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Abstract

Improved ground-imaging capabilities have enormous potential to increase energy, environmental, and economic benefits by improving exploration accuracy and reducing energy consumption during the mining cycle. Seismic tomography has been used successfully to monitor and evaluate geologic conditions ahead of a mining face. A primary limitation to existing seismic tomography, however, is the placement of sensors. The goal of this project is to develop an array of 24 seismic sensors capable of being mounted in either a vertical or horizontal borehole. Development of this technology reduces energy usage in excavation, transportation, ventilation, and processing phases of the mining operation because less waste is mined and the mining cycle suffers fewer interruptions. This new technology benefits all types of mines, including metal/nonmetal, coal, and quarrying.

The primary research tasks focused on sensor placement method, sensor housing and clamping design, and cabling and connector selection. An initial design is described in the report. Following assembly, a prototype was tested in the laboratory as well as at a surface stone quarry. Data analysis and tool performance were used for subsequent design modifications. A final design is described, of which several components are available for patent application. Industry partners have shown clear support for this research and demonstrated an interest in commercialization following project completion.

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1. Introduction

The ability to accurately image conditions within a rockmass permits superior resource characterization resulting in more efficient extraction. This ability relates directly to industry goals defined in the Mining Industry Roadmap for Crosscutting Technologies. The Roadmap calls for the development of imaging tools to:

- 1) sense, visualize, and predict geological anomalies in front of mining equipment,
- 2) reduce operational downtime to near zero,
- 3) detect difficult mining conditions,
- 4) minimize waste, and
- 5) precisely characterize ore bodies.

Achieving these goals will have the major benefits of greatly reducing the amount of energy consumed by mining operations, minimizing the environmental impact of extraction, and improving the economic competitiveness of U.S. mining operations.

Tomography is the method used in the medical field for generating a CAT- (Computer-Assisted Tomography) scan. The underlying concept is that the interior of a body can be imaged based on the evaluation of energy that has passed through the body (Radon, 1917). Seismic energy is used to delineate properties of a rock mass because seismic waves travel through different rock types with different velocities and different attenuation characteristics (Dines and Lytle, 1979). This ability has allowed geologic and stress-related anomalies to be imaged ahead of mining (Westman et al., 1995, Westman and Haramy, 1996).

A primary limitation to seismic tomography currently is the placement of sensors. The most accurate images are obtained when source and receiver locations completely surround the body of interest. This is difficult to achieve in the mining environment. In underground mines sensors can be attached to roofbolts in entries or in shallow boreholes off an entry. In surface mines, an array of hydrophones can be placed in a vertical borehole if the borehole will hold water. An array of only one or two geophones can be used in dry boreholes, whether vertical or horizontal, however such an array can be used in conducting a tomography survey only if the sensors are incrementally relocated during the survey. Not only does this practice severely limit the speed at which a survey can be completed, but conditions may change during the survey.

To fully understand the improvements to imaging capabilities allowed by the new geophone array, a brief review of other geophysical techniques used prior to tomographic imaging will be helpful. This review will include ground penetrating radar and seismic methods. A review of the history and theory of tomographic imaging itself will then be presented to properly illustrate the advances introduced by the multi-channel borehole geophone array.

1.1 Geophysical Methods

1.1.1 Ground Penetrating Radar

Ground penetrating radar (GPR), a useful technique for carrying out non-destructive geologic testing, detects dielectric contrasts within rock masses through the reflection of electromagnetic pulses. GPR has a history of being used to characterize rock masses and geologic abnormalities. In a gypsum quarry

in western Europe, a combination of GPR and seismic imaging was used to locate fractures and damaged areas inside pillars which presented indications of reaching their stress limits (Derobert, Abraham, 1999). Although quick and easy to use, a major limitation lies in its inability to yield information on the state of stress of the structure.

1.1.2 Seismic Methods

Another mapping method that has been used previously is channel mapping of coal seams, in which the coal seam forms a two-dimensional waveguide. In channel wave mapping, the dispersion of seismic energy within this waveguide allows mapping of underground faults (Mason et al., 1980). A major cause of the inaccuracies in mapping with channel waves is the placement of sensors on only two sides of the rock mass.

Both GPR and channel wave mapping experience problems with remote sensing, namely that they leave open many ambiguities of interpretation. The technique known as tomographic imaging offers a solution to these problems.

1.1.3 Tomographic Imaging

Seismic tomography produces a map of an object's internal properties in a non-invasive fashion (Radon, 1917). By measuring the travel times of a seismic wave between source and receiver points around a rock mass, it is possible to calculate a map of the distribution of physical properties influencing seismic wave velocity within a rock mass. Tomography was first adapted to the field of medicine (Hounsfield, 1973; Cormack, 1973) and subsequently to the geosciences (Dines and Lytle, 1979). For at least 20 years, tomography has been used in the mining industry to create images of geologic features as well as stress-related features (Buchanan et al., 1981, Mason 1981, Kormendi et al., 1986). A more recent mining-specific application of tomography is an adaptation which can image stress concentrations ahead of the longwall face by using the longwall shearer itself as the seismic source (Westman et al., 1996).

Velocity tomography creates a velocity map from signal time-travel data. In this specific type of tomography, the raypath and the velocity variations along the raypath are unknown variables. By representing the medium as a grid, a forward velocity model is constructed to estimate the travel-time and the refraction path of each ray. Refraction paths are estimated by back-projection across the grid from each receiver to the source. By propagating a finite difference wavefront across the grid from a known source location, the travel-times can be estimated. Differences between the estimates and the measured travel times are used to iteratively update the velocity grid from each receiver to the source. The process is repeated a specific number of times, or until no noticeable changes occur.

