Proof-of-concept testing of a deep seismic communication device

J.C. Squire, G.A. Sullivan and E.W. Baker
Professors at the Virginia Military Institute, Lexington, Virginia

G.W. Flathers
Graduate student at the University of Sheffield, England

Abstract

A mine collapse severs communication with trapped miners. Landlines are crushed and commercially available radios cannot penetrate hundreds of feet of dense, conductive earth without the use of regenerative repeaters that may also be crushed. This paper describes a proof-of-concept device that uses seismic P-waves, instead of radio waves, to allow communication of a code that represents prearranged messages, including the safe haven location identifier, number of people and air quality, from trapped miners to aboveground rescue units. The transmitter designed is about 0.03 m^3 (1 ft^3) in size and can broadcast for four hours from its 27-kg (60-lb) battery pack. The receiver consists of a geophone and a 2.5-kg (5.5-lb) signal conditioning unit attached to a laptop computer, which displays the communication signal in real time. Testing in a bituminous coal mine with an MSHA representative revealed the device was able to transmit through 271 m (890 ft) of overburden, at 0° and 12° from vertical, using 500 W of power.

Introduction

Despite the unparalleled technological advances of the past century, mining continues to be one of the most dangerous industries in America. A string of recent mining disasters, particularly the 2006 Sago Mine explosion in West Virginia and the 2007 Crandall Canyon Mine collapse in Utah, have highlighted the risks miners accept every day.

One of the most challenging aspects of a mine rescue is locating and then communicating with the victims trapped on the other side of a collapse. The Sago explosion prompted Congress to pass the Miners Act, mandating a number of safety devices. These included communication systems that can work following a collapse. Much work has and is currently being done to achieve these goals, especially in the communications area, yet there remain a number of difficulties. Current communication systems and many of the proposed systems, particularly landlines and most radios, require an unobstructed path to the surface. Unfortunately, neither of these devices work in the event of a complete block. Landlines are severed by the violent forces of the collapse, and commercially available leaky feeder radio systems are range-limited, due to the earth's shielding effects. While low-frequency radio wave signaling has long been demonstrated to work (Lagace et al., 1980) and extensive research has been done with through-earth radio signaling systems (Farstad et al., 1973; Pittman et al., 1985), commercially available personal emergency devices (PED) may not be practical for underground-to-surface communication, because they require physically large antenna networks that suffer from survivability concerns. A novel method to communicate using coupled magnetic fields has been recently announced (Barkand et al., 2006) although the deepest it has been shown to work is 82 m (270 ft).

Seismic waves offer another avenue for communication: signal conduction. The methods of seismic wave propagation are well understood theoretically (Chapman, 2006) and experimentally (White, 2000) and there exists a substantial literature of experimental methods using impulsive (explosive) seismic signals for geological subsurface mapping (Sheriff and Geldart, 1995). We propose an alternative type of seismic signaling, one that uses a continuous frequency-locked sinusoid whose frequency communicates a pre-defined message. This message could include a safe haven identification number, the number of survivors and air quality. The present paper reports tests of a prototype seismic communication device in a working mine in which transmitted signals were successfully received from a depth of 271 m (890 ft). While this pilot study does

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Figure 1 — The underground seismic transmitter.

not yet constitute a comprehensive analysis of deep seismic communication systems, it does show that the methodology can work under certain conditions and that further development is warranted.

Extremely low frequency seismic detector

Instead of using electromagnetic radiation, we developed a system that communicates directly to the surface through the rock overburden using seismic energy waves – the extremely low-frequency seismic detector (ELFSD). This system includes an underground transmitter that sends the signal and a portable receiver that collects the signal and sends it to a laptop computer for analysis and display. The battery-powered transmitter is placed underground with the miners in a safe-haven configuration. When activated by miners in an emergency, the transmitter will continually transduce a seismic energy signal into the ground at a frequency unique to each unit. The emergency seismic generator is power-limited by its battery source, so the received signal is a small fraction of the simultaneously collected environmental noise. The signal is extracted from the noise topside by integrating the frequency-specific seismic power from the transmitter over a period of time until it emerges from the background noise.

The use of continuous sinusoidal seismic waves is different than the typical application of seismology in geological exploration, which measures the time delay of wavefront arrival from an impulse wave triggered by a chemical explosion or an electromagnetic "thumper." While continuous wave transmission has been studied (White, 2000), there are currently no commercially available tools that use this technology as a basis of underground communication.

