Seismic Through-Rock Communication – an Alternative to Electrical Methods

***James C. Squire**, **Gerald A. Sullivan** and **Elizabeth W. Baker** describe their development of a method of sub-surface communication employing seismic waves. Signals have been received from a depth of 271m in a coal mine.*

Despite developments in safety methods and equipment, mining is still a dangerous industry, and coal mining is a good example of this. When there is an accident, rescuers need to know where trapped personnel are, how many there are, and other information such as air quality. To achieve this requires, as a minimum, effective communications from underground to surface. Unfortunately, these are the very circumstances in which communications between underground and surface can easily be disrupted.

The equipment described in this article was designed for mines rescue use, indeed the introduction relates specifically to the drawbacks of other methods used in mining. While the same pros and cons do not necessarily apply to caving, the method has shown to be effective in limestone geology. Experimentation by cavers could reap benefits.

Existing Methods

There doesn't seem to be an ideal emergency communication system for mines. Existing systems suffer from one or more significant defects: not good for two-way communication; not acceptable in hazardous environments; susceptible to damage in the event of an incident; too large for operational ease of use; lacking flexibility.

There are two principal methods which use cabling in some form: landlines which provide an effectively uninterrupted connection from underground to surface, and leaky feeder systems which rely on a coaxial or similar cable with a deliberately low level of screening so that it can both receive and transmit in its vicinity in the mine. The principal problem with both of these is that a fall of rock is likely to break the cable.

High-power radio transmissions from the surface can often be received at useful strength on the ground, but generating sufficient radio-frequency power for the uplink would seem to be a considerable challenge in an emergency situation.

Figure 1 – Testing the ELFSD Transmitter

Through-the-earth induction methods are frequently used for communication between a cave and the surface, but in the mining context investigations have indicated that the size of the loop antenna needed underground is more than can realistically be expected to be available.

An additional problem is that some of these systems are not suitable for use in hazardous environments (and in some cases the design is such that they could not gain the necessary approval from the safety authorities).

Historically, the two main methods used to communicate from below ground have been impulsive shocks, produced with explosive devices or by hammering on a pin driven into the rock [the latter was known in the north-east of England as 'jowling' – Ed]. These methods have the disadvantage that the acoustic energy is distributed across a potentially wide range of frequencies, which makes it difficult to detect the signal in a noisy environment. There is also the problem of fatigue when it's necessary to continue for a prolonged period. The method described here draws on these historical methods but aims at reducing the drawbacks.

Seismic Transmission

An inherent weakness with the traditional approach of transmitting acoustic energy is that much of the energy is carried in the high frequency bands that are severely attenuated by rock. We have developed an alternative approach that uses low frequency sinusoidal waves as a means to maximise energy transmission to the surface. The system has been named the Extremely Low Frequency Seismic Detector (ELSFD).

If we transmit a long-duration signal on an accurately-known frequency, and use sophisticated signal processing, the likelihood of detecting the signal is much greater. Seismic signals received by a surface geophone are integrated over time so that, as the data collection time increases, the presence of a clear spectral signal emerges through the noise floor. The longer the data collection period, the sharper and taller the peak becomes, making it possible to discriminate between multiple coded messages.

Different frequencies are used for different pre-defined messages. Furthermore, the message can include the identification of the safe haven from which the signal was transmitted and additional information such as the number of persons trapped, their condition, the air quality, etc. In the prototype system,

Introducing Seismology

While this article concerns the use of seismic techniques for through-rock communication, the ELFSD employs methods that are used for seismic prospecting (e.g. for oil) but with some important differences. Here we provide some background information on seismology, and how our application differs, to put the article into context.

For geophysical prospecting, seismic waves are created in the earth by a chemical explosion or an electromechanical ‘thumper’. These methods generate a broadband seismic signal. Seismic waves that are reflected or refracted by sub-surface discontinuities are then detected at the surface using an array of geophones, as shown below right, which convert vibrations in the earth into an electrical signal. The relative times at which signals are received by each of the geophones allow the structure of the sub-surface to be deduced.

The use of seismic waves for mines rescue, generated by hitting a rock bolt in a mine with a sledgehammer and received on the surface with a geophone was developed under sponsorship of the US Bureaux of Mines in 1974. However, the broadband seismic signals generated this way suffer from a high degree of loss due to the high level of attenuation of high frequency signals in the rock. Accordingly, the ELFSD uses a narrow band seismic signal at a low frequency with a low level of attenuation.

