

Safety in Mines Research Advisory Committee

Final Project Report

Pre-feasibility investigation to provide an early warning of roof falls prior to support installation

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Executive Summary

ISS International was contracted by SIMRAC to conduct a pre-feasibility investigation regarding the association of electromagnetic emissions and acoustic/ultrasonic emissions with rock failure. The presence of such emissions as a result of material or rock failure could have tremendous potential for the development of techniques to provide early warnings of rock failure. In the mining industry, falls-of-ground do occur frequently because of roof failure in underground excavations, causing safety and production problems.

In-situ or laboratory measurements of such emissions from rock failure are difficult to conduct because of difficulties in eliminating external emissions from interfering in the experiment.

Measurements were conducted at two sites in underground coal mines where seismic activity, electromagnetic, and acoustic/ultrasonic emissions were monitored for a period in a seismically active area. Electromagnetic emissions were measured using an ISS International multi-seismometer with a Rohde & Schwarz professional short wave receiver. Electromagnetic frequencies between 190 kHz and 30 MHz were monitored. Acoustic/Ultrasonic emissions were monitored with an ISS International multi-seismometer with 10 kHz accelerometer, an off-the-shelf microphone, and a custom built ultrasonic detector.

Results from the electromagnetic emission test site showed that some electromagnetic emissions were measured in the same time window in which seismic events were also measured. The results do suggest that the observed electromagnetic anomalies may be electromagnetic emissions that are emitted during roof failure. Measurement of background electromagnetic radiation also suggests that the electromagnetic anomalies are not considered to be artificial or background electromagnetic emissions. However, the results do not prove without any ambiguity that the observed electromagnetic anomalies can in fact be associated with roof failures. In order to make definite quantitative conclusions, sufficient data need to be collected on which a quantitative statistical analysis needs to be performed and equipment and data processing algorithms designed to minimise ambient noise levels.

Rock failure processes fall in the category of physical systems that exhibit the phenomenon of Self-Organised Criticality (SOC, please refer to literature study for more details). Such systems are characterised by power laws e.g. the Gutenberg-Richter cumulative number vs magnitude type distribution in mining and earthquake seismology. Since magnitude can be translated to corner frequency this power law also implies that a power law governs the cumulative number of acoustic and ultrasonic emissions versus frequency (refer to literature study). This power law (figure 2.3.3) behaviour implies a large number of high frequency (ultrasonic) acoustic emissions are present while a smaller number of low frequency acoustic emissions are associated with a process such as roof failure.

The acoustic/ultrasonic trial, however, did not measure any ultrasonic emissions associated with seismic roof activity. It is expected from the SOC theory that ultrasonic emissions are present, although their amplitudes were too low to be measured above the background noise level in this pre-feasibility study. (Alternatively, the background noise level that comprises noise from the underground environment, equipment and internal instrument noise were too high to enable measurement of the ultrasonic emissions.) No definite conclusions can be drawn at this stage whether or not acoustic/ultrasonic emissions can be measured with a system during or prior to rock failure. However, results suggest that improved system design could lower instrument noise levels resulting in reduction of total noise levels.

It is proposed that further measurements be conducted using a multi-array accelerometer/acoustic sensor based continuous seismic monitoring system (sensors coupled to rock surface and into holes) to quantify seismic events, electromagnetic, and acoustic/ultrasonic emissions in terms of location, amplitude, and source characteristics. Continuous monitoring technology (Standalone QS developed by ISS International) will provide bulk information during shorter monitoring periods and could improve the understanding of precursors. This access to bulk data can assist to further investigate the potential for using electromagnetic/acoustic/ultrasonic emissions as early warnings to roof failure. (Bulk data often reflects more about the processes involved than newly developed theories based on smaller amounts of data.) The access to a larger pool of data could also allow confirmation of the power-law behaviour of seismic/acoustic/electromagnetic events that are caused by failure of the roof of the excavations (SOC systems). Work that is funded internally is currently in progress at a site in a deep level gold mine to demonstrate the feasibility of continuous monitoring.

It is also proposed that further funding is made available to develop a low noise, sensitive ultrasonic receiver to be able to determine the presence of low intensity ultrasonic emissions.

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Glossary

Abbreviations

Fall-of-Ground	FOG
Electromagnetic	EM
Rohde & Schwarz receiver	RS
Multiseismometer	MS

Terminology

Seismo-electrical / pre-seismic / geo-electrical

A term that describes electromagnetic radiation which is emitted during rock or material failure. A seismo-electrical signal is thus associated with both a seismic and electromagnetic signal.

Stooping

A total extraction mining method used in underground coal mining.

VAN

A term used to describe a method used by a group under the leadership of Panayiotis Varotsos in Greece. This group claims to predict earthquakes using seismo-electrical emissions.

Seismic event

A confirmed seismic event as a result of roof failure in this particular research project.

Background seismic noise (Non-seismic event)

A seismic signal that is caused by mining personnel/machines and external environmental noise and which did not originate from rock/roof failure.

Background electromagnetic noise

Electromagnetic emission measured during zero seismic activity that thus refers to electromagnetic noise induced by underground personnel/machinery.

Electromagnetic anomaly

Refers to an electromagnetic signal that can be distinguished from the background electromagnetic signal.

1. Introduction

The possible presence of electromagnetic and acoustic/ultrasonic emissions as a result of material failure, or rock failure, has tremendous potential for the development of techniques to provide early warnings of rock failure. In the mining industry, falls-of-ground do occur frequently because of roof failure in underground excavations, causing safety and production problems.

The measurement of the pre-seismic emissions has large potential in areas such as earthquake prediction but also in the underground mining environment which is characterised by seismic events as result of stress concentration in rock surrounding open excavations. In the seismic monitoring industry, the measurement of pre-seismic electromagnetic emissions could provide very accurate information about the origin time of a seismic event due to the fact that electromagnetic radiation does travel much faster than seismic waves. In addition, pre-seismic electromagnetic/acoustic/ultrasonic measurements may be used to measure seismic activity in roofs of excavations that can be implemented to provide an early warning of fall-of-ground (FOG) system.

The aim of this research project was a pre-feasibility investigation to establish the potential to use electromagnetic/acoustic/ultrasonic radiation associated with rock failure in an underground environment to assist mining personnel in identifying roof areas of risk. The output of this project will be the identification of further research (if necessary) and specifications for development of equipment (if appropriate).

The first step in developing a methodology utilising pre-seismic emissions is to establish whether these emissions can in fact be measured and how it can be measured. Measurement of seismo-electrical emissions is problematic, as it is difficult to separate electromagnetic emissions from testing machines to those originating from the failing rock.

It was proposed to the SIMRAC committee that actual measurements in underground coal mines would achieve more than laboratory experiments as it will inevitably provide critical information on the actual implementation of such a technique. Underground measurements will yield information about levels of non-seismic electromagnetic/acoustic noise, or artificial sources.

As recommended by SIMRAC, representative sites were chosen to conduct the experimental work. A representative site was defined as a typical working area where machinery and underground personnel are present and where typical routine mining production tasks are performed. A site with known seismic activity in the roof was also critical.

The electromagnetic emission experiment was conducted in a goafing environment while the acoustic/ultrasonic measurements were conducted in a longwall environment. Two separate experiments (phase 1 and 2) were thus

conducted to record electromagnetic emissions, and acoustic/ultrasonic measurements.:

- Brandspruit 2 shaft (SASOL) - Section 32 was selected as a suitable test site for conducting the electromagnetic emission experiment. Electromagnetic measurements were performed with a high quality Rohde and Schwarz short wave radio and the ISS International Seismic System. An active rod antenna was utilized. A small pocket short wave radio was also utilised. A range of electromagnetic frequencies between 9 kHz and 30 MHz was monitored.
- Acoustic/Ultrasonic measurements were conducted in a longwall environment at New Denmark colliery (AngloCoal). Acoustic/Ultrasonic emissions were monitored with an ISS International multi-seismometer with uni-axial accelerometer, an off-the-shelf microphone, and a custom built ultrasonic detector.

The report entails the results of the literature survey that served as background information to the project as well as to guide the efforts in this research project. The results obtained in both experiments are also discussed in detail with recommendations and conclusions for proposed future work.

2. Literature Survey

2.1. Some past and current research conducted in an attempt to detect electromagnetic emissions

Various papers have been published by researchers in which the measurements of pre-seismic electromagnetic emissions from rock failure have been claimed to be measured. In particular, one group of researchers in Greece, commonly referred to as VAN (Panayiotis Varotsos and co-workers) claim that they can successfully predict earthquakes in Greece by measuring electromagnetic emissions prior to earthquakes. These electromagnetic emissions are also commonly referred to as geo-electrical precursors. Uyeda (*Uyeda: 1997*) supports the VAN method.

Various other researchers in Greece (*Stravakakis:1998*) have criticised VAN regarding the scientific method and credibility of their claims in predicting earthquakes. Geller (*Geller: 1997*) has published various articles in which he criticised the VAN method. The main arguments presented against the VAN method are:

1. VAN claims that electromagnetic precursors are measured before an actual earthquake which are then used to provide an earthquake warning. However, no electromagnetic emissions have been measured at the time of the actual earthquake. In the same manner no seismological precursors are measured at the time when the electromagnetic precursors are claimed to be measured.
2. Many measurements of EM precursors have been made at a single observatory and have not been measured at other VAN observatories in Greece.
3. There appear to be evidence that many of the electromagnetic emissions measured by VAN are in fact generated by artificial sources such as digital radio-telecommunications transmitters and other industrial sources. These sources have been measured and identified by independent observations.

Nesbitt (*Nesbitt: 1994*) conducted two experiments to monitor EM radiation at seismically active sites, approximately 2000 m's underground in a South Africa deep gold mine. One receiver was used to measure EM radiation at 40 kHz, while a second receiver monitored discreet frequencies between 100 kHz and 1.1 MHz. Although some indications of seismic events being accompanied by EM radiation have been observed, no definite conclusions were, and could have been made.

