Morse code S.O.S. signal at a range of 385 ft through-the-earth.

MATHEMITE Phase I Test Sites and Protocols. The MATHEMITE prototypes were evaluated at two separate test sites (see Figure 7). The first test site, facilitated through the project's mining consultant, Mr. Bob Ferriter (Colorado School of Mines, Golden, CO), was the Edgar Mine (Idaho Springs, CO), a retired metal/nonmetal mine now operated as a training mine by the CSM. The second test site was the NIOSH experimental mine, a coal mine located on the campus of the NIOSH Office of Mine Safety and Health Research (OMSHR) in Pittsburgh, PA.

MATHEMITE Phase I Prototypes and Test Setup. Two generations of MATHEMITE system prototypes were developed and tested in a mine environment in Phase I. The Gen I prototype included a ZPT that incorporated two ¾ in. neodymium magnets (magnetic moment of 8 Am^2 each) and a unique gear system that ensured the rotation frequency of the two magnets differed by a fixed ratio. Two such prototypes, with 6.7% and 11.25% frequency ratios, were assembled and tested in order to evaluate the capability to recognize individual beacon signals. The Gen II ZPT (shown on the right in Figure 8) incorporated a single 1½ in. neodymium magnet (magnetic moment of 65 Am^2). The gear system in this case provided an approximately fivefold increase in the rotation frequency (close to the ideal frequency for TTE transmission at ~10 Hz). Thus the goal of the Gen II ZPT prototype was to increase the range of TTE transmission. Both prototypes contained no electrical components and were completely mechanically powered by a hand crank.

EXPERIMENTAL MINE
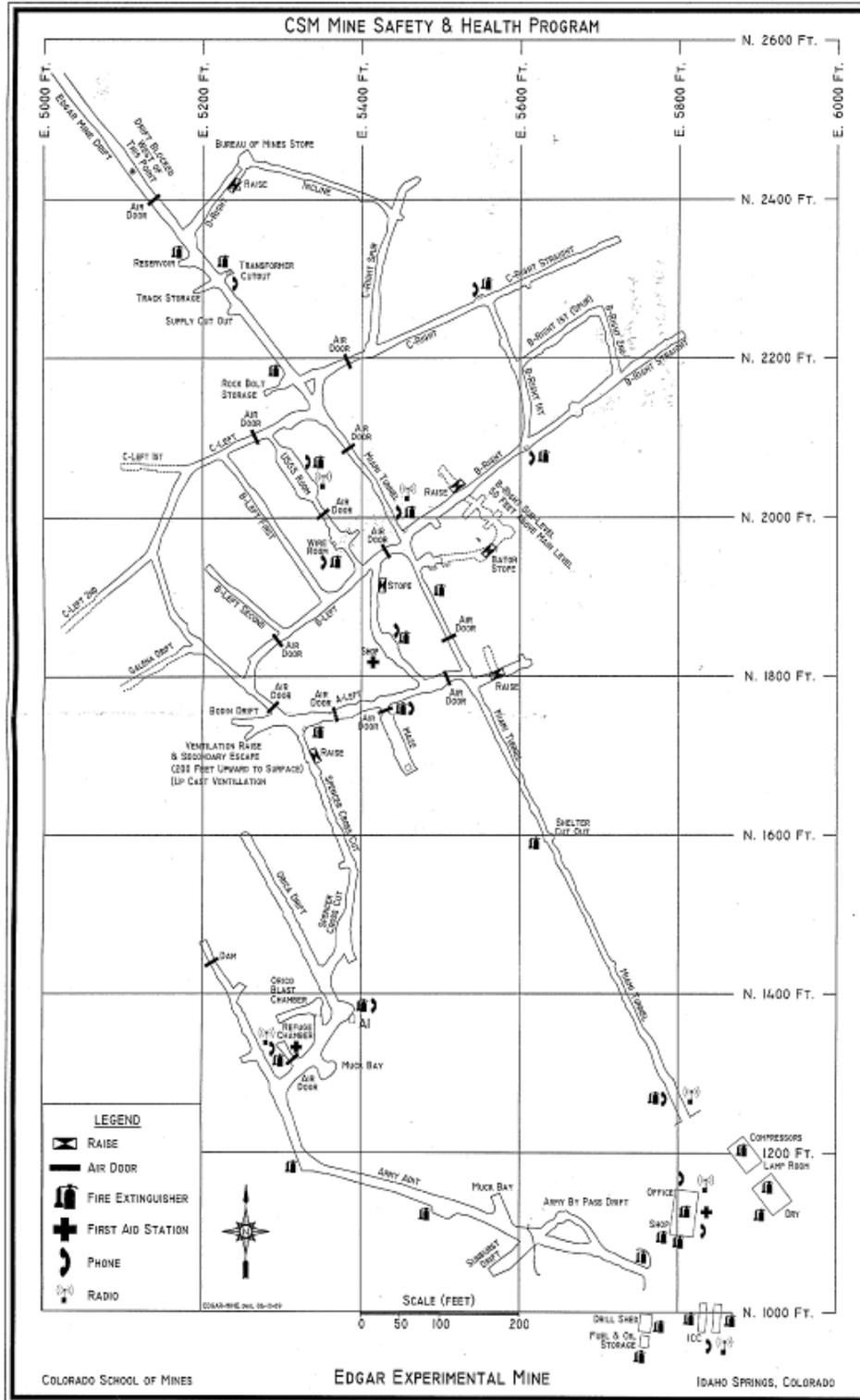
Figure 7. Maps of the NIOSH Experimental Mine.