Tomographic methods usually involve some sort of iterative algorithm to invert the traveltimes (Dines and Lytle, 1979; Peterson et al., 1985). A problem with these techniques is a tradeoff between resolution and stability of the solution. At some point, as one attempts to see smaller features, the inversion becomes unstable and velocity artifacts appear. Velocity artifacts are seen as fluctuations of values between adjacent points and the smearing of anomalous zones. Therefore, too few iterations will produce an image which lacks detail, and too many will overfit the data, and produce an image with an abundance of artifacts. A cross-validation method can determine the number of iterations needed (Peterson and Davey, 1991). Also, this method can give a way to determine several solutions to a non-unique problem, which can be then averaged to produce an image that may be an improvement over a single solution obtained using all the data at once.

To complete a tomographic survey, a seismic source must be selected. Several factors must be considered, including cooperation with mining operations, regularity of signal and amount of energy. Sources, including mining-induced seismic activity (Young, 1992), mining equipment, and manually input energy (Westman and Haramy, 1996) are all possible considerations. For surveys at a quarry, drilling activity can be used as the source. The longwall shearer has been used as the source within underground coal operations as it provides a relatively high amplitude signal.

The ability to place a large number of sensors deep in a borehole will make cross-hole and underground tomography surveys significantly more accurate and cost-effective. Currently, seismic tomography surveys can only be completed in one of three ways – by moving one or two sensors to multiple positions, by using hydrophones in a vertical, water-filled hole, or by not using boreholes for sensor locations. Performance of imaging surveys in the first method described is inaccurate and costly, because the same source locations must be used multiple times with the sensors moved to different locations, the sensor location may not be accurate, and the source characteristics may be altered at different initiation times. The second approach will be improved upon by allowing surveys to be conducted in horizontal holes or dry vertical holes. The accuracy of the results obtained using the third approach will be improved by making additional sensor locations available, thereby increasing the raypath coverage within the target area.

1.2 Project Team Members

The facilities and equipment required for the project include laboratory space for assembly and initial testing of the sensor array, field sites at surface and underground mines for field testing, data acquisition equipment, and data analysis equipment. The laboratory space and data analysis equipment will be provided by Virginia Tech. The field sites will be provided by CONSOL Energy and Salem Stone. The data acquisition equipment will be provided by NSA Geotechnical Services.

The prime applicant was the Department of Mining and Minerals Engineering of Virginia Polytechnic Institute and State University. Erik Westman, an Assistant Professor in the department, was the principal investigator. A graduate research assistant used the project as the basis for a Master of Science thesis.

1.2.1 Virginia Tech

Erik Westman, with the Mining and Minerals Engineering Department at Virginia Polytechnic Institute and State University (Virginia Tech), has been involved in the development of seismic tomography for mining applications for more than 10 years and has several publications on the subject. While at the Denver Research Center of the U.S. Bureau of Mines, Dr. Westman was the Principal Investigator of a project developing seismic tomography for imaging stress distributions in advance of the longwall face. The project had over \$500,000 annual funding and seven researchers. Dr. Westman also developed an MSHA-approved intrinsically safe seismic data acquisition system for use in underground coal mines.

Virginia Tech will oversee the project, provide laboratory space for assembly and testing, and order and assemble the components. Following laboratory testing, Virginia Tech will complete the data acquisition and analysis steps at the field sites, and evaluate the test results. This cost sharing will be derived from machinist costs and principal investigator time during the academic year.

1.2.2 CONSOL Inc.

CONSOL is one of the largest coal companies in the United States, with 2002 coal production of over 66 million tons. CONSOL currently has 20 mining complexes, located mainly east of the Mississippi River. At most of their underground mines they use high-extraction longwall mining technology, leading the U.S. industry in the usage of these systems.

CONSOL provided access to an underground coal mine for field testing of the geophone array. CONSOL personnel provided input on the array design and reviewed laboratory and field data.

1.2.3 NSA Geotechnical Services, Inc.

NSA Geotechnical Services, Inc., located in Golden, CO, is a full service engineering company, specializing in mining engineering, geotechnical engineering, mine and tunnel design, geological evaluation, management and operations evaluation. NSA has provided approximately 50 seismic surveys to the mining and civil engineering industries over the last 3 years. NSA is a leading-edge engineering company which is likely to use the technology for consulting work in ground imaging with seismic tomography.

NSA provided data acquisition equipment for the laboratory and field tests. This equipment included a 24-channel engineering seismograph and intrinsic safety barriers for use in an underground coal mine. NSA personnel reviewed component design. Finally, NSA provided access to their state-of-the-art seismic tomography software for generation of the tomograms after field data acquisition.

1.3 Energy, Environment, Economic Benefits

Improved imaging capabilities produce energy, environmental, and economic benefits by increasing exploration accuracy and reducing energy consumption by U.S. mining companies. Identification of ore boundaries prior to development allows proper planning, including mining method, equipment, and mine life. During mining, energy consumption is reduced by locating anomalous conditions before such conditions present hazards or result in loss of production. Ventilation energy is reduced because anomalous conditions ahead of mining can be located prior to mining, thus reducing the frequency and severity of rooffalls, which impede mine ventilation. Finally, because less waste material is mined, processing energy consumption will be reduced as less separation is required.

U.S. mining competitiveness is promoted by increased ability to image conditions ahead of mining. Project support from mining companies demonstrates the desire of the industry to have this technology developed. As the end user, the industry benefits by having this technology available for a variety of imaging surveys. Further, incorporation of industry partners in the project ensures that the technology developed is practical for use by the industry.

2. Experimental

The goal of this project was to develop a 24-channel array of seismic sensors capable of being mounted in a dry vertical or horizontal borehole. This array significantly increases the accuracy of tomographic imaging of conditions ahead of mining by allowing source and receiver locations to completely surround the area of interest. The approach used was to design, assemble, test, evaluate, and redesign.

2.1 Proposed Approach

2.1.1 Design

Three primary components are crucial to the design. Conventional borehole measuring devices are lowered into vertical holes, while attached to cables; a stiff placement method is required for horizontal boreholes. Second, a unit which houses the geophone and allows clamping to the borehole wall must be designed. Finally, the geophone must be electrically connected to the data acquisition system with appropriate cable and connectors. A two-inch diameter borehole is the minimum target size for all components to fit within. The clamping device must allow boreholes up to a maximum of six inches in diameter to be used.