A third group of researchers at the Spokane Research Laboratory and lead by D Scott (9) (UK National Institute of Occupational Safety and Health) claim to have

developed a methodology for establishing a baseline for measuring electromagnetic emissions during the mining cycle. The group installed an electromagnetic monitoring system comprising an accelerometer and electromagnetic antenna at Galena Mine, Kellogg, ID, for several months. However, the acquired data are suspect because of inherent mine electromagnetic noise, such as electrical interference from mine systems. Further work in progress.

The literature review does provide some evidence that electromagnetic emissions do accompany the fracturing of materials (specifically quartzite which is a piezoelectric material). Some laboratory and in-situ experiments have been performed in which the measurement of electromagnetic radiation associated with material failure is claimed. However, such emissions have not been used to detect imminent rock failure in underground mines.

Some very important conclusions can be drawn from the past experimental and theoretical work:

1. In order to measure pre-seismic electromagnetic emissions, all other non-seismic (artificial) electromagnetic noise needs to be identified and isolated.
2. Measurements need to be of such a nature that a proper statistical analysis can be performed on the data. In other words, data of sufficient volume need to be collected to prove statistically that pre-seismic electromagnetic emissions are measured. Criticism regarding VAN in this regard is that VAN's predictions have not been proved successful beyond random chance.
3. It has been documented that electromagnetic emissions have a fairly broad bandwidth although no accurate information is available on typical frequencies one could expect to measure.
4. The piezoelectric effect has been proposed as the key mechanism by which EM is produced together with rock failure. The piezoelectric effect is a mechanism by permanently-polarized material such as quartz (SiO_2) produces an electric field when the material changes dimensions as a result of an imposed mechanical force. These materials are piezoelectric, and this phenomenon is known as the piezoelectric effect. This is also the principle of operation of quartz clocks.

2.2. Acoustic/Ultrasonic techniques

Acoustic/ultrasonic emissions are the result of stress waves produced by the sudden internal stress redistribution of a material that is caused by changes in the internal structure. Possible causes of internal structure changes include crack initiation and growth, crack opening and closure and dislocation movement. Most of the sources of acoustic emissions are damage related and are commonly used to predict material failure.

Measurement of ultrasonic emissions (> 30 KHz) can be used to remotely and non-destructively evaluate materials that are under high and/or dynamic stress regimes. Emitted stress waves are detected in practical measurements by coupling piezo-electric sensors to or near the surface of the structure under study.

Ultrasonic techniques, especially when implemented with multi-transducer arrays are particularly useful for (please refer to Figure 2.2.1):

- delineating the amount,
- temporal and spatial location
- and orientation of fractures within the monitored volume.

Results from these measurements are usually integrated with other physical measurements and with continuum/micromechanical models. Integration can assist in understanding failure mechanism in a target volume as well as providing possible precursory information especially when a system monitors emissions continuously similar to seismic systems like the ISS.

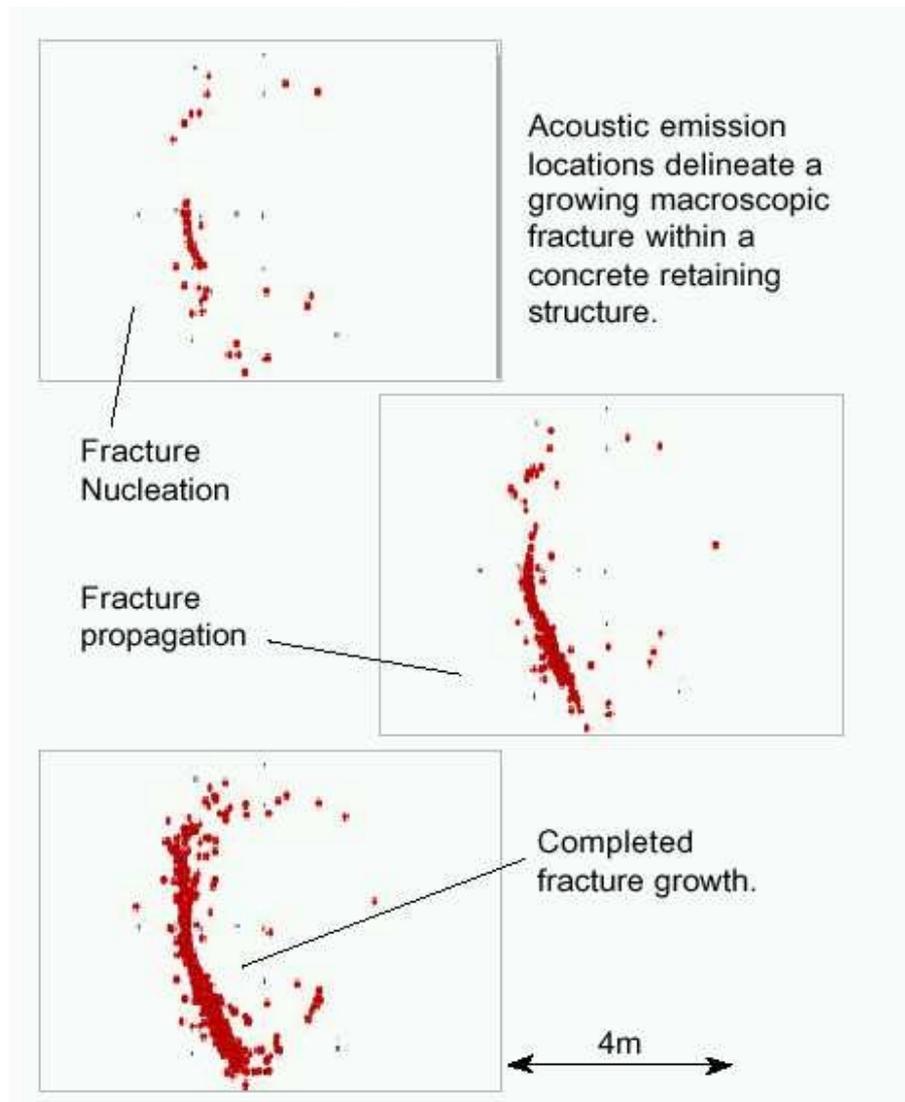


Figure 2.2.1. Location of acoustic events for characterizing fracturing

Similarly to seismic monitoring, measurement of acoustic and ultrasonic emissions have applications in civil engineering for example to optimise the design of concrete structures.

Other applications include the following:

- Monitoring of concrete curing processes allowing more efficient construction. Transducer arrays are designed with multiple transmitters and receivers to give a high density of measurements.
- Monitoring of critical structures for possible crack damage in the volume. Fluid and contamination pathways can be delineated and give early warning of any destabilisation process.
- Long term monitoring allowing the structure's performance to be assessed and aid in the design of any subsequent engineering solutions.

Common problems of this technique as reported in the literature is contamination of data with noise, reliability and difficulty in achieving repeatability as well as difficulty in solving/modelling wave form propagation.

2.3 Systems at a critical point - Self organized Criticality (SOC)

The concept of SOC is defined in analogy with the equilibrium critical phenomena. Bak et al [10] considered a model representing a dynamically driven, non-equilibrium open system that exhibits behaviour similar to critical phase transitions. It must be noted that the model does not represent all dynamically driven systems but those with threshold dynamics. Locally, at each position in space, the dynamic variable (e.g. stress, energy etc) or its derivatives have a maximum allowed value. When this maximum is exceeded because of external perturbations, the system responds by redistributing e.g. energy to surrounding positions. As an explicit example consider a pile of sand on a flat table.

The dynamic variable in this case is the height of the sand column at a point and its derivative is the local slope of the pile. When the local slope exceeds a certain value because of an external agent adding sand, the pile responds by redistributing sand to neighboring positions by means of avalanches.

Bak et al [10] observed that the model evolves to a state where fluctuations on all length scales are present. In the present case the fluctuations are the relaxation events, where we have assumed that there exists a way of quantifying the response to external perturbations. Similar to equilibrium critical phenomena, power law correlations and scaling is observed in this state. Specifically, event size distributions for the relaxation events show power law behaviour. These power law

event size distributions were considered as evidence that the model has fluctuations on all length scales.

It was suggested that the power law distributions are a manifestation of some underlying long-range correlation between microscopic degrees of freedom of the model and thus of a system at a critical point.

The analogy with equilibrium critical phenomena seems to hold well, but unlike the situation in equilibrium systems, it seems as if there are no external parameters such as temperature or pressure that have to be tuned explicitly to special values to observe the critical behaviour. Hence the name self-organized criticality.

The other feature of systems that exhibit SOC behavior is that there is a separation of time scale. The relaxation events occur at a time scale much shorter than the time period required for the local dynamic variables to reach its threshold value. In practice this is equivalent to saying that there are no external perturbations during relaxation events.

2.3.1. Earthquakes/rockmass response to mining as examples of SOC systems

Earthquakes occur due to the relative motion of tectonic plates along faults in the crust of the earth. Because of friction between plates, they are prevented from moving relative to each other in a smooth manner. The plates stick together until the stress at the interface exceeds the solid friction between them. Once this happens, the plates slip.

The phenomenon described above has some of the features of a SOC system. Clearly the stress at the interface between the plates is the dynamic variable with a threshold value equal to the solid friction between plates, which occurs on a scale of a few centimeters per year, serves as the slow driving force. The process of accumulating stress occurs over many years, while the release thereof happens in a few seconds. There is thus clearly a separation of time scales.

The size of an earthquake is characterized by the amount of energy E released when the plates slip. The distribution of earthquake sizes is found to be a power law $P(E) \sim E^{-B}$. This is known as the Gutenberg-Richter law for earthquake sizes. The exponent B shows some geographical dependence, but usually falls in the interval 1.8 to 2.2. Another quantity of interest is the temporal frequency of aftershocks following a large earthquake. It also follows a power-law $n(t) \sim t^{-A}$ where $n(t)$ is the number of aftershocks occurring a time t after major earthquake. This relation for the aftershocks is known as Omori's law. The exponent A has values lying between 1 and 1.5.

Even though the earthquake sizes have a broad distribution, there appears to be a maximum size that earthquakes can have. This maximum size is determined by the thickness of the layer of the earth's crust. This is an example of a finite-size.