Transmitter

The seismic transmitter, Fig. 1, is constructed from a modified speaker mounted in a rigid frame. In conventional applications, a speaker's voice coil moves to compress/ rarify air. The ELFSD transmitter operates in an inverse manner by fixing the speaker's voice coil to a base plate that is compressed against the roof of the mine. Seating pressure is created by unscrewing the threaded legs of a tripod. The permanent magnet body of the speaker is suspended over the baseplate by radial flexure springs, which are adjusted to support the speaker in the neutral position. A continuous sine wave is generated by a crystal-locked microprocessor and is amplified to provide 500 W of power. A 27-kg (60-lb) rechargeable battery pack provides four hours of operation at maximum power. Because the voice coil is connected to the baseplate, the much heavier body of the speaker is forced to oscillate. The vertical motion is transduced to seismic energy in the form of longitudinal P waves, tuned to a frequency where earth attenuation is minimized. We experimentally found one suitable band in the 65-80 Hz region. This band was chosen because in prior testing in limestone caverns, we found the lower frequencies occupied by significant confounding noise sources, such as 60 Hz powerlines, while higher frequencies suffered from a greater degree of attenuation, as noted by others (McDonal et al., 1955, showed increased attenuation of vertically traveling compression wave frequencies above 100 Hz). Since the earth is relatively stiff, there is little net motion. If the legs press the transmitter against the wall so that the baseplate does not vibrate, there is negligible power loss to acoustic energy. In fact, when the transmitter was adequately secured against the roof, ambient noise 3 m (9 ft) from the device fell to 73dBspl from 97dBspl when partially unsecured, indicating the degree of power lost to acoustic transmission from poor coupling.

Use of sinusoidal power at a single frequency more efficiently transduces signals than thumping the soil at a regular frequency, as is done in seismic exploration, since each thump/ impulse spreads its power over a broad frequency spectrum. This is because the Fourier transform of a time impulse train from thumping is itself an impulse train in the frequency domain with frequency power distributed at integer multiples of the fundamental thumping frequency. Components at higher frequencies are attenuated, unlike the single frequency-domain impulse of a pure sinusoid, whose frequency can be targeted for minimum earth attenuation.

Receiver

The receiver subsystem shown in Fig. 2 is a 0.007-m^3 (0.25- ft^3), 2.5-kg (5.5-lb) device used by emergency services to collect signal from the ground and send it to a laptop for digital signal processing and display. Because of its small size, the receiver can be deployed only when needed. The receiver itself has three subsystems: a geophone, a signal conditioning circuit and a data acquisition device (DAQ). Both the geophone and the DAQ are commercial off-the-shelf products.

The seismic signal is collected on the surface through a conventional 20 Hz+ coil-and-magnet geophone rigidly mounted on a cylindrical bulkhead at the bottom of a 10.2-cm (4-in.) aluminum tube. This tube also houses the custom signal conditioning circuitry. The geophone spike exits from the bottom of the receiver tube and is pushed by hand directly into the displaced soil at the topside location. A metal bulkhead sealing the top of the tube creates a Faraday cage around the geophone and signal conditioning electronics to reduce capacitively coupled noise. The low permeability of the metal reduces magnetically coupled noise. After collection, the transmitted signal is approximately 100,000 times weaker than ambient noise. The signal conditioning circuitry both amplifies the

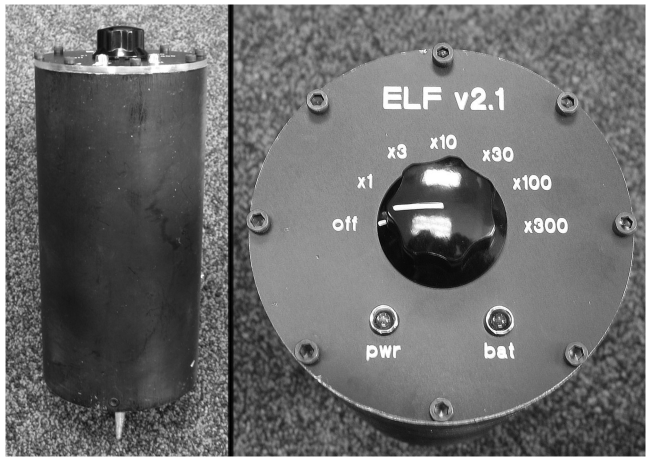

Figure 2 — The seismic receiver incorporates a geophone, signal-conditioning circuitry, amplifier and a DAQ to convert the voltage signal to a digital signal for processing on a laptop. The geophone is visible as the spike at the bottom of the electromagnetic noise-shielded case; the amplifier controls are visible on the top plate.

signal 1,000 fold and removes signal power outside the 65-80 Hz passband. While these measures remove 90% of unwanted noise and 99% of ubiquitous 60-Hz contamination, the noise still exceeds signal power roughly 10,000 fold. This signal is digitized and collected on a laptop computer for Fourier analysis using a 24-bit commercial off-the-shelf DAQ (National Instruments USB-9234).