Seismologists refer to P waves (primary or pressure waves) and S waves (secondary or shear waves). P waves consist of alternating compressions and refractions so the vibrations are longitudinal, that is in the direction of travel of the wave. S waves move as a shear or transverse wave so motion is perpendicular to the direction of propagation. The ELFSD generates a seismic P wave.

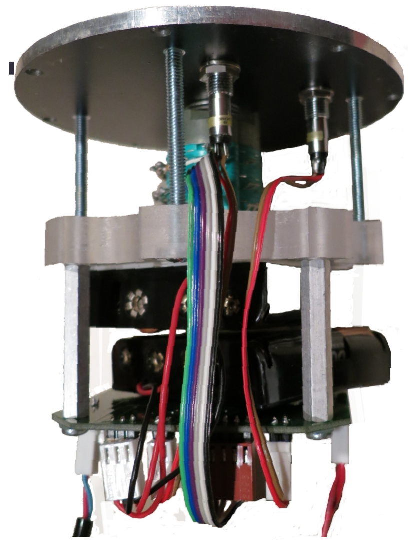

Figure 3 – Internal Arrangement of the Receiver

eight frequencies were used to define preset messages.

When choosing a frequency it is advisable to avoid those that suffer excessively from seismic noises. Frequencies which are commonly found in mines, such as those related to mains electricity supplies should also be avoided (for example, 60Hz in the US or 50Hz in Europe).

Demonstration System

To test these ideas, a proof-of-concept system was built, working in the range of 65 to 80Hz. This frequency range was chosen because it had been found experimentally in limestone caverns that there was increased attenuation at frequencies above 100Hz, and frequencies in the region of 60Hz would be liable to interference from electricity supplies.

A summary of the system is provided below. Additional details can be found at (Squire *et al*, 2009). The References section also provides additional material on the ELSFD, all of which can be found on James Squire’s website, **jimsquire.com**.

Transmitter

The transmitter consists of a modified loudspeaker. During conventional use of a loudspeaker, a speaker coil moves to compress or rarefy the air. The ELFSD transmitter operates in an inverse manner by fixing the voice coil to a base plate which is compressed against the roof of the mine with the permanent magnet body of the loudspeaker suspended over it. Because the voice coil is connected to the base plate, 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. Since the earth is relatively stiff, there is little net motion.

If the assembly is mounted on legs that press the transmitter against the rock so that the base plate does not oscillate, as shown in the photograph on the previous page, there is negligible loss to acoustic energy. In fact, when the transmitter was correctly secured against the roof, ambient noise 3m from the device fell to 73dB from 97dB when partially unsecured, indicating the loss of power to acoustic energy that occurs due to poor coupling.

The coil is driven by a 500W amplifier at a frequency set by a crystal-controlled microprocessor. The unit is powered from a rechargeable battery weighing 27kg and giving an operating duration of four hours.

Receiver

The receiver, as used by emergency services, consists of a geophone, custom signal-conditioning circuitry, and a data-acquisition device. Data is transmitted to a laptop for signal processing and display. The weight of this subsystem is 2.5kg and is shown in *Figure 4*.

The signal is detected by a conventional 20Hz+ coil-and-magnet geophone. It is mounted on a cylindrical bulkhead at the bottom of a 102mm aluminium tube which also houses the digital acquisition circuitry. The geophone spike exits from the bottom of the receiver tube and is pushed by hand directly into the displaced soil at the surface location. The tube forms a Faraday cage around the signal-processing circuitry to reduce capacitively-coupled noise.