The power-law distribution is thus relevant up to a certain scale after which system size has to be compensated for.

Figure 2.3.1 shows a power law distribution (Guthenburg-Richter plot) of Cumulative number of seismic events versus magnitude for a deep level gold mine in the Klerksdorp goldfields. This power law distribution characterizes rockmass response to mining as well the seismic hazard that is posed to workplaces, and suggests a SOC type system.

The power law can be written in the form

$$\log N(m) = a - bm ,$$

where $N(m)$ is the expected number of events not smaller than magnitude m , and a , b are constants.

The Gutenberg-Richter relation implies a power law distribution i.e. the absence of a characteristic size, and as a consequence, puts no limit on the maximum earthquake size. Thus if the distribution of large earthquakes is also a power law, then it must have an exponent that is larger than that for smaller ones.

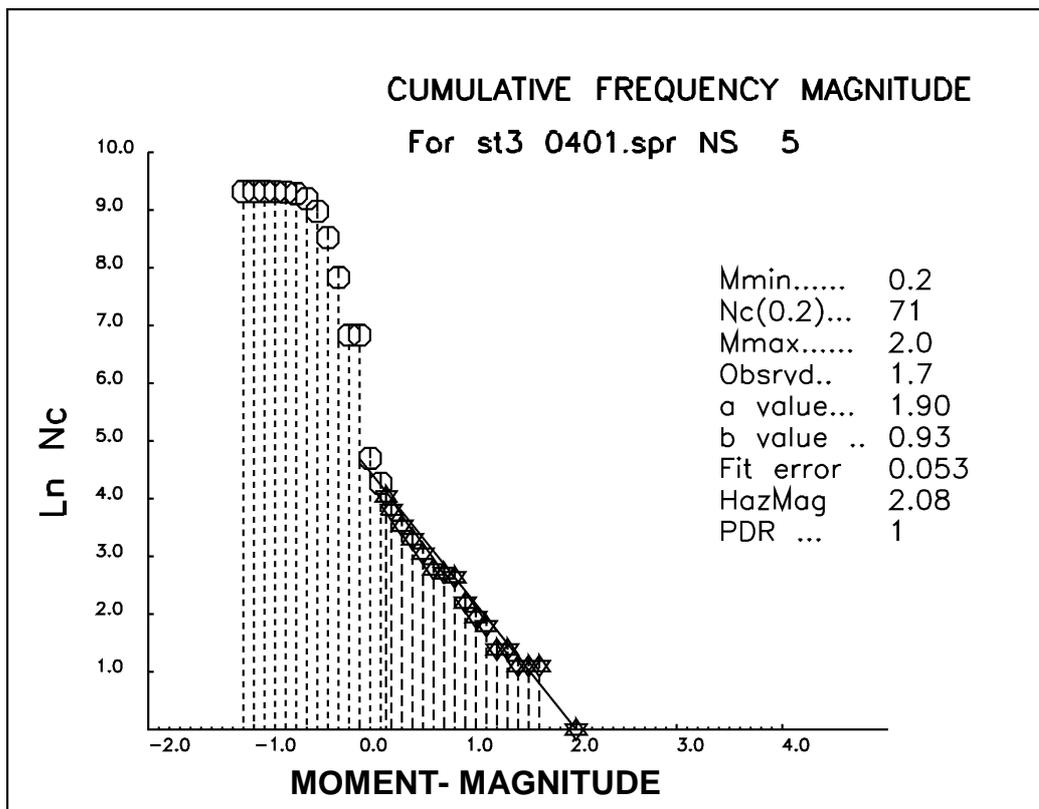


Figure 2.3.1. Power law distribution of seismic event size in terms of moment magnitude. Seismic events occur as a result of rockmass response to mining (from deep level gold mine in South Africa)

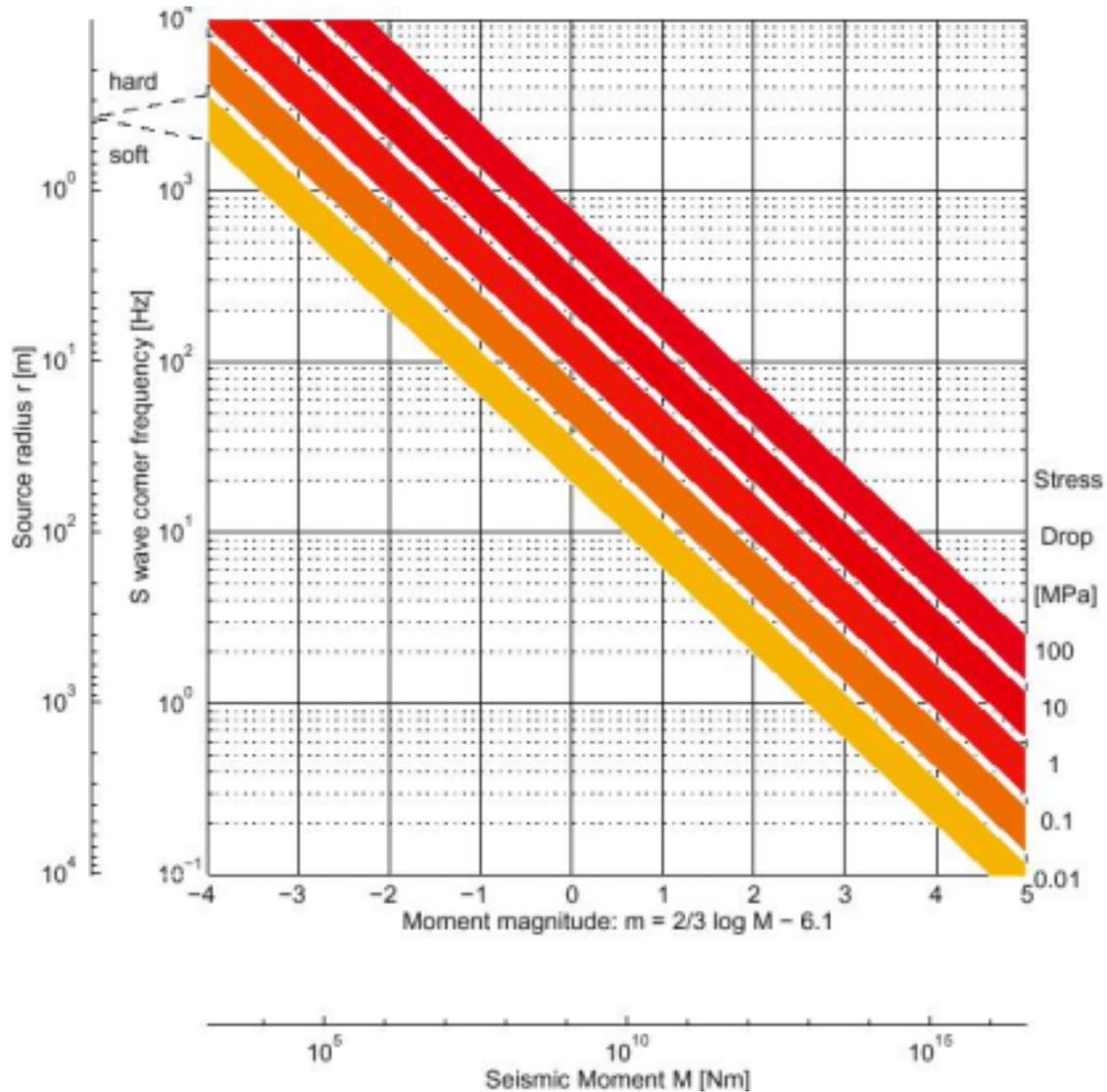


Figure 2.3.2. Corner frequency as a function of seismic moment

Figure 2.3.2 shows further that a high corner frequency¹ characterizes a small moment type event at a specific stress drop. In the time domain the corner frequency is associated with the largest amplitude of ground motion (main pulse) and therefore also proportional to the frequency of the acoustic emission associated with the event. Underground observations such as the high pitch audible sound associated with e.g. stress fracturing (i.e. small moment magnitude /large radiated energy events) and the low audible frequencies observed with larger magnitude

¹ The frequency at which a source radiates the most seismic energy observed as the maximum on the source velocity spectrum or as the point at which a constant low frequency trend and a high frequency asymptote on the recorded source displacement spectrum intersect. The corner frequency is inversely proportional to the characteristic size of the source. **size, l , [m]:**
 $l = c / f_0$ $c = 2500$ m/s for S-wave in hard rock

(i.e. large moment events) associated with geological features confirms this and also suggest the following:

Bearing in mind the Gutenberg-Richter power law that governs a SOC system such as rockmass response to mining AND the fact that corner frequency is inversely proportional to source size, one would expect that a large number of events with high acoustic frequencies should be present while a smaller number of events with low frequencies be present.

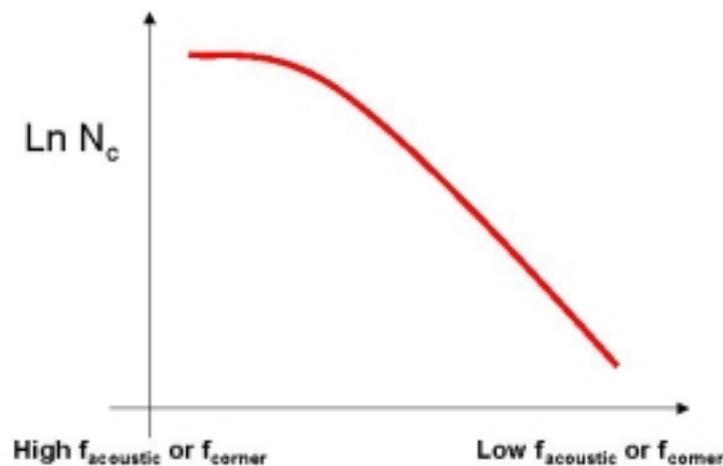


Figure 2.3.3. Conceptual Gutenberg-Richter distribution with event size expressed in terms of corner or acoustic frequency

3. Research Methodology

3.1 Introduction

The initial scope (as defined by SIMRAC) of this particular project called for a detailed literature survey as well as laboratory experiments to establish whether electromagnetic/acoustic emissions emitted during rock failure can be measured. The problem with laboratory experiments is the difficulty in eliminating electromagnetic interference from associated electromagnetic emissions. An actual underground trial measurement was proposed to monitor electromagnetic/acoustic/ultrasonic emissions during roof failure. A simple methodology was employed in which potential emissions were monitored together with seismic emissions in an area with known seismic activity. Seismic events were monitored and recorded, and emissions before, during and after the seismic event were also recorded. Investigation of the occurrence of electromagnetic/acoustic/ultrasonic radiation before a seismic event will indicate

whether these emissions associated with roof failure can and have in fact been measured.

