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From: Stephen Kenyon [skenyon@cecinet.com]
Sent: Wednesday, March 22, 2006 5:12 PM
To: zzMSHA-Standards - Comments to Fed Reg Group
Subject: MSHA RIN 1219-AB44

In response to MSHA Request for Information RIN 1219-AB44 Creative Engineering Concepts, Inc. offers the attached white paper describing a Rapid Deployment Seismic Location System. We have been researching this for the last few years in the context of a mobile system and have developed some of the algorithms. However, it has become clear that a system is necessary that is more portable and can be deployed to a mine emergency site in a matter of hours to begin search and rescue operations.

The Rapid Deployment Seismic Location System is not currently developed. The development will require approximately 18 months to complete. A version of the system for permanent installation at mines is feasible and would provide continuous monitoring of seismic signals. In this configuration seismic search and rescue operations could begin immediately in the event of an accident.

The attached paper describes the system from a functional point of view. Therefore, we have not included supporting mathematics and algorithm descriptions. These can be provided in subsequent discussions. Please contact the undersigned for further information.

Sincerely,

Stephen Kenyon, President
Creative Engineering Concepts, Inc.

703-359-5959

AB44-COMM-56

CECI Creative Engineering Concepts, Inc.

Rapid Deployment Automated Seismic Location System

Response to

Mining Safety Health Administration

RIN 1219-AB44

Creative Engineering Concepts, Inc. 3545 Chain Bridge Road, Suite 6, Fairfax, VA 22030 (703)359-5959

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RAPID DEPLOYMENT AUTOMATED SEISMIC LOCATION SYSTEM

1 INTRODUCTION

The Mine Safety and Health Administration has been using an seismic location system for search and rescue for a number of years. While successful, the system is constructed using dated technology. In some cases it is not possible to obtain spare parts for some of the equipment since their manufacturers have discontinued the parts. The present SLS is housed in a large van, making rapid deployment to remote sites difficult or impossible. The evolution of signal processing electronics and the greatly increased speed of computers allow the development of a new generation system with vastly greater capabilities. Further, development of new signal processing algorithms has expanded as the technology to support them has made their application practical. In response to RIN 1219-AB44, CECI presents a portable system architecture for rapid deployment and a number of proprietary techniques for accomplishing seismic search and location in a more efficient and timely manner.

2 SEISMIC LOCATION METHODS

An array of geophones and associated electronics is placed over the search area with a spacing that is approximately equal to the depth of the expected vibration source from signaling miners. When miners pound on the roof or walls of a mine these signals are received by the different geophones at different times. If the speed of sound through rock and soil is known (or measured), the time delay differences can be translated into measurements of the distance differences from the miners or other vibration sources to each of the geophones. The positions of the geophones are accurately known by surveying their location when they are installed. While the distance from the signaling miners to each sensor is not known, a set of equations can be solved using the distance differences from the miners to each geophone sensor to find these distances. Once this is complete, a geometric model can be used to determine the location of the miners based on the intersection of lines from the miners to each geophone. It should also be noted that newly proposed signal analysis algorithms can be used to automate the geologic survey, solving for the speed of sound from a test signal or explosive charge from a known location.

In practice it can be difficult to obtain the needed measurements. Miners are instructed to pound on internal mine surfaces ten times with about one second between blows. This is repeated approximately every fifteen minutes. Therefore, the miners are only signaling about one percent of the time, and rescue personnel are not aware of when this signaling will occur. In addition to listening for relatively weak seismic signals, we find that the search must be conducted in a noisy environment where pumps, fans, drills, and other equipment are operating. However, the seismic array and sophisticated computer algorithms can be used to cancel these noise sources by projecting a seismic "hole" in the directions of the noise and suppressing frequencies where continuous noise from these sources is found. What remains is an enhanced set of seismic signals that can be more readily searched for signaling miners.

Since the rescuers and the search personnel don't know the location of the miners or the time that they will signal, all of the seismic signals are digitized and stored on a computer hard drive. This allows computer algorithms to search past time for the miner's signals. Further, since we know that the ten blows in a signal from the miners will have fairly uniform timing, we can apply a specialized computer filter that listens for and enhances similar sounding impulsive signals that occur with approximately one second spacing. Once a signal has been found by any of the sensors it is further enhanced to remove echoes and reverberation. At this point the searchers know the point in time where the signaling occurred and can concentrate on finding these signals on the other sensors. Computer algorithms then enhance the remaining sensor signals and measure the time differences from the miners' signals to each of the sensors.