2.1.1.1 Placement

While the sensors can be lowered into a vertical borehole, an efficient method must be developed to place the geophones in a horizontal borehole. The horizontal borehole may be of great length. In the case of a tomography survey in a longwall coal mine, for example, a horizontal borehole may have a length of 300 m or more. Additionally, if methane drainage boreholes are used the placement method must not have the ability to generate a spark which could potentially ignite the methane. The placement mechanism must be of small enough dimension that it will fit in the borehole without difficulty and must allow geophone orientation to be maintained without confusion.

Square aluminum tubing has been used previously in mining applications for placing instrumentation in boreholes. Aluminum tubing is preferred over steel as it cannot generate a spark when struck. Square tubing is advantageous as the geophone orientation can be easily maintained, where as the potential for confusion or rotation would be much higher with round tubing. Another advantage of using aluminum tubing, rather than a more customized design, is its ready availability. Standard tubing lengths of 1.8 meters will be used – longer lengths would require fewer connections, but would be unwieldy to manage in the underground environment.

2.1.1.2 Sensors, housing and clamping unit

Geophones and accelerometers have been used previously in mining-related seismic surveys. Geophones are preferred for this application because accelerometers must be powered, and therefore require additional cabling. The GeoSpace GS-20DH geophone has been used by the principal investigator previously in underground applications with excellent results. It is characterized by broadband response, small size, and high sensitivity. Fiber optic geophones were also considered however do not currently possess the necessary sensitivity. If satisfactory sensitivity is achieved by the time of component assembly, however, these sensors would be an excellent option for this application because no electronic signal would be generated in the methane-rich atmosphere and the transmitted signal would not be corrupted by electromagnetic interference.

A simple, yet durable housing for the geophone and borehole wall clamp is required. The unit must house up to three mutually orthogonal geophones to allow all three components (compressional, vertical shear, and horizontal shear) of a seismic wave to be measured if desired. The housing must also attach easily to the placement rods. These units will be manufactured by a Virginia Tech machinist.

Figure 1 shows a simplified preliminary design for the unit which houses the geophone and the borehole wall clamp. The unit has room for an additional two geophones, if desired for future studies. The

design is based on existing borehole tools. For horizontal boreholes, the unit attaches to the placement rod; for vertical boreholes, the unit attaches to a cable and is lowered into the hole.

2.1.1.3 Cabling and connectors

Cabling and connectors must be durable and provide a high-quality signal from the geophone to the recording system. A twisted pair of cables transmits the electronic signal from each individual geophone. Twisted pair cable is used because it reduces the crosstalk from adjacent cables. A foil

Figure 1. Simplified preliminary design of geophone housing and clamping unit

shielding surrounding each pair further reduces crosstalk, this shielding will be grounded to meet MSHA intrinsic safety requirements. The jacket surrounding the cable must be durable to withstand the abrasion of rubbing on the borehole walls. To minimize the diameter of the cable, all twisted pairs are contained within one jacket. Belden cable 9995, or a similar 24-pair cable, will be used for transmitting the signal from the geophones. Two cables will be assembled for use in different borehole lengths, the first with geophones at 3 m spacings and the second with 12 m spacings. Both of the cables have a 20 m length between the data acquisition connector and the closest geophone.

A separate three-conductor cable is required for the clamping mechanisms. After the geophones have all been emplaced in the borehole, all the clamping mechanisms will be activated concurrently.

A wire-rope retrieval cable will be employed to assist in geophone movement if the array becomes lodged within the hole. The retrieval cable will be linked to each housing.

Military-style connectors will be used as they are dust-resistant, durable, and readily available.

2.1.2 Assemble and Test

Following design steps and component acquisition, the arrays will be assembled and tested. Assembly occurs at the Plantation Road laboratory of the Department of Mining and Minerals Engineering, Virginia Tech. Primary assembly duties lie with a graduate student, overseen by the principal investigator.

Laboratory testing focuses on the clamping and placement components. A two-inch inside diameter section of PVC pipe will be used to simulate the borehole. Multiple trials of placement, clamping, and unclamping will be performed to ensure repeatability of these processes. This testing will again be conducted at Virginia Tech by a graduate student, overseen by the principal investigator.

Upon satisfactory completion of laboratory testing, the array will be submitted to MSHA for an Experimental Permit to allow it to be used in a methane drainage borehole of an underground coal mine. This process may take several months to a year, depending on the backlog at the MSHA Approvals and Certification Center. In the interim, field testing and data analysis will be completed at a surface mine.

Field testing will be conducted in dry, vertical holes at a limestone quarry and, following MSHA approval, in horizontal holes at an underground coal mine. Sensor performance, in terms of frequency response and sensitivity, will be evaluated. Testing at the surface mine will be conducted in vertical holes using the cable with 3 m geophone spacing. The testing will consist of placing the sensors in a dry, vertical borehole, then generating seismic waves at the ground surface with a sledge hammer at increasing distances from the borehole collar. A graduate student will conduct the entire test, with oversight by the principal investigator. Two weeks are allotted for the surface tests, including travel and mobilization/demobilization.

In the underground coal mine the geophone array will be placed in a methane drainage borehole following MSHA approval. The cable with 12 m spacing will be used because it is anticipated that the drainage hole will traverse nearly the entire panel, a distance of up to 300 m. A subsequent methane drainage borehole will be collared adjacent to the first hole, then drilled at a 45° angle away from the first hole. Recordings of the seismic signals generated by the drilling will be taken at two-minute intervals. Following completion of the angled hole, a second hole will be drilled parallel to the geophone hole but at a 50 m distance. The data recorded during the drilling of these holes will be analyzed for frequency content, attenuation/distance relationships, and correlation of seismic signal between adjacent geophones and sequential records. The results of these surveys will be used to generate tomograms. At the discretion of the mine, the holes may be located in an area with known anomalies. As with the surface test, the principal investigator will direct the testing process, while a graduate student staffs the entire test.