3.2 Data acquisition

The underground experiments were conducted using an integrated seismic and electromagnetic/ultrasonic monitoring system with the following list of components:

- Rohde and Schwarz Radio Receiver
- Active Rod Antenna
- Small commercial short-wave radio (pocket size)
- ISS International Multi-Seismometer
- ISS International Ruggedized Data Logger
- 100 Hz uni-axial geophone
- Accelerometer
- Ultrasonic detector

3.2.1 Rohde & Schwarz professional short-wave receiver

A Rohde & Schwarz ESH 3 test receiver covering a frequency band of 9 kHz to 30 MHz was used to measure electromagnetic emissions underground. The test receiver has the following functions:

- Demodulation modes (F3, A3J, A3, A1, A0, AUS OFF) which contain amplitude and frequency demodulation modes.
- Speaker and Audio output (Audio output was used to feed data into the ISSI Multi Seismometer)
- Generator output for two port and remote frequency measurements.
- Supply and coding for a range of test antennas and probes.
- RF attenuation
- Auto ranging and display
- Analog indication of measured data with range limits
- Digital frequency display
- Analog frequency-offset indication
- Measurement time settings

- Display modes
 - average value
 - peak value
 - CISPR
 - pulse spectral density
- Storage of nine complete device settings
- Automatic frequency scanning
- Programming via IEC bus

3.2.2 Active rod antenna

A broadband active rod antenna HFH 2-Z1 was used. This antenna is a general-purpose receiver antenna and measures the electrical field-strength component. The frequency range specified is 9 kHz to 30 MHz.

3.2.3. Small commercial pocket radio

A small off-the-shelf pocket size radio was also used to record data in the short wave band. The available frequency band was from 2 MHz to approximately 30 MHz.

3.2.4 Multi Seismometer (ISS International Ltd)

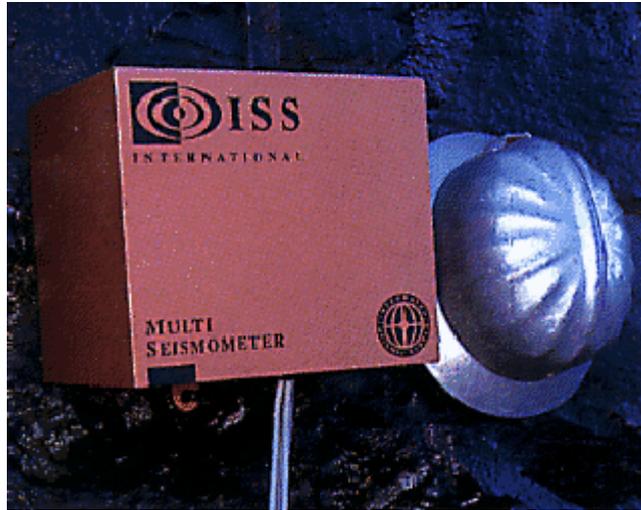
An ISS International Multi Seismometer configured for geophones was used to record the seismic and EM data.

Acquisition software: ISSI Runtime system

Processing software: ISSI XMTS
ISSI MdiSeis

The Multi-Seismometer (MS)

The ISS Multi Seismometer (MS) is a multichannel multi-functional data acquisition unit. It provides the essential functions of digitizing, triggering, timing, storage and



communication for multiple uni-axial or tri-axial seismic sensors. In addition, slowly varying ("non-seismic") signals may be sampled, and control, alarm or scram outputs may be switched whenever seismic or non-seismic inputs exceed preset levels. Trigger and alarm levels may be set from the central site. Timing may be synchronized to the central site or to a local Global Positioning System (GPS) receiver.

- The unit can record signals which vary widely in amplitude, duration and frequency content:
- The dynamic range in amplitude is 132 dB, being the ratio of the largest acceptable signal to the quantization noise level.
- The dynamic range in duration of a recording, being the time interval from detection of a trigger until the signal returns to near background level, may vary by a factor of 100. For example, at a sample rate of 10 kHz, the shortest recording would be 50 ms and the longest 5 s. Assuming that the P wave to S wave separation accounts for half its duration, this translates to source to sensor distances of less than 250 m and up to 25 km. At 200 Hz sampling, these times and distances become 2,5 s to 4 min and 12,5 km to 1250 km respectively.
- The dynamic range in frequency - while the initial sampling rate is fixed by the sensor bandwidth and matching anti-aliasing filter, the final sampling rate may be reduced by a factor of up to 25 through decimation, depending on the dominant frequency of the recorded signal. This yields a proportional saving in transmission time and storage space at the central site.

Throughput depends mainly on the bandwidth of communication to the central site. At 115kb/s seismograms of up to 10 000 events per day may be sent to the central

site from each MS.

Note: Three uni-axial sensor sets may be used to obtain wider coverage in place of a tri-axial set.

Functions

- Calibrates and monitors one to three triaxial or nine uniaxial sets of geophones or accelerometers
- Reads up to 32 nonseismic sensors on request keeps network time provided by central control site (CS) or GPS
- Triggers on seismic events, rejects triggers which do not match seismic event pattern
- Describes all triggered events to the central computer in terms of time, amplitude and duration
- Allows for automatic decimation
- Transmits seismograms to CS
- Keeps a number of decimated seismograms if triggers are faster than transmission permitting the CS to determine transmission priority
- Optionally switches on an alarm and/or informs the CS when seismic or nonseismic values exceed set limits

Description

The MS collects data from up to 3 sets of triaxial or nine sets of uniaxial seismic transducers and up to 32 nonseismic transducers. When configured as a part of an ISS network, data from each trigger is forwarded to a central computer. The information is also used to switch remote alarms or inform the central computer when preset values are exceeded. The MS is packaged to operate in an underground mining environment.

Characteristics

- Remote control output
- Watchdog timer
- Remote alarm output
- Communication channel modem
- Power supply 110-220 VAC, optionally with internal battery backup or 12 VDC
- Real time clock resolution - 1 sample
- The MS requires one A/D converter for each set of triaxial or three uniaxial seismic sensors and one for nonseismic inputs. Three types of seismic A/D converters are available. The standard A/D converter is supplied as a G type, which provides a calibration pulse to geophones, or an A type which supplies power to accelerometers. The AW type is intended specifically for wideband accelerometers.

Standard A or G type seismic A/D

Dynamic range	132 dB
A/D resolution	14 bits
Channels	3
Max signal bandwidth [Hz]	4 000
Max sampling rate per component [sample/s]	32 000

Linear 24-bit GL seismic A/D

Dynamic range (@160 Hz bandwidth)	121 dB
Signal to distortion ratio	110 dB
A/D resolution	24 bits
Channels	3
Signal bandwidth [Hz]	20 to 320
Sampling rate per component [sample/s]	50 to 800
Absolute sample timing accuracy [ms]	1
Switchable front end gain stage	2 ranges

Reconfigurable AR and GR seismic A/D

Dynamic range	112 dB
Signal to distortion ratio	100 dB
A/D resolution	24 bits

Channels	4
Signal bandwidth [Hz]	800 to 10000
Sampling rate per component [sample/s]	2000 to 24000

Wideband AW type seismic A/D(d- type)

Dynamic range	132 dB
A/D resolution 20 bits Channels	3
Signal bandwidth [Hz]	10 000
Sampling rate per component [sample/s]	24 000
Accelerometer power supply	

Non-seismic A/D

Full scale input	-5 V to +5 V or 4 mA to 20 mA
Resolution	12 bits
Channels	32, as standard one is dedicated to internal temperature measurement

Environment

Humidity	up to 100%
Temperature	up to 50xC
Splash proof	exceeding IP54
Size	W = 265 mm; H = 225 mm; D = 175 mm
Weight	< 5 kg excluding battery
Power consumption	< 6 W
Rust proof	
Physical Rugged construction	

3.2.5 Data Logger

The RockRadar ruggedized laptop was used to acquire data and to run the ISSI Runtime system. The RockRadar data logger is a fully standalone laptop designed for use in rugged conditions encountered in underground mining conditions.

The data logger unit can be seen in Figure 3.2.5.



Figure 3.2.5: Radar Data Logger with a TERRADAT ruggedized notebook mounted onto the docking station.

The main component of the data logger is a ruggedized notebook computer, the ToughNote from Terradat UK (Figure 3.2.5(a))



Figure 3.2.5(a): ToughNote

The specifications of the notebook are as follows:

- Processor Intel Pentium 266MHz MMX
- 512KB L-2 Burst cache
- Memory Standard 32MB expandable to 128MB
- Storage 6.4GB HDD upgradeable to 4.3GB, 6.4GB, or 8.1GB
- Flexi-bay holds: 24x CD-ROM / 1.44 MB floppy / LS-120 super floppy drive (option)
- DVD/MPEG II (optional)
- Display 12.1" 800x600 TFT or 13.3" 1024x768 TFT Colour LCD with anti-glare filter
- 64 bit 2MB PCI graphics
- Keyboard Waterproof, 89 key Windows 95 ready
- Mouse Integral waterproof touchpad mouse
- Multimedia 16 bit Sound Blaster compatible with integrated stereo speakers
- DVD / MPEGII option (fits in floppy bay)
- Dimensions 312 x 246 x 62.5mm
- Weight 4.3 kg / 9.5 lb. with Flexi-bay module
- Connectivity 2 Type II PCMCIA Slots. 2 enhanced serial (UART 16550 compatible), 1 parallel, IrDA wireless port, floppy, fax/modem, external CRT, LAN, audio, PS/2, microphone, speaker. Dock station
- Power Low battery warning / APM. Autosensing 110/230v mains charger.
- Removable 36WH Lithium primary battery and optional Li-ion secondary battery
- Operating system Windows 95/98/2000, Linux or NT4 Workstation

Options

- Sound Sound card is standard
- Modem: Internal 56K Fax/Modem
- PCMCIA Wireless GSM radio modem
- Keyboard: Protective anti-dust membrane
- Back-lit keyboard option
- Screen: Touch screen option (12" TFT only)
- Network: LAN 100 Base T card
- Charging/Supply Secondary Li-ion battery (swaps with CD/floppy)
- Dual battery external charger
- 10-32V vehicle adapter
- 24-30v truck charger
- Optional Solar Panels
- External charger for secondary battery
- Memory Upgrades to 64 or 128 MB total
- Docking solutions Dockunder (1S, 1P, 1 PS/2, 1 PCI slots)

Data transfer and communications were performed via the serial port on the ruggedized data logger.