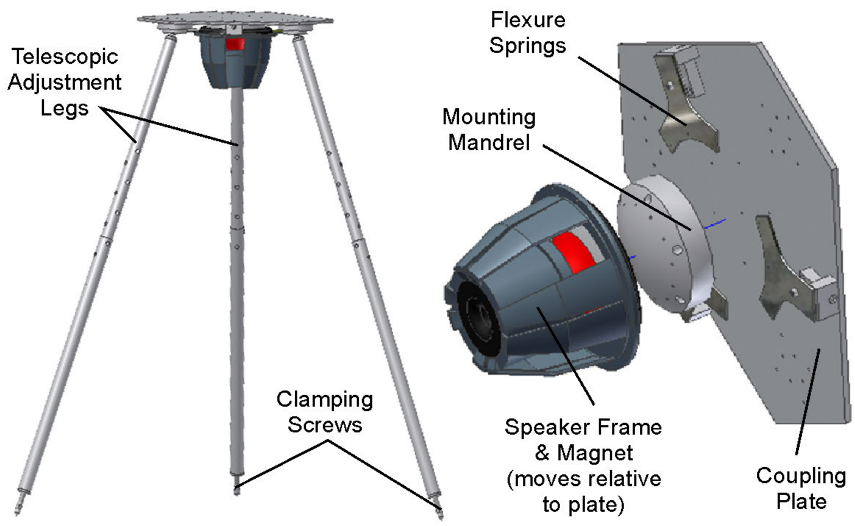

Figure 2 – Mechanical Arrangement of the ELFSD Transmitter

Figure 4 – The ELFSD Receiver

After collection, the signal is approximately 100,000 times weaker than the ambient noise. The signal-conditioning unit amplifies the signal and removes signals and noise (including 60Hz) outside the desired frequency range. The remaining signal, which is still 10,000 times weaker than the noise, is digitised using a National Instruments USB-9234 DAQ and sent to a laptop computer. Here the data is stored and a Fast Fourier Transform is carried out in real time, once per second. The result is displayed as a plot of power versus frequency.

Figure 5 – The receiver has also been used underground.

Results

Initial proof-of-concept testing was carried out at Natural Bridge, Virginia, a limestone cave with karst overburden. Tests were conducted at depths from 18 to 76m using a 250W transmitter. The test frequency was varied in 1Hz steps in from 65 to 80Hz. In each case, the emergency signal rose above the noise floor within 30 seconds of transmission to produce a successful decode. Ceiling angles varying from 0 to 20° from the horizontal had no effect on received signal strength although the more off-axis ceilings made it challenging to secure the transmitter assembly tightly against the rock using the tripod assembly that can be seen in *Figure 1*.

Following this successful initial test, permission was obtained to trial the system in a working coal mine, namely Excel Mine #3 in Pikeville, Kentucky. Testing was carried out through multiple layers of sandstone, shale, claystone and coal in a tunnel-free area. The ceiling angle was up to 12° off horizontal. With a power of 500W and a frequency of 70.8Hz, a range of 300m vertically and 800m horizontally was achieved.

The spectrum results for 10 and 108 seconds of data, with the receiver vertically over the transmitter, can be seen in the two graphs in *Figure 6*. The emergence of a signal on a specific frequency can be clearly seen on the plot representing 108 seconds of processing.

If the received signal-to-noise power was 10 times weaker, it would require 10 times longer to generate a similar plot. 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, this corresponds to a resolution of 1/108 = 9.3mHz on either side of the precise frequency that would be measured if the received signal were of infinite length. That 9.3mHz spread on each side creates an 18.6mHz main lobe bandwidth, which compares well with the 20.1mHz 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.

Reducing the transmitter power to 250W resulted in complete loss of signal which suggests a non-linear relationship between transmitted and received power. This was an unexpected result that requires further investigation.

Conclusions

The results from the initial tests in Natural Bridge, Virginia and Excel Mine #3 in Pikeville, Kentucky look extremely promising but there are further steps which would seem to be necessary before we have a fully operational system. In addition, some new avenues of related research are possible. The following are some questions that we are

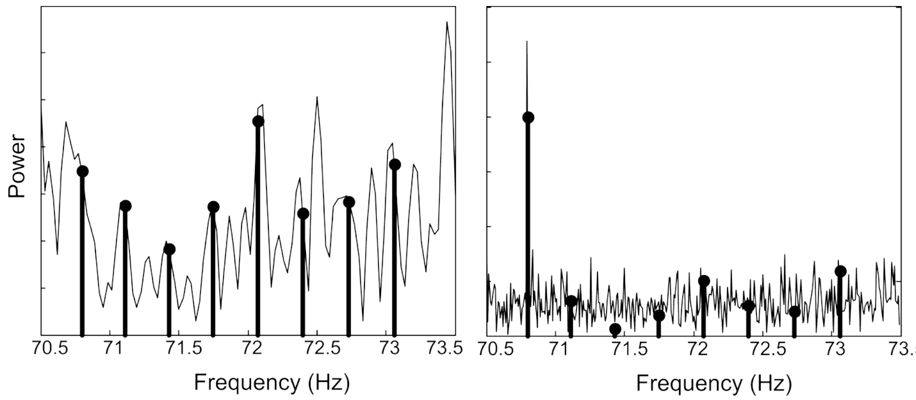

Figure 6 – The received signal is analysed for one of eight different frequencies with the transmitter 271m underground. Plots show the processed data after 10 seconds (left) and 108 seconds (right). After 108 seconds the first frequency has clearly risen above the noise floor.