Figure 7 (cont.). Edgar Mine.

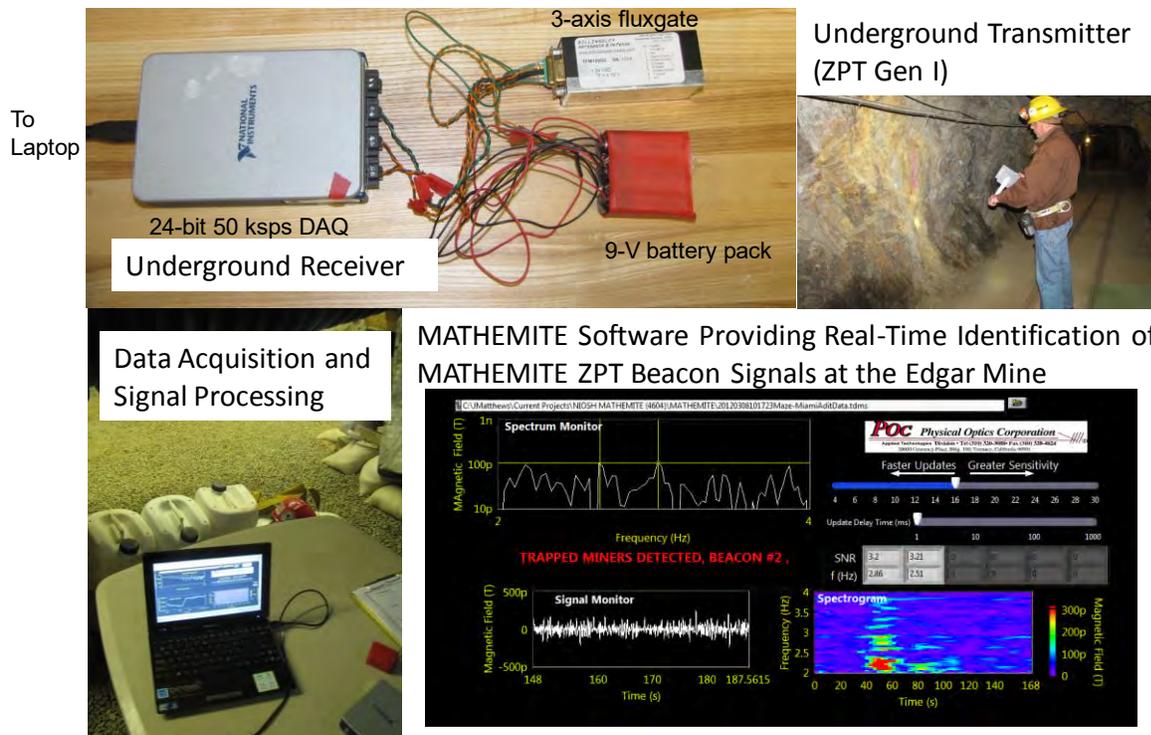The two test sites where the MATHEMITE Phase I prototypes were tested.

Figure 8. The Gen I MATHEMITE system prototype tested at the Edgar Mine included a miniature 3-axis fluxgate magnetometer powered by three 9 V batteries, a USB-powered data acquisition unit, a laptop computer with data acquisition and signal processing software, and a scaled-down ZPT with two ¾ in. permanent magnets rotating with a fixed frequency ratio. Two separate transmitters with distinct frequency ratios were tested simultaneously and successfully recognized by the MATHEMITE software amid mine environmental noise.