3.2.6 Sensor - 100 Hz geophone

A 100 Hz uniaxial geophone was used to record seismic waves. The sensor was mounted to the roof using quickset cement and was positioned vertically.

3.2.7 Sensor- 10 kHz Accelerometer

All measurements at site 2 were performed with an uni-axial accelerometer comprising an A-10000 accelerometer from ISS International. The sensor was set in a rugged tri-axial epoxy sensor holder with an integral signal cable. The sensor was mounted to the roof with quickset cement and was positioned vertically.

The specifications for the A 10000 sensor are as follows:

Resonant frequency	>20kHz
Sensitivity	100 mV/g
Frequency range	(+3 dB)
Transverse sensitivity	<2%
Broadband noise floor	100 fg
Maximum acceleration	50 g

3.2.8 Ultrasonic detector

An ultrasound detector was constructed to measure ultrasonic (≥ 20 kHz) emissions from the rock.

The detector comprises an ultrasonic transducer, a pre-amp, an oscillator-mixer circuit, a second-order low pass filter and an audio amplifier. The detector operates on the principle of frequency division to downgrade an ultrasound signal to an audible signal. The circuit provides a 7kHz range around the oscillator frequency of 40 kHz, i.e. the ability to detect ultrasonic signals from 36.5 to 43.5 kHz.

The specifications of the ultrasonic transducer are the following:

center frequency	40 kHz
Sound pressure level (dB)	121
Sensitivity (dB)	-59
-6 dB Directivity typical degrees	55
Capacitance	2100

3.2.9 Microphone

An off-the-shelf microphone was obtained to monitor audible emissions from the rock that is associated with failure. The microphone was interfaced with the MS to allow recording of audio signals. The specifications of the microphone are as follows:

Cable	2.44 m shielded cord with 3.5 mm 3-conductor gold plug
Sensitivity	-67dBV/uBar, -47 dBV/Pascal +- 4 dB
Power source	1.5 Vdc
Impedance	2 kohm
Frequency range	100 Hz to 16 kHz

3.3 System configuration

3.3.1 Site 1- Brandspruit

The MS has three inputs of which one was used to monitor seismic activity via the 100 Hz geophone. The uniaxial geophone was mounted with quickset cement onto the sandstone roof. The rod antenna was placed on the floor between pillars. The small short-wave radio was positioned next to the larger rod antenna. The output of the RS radio and the small radio was fed into the remaining two channels of the MS. The MS thus recorded the following channels:

1. Seismic ground motion via geophone
2. Pocket radio measured electromagnetic emissions
3. RS radio measured electromagnetic emissions

3.3.2 Site 2- New Denmark

The system was constructed to measure on the following three channels:

1. Seismic ground motion via a 10 kHz accelerometer
2. Acoustic measurements with a microphone between 100 Hz and 16 kHz

3. Ultrasonic measurements with ultrasonic detector between 36.5 and 43.5 kHz

3.4 Site selection

3.4.1 Brandspruit Colliery

Sasol Brandspruit 2 shaft Section 32 (Sasol Secunda colliery) was selected as a test site for data acquisition because of the following reasons:

1. Mining method is total extraction with stooping. Goafing provides a seismically active roof with roof fracturing.
2. Site is representative of typical mining site with mining continuing in the area during the duration of data acquisition.

3.4.2 New Denmark Colliery

A longwall-mining environment was selected for the second phase of the project for its applicability to this particular roof monitoring technique. Measurements were conducted as close as possible to areas of seismic activity in the roof.

3.5 Acquisition methodology

3.5.1 Site 1 - Brandspruit

Electromagnetic emissions were monitored at the following frequencies:

190 kHz
200 kHz
500 kHz
1000 kHz

2.31 MHz
2.50 MHz
4.91 MHz
10.0 MHz
29.9 MHz

The MS was configured to trigger on any of the three channels on an incoming signal of specified amplitude above the noise level. Thus, the system would trigger if an incoming seismic wave (from roof failure or mining induced noise) is observed, and will at the same time record the EM radiation observed by the RS radio and the hand-held radio. A buffer of approximately 60-70 milliseconds allowed the MS to record 60-70 ms before the seismic wave (The EM radiation travels much faster than the seismic wave and will arrive before the seismic wave if both were generated from the same source event). In the same manner the system will also trigger if an incoming EM signal above the noise level is observed.

Both radios were tuned off station - specific attention was given to ensure that no coherent EM signal was being monitored by both radios and the seismic system.

3.5.2 Site 2 - New Denmark

The system was configured to trigger on any one of the three channels when a signal of higher amplitude than the background noise amplitude is observed. In this manner the system will thus trigger if an acoustic signal is observed although no noticeable ground motion via the accelerometer was measured. The ultrasonic sensor and microphone was mounted on a tripod approximately 30 cm from the roof beneath the accelerometer which was mounted to the roof using quickset cement.

During the second day of measurement the ultrasonic detector was moved to the floor to give better coverage for measuring possible ultrasonic emissions. Measurements took place in the Main Gate and Tail sections with measurements in the Tail sections conducted approximately 20-30 metres from the actively mined longwall. Measurements were conducted for three shifts as follows:

Day 1 - Main Gate section: Measurements conducted from 11h00 to 12h15. Area appeared to be relatively seismically quiet further discussions on site with mining

personnel.

Day 2 - Tail Gate section: Measurements conducted from 7h00 to 10h45. Approximately 20 to 30 metres from actively mined longwall. No mining during time of measurements as maintenance conducted during this time period. Area seismically active with a number of seismic events being audible and being recorded.

Day 3 - Tail Gate section: Same area as day 2. Area less active.

The system was tested for functionality at the underground measuring area by manually triggering the system. A small hammer was used to impact the roof near the accelerometer that was monitored by the seismic system. To test the ultrasonic sensor functionality, lock keys were shaken close to the ultrasonic sensor. These functionality tests are discussed and presented in the 'results' section.

4. Results

4.1 Site 1 - Brandspruit

4.1.1 Site 1- Analysis of seismic events

During the data acquisition period, seismic events were confirmed by the operator who recorded audible seismic events ('bumps') in the fieldnotes. The seismic event was correlated using the time of the event. Amongst seismic events, a large number of non-seismic events were also recorded. These events were mining-induced noise generated from mining machinery and personnel.

The electromagnetic emissions/noise measured by the pocket radio showed very few electromagnetic anomalies while the R&S radio showed clear electromagnetic anomalies. The R&S measurements were thus used in the data analysis.

Every valid event which has been registered by the seismic system is presented in time domain. Three time series data are presented which are:

Top: Seismic waveform

Middle: Electromagnetic emissions monitored by pocket radio

Bottom: Electromagnetic emissions monitored by RS radio

All data are presented on the same time-scale (measured in seconds) although the amplitude scale does vary. All signals are magnified to fill a window vertically and the maximum amplitude can be observed on the y-axis. The following section describes the seismic events which were measured at pre-defined electromagnetic frequencies.

The following information is presented in the tables:

- Time of seismic event,
- Maximum amplitude of seismic event which provides an indication of the relative amplitude of the seismic event,
- The third column indicates whether an electromagnetic anomaly was also observed in the particular time window,
- Comments in which the approximate delay in time between the electromagnetic anomaly and the seismic event is given. This information can be used to provide an indication of the distance from the source location of the seismic event to the measurement position.

4.1.1.1 Measurements at 190 kHz

Table 4.1.1.1			
Time of Event	Maximum amplitude of seismic event	Electromagnetic anomalies observed?	Comments
20:16:08	0.003	No	
20:15:44	4e-4	No	
20:15:26	7e-5	No	
20:15:24	4e-4	No	
20:15:34	9e-4	No	
20:08:49	2e-5	No	
20:08:50	2e-5	No	
20:22:39	0.001	No	
20:08:51	0.003	Yes	Delay of approximately 130 milliseconds

20:48:00	0.001	No	
20:29:31	0.002	No	
20:27:49	9e-4	No	
20:23:14	0.001	No	
20:48:04	3e-4	No	
20:40:30	0.004	Yes	Delay not possible to calculate
20:42:24	0.002	Yes	Delay = 10 ms
20:45:44	0.001	Yes	Delay = 20 ms
20:47:07	0.004	No	
20:50:05	-	No	

A total of nineteen events were recorded at 190 KHz. On four of these events, electromagnetic anomalies were observed as indicated in the above table. This gives a percentage of 21% for EM emissions observed together with seismic emissions.

4.1.1.2 Measurements at 500 KHz

Table 4.1.1.2			
Time	Seismic Amplitude	EM?	Comments
10:52:21	1e-4	Yes	Delay = 40 ms
11:05:26	1e-4	Yes	Delay = 16 ms
10:28:47	9e-4	Yes	Delay = 0 ms
10:23:02	4e-4	No	
11:47:35	2e-4	No	

A total of five events were observed of which three showed evidence of EM. This results in a percentage of 60% for EM anomalies observed together with seismic events.

4.1.1.3 Measurements at 1.0 MHz

Table 4.1.1.3			
20:00:15	5e-5	No	
20:04:12	0.001	No	

Only two events recorded with no EM observed.