Elephants Meet the ULSFD

When we were designing the ULSFD we never once thought about an elephant. But in early June 2012, two of us (James Squire and Gerald Sullivan) found ourselves surrounded by pachyderms in sub-Saharan Africa, in a BBC production, Richard Hammond's Miracles of Nature, starring daredevil broadcast journalist Hammond, of Top Gear fame. The purpose of that journey was to demonstrate how our ELFSD, could be used to replicate the way elephants communicate with one another over long distances.

We had no idea who Richard Hammond was because we don't watch enough television, I guess, but if you ask the cadets, they all know who is because they all watch his show, Top Gear. At first we were asked to travel to Rosamond, California to demonstrate the ELFSD's usefulness in a staged explosion of an abandoned gold mine. We were able to demonstrate the ability to send signals through several hundred feet of rock.

Two weeks later, we were invited to travel with Hammond and his team to Botswana, where we were to demonstrate that the ELFSD could also be used to mimic the ultra low frequency waves that elephants use to communicate with one another. Elephants produce such waves in their vocalizations, and scientists believe that those waves can then be transmitted through the ground.

The episode of Miracles of Nature shows a herd of bull elephants doing a rather abrupt U turn in the device's direction when the ELFSD was turned on and set to the frequency of a female elephant. It certainly seemed like they did respond to the signals but the jury's still out for me. It did seem like it was happening more often than chance would dictate. However, the question in my mind is "Was this solely through the ground they were feeling this?" There's also the possibility that they were hearing the ELFSD's frequencies as well as feeling them. Richard Hammond's Miracles of Nature is available as a DVD, published by the BBC and priced at £12.99 from **www.bbcshop.com** and other retailers.

currently considering.

Why is the receiver response apparently so sensitive to the transmit power level?

What effect (if any) would geophysical conditions have on the system behaviour?

Would installing the system in an explosion-proof box, as legally required in the potentially explosive atmosphere of coal mines, introduce any problems?

Given that the output of the transmitter system consists of seismic waves, could the electronics be replaced by a pneumatic system powered directly from cylinders of compressed air, thereby eliminating all issues concerning the use of electrical or electrical equipment in explosive atmospheres?

Can the system be adapted to also provide communication from the surface to miners underground, thereby enabling a two-way exchange of information?

The Authors

James Squire is a Professor of Electrical Engineering at the Virginia Military Institute.

Dr. Squire received a BS from the United States Military Academy and his PhD from the Massachusetts Institute of Technology. He was awarded a Bronze Star in the Army during Desert Storm and was selected as Virginia's Rising Star professor in 2004. He is a licensed Professional Engineer, a named inventor of ten patents, and maintains an active consulting practice in the fields of endovascular stent design, patent litigation, and instrumentation.

Jay Sullivan is a professor of Mechanical Engineering at the Virginia Military Institute (VMI), received his B.S.M.E. from the University of Vermont and his Ph.D. from Rensselaer Polytechnic Institute.

He has held teaching positions at the University of Michigan-Dearborn, and the University of Vermont. Prior to joining the faculty at the Virginia Military Institute in the fall of 2004, he was employed by JMAR Inc. where he was involved in research and development of X-ray lithography systems for the semiconductor industry. His interests include mechanical design, materials, acoustics applications and controls.

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Dr. Baker received her B.A. from University of North Carolina – Chapel Hill, her MBA from University of Arizona, and her Ph.D. from Virginia Commonwealth University. She focuses her research and practice activities in information systems and entrepreneurship, with over 13 papers published and started 4 businesses from university activities. Her TEDx talk from TEDxWakeForest focuses on her work in commercialization.

Intellectual Property

A patent was applied for in the names of James C Squire, Gerald A Sullivan and George W Flathers III on 11th April 2008 and granted on 30th November 2010 – see (Squire et al, 2010a).

The Virginia Military Institute owns the IP, and it is being marketed by a third-party spinoff called VMIne, LLC.

References

Squire J. C. et al (2009), *Proof of Concept Testing of a Deep Seismic Communication Device*, Transactions of the Society for Mining, Metallurgy, and Exploration, Vol. **326**, pp. 97-100.

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