Two commercial receivers were used in the mine tests: for the Gen I prototype, a 3-axis miniature fluxgate magnetometer (Billingsley Aerospace and Defense, Germantown, MD) was used, while a single-axis induction coil magnetometer (LEMI-120, KMS Technologies, Houston, TX) was used for the Gen II prototype. Also shown in Figure 8 is the 24-bit 50 ksps 4-channel USB data acquisition module (NI9239, National Instruments, Austin, TX) which provided high-resolution digital data to a laptop computer for analysis. The 3-axis fluxgate was powered by three 9 V batteries, the induction coil was powered by two 9 V batteries, and the DAQ was USB-powered via the laptop. LabVIEW-based data acquisition and signal processing software was developed to recognize and distinguish individual beacon signals from mine noise (screenshot of GUI in Figure 8).

The Gen I prototype was first tested at the Edgar Mine on March 8, 2012 (see Figure 8). The Gen I and Gen II prototypes were tested at the Edgar Mine on May 16, 2012 (data from these tests are shown in Figures 8 and 10), and at the NIOSH Experimental Mine on July 13, 2012 (see Figure 9). The test protocol for the Gen I prototype was as follows: t=0: Beacon #1 on; t=30 s: Beacon #2 on; t=60 s: Beacon #1 off; t=90 s: Beacon #2 off. Tests with the Gen II prototype were conducted with a Morse code S.O.S. protocol (dot-dot-dot-dash-dash-dash-dot-dot-dot) where a 5 sec transmission represented a dot, a 10 sec transmission represented a dash, and a 5 sec interval was allowed between transmission of each dot or dash.