Although the Fourier analysis technique driving the ELFSD's software analysis was derived almost two centuries ago, only in the past five years has enough computing power been available to enable it to be used in a laptop to provide real-time results. Specifically, the incoming signal is stored in the laptop as it is collected; once a second the entire signal length is analyzed to determine the amount of power present at every frequency. These results are graphically displayed in a power vs. frequency plot (Fig. 3) in real time. In the first few seconds, noise dominates the signal (left panel), but soon the integrated power of the emergency signal rises above the noise floor (right panel). The frequency of the emergency signal communicates information; the transmission band can be divided into several thousand different potential signals, allowing each transmitter to be uniquely keyed to its pre-surveyed safe haven location. Further information can also be communicated; for example, in the prototype we developed, the transmitter has switches enabling the user to communicate the approximate number of trapped miners and air quality. Each combination is encoded as a unique frequency. For example, if the Safe Haven #16 transmitter is turned on and its switches are set to indicate seven trapped personnel and poor air quality, then its crystal-controlled microcontroller translates that into a 70.8-Hz signal. After a few seconds, the receiver sees a power peak at 70.8 Hz rise above the noise floor and uses a database to identify that the frequency corresponds to Safe Haven #16, seven miners and poor air quality. Interference from multiple transmission paths can be modeled as adding phase-shifted signals of the identical transmit frequency, which may reinforce or weaken the primary signal, depending on the phase differential.

The transmitted signal may be analyzed in the frequency domain as an impulse at the desired transmit frequency convolved with a sinc function whose bandwidth is inversely proportional to the time that the signal has been transmitted. If the earth can be modeled as a system with linear energy dissipative elements and linear energy storage elements (i.e., elastic elements), then the received signal bandwidth similarly should be inversely proportional to the transmission time. For instance, in ten minutes, this corresponds to approximately 2/600 s = 3.4 mHz resolution (the factor of two corresponds to the dual-sided mainlobe). Energy-dissipative and storage characteristics of the earth, poorly modeled by a first-order Taylor series, will smear the fundamental frequency and limit the ultimate system frequency resolution.

Multiple safe havens may transmit simultaneously without interference if their peaks are differentiated by the minimum frequency resolution of the system; this causes multiple peaks. The transmitter could potentially be modulated by turning it on and off at regular intervals to distinguish its signal in the unlikely case that a frequency-locked narrowband environmental noise signal existed on one of the preset broadcast frequencies.

Test results

Proof-of-concept testing was performed in limestone caverns (Natural Bridge, Virginia) with a Karst topography overburden. Five tests were performed at depths ranging from 18 m (60 ft) to 76 m (250 ft) using a 250W transmitter. Ceiling angles varied from horizontal to 20° from horizontal, with no effect on received signal strength; however, the more off-axis ceilings made it challenging to tighten the transmitter against the ceiling. Transmission frequencies from 65 to 80 Hz were tested in 1-Hz increments. In each case, a signal was received and decoded within 30 seconds of transmission. These preliminary results led to a one-time MSHA exemption to test at Excel Mine #3 in Pikeville, Kentucky. It was tested at a depth of 271 m (890 ft) through multiple striations of sandstone, shale, claystone and coal. There were no tunnels between the underground site and the topside receiver site. The mine was active at the time of testing. Three controls were run in which the receiver was operated without the transmitter being active, to determine background frequency contamination and to verify the receiver hardware. Four tests were run with the transmitter active: two were run vertically over the transmission site using 500 W of power, one was run vertically over the transmission site using 250 W of power and one was run 12° off the vertical axis using 500 W of transmitter power. The receiving unit's geophone was pushed by hand into the topside soil. There was approximately 7.5 m (25 ft) of reworked soil at the topside location that had been displaced approximately one year prior. Unfavorable topsite conditions prevented more extreme off-axis testing, since the surveyed location provided was unfortunately bordered by active roads on three sides and a cliff on the fourth. Transmission signals were sent at 70.800 Hz using 500 W of transmitter power.