4.1.1.4 Measurements at 2.31 MHz

Table 4.1.1.4			
17:26:11	1e-5	No	
17:14:54	4e-4	Yes	Delay = 18 ms
17:04:13	2e-4	No	
17:10:23	2e-4	No	
17:12:31	3e-4	No	
16:52:22	0.004	No	
16:55:07	0.009	No	
17:13:56	3e-4	No	

A total of eight events recorded with 1 EM observed which gives 12.5 % for EM anomalies observed together with seismic events .

4.1.1.5 Measurements at 2.5 MHz

Table 4.1.1.5			
21:00:43	0.003	No	
21:07:29	6e-4	Yes	Delay = 36 ms
20:54:41	5e-4	No	

21:07:34	5e-4	Yes	Delay = 40 ms
21:16:28	1e-4	Yes	Delay = 60 ms
21:16:37	4e-5	No	
21:32:14	0.002	No	
21:02:08	-	No	

Eight events observed with three possible EM's observed. This calculates a 37.5 % observation for EM anomalies observed together with seismic events

4.1.1.6 Measurements at 4.92 MHz

Table 4.1.1.6			
09:49:32	5e-4	Yes	Delay = 44 ms
09:47:23	2e-4	Yes	Delay = 66 ms
09:46:33	5e-4	Yes	Delay = 50 ms
09:44:34	4e-4	Yes	Delay = 52 ms
11:34:30	3e-4	Yes	Delay = 35 ms Delay = 5 ms
11:00:11	-	-	-

A total of six events observed with five possible EM's, producing the highest positive observation of 83.3 %. A typical example is shown in Figure 4.1.6 where the observed electromagnetic anomaly is indicated.

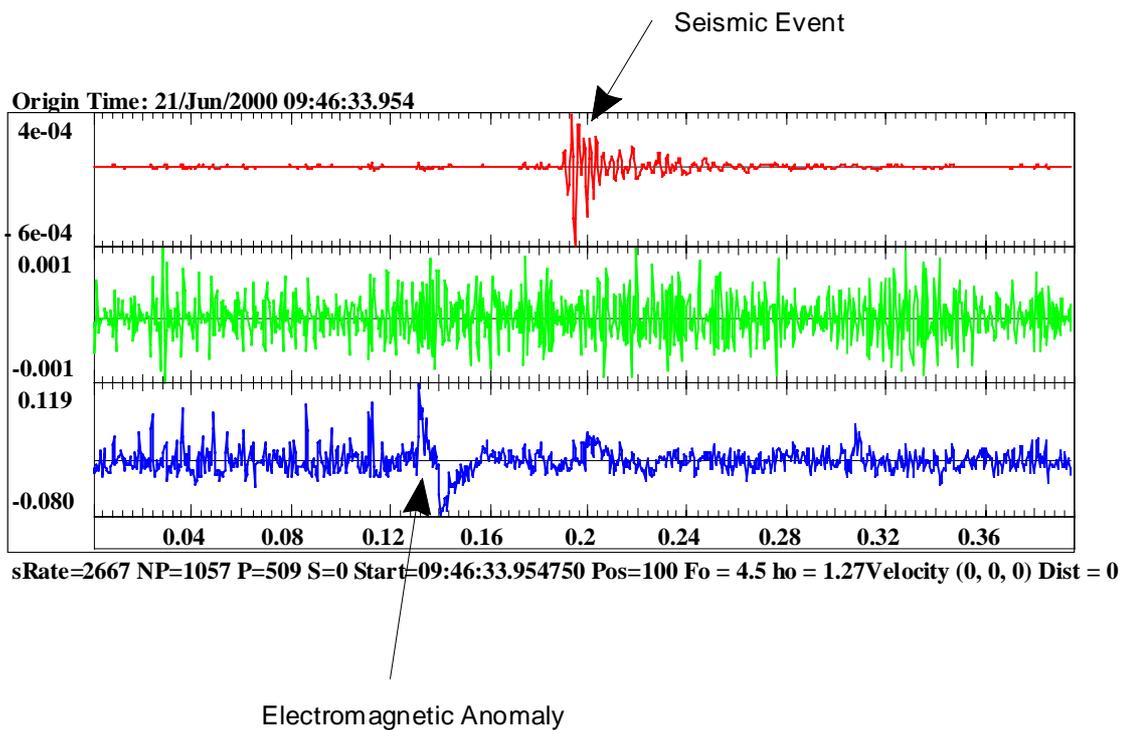


Figure 4.1.1.6 Electromagnetic anomaly associated with seismic event

4.1.2 Site1 - Analysis of background electromagnetic noise

In addition to confirmed seismic events, a large number of background seismic and electromagnetic events were observed. These are caused by underground seismic and electromagnetic noise. Typical sources for these events were:

- Induced vibration by mining machinery;
- Vibration caused by underground personnel;
- Electromagnetic interference by electrically powered equipment.

Although analysis of some of these events may suggest that the events are also seismic events originating from roof failure, these could not be correlated with field notes in which the time and date of a confirmed seismic event were recorded.

However, there may be discrepancies when a large number of events were triggered in a short period of time when the system needs to process all the incoming events. In such a case, it is not always possible to correlate an audible seismic event to a specific time. Only the actual confirmed seismic events (correlated with audible confirmation during data acquisition) were used in the data analysis.

The non-confirmed seismic and EM events were used to provide a qualitative assessment of the level and nature of underground mining induced seismic and electromagnetic noise.

Non-seismic events include possible seismic events that could not be confirmed with audible events at the time of the survey as well as other mining-induced seismic and EM events. Non-seismic events are analysed to provide a qualitative assessment of background EM radiation in the underground environment. Background EM is thus defined as mining-induced EM radiation not associated with a seismic event.

Non-seismic events were monitored at the following different frequencies: 190 kHz, 200 kHz, 500 kHz, 1.00 MHz, 2.31 MHz, 4.91 MHz, 10.00 MHz, 29.99 MHz using the R&S radio. **Note that EM is observed on the bottom cross section while the seismic signal is observed on the top cross section.**

4.1.2.1 Background at 190 kHz

Distinct EM anomalies were observed at 190 kHz by the R&S radio. Refer to event 20:19:47 in which a clear periodic EM signal can be observed although the signal appears to be sporadic - possibly associated with mining-machinery. The approximate frequency observed is eight cycles in a 0.60 seconds time duration that gives a frequency of approximately 13 Hertz (Hz). A spike could also be observed in some of the data (Example Event 20:16:55) of which the origin is unknown.

The background EM anomalies described above were not observed together with seismic events recorded at 190 kHz.

4.1.2.2 Background at 200 KHz

A very distinct EM anomaly could be observed (refer to Event 19:56:23) which is probably caused by electrically power mining machinery.

4.1.2.3 Background at 500 KHz

No clear EM anomalies observed although a distinct EM anomaly could be observed on Event 11:51:13.

4.1.2.4 Background at 1.00 MHz

EM anomalies with a very clear shape can be observed at 1.0 MHz (Event 19:56:32). Duration is approximately 20 milliseconds which also appears to be equal to the period of the anomaly. This results in a frequency of 50 Hz - interpreted as being induced by electrical machinery.

4.1.2.5 Background at 2.31 MHz

Although no significant EM patterns/anomalies can be observed on the majority of EM observed, a few EM observations do show a clear EM pattern (Refer to Event 17:33:02). This event shows a clear EM pattern observed which is repeated approximately every 60 milliseconds.

4.1.2.6 Background at 2.5 MHz

No clear EM anomalies/patterns could be observed.

4.1.2.7 Background at 4.92 MHz

No clear EM anomalies/patterns were observed.

4.1.2.8 Background at 10.0 MHz

A clear EM anomaly could be observed on Event 09:22:00 which is similar to the EM pattern observed at 1.0 MHz.

4.1.2.9 Background at 29.99 MHz

No clear patterns or EM anomalies could be observed.

4.2 Site 2 - New Denmark

4.2.1 Analysis of Seismic Measurements

During the data acquisition process, the operator noted times of all audible seismic events and correlated with events triggered by the system. Background seismic noise/man-made events caused by machinery and underground mineworkers were thus eliminated from recorded seismic events using this correlation method.

The following six events (catalogue number derived from date and time) out of a catalogue spanning approximately 1000 events were confirmed to be seismic events by correlating event time with audible confirmation of seismic event on site, as well as inspection of the seismic waveform:

Event characterised by time
073607
075950
081340
081952
080825
083753

Dominant frequencies of seismic events varied from relatively low (frequency peak at 100 Hz) up to a 1000 Hertz.

Refer to Appendix 3 for waveforms and frequency spectra.

4.2.2 Analysis of Audible background measurements

A large number of acoustic measurements (with no visible seismic and/or ultrasonic signals in the same time window) were measured. The number of acoustic measurements are of the order of 1 magnitude more than the number of recorded seismic events. This may be due to the high level of acoustic background from system operator(s), running water, etc.

An example of audible background emissions observed, is presented. In the figure below the audible signal recorded by the microphone, is displayed. The total time window is 0.09 seconds (90 milliseconds). These observations represent typical acoustic noise recorded underground.