2.1.3 Evaluate, Redesign, Commercialize

Clamping repeatability, placement ease, and sensor response will be evaluated during laboratory and field testing. Tomograms, based on the relationship between amplitude attenuation and material type (Shea-Albin et al., 1991; Westman and Haramy, 1996), will be generated for the material between the source and receiver locations. These tomograms will be validated when the area is mined through.

Based on the results of the field tests the array design will be altered and finalized. It is anticipated that the final design will be eligible to be patented. Industry sponsors of the project have expressed significant interest in commercialization.

2.2 Approach Taken

The development of a seismic tomography technique or system which provides valuable information at a low cost, in terms of capital investment and in terms of interference to operations and understanding of the operational properties (Westman et al., 1996) will greatly benefit the industry. The system could result in energy savings by helping to prevent unnecessary excavation and to provide a chance to avoid or plan for problematic areas, such as a sandstone roll in a longwall or an area of drastically different stresses for example. Also, the system would become a life-saving system, as the prediction of stresses and changes in the country rock could be used to predict roof failures or even dangerous cracks along the edge of a highwall. High stresses in the vicinity of a longwall face can be troublesome, and if predicted and prevented serious trouble or shutdown can be avoided.

Three issues have been targeted within the currently-funded project that are felt to be worthy of research:

1. placement of the sensors in a long, horizontal borehole (i.e. methane drainage borehole within a longwall panel),
2. a simple, robust, MSHA-acceptable clamping unit, and
3. orientation of the geophones within the borehole

Each of these issues will be addressed individually.

2.2.1 Sensor Placement

Placing the geophone array into a horizontal borehole, up to 300 m long, is a challenge. The project proposal described emplacing the sensor array by pushing square aluminum tubing into the methane drainage borehole. After further consideration, it was judged that this technique would be problematic for the length of holes anticipated in the project. The force required to push the tubing and array would be difficult to produce.

The alternative developed is to push an anchor to the end of the drainage borehole using the drill and steel used in making the hole originally. The proposed anchor would have a pulley attached which will allow the array of sensors to be pulled into the hole after the steel has been withdrawn. A camming rock anchor was chosen for trial as the anchoring unit. A pulley will be attached to the anchor. Two steel cables will trail the anchor as it is emplaced, one cable for locking the mechanism and the other for attaching to the sensor array (Figure 2).

2.2.2 Clamping Unit

More time was spent on the design of the clamping unit during the first year of the project than on any other issue. The project proposal called for an electric motor within the geophone housing to press an arm out and lock against the borehole wall. However, because a specific objective of the project is to develop an array that will be used in methane drainage boreholes, for safety reasons it was decided to consider non-electric alternatives for clamping.

Figure 2. Proposed anchor system for emplacing array in horizontal borehole

The initial alternative design was to use an inflatable bladder that would act between the array housing and a hinged arm. A prototype was constructed and tested in vertical blastholes at a local quarry (Figure 3). The design was found to be clumsy to place and the air pressure bled out of the system, resulting in poor coupling with the borehole walls.

Figure 3. Testing of initial, bladder-based prototype at quarry.

A subsequent design considered was to use an air spring (Figure 4) to press directly against the borehole wall. An air spring of small enough size, however, was not found. While an air spring of the necessary size may be constructed by a machinist, the third alternative is potentially a superior design.

Figure 4. Examples of air springs.

The third design is very similar to the initial design described in the proposal, however instead of incorporating an electric motor, a pneumatic cylinder is used. The cylinder is normally extended, but when air pressure is applied the rod is retracted, pressing the arm out. Photos of the clamping mechanism are shown as Figures 5 and 6. The clamping mechanism will be attached inside a piece of PVC tube. The tube will also house the geophone and will have a slot through which the locking arm will extend. One air line will service all of the housings in a hole.

2.2.3 Geophone Orientation

The proposed design uses single geophones at each location, as opposed to three-component geophones. To obtain meaningful measurements, therefore, the geophones must all be oriented in the same direction. Prior research has accomplished this by suspending the geophone in oil, allowing it to rotate as needed to remain vertical. Other methods have used gimbal mounts to allow the geophone full rotation. Another

possibility is to mount the geophone within a module which is contained in the housing but coupled with a viscous material. The viscous material (e.g. honey or heavy grease) should transfer the stress waves with little attenuation, while still allowing the module to rotate. The module would be weighted so that it will be self-orienting.

2.2.4 System Components

The designed system is composed of the geophone, a pneumatic-cylinder-based locking mechanism, and data cable for transmitting the signal from the geophone to the seismograph. The GeoSpace GS 14 L9 geophone was selected for its small size, broadband response and its ability to operate in any position. The locking-arm mechanism is a Bimba 062-RP pneumatic cylinder which retracts under applied pressure. This cylinder is spring-loaded so that when the air pressure is released, the arm will collapse, allowing the array to be withdrawn from the borehole. The cable selected was Belden 8185. This cable was chosen because it had at least 24 twisted-pairs, each individually shielded. Individual shielding is required by MSHA so that in the event of a cable break the likelihood is reduced of the positively-charged wires joining and shorting against several negatively-charged wires, resulting in the generation of a spark. Consideration was also given to the overall diameter of the cable, as smaller diameter components are preferred. The Belden 8185 cable has 25 twisted pairs and an overall outside diameter of less than 21 mm. Specifications for the geophone, pneumatic cylinder, and data cable are included as Appendix A. Construction drawings for the array are shown in Appendix B.

Figure 6. Pneumatic cylinder-based clamping mechanism, close-up.

Figure 7. End view of geophone module.

Figure 8. Side view of geophone module.

3. Results and Discussion

3.1 Laboratory Testing

Project personnel conducted laboratory tests to determine whether resonant frequencies from the geophone housing and locking arm were being added to the true signal. The tests were conducted by comparing the signal from a light hammer tap on top of the block as recorded by two sensors. One sensor was located in the geophone array, emplaced in the borehole. The other sensor was embedded within the block, representing the true signal, unaffected by the borehole or the array.