Spectrogram of Raw Data at NIOSH Experimental Mine

Processed Data from NIOSH Experimental Mine Showing Transmitted S.O.S. Signal
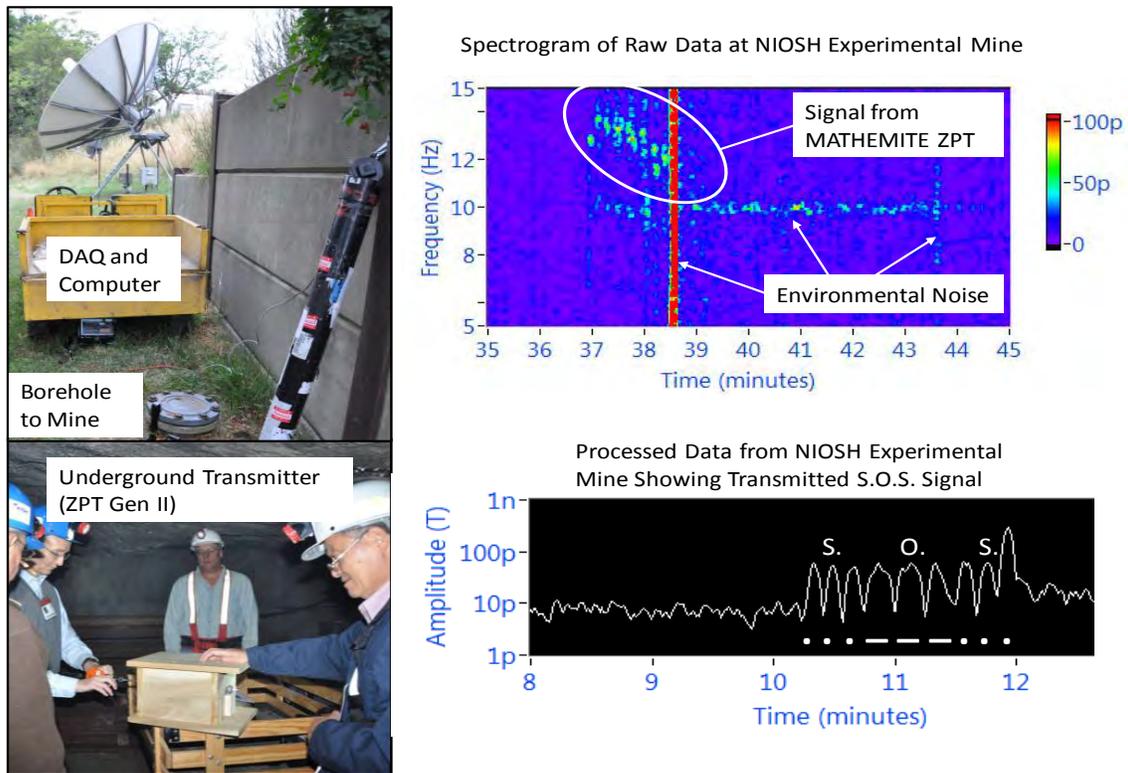
Figure 9. The Gen II MATHEMITE system prototype demonstrated at the NIOSH Experimental Mine added a single-axis induction coil receiver and a ZPT with a single 1½ in. permanent magnet rotating at 11–13 Hz. A Morse code-based communication protocol was used to transmit an S.O.S. signal from the mine to the surface through ~110 ft of overburden.
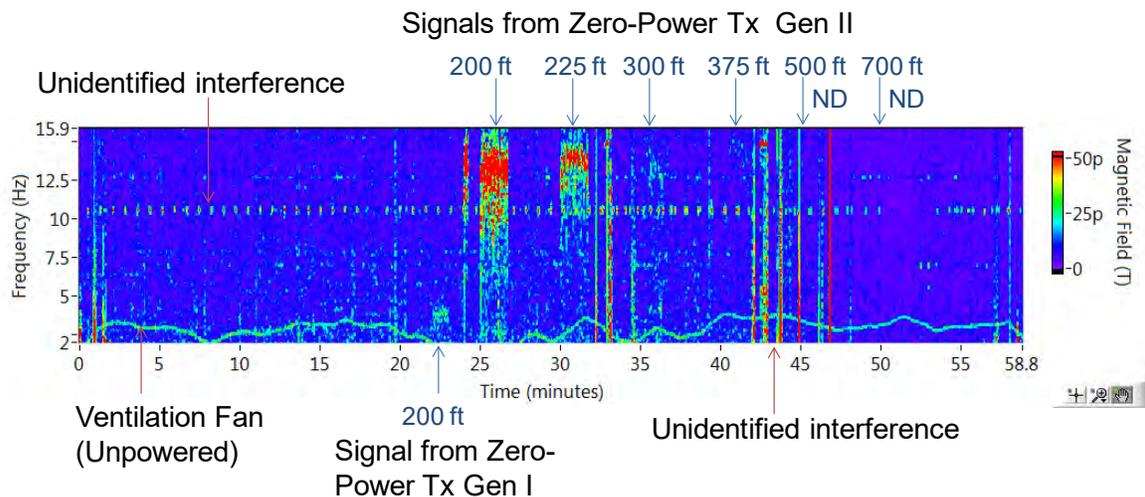
Figure 10. Spectrogram obtained at the Edgar Mine with the 2nd generation MATHEMITE system prototype. The surface receiver was located 200 ft above the mine level where the ZPTs were operating. To gain range, the transmitters were moved laterally within the mine. Note the number of interference signals (including an unpowered ventilation fan drifting between 2 and 4 Hz, several broadband spikes, and a 11 Hz pulse repeated about once per second) through which the transmitted signals were detected.

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MATHEMITE Phase I Data Analysis and Interpretation. A spectrogram (false-color magnetic field plot versus frequency and time) of the signal from the single-axis induction coil from one of the datasets acquired at the Edgar Mine on May 16, 2012, is shown in Figure 10. The receiver was located at the surface close to a ventilation shaft, 200 ft vertically above the mine level. The transmitters were located in the mine, initially directly beneath the receiver, then moved laterally to gain range. The Gen I transmit signal is visible ~22 min into the data record at ~3 Hz. Significantly stronger signals from the Gen I transmitter are visible from minute 25 onward. Transmissions from the Gen II prototype were recognizable up to a 375 ft range. No signals were detected at the 500 ft and 700 ft ranges; therefore, we conclude that the range lies somewhere between 375 and 500 ft, probably close to 400 ft.

The results of the Edgar Mine tests, summarized in Table 4, were compared with a finite element model simulation using the estimated transmitter magnetic moments and transmitter and receiver placements. Agreement between measurement and simulation was within the experimental uncertainties, from which we conclude that both the estimated magnetic moment of the transmitters and the model of through-the-earth transmission for the Edgar Mine environment are accurate, at least to within about 20%.