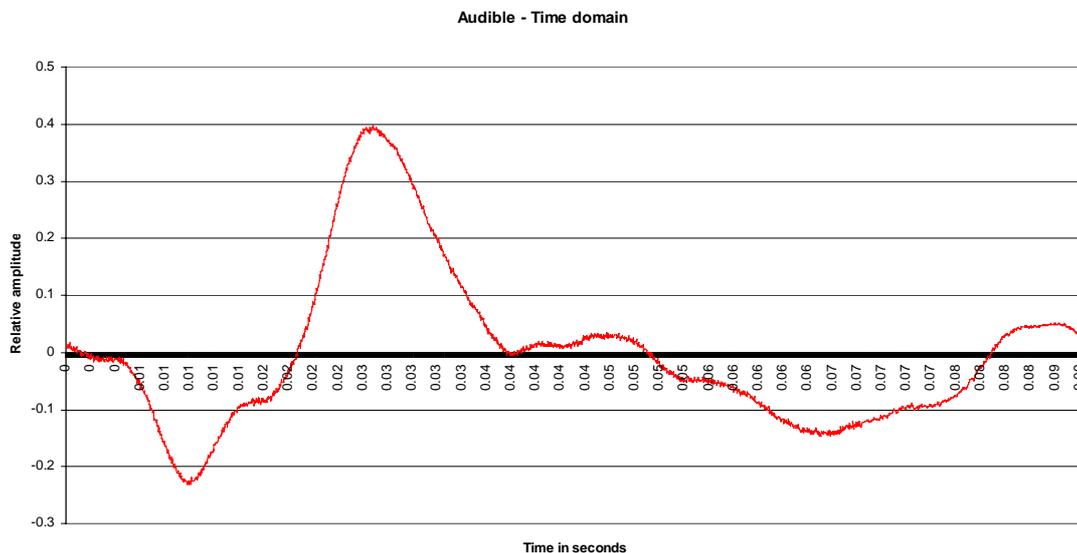


Figure 4.2.2.a. Acoustic (audible) emission recorded by microphone

As can be observed from Figure 4.2.2.b, background audible noise recorded by the microphone was typically of very low frequency (less than 100 Hz).

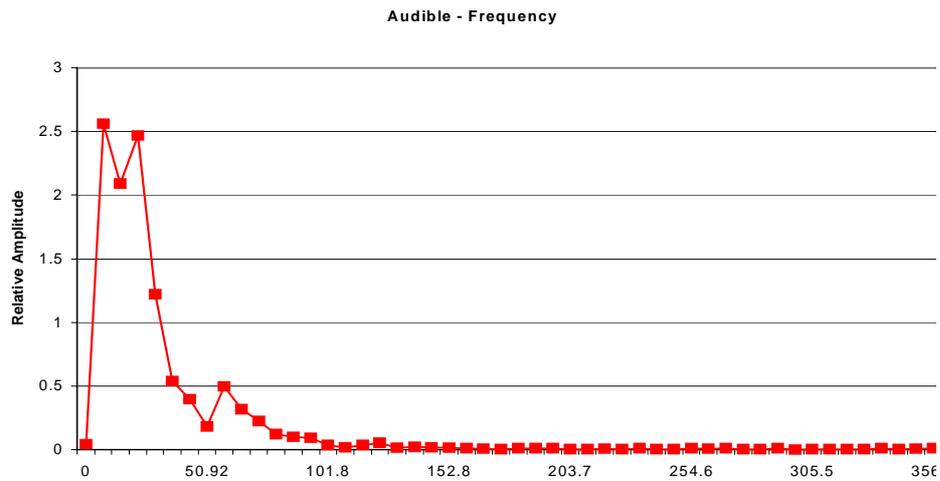


Figure 4.2.2.b. Acoustic (audible) emission frequency spectrum.

4.2.3 Analysis of Acoustic Measurements

Ultrasonic emissions possibly associated with rock failure were monitored together with seismic and audible emissions. The observed seismic events that were recorded by the accelerometer (described in 4.2.1) were investigated for the presence of associated acoustic/ultrasonic emissions recorded with the acoustic/ultrasonic system on a second channel. The following figure is a typical example of recorded data from the ultrasonic detector. (This example is recorded together with the seismic event (**181340**) presented in 4.2.1).

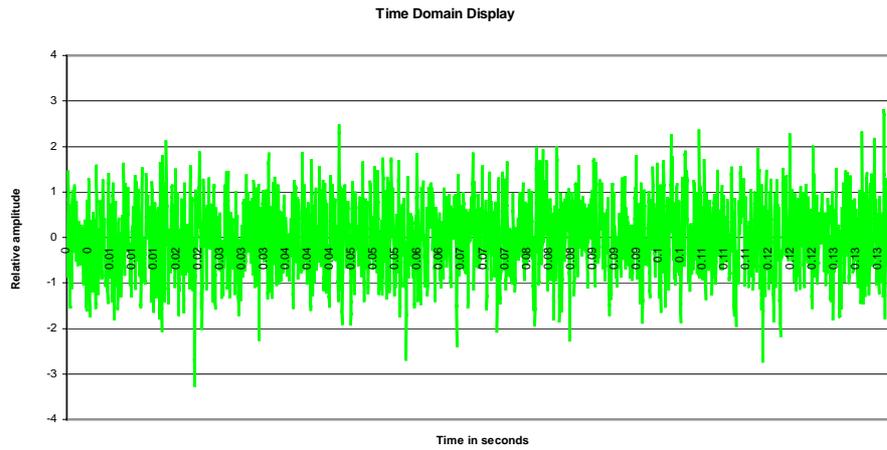


Figure 4.2.3. Signal from ultrasonic channel recorded together with seismic event

4.2.3.1 Key triggers

A number of artificial ultrasonic emissions were recorded during the data acquisition period to test the functionality of the system. Ultrasonic emissions were generated by shaking keys (known source of ultrasonic energy and described in various sources) a distance of 0.5 metres from the ultrasonic detector. Figure 4.2.3.1 shows the recorded ultrasonic emissions from such a simple test.

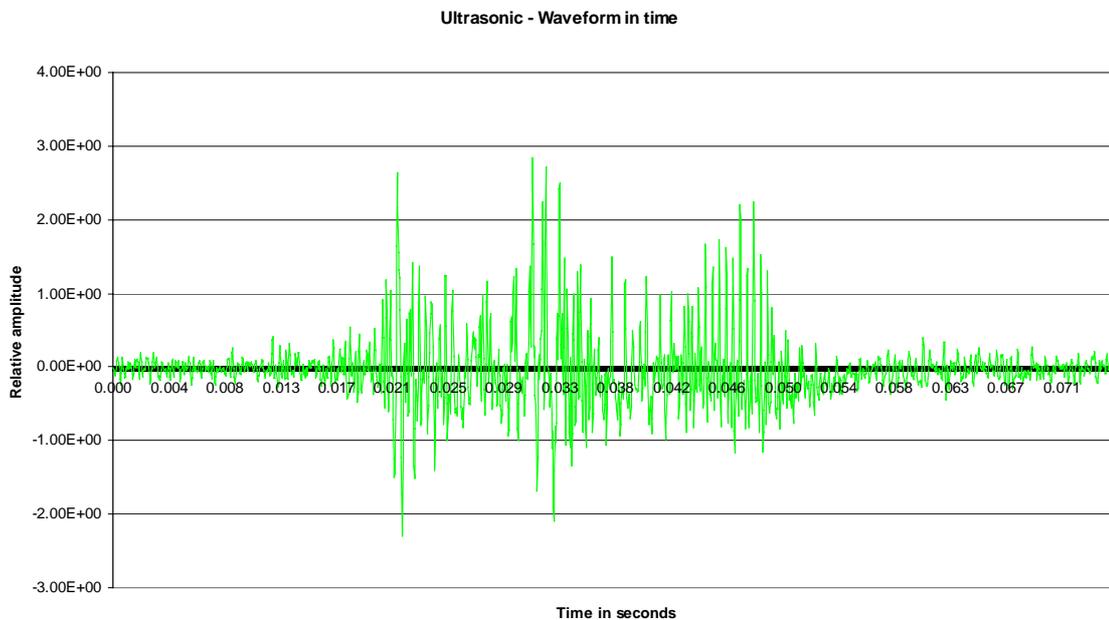


Figure 4.2.3.1 Ultrasonic measurements recorded by shaking of keys

4.2.3.2. Noise level analysis

An estimate of signal-to-noise ratio can be derived from the ultrasonic key triggers and the background ultrasonic noise level recorded underground. Relative background ultrasonic levels varied between 0.1 and 0.2 (note this is a relative amplitude) by inspection of ultrasonic amplitudes recorded together with seismic events. Using the data from the calibration described in 4.2.3.1 (see figure 4.2.3.1), it can be seen that recorded amplitudes varied between 1.0 and 2.0, which are 10 times larger than the recorded background amplitudes. The ultrasonic source was located at 0.5 metres from the ultrasonic detector. Relative signal-to-noise ratio is thus estimated to be approximately 10 for this particular data example. This implies that 'natural' ultrasonic emissions at 0.5 m away from the detector, using this particular detector and environment need to have relative amplitudes larger than 0.2, otherwise it will not be detected above the noise level.

4.3 Discussion

4.3.1 Site 1 - Brandspruit

EM anomalies have been observed in the same time window as for seismic events observed. EM anomalies are defined as a clearly visible change in the EM signal which is visible above the background electromagnetic noise level.

The highest presence of EM anomalies in association (in the same time window of less than a second) with seismic events was observed at a frequency of 4.91 MHz. Here five out of the six events was accompanied by EM anomalies. IF one looks at the background EM monitored at this particular frequency (Events 09:00:43, 11:17:10, 09:50:43, 09:39:45, 11:34:28) the amplitude of the background EM varied from as low as $3e-4$ up to a maximum of 0.092) Note that these values are relative values but can be used to draw conclusions regarding relative amplitudes of EM anomalies.

The data do suggest that these EM anomalies could be associated with electromagnetic emissions that have been emitted from rock failure because of the following:

- The maximum amplitudes of EM anomalies observed at 4.92 MHz varied between 0.079 to 0.134 that are higher than the maximum amplitudes of background EM observed at this frequency. EM anomalies observed in the same time window as seismic events do

have larger amplitudes than background EM noise which does suggest that these EM anomalies are not random background EM noise, but coherent EM events.

- EM anomalies at 4.92 MHz were observed with clear distinct shapes that were not observed in the background EM signals.

- In all of the cases, EM anomalies were observed *before* and *during* the seismic event in time. As electromagnetic waves travel much faster than seismic waves, this supports the postulation that these EM anomalies are associated with seismic events. Typical differences in arrival times between the two different waves were from 35 to 66 milliseconds. If one assumes a typical compressional wave velocity of 2500 m/s and use the arrival time of the EM event as zero time for the seismic event, the distance from the seismic event to the measuring point can be calculated. Typical distances calculated range from 80 to 150 metres that are plausible considering the experimental setup.