A concrete test block was built to aid with this study. Figures 9 through 11 show the construction of the test block. In Figure 9 it can be seen that the bottom of the block was textured to reduce the reflected signal. Figure 10 shows the emplacement of the ‘control’ geophone within the block, adjacent to the borehole. Figure 11 shows the block after the concrete had been poured. Prior to testing, the concrete was allowed to cure for several days, and the white PVC pipe was removed from the ‘borehole.’

Figure 9. Bottom of block textured to reduce reflected signals.

Figure 10. Location of 'control' geophone within block, adjacent to borehole.

Figure 11. Completed test block. Block was allowed to cure and white PVC pipe was removed from 'borehole' prior to testing.

Results of the testing were encouraging and can be seen in Figures 12 and 13. Figure 12 shows a typical signal recorded in the time domain. The signal recorded by the geophone embedded in the block is shown in yellow while that recorded by the geophone in the hole is shown in maroon. Figure 13 shows the same signal in the frequency domain.

The results show that, while there is an expected reduction in signal amplitude, when comparing the geophone in the block to the geophone in the borehole array, there are no added resonant frequencies. Additionally, it can be seen that there is no reflected signal off the bottom of the block.

Figure 12. Comparison of signals recorded by geophone in borehole array and by geophone embedded in test block.

Figure 13. Comparison of frequencies recorded by geophone in borehole array and by geophone embedded in test block.

3.2 Field Testing at Surface Quarry

Project personnel conducted field tests to determine the ability of the array to record seismic signals in the field. The experiment was conducted by dropping an array of four geophones down a vertical borehole at a quarry located near the Virginia Tech campus. Blastholes were being drilled near the highwall. The hole depths were approximately 80 feet and the experimental design included locating sensors at 20, 40, 60, and 80 feet. One geophone was inadvertently disconnected, and unwittingly acted as a control sensor. Data were recorded as the drilling progressed in nearby holes (typically 30 to 50 feet distant), with the drill bit acting as the seismic source.

Results of tests at the quarry showed a clear signal being recorded. A comparison of frequency distributions, shown in Figures 12 and 13, shows that Channel 1, which was not plugged in, has no significant signal from the drill as compared to Channel 2 which shows energy between 40 and 100 Hz. The signal shown in Figure 13 is likely from electrical noise within the data acquisition system.

Figure 12. Recorded signal, in frequency domain, of control channel which was not connected. Energy shown is from electrical noise within the data acquisition system.

Figure 13. Recorded signal, in frequency domain, of channel which was connected. Energy shown between 40 and 100 Hz is from drilling in nearby blasthole.

3.3 Field Testing at Longwall Coal Mine

Testing of the geophone array was attempted at CONSOL Energy's Buchanan coal mine during the week of March 3, 2003. The other industry cooperator, NSA Engineering Inc., made a seismograph available to assist with the testing. The borehole was located in the barrier pillar portion of the 4th Right longwall panel. The borehole was drilled by the degasification drill crew for the sole purpose of testing the geophone array. The borehole was drilled approximately 6 weeks prior to the time of testing.

The US Department of Labor, Mine Safety and Health Administration (MSHA) approved the Experimental Permit to allow the geophone array to be tested at CONSOL Energy's Buchanan coal mine. The permit was based upon intrinsic safety barriers located between the geophones and seismograph, eliminating the potential for spark-generating voltage to travel from the seismograph, in fresh air, to the geophones, in return air. Details of the system are included as Appendix C.

The first day of the test (March 4) was spent spotting the array at the borehole collar location. During the second day, a 'crawler' unit was placed in the borehole to 'crawl' to the end of the 960-ft long borehole and anchor itself, allowing the array to be pulled in by a cable and pulley. Unfortunately, the crawler did not function as hoped, and was not able to get further than about 20 ft. The problem was due to a combination of factors including the borehole being larger in diameter than expected, the walls of the borehole being wetter (muddier) than expected, and the locking arms on the crawler not extending far enough. The evening of the second day, we purchased 300 ft of 0.75-in diameter PVC pipe and planned to push the array into the hole on the third day. On the third day of testing, the array was pushed into the hole with the PVC pipe. Unfortunately, the hole was blocked at a distance of 60 ft.

Consol Energy continues to express a high level of interest in the project and has agreed to drill another borehole for testing. This hole will be located in the barrier panel portion of the 5th Right longwall panel at the Buchanan mine.

4. Conclusions

The ability to accurately determine conditions in advance of the face can greatly improve the energy efficiency of a mining operation. Seismic tomography, an imaging method, can be used to achieve this ability and provides the best results when sensors completely surround the area of investigation. A borehole geophone array was developed to improve the ability of sensors to surround the area of interest. The simple, rugged array has been tested in the laboratory and the field and found to function satisfactorily.

The project conclusions can be summarized as:

1. a low-cost, rugged, MSHA-permissible borehole geophone array was developed,
2. laboratory tests showed that the locking mechanism did not significantly alter the quality of data recorded,

3. field tests showed successful deployment of the prototype array,
4. two components of the design have the potential to be patented,
5. NSA Geotechnical Services, Inc is willing to commercialize the array, and
6. The outcome of this research will be an enhanced ability to locate anomalies in advance of mining, thereby reducing the energy consumption during the mining process.

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Appendices

Appendix A – Specifications for Array Components

GeoSpace G-14-L9 Geophones

Source: www.geospacelp.com

GS-14

GS-14
Geophone

- G** Geo Space Corporation manufactures high quality, low cost geophones for a variety of industrial and military uses. These geophones have an unlimited shelf life and provide years of trouble-free service in applications where accurate motion sensing is required.
- G** The GS-14 is a miniature, self-generating velocity detector designed for rugged environments. It withstands extreme shock with no change in performance characteristics. The GS-14 has been used as a reliable component in sonobuoys, smart fuses and intrusion detection systems.
- G** The GS-14 is sensitive to motion along its longitudinal axis and is designed to operate in any position from vertical to horizontal. Both medium and high sensitivity models are available. With a natural frequency of 28 Hz, the GS-14 is an ideal motion sensor for frequencies in the acoustic spectrum.