Table 4. Summary of Measurements at Edgar Mine and Comparison with Finite Element Model Predictions

Overburden	Total Range	Gen I (16 Am^2)		Gen II (65 Am^2)	
		Measurement	Simulation	Measurement	Simulation
0	140 ft	30 pT	-	85±30 pT	-
0	225 ft	6 pT	-	12±5 pT	-
0	385 ft	ND	-	2±1 pT	-
0	590 ft	ND	-	ND	-
200 ft	200 ft	7 pT	10 pT	40±5 pT	44 pT
200 ft	225 ft	ND	7 pT	20±5 pT	25 pT
200 ft	300 ft	ND	1.3 pT	4±2 pT	6 pT
200 ft	375 ft	ND	0.5 pT	3±1 pT	1 pT
200 ft	500 ft	ND	0.7 pT	ND	1 pT
200 ft	675 ft	ND	0.2 pT	ND	1 pT

The mine tests with the MATHEMITE Phase I prototypes successfully validated the modeling and predictions for TTE transmission using permanent magnets and confirmed that TTE transmissions can be detected in a mine environment. Through-the-earth transmissions were recorded up to 385 ft in the Edgar Mine using a single 1½ in. magnet, and testing at the NIOSH Experimental Mine confirmed that at the MATHEMITE operating frequency, the conductivity of coal mines does not significantly affect the TTE transmissions.

4.0   EXPLORATION OF MATHEMITE SYSTEM COMMERCIAL POTENTIAL

The primary application for MATHEMITE as a complete system is mine rescue operations, where it provides the rescue command center with critical information on the location and status of trapped miners in an emergency situation such as a fire, an explosion, or a mine collapse. As a complete system, MATHEMITE also has potential commercial applications for "cavers" and scientific expeditions that venture into underground territory. There are potential applications in homeland security and defense, where it can be used as a part of strategic communications systems or as a communications link for military radios operating in non-line-of-sight situations (e.g., tunnels, mountains).

The handheld underground receiver, which incorporates magnetic sensors and embedded signal processing in a low-power, lightweight package, can itself have a wide variety of applications, due in large part to the increasing interest in sensor payloads for new small unmanned systems (robotic ground vehicles for IED deactivation, unmanned underwater vehicles for mine detection, unmanned aerial vehicles for magnetic anomaly detection, power-line avoidance, and airspace deconfliction). A summary of commercial and military/government applications is included below.

Commercial Applications: A magnetic noise-reduction system for small unmanned or mobile systems has applications in:

- Geological surveying
- Airspace deconfliction
- Emergency mine communications
- Storm monitoring

- Search and rescue
- Local law enforcement
- Biomagnetic imaging
- Archaelogical prospecting

Military and Government Applications: Small unmanned vehicles equipped with scientific-grade magnetometers and a magnetic noise-reduction system could be used for:

- Magnetic anomaly detection
- Unexploded ordnance detection
- Underground tunnel detection
- Power generator detection
- IED initiator detection

- Ground vehicle detection
- Underwater mine detection
- Power line navigation
- Through-the-earth communications
- Space situational awareness

Size of the Market: Approximately 1300 coal mines, with 88,000 workers, are operational in the U.S., of which ~40% are underground mines. If just 10% of underground coal mines purchased MATHEMITE systems for 30% of their workforce, this would total ~1000 units of the MATHEMITE underground unit. Each mine would require far fewer surface units than underground units and, depending on the size of the mine, these could be just a single surface unit. From these estimations, we would have ~50 mines purchasing MATHEMITE units for 1000 underground workers. The cost of a complete MATHEMITE system, including 1 surface unit and 20 underground units, would total ~$144k, and for the total market share of 50 mines, would equal ~$7.2M, a sizable market for a company such as POC with annual revenue of ~$30M. We anticipate that initial sales will be for single surface–single underground systems that would allow mining companies to evaluate the technology and incrementally expand it with further underground units at a later date. Hence our initial manufacturing plan (see below) is based on sales of MATHEMITE systems comprising a 1 surface and 1 underground unit at a price of $27.7k. If a total of 13 mines out of an estimated 520 underground coal mines in the U.S. (2.5%) purchased the MATHEMITE units, this would result in initial annual sales of $360k.

Quantitative Commercialization Results: Preliminary estimates of the market niche that the MATHEMITE technology can capture are presented in Table 5. The estimate for the first year after Phase II completion is based on two key considerations: our manufacturing capability and our presence in the commercial market. To date, POC can produce 13 MATHEMITE systems per year—generating a revenue of $360k. With available expansion space in our manufacturing facilities, we can accommodate a fivefold increase in 2 years (~$1.8 M in revenue) in production volume before we seek contract manufacturing to handle higher volumes in order to reach a target of $20M five years after completion of Phase II. The total internal and external investments needed for expansion of production volume are also indicated in Table 5.