Directly over the source we received the spectrum shown below after 10 seconds of data collection (Fig. 3, left panel) and 108 seconds (right). If the received signal-to-noise power was 10 times weaker, it would require 10 times longer to generate a similar plot. All three experiments using 500 W of transmitter power provided essentially identical results, including the one taken 12° off vertical. Linear signal theory predicts the resolution of a received sampled signal is equal to the inverse of the time in which it is acquired. For the 108-second signal,

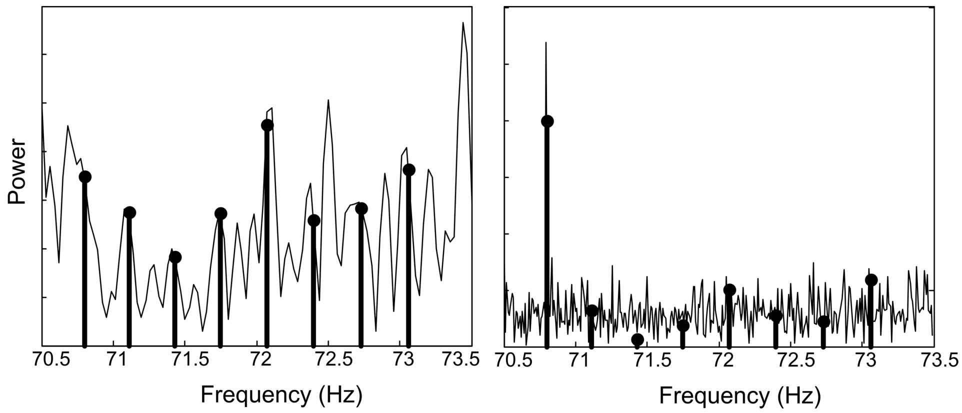

Figure 3 — The received signal is being analyzed in real time for one of eight possible transmitter frequencies. The left panel shows data collected on the surface with the transmitter 271 m (890 ft) directly below after 10 seconds. The right panel shows the same signal after 108 seconds; there is clearly a signal being broadcast on the first of the eight preselected frequency bands that rise above the noise floor. Control data without the transmitter in operation appeared essentially identical to the right panel, without the spike at 70.800 Hz.

this corresponds to a resolution of 1/108 = 9.3 mHz on either side of the precise frequency that would be measured if the received signal was of infinite length. That 9.3-mHz spread on each side creates an 18.6 mHz main lobe bandwidth, which compares well with the 20.1 mHz measured bandwidth. Longer reception times were not available with the first generation collection software, as it provided real-time frequency power analysis at the expense of limiting collection times to less than two minutes.

The experiment was repeated at half power using 250 W of transmitter power, with the receiver vertically positioned over the transmitter. Only environmental noise was observed, indicating a non-linear relationship between transmitted and received power. This unexpected result requires additional testing, planned with improved signal acquisition software that permits real-time signal acquisition over essentially unlimited time periods to quantify the relationship between transmitted and received power, as well as testing at alternative locations to determine if these effects are universal or idiosyncratic.

This study was conducted to determine if seismic power is a reasonable candidate for further investigation of emergency communication systems, and as such demonstrated its potential feasibility. A serious limitation of these preliminary results that must be next addressed is that the effects of different geophysical characteristics on signal transmission, including geologic composition, bedrock separation, intermediate tunneling and surface soil composition, remain unknown. Futher testing is also planned to elucidate the effects of transmitter power upon the time required to observe the signal, the relationship between larger off-axis receiver angles and system bandwidth frequency resolution limits. Future transmitters will be enclosed by an explosion-proof container to allow the system to become MSHA approved. The explosion-proof box contains the batteries, electromagnetic coil and control systems. A force-tranducing threaded rod exits the top face of the explosion-proof container through a pressure-rated seal and is firmly affixed to the mine roof by rotating the threaded rod.

Conclusion

This pilot study demonstrates it is possible to construct a communications system that permits direct belowground-to-aboveground transmission of prearranged message codes through at least 271 m (890 ft) of overburden using 500 W of seismic power, and invites further investigation to elucidate limitations and generalization of results at varied sites. In particular, the system could communicate a message in less than two minutes, despite the uncontrollable seismically-intense active mining environment with substantial narrowband noise generators operating in the immediate vicinity of the test site.

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