GS-14 Specifications

	GS-14-L3	GS-14-L9
Functional		
Sensitivity ($\pm 15\%$)	290 mV/ips	600 mV/ips
Natural Frequency ($\pm 20\%$)	28 Hz	28 Hz
Coil Resistance ($\pm 5\%$)	570 ohms	1500 ohms
Coil Inductance	45 mh	90 mh
Damping Factor ($\pm 30\%$)	0.18	0.28
Damping Constant	172	738
Displacement Limit	0.09 in	0.09 in
Inertial Mass	0.076 oz	0.076 oz
Orientation Angle	$\pm 180^\circ$	$\pm 180^\circ$
Mechanical		
Height	0.68 in	0.74 in
Diameter	0.66 in	0.75 in
Weight	0.67 oz	0.95 oz
Environmental (All Models)		
Operating Temperature	-45° to 100°F	-45° to 100°F
Storage Temperature	-45° to 100°F	-45° to 100°F
Shock	5000 G	1000 G

Notes:

1. Reference temperature for functional parameters is 75°C
2. Orientation angle is referenced to vertical.
3. Damping factor is ratio of critical damping.
4. Sensitivity, natural frequency, coil resistance and damping factor are 100% tested. Consult the factory for special tests required to guarantee other functional parameters and shock limits.

Click [HERE](#) to load chart for Seismic Detector Response Curve Output VS. Frequency (GS-14-L3 &

GS-14-L9). (115 KBytes)

Specifications are subject to change without notice.

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Seismic Detector Response Curve Output vs. Frequency Charts

GS-14-L3

GS-14-L9

Please contact Geo Space for response curves for other geophone/hydrophone frequencies and resistances.

GS-14-L9

Please contact Geo Space for response curves for other geophone/hydrophone frequencies and resistances.

Specifications are subject to change without notice.

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Bimba 062-RP Pneumatic Cylinder

Source: www.bimba.com, accessed Oct.23, 2003.

7/8" Bore Air Cylinders

- Ground and Polished, High Strength Carbon Steel Piston Rod Standard – 303 Stainless Steel Rod Available as an Option – Bronze Rod Guide Bushing Standard
- Force Exerted Approximately 0.6 of Air Line Pressure
- Enclosed Spring Force: 3 lbs. Relaxed – 6 lbs. Compressed
- Cushion Quiet Bumpers Standard on All Models

OPTIONS:

NO CHARGE:

- **MAGNALUBE G (G)**
- **PORTS ROTATED (K)**
- **NO THREAD (NT)**
- **SIDE PORTED REAR HEAD (Q)**
Add .28" to nose mount overall length
- **PIVOT BUSHING (Y)**
.250" ID

EXTRA EXTENSION (EE)

- Single, reverse and double acting, add \$0.70 per inch of extension
- DXDE, add \$0.90 per inch of extension; extension added to each end

☐ Enter Stroke Length as 3rd Digit

OPTIONS continued...

MAGNET (prefix M) – Add \$8.40

- All models add .125" to overall length
- Stainless steel rod becomes standard with this option

LOW TEMPERATURE (N)

Temperature Range: -40° to 200°F

- Single acting add \$0.55
- Reverse acting add \$0.80
- Double acting add \$1.05
- DXDE add \$1.35

HIGH TEMPERATURE "U" CUP SEALS (V)

Temperature Range: 0° to 400°F (-18° to 205°C)

- Single acting add \$4.10
- Double acting add \$10.60
- DXDE add \$13.45
- Reverse acting add \$7.05

MOLYCOATED BODY (F)

- Add \$2.30 per inch of stroke

NON-LUBE SERVICE (E)

- Single acting add \$3.40
- Double acting add \$7.85
- DXDE add \$11.25

STAINLESS STEEL ROD (prefix SR)

- Add \$1.75
- Standard on DXP, DXDE, and M option

MODEL/PRICE	DESCRIPTION/WEIGHT (lbs.)	DIMENSIONS
<p>06□</p> <p>\$12.10 BASE PRICE Add \$2.10 per inch of stroke</p>	<p>Single Acting – Spring Return – Front Nose Mounting</p> <p>Standard Stroke Lengths: ½", 1", 1½", 2", 2½", 3", 4"</p> <p>Maximum Stroke – 6"</p> <p>Optional Stainless Steel Rod</p> <p>Optional Accessory: D-129 Mounting Bracket</p> <p>Base Weight: .17</p> <p>Adder Per Inch of Stroke: .09</p>

<p>06□-NR</p> <p>\$14.30 BASE PRICE Add \$2.10 per inch of stroke</p>	<p>Single Acting – Non-rotating Hexagon Rod – Spring Return – Front Nose Mounting</p> <p>Standard Stroke Lengths: ½", 1", 1½", 2", 2½", 3", 4"</p> <p>Maximum Stroke – 6"</p> <p>Optional Stainless Steel Rod</p> <p>Optional Accessory: D-129 Mounting Bracket</p> <p>Base Weight: .17</p> <p>Adder Per Inch of Stroke: .09</p>

<p>06□-NRP</p> <p>\$17.90 BASE PRICE Add \$2.10 per inch of stroke</p>	<p>Single Acting – Non-rotating Hexagon Rod – Pivot Type – Spring Return – Rear Pivot Mounting</p> <p>Standard Stroke Lengths: ½", 1", 1½", 2", 2½", 3", 4"</p> <p>Maximum Stroke – 6"</p> <p>Optional Stainless Steel Rod</p> <p>Optional Accessories: D-166-3 Piston Rod Clevis, D-167 Pivot Brackets</p> <p>Base Weight: .17</p> <p>Adder Per Inch of Stroke: .09</p>