Table 5.   Quantitative Commercialization Results

	2015	2016	2017	2018	2019	2020
Investment Level	$100k	$300k	$500k	$2M	$3M	$ 2M
Total Revenues	$360k	$700k	$1.8M	$5M	$12M	$20M

5.0   FUTURE DEVELOPMENT FOR ADVANCING THE MATHEMITE TECHNOLOGY

Based on the successful Phase I results, POC developed a plan for completing the MATHEMITE development in Phase II. This plan was developed based on input from NIOSH OMSHR personnel, and a Phase II proposal was submitted to CDC on August 5, 2012. The technical objectives and tasks for the proposed Phase II development are outlined below.

Phase II Technical Objectives

Objective 1.   Development of a MATHEMITE system design and concept of operations for TTE communications between surface and mine with up to 2000 ft of overburden.

Objective 2.   Characterization of mine environment in the 0.01 Hz to 10 kHz range.

Objective 3.   Development of a full engineering prototype MATHEMITE system.

Objective 4.   Demonstration of TTE communications with the MATHEMITE prototype.

Objective 5.   Development of a strategy for transitioning the MATHEMITE product to mine use.

To meet these objectives, the following research questions will be answered:

1. What is the nature of mine environmental noise and interference in the 0.01 Hz to 10 kHz frequency range?
2. How does the mine environment affect the range of a TTE communications system?
3. What is the optimal approach to mitigate the environmental noise?

Project Tasks

Task 1.   *Optimize the MATHEMITE System Design (Months 1 to 6) (Objective 1)*

Task 2.   *Develop the MATHEMITE Concept of Operations (Months 1 to 6) (Objective 1)*

Task 3.   *Develop the Surface Receiver Components (Months 2 to 5) (Objectives 1, 3)*

Task 4.   *Develop the Surface Transmitter Components (Months 3 to 6) (Objectives 1, 3)*

Task 5.   *Collect Field Data from Mine Environments (Months 3 to 9) (Objective 2)*

Task 6.   *Analyze Field Data to Characterize the Mine Environment (Months 4 to 10) (Objective 2)*

Task 7.   *Develop MATHEMITE Communication Protocol (Months 7 to 11) (Objective 1)*

Task 8.   *Develop MATHEMITE Signal Processing Algorithms for Mitigation of Mine Environmental Noise and Interference (Months 9 to 12) (Objective 1)*

Task 9.   *Develop the MATHEMITE Underground Handheld Receiver (Months 6 to 12) (Objectives 1, 3)*

Task 10.   *Develop the Mechanical Design of the MATHEMITE Underground Zero Power Transmitter (Months 6 to 12) (Objective 3)*

Task 11.   *Develop the Safety Procedure and Infrastructure for Handling Large Pull-Force Magnets (Months 9 to 15) (Objective 1)*

Task 12.   *Fabricate and Assemble the MATHEMITE Underground Zero Power Transmitter (Months 12 to 18) (Objective 3)*

Task 13.   *Conduct Laboratory Testing of the MATHEMITE Prototype System (Months 17 to 20) (Objective 4)*

Task 14.   *Develop Protocol for Testing the MATHEMITE Prototype in a Mine Environment (Months 19 to 21) (Objective 4)*

Task 15.   *Demonstrate Through-The-Earth Communication with the MATHEMITE Prototype in a Mine Environment (Months 22 to 24) (Objective 4)*

Task 16.   *Develop Plan for Transitioning the MATHEMITE System to Mine Use (Months 22 to 24) (Objective 5)*