4.3.2 Site 2 - New Denmark

A total of six known seismic events and associated acoustic emissions were measured. Inspection of the database and signal analysis (aimed at retrieving dominant frequency of recorded signals) revealed that associated ultrasonic emissions were not measured above background noise level.

The following table lists the seismic events recorded. Dominant frequencies between 50 and 600 Hertz were observed.

Event characterised by time	Dominant frequencies (Hertz)	Ultrasonic emissions ?
073607	400-600	No
075950	200-600	No
081340	400-600	No
081952	50-200	No
080825	50-150	No
083753	200-400	No

4.3.2.1 Presence of ultrasonic emissions

Audible acoustic emissions are clearly observed together with seismic events: Seismic events can be clearly heard underground, and are also observed when measured with a microphone. Acoustic emissions are thus present in the audible frequency range (20 Hz to 20 kHz). The rockmass, as a system that responds to mining in the form of seismic events as well as associated acoustic/ultrasonic emissions are considered a near critical system and therefore exhibiting Self-Organized Criticality (SOC) (see literature study). (If a sufficient number of audible events were recorded one could start 'filling up' the right end of Figure 2.3.3 with the low frequency emissions.) One would therefore expect that emissions in the ultrasonic frequency range (>20 KHz) must also be present if acoustic emissions are measured. The expected power law behaviour would (Guthenburg-Richter type distribution) describe a large number of events with local magnitude less than zero and associated ultrasonic (high) dominant centre frequencies.

A population comprising ten's to hundreds of events would be required to establish such a power law empirically. In the three days at New Denmark, only six useful data points were recorded which do not provide a useable population.

4.3.2.2 Amplitude of ultrasonic emissions

The amplitude of ultrasonic emissions upon reaching the ultrasonic detector depends on the following factors:

1. Distance between source of emission and detector influences the amplitude as a result of attenuation of ultrasonic energy. Due to safety and logistical issues, it was extremely difficult to position the detector very close to a seismic event in an underground environment. In this particular study, typical distances between source and receiver are not known, but are estimated to be in the order of 10's of metres. It is the opinion of the authors that no seismic event occurred closer than 5 metres from the ultrasonic detector.
2. The maximum amplitude of the acoustic/ultrasonic energy generated at the location of the source seismic event. It is expected that the ultrasonic emissions have amplitudes less than the audible sound and dependant on the source size e.g. the area in the rock that experiences stress redistribution and radiate acoustic energy (which also determines the amplitude of ground motion at the sensor).

4.3.2.3 Sensitivity of ultrasonic detector

The sensitivity of the ultrasonic detector is critical in measuring ultrasonic emissions. Sensitivity here refers to the smallest detectable amplitude (above total noise levels) and frequency response of the ultrasonic detector. Obviously, the sensitivity needs to be viewed in conjunction with the system background noise (see next section 4.3.2.4) which in this case comprises the ambient noise generated by mine systems and electronic noise generated internally by the ultrasonic measuring system.

The ultrasonic detector needs to be able to measure an ultrasonic signal that is suggested from the field measurements to be 10 times larger in amplitude than the measured background noise level in a typical coal mine. The frequency response needs to be sensitive to ultrasonic emissions with dominant frequency larger than 20 kHz.

4.3.2.4 Background ultrasonic noise level

The level of background ultrasonic noise level introduced by the system comprising the environment and the electronic measuring equipment is critical in measuring ultrasonic emissions. If background levels are higher than the ultrasonic emission of interest, no signal will be measured above background ultrasonic noise. It is therefore very important to measure the background ultrasonic emission level before the feasibility of measuring ultrasonic emissions as a result of rock failure can be determined.

The fact that no ultrasonic emissions were measured in this trial may be attributed to the possibility that the ultrasonic emissions were of very low amplitude and thus smaller than the background noise level of 0.2 relative amplitude units.

5. Conclusions and Recommendations

5.1 Conclusions

In this research project some electromagnetic anomalies have been measured in the same time window for confirmed seismic events. At a centre frequency of 4.92 MHz, electromagnetic anomalies were observed together with seismic events on 80% of the confirmed seismic events. The results thus do suggest that the observed electromagnetic anomalies may be electromagnetic emissions that are emitted during roof failure. Measurement of background electromagnetic radiation also suggests that the electromagnetic anomalies are not considered to be artificial or background electromagnetic emissions.

However, the results do not prove without any ambiguity that the observed electromagnetic anomalies can in fact be associated with roof failures. In order to make definite quantitative conclusions, sufficient data need to be collected on which a quantitative statistical analysis needs to be performed. Background electromagnetic anomalies have been measured which may be misinterpreted as electro-seismic anomalies, which can only be isolated from the data using statistical methods.

The amplitudes of possible electromagnetic/acoustic/ultrasonic anomalies produced during the monitoring period are critical in drawing final conclusions. To measure a signal, one needs to measure this signal above the noise level. If the signal is smaller than the background noise level, it is not possible to measure it. In this particular experiment it may have been the case where the electromagnetic/acoustic/ultrasonic signal, although present, was not observed above the background noise level. The distance from the event to the measuring point is also important as electromagnetic, acoustic and ultrasonic waves are attenuated through rock which implies that emissions from far away roof failures, may not have sufficient amplitude at the measuring point, and is part of the background noise level. This problem could be solved by using higher quality ultra-sensitive equipment with a wide frequency response.

In this pre-feasibility study no acoustic/ultrasonic emissions associated with seismic events were measured above the noise levels. However, no conclusions about the presence of acoustic/ultrasonic emissions can be made at this stage with limited information about amplitudes and background levels. Results suggest that improved system design could lower instrument noise levels resulting in reduction of total noise levels.

The collection of a large volume of data in an underground coal mine does focus on the need for intrinsically safe equipment. Without intrinsically safe equipment, no permanent (weeks to months) installation of equipment is possible which necessitates the monitoring on a shift by shift base. This necessitates the need for qualified mining personnel to supervise the data collection process. The scope of this particular project did not allow for an extensive data collection period and data was collected without using intrinsically safe equipment. Continuous monitoring, that is possible with newly developed technology by ISS International, could solve this problem by providing more data in a shorter period of time.

5.2 Recommendations

To prove the routine ability to measure electromagnetic/acoustic/ultrasonic emissions associated with rock failures a large volume of data with various acquisition settings needs to be collected. Providing continuous monitoring could be performed with capable and intrinsically safe equipment based on 24-bit sigma

delta technology source parameters can be correlated with amplitudes/intensity of measured emissions.

The following are proposed for future work:

1. Current electromagnetic measurements were conducted using an off-the-shelf rod-antenna that measures electrical field strength. It is also proposed that measurements be conducted with an optimised loop type of antenna that measures magnetic field strength. It is also imperative that antennas are optimised for this particular environment and be made sensitive enough to measure low amplitude electromagnetic signals.
2. Acoustic/ultrasonic measurements need to be conducted using a high quality low noise wide-band ultrasonic detector preferably interfaced with a continuous seismic monitoring system like the newly released Standalone QS (ISS International Ltd). Multi-array accelerometers and ultrasonic sensors that are coupled directly to the target rockmass should be used and data should be recorded over longer periods than the scope of this experiment allowed. Continuous monitoring, as performed with the Standalone QS, will result in more information obtained in a shorter period of time. Bulk data often reflects more about the processes involved than newly developed theories based on smaller amounts of data. This could lead to more results obtained in a shorter period of time.
3. The access to a larger pool of data could also allow confirmation of the power-law behaviour of seismic/acoustic/electromagnetic events that are caused by failure of the roof of the excavations (SOC systems).
4. The output from the continuous seismic/acoustic/electromagnetic monitoring system should be used to determine location, magnitude/intensity, and estimated origin time of seismic events, electromagnetic and acoustic events created during roof failure. This will allow for calculation of seismic/acoustic velocities, location and the estimated arrival time of possible electromagnetic/acoustic/ultrasonic emissions associated with a particular seismic event. The actual arrival time of emissions can then be correlated with calculated seismic event arrival times that will give an improved confirmation of the association of the emission with a seismic event as result of roof failures. Quantification of source parameters will also provide information on the source volume involved during roof failures.
5. It is proposed that measurements be conducted by the temporal installation of a continuous seismic monitoring system interfaced with an electromagnetic/acoustic/ultrasonic emission monitoring system. The data should be collected for a period spanning several rockmass response-to-mining cycles in a steeping environment that is seismically active.
6. Intrinsically safe equipment and installations are required.

References

1. **Brady, B. T, Rowell, G. A. 1986.** Laboratory Investigation of the electrodynamics of rock fracture. *Nature Vol 321*.
2. **Derr, J. S. 1986.** Luminous phenomena and their relationship to rock fracture. *Nature Vol 321*.
3. **Geller, R. J. 1997.** VAN cannot predict earthquakes - nor can anyone else. *International Centre for Disaster-mitigation Engineering (INCEDE) Newsletter, Vol 5-4*.
4. **Gokhberg, M. B, Morgounov, V. A 1982.** Experimental measurement of electromagnetic emissions possibly related to earthquakes in Japan. *Journal of Geophysical Research, 87:7824-7828*.
5. **Nesbitt, A. C. 1994.** Investigations of the emissions and propagation of electromagnetic energy from stressed quartz rock underground. *M.Sc. Dissertation. Johannesburg: University of the Witwatersrand., 174p*.
6. **Stravarakakis, G. 1998.** Claims of success in using geoelectrical precursors to predict earthquakes are criticised - and defended. *Physics Today, January*.
7. **Uyeda, S. 1997.** The VAN method of short-term earthquake prediction. *International Centre for Disaster-mitigation Engineering (INCEDE) Newsletter, Vol 5-4*.
8. **Yoshida, S. 1997.** Electrical potential changes associated with slip failure of granite: Pre-seismic and co-seismic signals. *Journal of Geophysical Research, 102:14883-14897*.
9. **Scott,D. 2001.** Investigation of Electromagnetic precursors to rock bursting. *World Wide Web <http://www.cdc.gov/niosh/mining/projects/ioept.html>*
10. **Bak, C. Tang and K. Wiesenfeld, Phys. Rev. A 38, 364 (1988)**