7/8" Bore Air Cylinders

MODEL/PRICE	DESCRIPTION/WEIGHT (lbs.)	DIMENSIONS
06□-P \$15.40 BASE PRICE Add \$2.10 per inch of stroke	Single Acting – Pivot Type – Spring Return – Rear Pivot Mounting Standard Stroke Lengths: $\frac{1}{2}$ ", 1", 1½", 2", 2½", 3", 4" Maximum Stroke – 6" Optional Stainless Steel Rod Optional Accessories: D-166-3 Piston Rod Clevis D-167 Pivot Brackets Base Weight: .17 Adder Per Inch of Stroke: .09
06□-R \$17.85 BASE PRICE Add \$2.10 per inch of stroke	Reverse Single Acting – Pull Type – Rod Normally Extended – Front Nose Mounting Standard Stroke Lengths: $\frac{1}{2}$ ", 1", 1½", 2", 2½", 3", 4" Maximum Stroke – 6" Optional Stainless Steel Rod Optional Accessory: D-129 Mounting Bracket Base Weight: .20 Adder Per Inch of Stroke: .09
06□-RP \$21.15 BASE PRICE Add \$2.10 per inch of stroke	Reverse Single Acting – Pivot and Pull Type – Rod Normally Extended – Spring Return – Rear Pivot Mounting Standard Stroke Lengths: $\frac{1}{2}$ ", 1", 1½", 2", 2½", 3", 4" Maximum Stroke – 6" Optional Stainless Steel Rod Optional Accessories: D-166-3 Piston Rod Clevis D-167 Pivot Brackets Base Weight: .20 Adder Per Inch of Stroke: .09
06□-D \$16.05 BASE PRICE Add \$1.35 per inch of stroke	Double Acting – Air Return – Front Nose Mounting Standard Stroke Lengths: $\frac{1}{2}$ ", 1", 1½", 2", 2½", 3", 4", 5", 6" Maximum Stroke – 12" Optional Stainless Steel Rod Optional Accessory: D-129 Mounting Bracket Base Weight: .25 Adder Per Inch of Stroke: .03
06□-DXP \$21.20 BASE PRICE Add \$1.35 per inch of stroke	Double Acting – Double End or Rear Pivot Mounting – Air Return Standard Stroke Lengths: $\frac{1}{2}$ ", 1", 1½", 2", 2½", 3", 4", 5", 6", 7", 8", 9", 10", 11", 12" Maximum Stroke – 32" Stainless Steel Rod Standard Optional Accessories: D-166-3 Piston Rod Clevis D-129 Mounting Bracket D-13498-A Pivot Bracket Base Weight: .32 Adder Per Inch of Stroke: .03

Belden 8185 25-pair Data Cable

Source: www.belden.com, accessed Oct. 24, 2003

8185 Paired - Low Capacitance EIA RS-232/422

For more information please
call

1-800-Belden1

See Put-ups and Colors

**Color Code Chart : No. 3 for
Paired Cables (Belden
Standard).pdf**

Description:

24 AWG (7x32) Stranded tinned copper conductors. Individually Beldfoil® shielded twisted pairs with #24 AWG Stranded tinned copper drain wire. Datalene® insulated. Overall Beldfoil® Shield plus tinned copper braid shield (65% coverage), PVC jacket.

PHYSICAL CHARACTERISTICS:

CONDUCTOR:

Number of Pairs	25
Total Number of Conductors	50
AWG	24
Stranding	7x32
Conductor Material	TC - Tinned Copper

INSULATION:

Insulation Material Trade Name	Datalene®
Insulation Material	FPE - Foam Polyethylene

PAIR:

Pair Lay Length	1.5 in.
Pair Twists/ft.	8
Pair Shield Material Trade Name	Beldfoil®
Pair Shield Type	Tape
Pair Shield Material	Aluminum Foil-Polyester Tape
Pair Shield % Coverage	100 %

PAIR SHIELD DRAIN WIRE :

Pair Shield Drain Wire AWG	24
Pair Shield Drain Wire Conductor Material	TC - Tinned Copper

Pair Color Code Chart :

8185 Paired - Low Capacitance EIA RS-232/422

Number	Color	Number	Color
1	Black and Red	14	Green and White
2	Black and White	15	Green and Blue
3	Black and Green	16	Green and Yellow
4	Black and Blue	17	Green and Brown
5	Black and Yellow	18	Green and Orange
6	Black and Brown	19	White and Blue
7	Black and Orange	20	White and Yellow
8	Red and White	21	White and Brown
9	Red and Green	22	White and Orange
10	Red and Blue	23	Blue and Yellow
11	Red and Yellow	24	Blue and Brown
12	Red and Brown	25	Blue and Orange
13	Red and Orange		

OUTER SHIELD:

Outer Shield Trade Name	Beldfoil®
Outer Shield Type	Tape/Braid
Outer Shield Material :	

Layer Number	Material Trade Name	Type	Material	% Coverage (%)
1	Beldfoil®	Tape	Aluminum Foil-Polyester	100
2		Braid	Tinned Copper	65

OUTER JACKET:

Outer Jacket Material	PVC - Polyvinyl Chloride
-----------------------	--------------------------

OVERALL NOMINAL DIAMETER:

Overall Nominal Diameter	.822 in.
--------------------------	----------

MECHANICAL CHARACTERISTICS:

Operating Temperature Range	-40°C To +60°C
Bulk Cable Weight	414 lbs/1000 ft.
Max. Recommended Pulling Tension	487 lbs.
Min. Bend Radius (Install)	8.25 in.

APPLICABLE SPECIFICATIONS AND AGENCY COMPLIANCE:

APPLICABLE STANDARDS:

NEC/(UL) Specification	CM
CEC/C(UL) Specification	CM
AWM Specification	2493

FLAME TEST:

UL Flame Test	1581 Vertical Tray, VW-1
---------------	--------------------------

PLENUM/NON-PLENUM:

8185 Paired - Low Capacitance EIA RS-232/422

Plenum Number N

ELECTRICAL CHARACTERISTICS:

Nom. Characteristic Impedance	100 Ohms
Nom. Capacitance Conductor to Conductor @ 1 KHz	12.5 pF/ft
Nom. Cap. Cond. to Other Cond. & Shield @ 1 KHz	22 pF/ft
Nominal Velocity of Propagation	78 %
Nom. Conductor DC Resistance @ 20 Deg. C	24 Ohms/1000 ft
Ind. Pair Nominal Shield DC Resistance @ 20 Deg. C	18 Ohms/1000 ft
Nominal Outer Shield DC Resistance @ 20 Deg. C	2.4 Ohms/1000 ft
Max. Operating Voltage - UL	300 V RMS
Other Maximum Continuous Currents	1.0 Amps Per Conductor @ 25°C

PUT-UPS AND COLORS:

Item	Description	Put-Up (ft.)	Ship Weight (lbs.)	Jacket Color	Notes
8185 060100	25 FS PR#24 FHDPE SH PVC	100	34	CHROME	C
8185 0601000	25 FS PR#24 FHDPE SH PVC	1000	356	CHROME	C
8185 060500	25 FS PR#24 FHDPE SH PVC	500	160.5	CHROME	C

C = CRATE REEL PUT-UP.