6.0   CONCLUSION

Even as we move into the 21st century, mining accidents are still a regular occurrence, often resulting in the loss of dozens of lives. Many of these fatalities can be averted in the future with a reliable emergency communications system in place to provide life-saving information to search-and-rescue parties and to trapped miners. To solve this problem, Physical Optics Corporation (POC) developed, in Phase I, the MATHEMITE system design. The MATHEMITE design incorporates a zero-power transmitter (ZPT) based on mechanical rotation of permanent magnets. As a crank-shaft is rotated by the miner, a system of gears turns a system of high-strength permanent magnets at ultra low frequencies, between 5 Hz and 15 Hz, optimal for long range through-the-earth (TTE) communication in a coal (or other) mine. Individual magnets within the transmitter rotate at different frequencies, with a unique ratio serving to identify the transmitter and distinguish it from environmental interference at the receiver on the surface (outside the mine). In order to improve the efficiency of information transfer at low bit rates, MATHEMITE incorporates a novel message-encoding method based on commonly used words or phrases—rather than ASCII text—that results in at least a fourfold improvement in message transfer rate for 99.5% of messages. MATHEMITE also includes a mine receiver (a handheld device no larger than a walkie-talkie) that receives messages from a surface transmitter and displays them as text using less <1 W of power. Operation in the 5–15 Hz band ensures that mine-to-surface communications can be maintained in all emergency situations—unlike current leaky feeder or medium frequency (MF) radios, which require unbroken tunnels or conducting lines. To demonstrate the feasibility of the MATHEMITE design, POC developed two generations of MATHEMITE prototypes over the course of Phase I and tested them in metal/nonmetal and coal mine environments. Novel communication protocols and algorithms for recognizing the transmitted signal amid environmental mine noise were also developed and evaluated in the mine tests as part of the Phase I effort. The longest range at which a signal was detected in mine testing of the MATHEMITE Phase I prototype was 385 ft., in which an S.O.S. signal was transmitted in Morse code. The prototype was demonstrated to technical personnel at the NIOSH Office of Mine Safety and Health Research (OMSHR) on July 13, 2012, by transmitting an S.O.S. signal in Morse code with the MATHEMITE prototype system from within the NIOSH Experimental Mine to a surface receiver 110 ft above the mine. In addition, the experimental results showed the feasibility of our novel approach to mitigating environmental interference and reducing false positives, based on unique frequency ratios. Experimental results showed good agreement with our system model, which allowed us to develop a full-scale design to meet the 2000 ft TTE communication range recommended by NIOSH OMSHR personnel. The advantages of MATHEMITE also make the technology commercially attractive, since it is based largely on the integration of existing technologies. The potential markets for the proposed transceiver include not only mine safety but also construction and energy industries, in addition to numerous military and security applications. As a result, POC's proposed research will significantly and positively impact the safety of personnel involved in underground operations by providing a reliable, compact, through-the-earth communications system. This directly supports the mission of the National Institute for Occupational Safety and Health to improve the safety and health of mining workers. Based on the success of the Phase I feasibility demonstration, POC developed a plan to complete the development of an MSHA-compliant system and submitted a Phase II MATHEMITE proposal on August 5, 2012, based on this plan.

7.0 BIBLIOGRAPHY & REFERENCES CITED

5. http://www.cdc.gov/niosh/mining/statistics/disall.htm.
6. http://www.cdc.gov/niosh/mining/statistics/images/fc20.gif.
7. http://www.cdc.gov/niosh/mining/mineract/commtrack/workshop2009/CommBasics-Snyder.pdf.
4. Lockheed Final Report NIOSH Controact No. 200-2009-32021.
3. http://www.cdc.gov/niosh/mining/mineract/pdfs/miner-act-pl109-236.pdf.
8. http://www.netl.doe.gov/KeyIssues/mining/communication.pdf.
1. J.A. Durkin, "Vertical Magnetic Noise in the Voice Frequency Band Within and Above Coal Mines," U.S. Department of the Interior, Bureau of Mines, Report of Investigations, vol. 8828, pp. 1-27, 1983.
2. M.R. Yenchek, G.H. Homce, N. Damiano, and J. Srednicki, "NIOSH-Sponsored Research in Through-the-Earth Communications for Mines – A Status Report," *IEEE Industry Applications Society Annual Meeting*, pp. 1-7, 2011.
9. http://www.kjmagnetics.com.
10. J.R. Wait, "Antennas in the Geophysical Environment – Some Examples," *Proc. IEEE*, vol. 80, no. 200, 1992.
11. G.S. Kang, T.M. Moran, and D.A. Heide, "Voice Message Systems for Tactical Applications (Canned Speech Approach)," Naval Research Laboratory Report No. NRL/FR/5531—93-9569, 1993.
12. Title 30, Code of Federal Regulations, Section 7.64, Mine Safety and Health Administration, http://www.msha.gov/30cfr/7.64.htm.
13. http://www.msha.gov/S&HINFO/RockDusting/RokDok.pdf.