Revision Number: 1 Revision Date: 11-06-2002

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Appendix B – Construction Drawings for Geophone Housing

Front View

Right Side View

Actuating Degas Hole Geophone Apparatus

Drawing #: Full
Assembly

Drawn By: W. Johnson
Checked By: E. Westman
Date: August 21,2003

Parts List

1 - Lid Assembly
2 - Body Assembly

Isometric View

Top View

Note:
Lid assembly is hinged by
2 nails through the end cap
on the body assembly.
Swing arm is attached by a
screw to the piston spacer.
Piston is retracted.

Department
of Mining and
Minerals
Engineering

Front View

Right Side View

**Actuating
Degas Hole
Geophone
Apparatus**

Drawing #: Body
Assembly

Drawn By: W. Johnson
Checked By: E. Westman
Date: August 21,2003

Parts List

1 - Body (PVC Pipe)
2 - End Caps (PVC Caps)
3 - Piston Assembly

Isometric View

Top View

Front View

Right Side View

Actuating Degas Hole Geophone Apparatus

Drawing #: Lid Assembly

Drawn By: W. Johnson
Checked By: E. Westman
Date: August 19,2003

Parts List

1 - Lid Body (PVC Pipe)
2 - Swing Arm Bracket
3 - Swing Arm
4 - Geophone

Isometric View

Top View

Front View

Right Side View

**Actuating
Degas Hole
Geophone
Apparatus**

*Drawing #: Piston
Assembly*

Drawn By: W. Johnson
Checked By: E. Westman
Date: August 21,2003

Parts List

1 -Air Hose Input/Output
2 -Piston swing arm spacer
3 -Air Cylinder

Isometric View

Top View

Note:
Spring return air cylinder
Mfg'd by Bimba Mfg. Co.
Part No. - 064-P
Piston drawn in retracted
position

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Minerals
Engineering

Technical drawing of a mechanical part. The drawing shows a rectangular block with a circular hole and a rectangular slot. The dimensions are as follows:

- Top horizontal dimension: 0.25"
- Bottom horizontal dimension: 0.5"
- Right vertical dimension: 0.4"
- Circle diameter: Ø0.14"

Technical drawing of a stepped cylindrical part. The drawing shows a side view with a central vertical axis. The part has a total height of 1" and a total width of 0.5". The top section has a height of 0.5" and a width of 0.1". The bottom section has a height of 0.5" and a width of 0.5". The top section is shaded with horizontal lines, and the bottom section is shaded with vertical lines. Dimension lines indicate the 0.1" width, 0.5" height, and 0.5" width. A 1" height dimension is also shown on the right side.

Technical drawing of a mechanical part, likely a cross-section of a shaft or a similar component. The drawing shows a central circular feature (hole or bore) with a diameter of 0.5". The overall width of the part is 0.4". The thickness of the part is 0.1". The drawing includes dimension lines and arrows indicating the measurements.

Drawn By: W. Johnson
Checked By: E. Westman
Date: August 20, 2003

Parts List

[illegible]Department
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Technical drawing of a vertical component with dimensions in inches. The component has a total height of 1.96 inches. It features a top circular feature with a diameter of Ø0.2 inches and a bottom circular feature with a diameter of Ø0.1 inches. Horizontal dimensions include 0.19 inches for the top and bottom widths, 0.38 inches for the distance from the left edge to the center of the top feature, and 0.15 inches for the distance from the right edge to the center of the bottom feature.

Figure 1 is a schematic diagram of the test specimen. It is a vertical cylinder with a central hole. The top and bottom sections of the cylinder are filled with a grid pattern, while the middle section is empty. A dimension line at the bottom indicates a diameter of 0.1 inches.

[illegible]

Parts List

[illegible]Department
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Front View

Right Side View

**Actuating
Degas Hole
Geophone
Apparatus**

Drawing #: Swing Arm
Bracket

Drawn By: W. Johnson
Checked By: E. Westman
Date: August 20,2003

Parts List

Swing Arm Bracket

Isometric View

Top View

Technical drawing of a vertical rectangular plate with a central circular hole. The plate has a total height of 1.29 inches and a width of 0.28 inches. The hole has a diameter of 0.29 inches. The distance from the bottom edge of the plate to the bottom edge of the hole is 0.5 inches.

Side View

0.14"

0.4"

0.4"

0.06"

Air Hose Input/Output
<p>1. Connect the air hose to the air inlet on the back of the unit.</p> <p>2. Turn the air valve on the back of the unit to the "ON" position.</p> <p>3. The air hose will now supply air to the unit.</p>

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Engineering

Front View

Right Side View

**Actuating
Degas Hole
Geophone
Apparatus**

Drawing #: End Cap

Drawn By: W. Johnson
Checked By: E. Westman
Date: August 21,2003

Parts List

End Cap

Note:
The end of the Cap has a
0.8" Hole for wiring the
geophone

Isometric View

Top View

Appendix C – Experimental Permit Drawing as submitted to MSHA

Notes:

1. Drain wire from foil shield is grounded to barrier
2. Both the steel enclosure case and the barriers are grounded to mine ground by tying leads together at isolation transformer ground; one ground lead to steel barrier enclosure and other to mounting strip for Stahl barriers.