CECI proposes two signal processing algorithms for obtaining these time differences. The first algorithm uses cross-correlation functions to find the time differences where sensor signals are most similar. The second method estimates what the time delay differences would be if the source were coming from a particular underground region. The seismic array can be focused on multitude of these regions. The region or volume searched that results in the strongest signal indicates the most likely source of the signaling.

Once the time delay differences have been found by either method, the previous and subsequent data can be rapidly searched to identify other signals that originate from the same location. These additional measurements, if present, are used to refine the accuracy of the position solution.

3 RAPID DEPLOY SEISMIC LOCATION SYSTEM OVERVIEW

The new Seismic Location System (SLS) detects and locates underground vibration from trapped miners and is designed for rapid deployment and setup. The system includes a set of geophone subarray pods, each containing a high-resolution digitizer, digital signal processor, GPS receiver, and WiMax wireless network transceiver. A small base station computer receives the seismic signals from all of the geophone pods in the network and stores these signals in a database for signal processing and micro-seismic search. This database is made available to a set of laptop computers over a local area network. The laptop computers are equipped with powerful signal processing and analysis software that allow them to:

1. cancel seismic noise and vibration interference,
2. detect vibration signals from trapped miners,
3. enhance the seismic signals by removing distortion and reverberation and
4. search and determine the location of the miners.

Generally speaking the algorithms must search in time to determine when the miners are signaling, and then search in space to determine the location of those signals. The search can proceed faster if more laptop computers work on the data in parallel. Further, in many cases it may be possible to transmit the seismic signal data using the Internet where it can be searched by many people using many computers at remote locations.

The new system will be designed to be packed in suitcases or small shipping crates that can be quickly transferred to the field using a car, SUV, small plane or helicopter. The SLS base station can be set up in an on-site building, a tent, or a locally leased van. To support rapid deployment, it is necessary to design the geophone pods to consume a minimum of power. This will reduce the size of the necessary batteries and extend the time between battery replacements. As a goal we plan for operation over an entire search mission without battery replacement. Similarly, reduction of the power consumption of the base station equipment is equally important. While the use of batteries and an inverter will support base station operation for short periods of time, commercial power or a small generator will be required for continuous operation. Power may also be derived from a vehicle if necessary.

All of the sensor pods and the base station communicate using a wireless network. Synchronization of clocks and precise location of the subarray pods will be accomplished using GPS satellite receivers in each sensor pod and at the base station. Subarray pods that cannot receive GPS due to terrain may require manual survey to establish their location. However, this manual survey can be done faster when at least some of the sensor subarray pods receive GPS. Bearing angles from these locations to pods that are not receiving GPS can be obtained using a transit. The computer system can then solve for the location of pods that were not able to self-survey using GPS. Communication within the wireless network is bi-directional and will employ the internet TCP/IP protocol, allowing for automatic relaying of the seismic data from distant subarray pods that may be out of range of the base station. In addition, Network Time Protocol will be used as a backup to synchronize subarray pods that cannot receive GPS timing signals.

Processing algorithms with improved sensitivity, noise rejection and automated time difference estimation are features that will reduce the time to perform seismic location. This system local network capability can also be coupled with a remote network capability supporting the analysis of the collected seismic signals from a distant location such as a larger facility located at MSHA.

Since time is critical in the event of an accident, it is also possible to permanently install a version of the system at a mine location and perform a "mine calibration". Once the geophones have been installed and the system is activated, the system is calibrated by pounding on the walls or roof of the mine in various locations, much as a miner would under emergency conditions. The system then focuses the seismic array on these locations and associates the actual locations with the seismic measurements. This makes subsequent searches faster and more accurate. The equipment and installation costs for such a system will also be reduced. Site surveys should be updated as the mine characteristics change over time.

Since the new system will operate in the digital domain, it is relatively easy to introduce specific algorithm modifications that lend it to a broader range of applications. These include locating persons in collapsed buildings and structures caused by terrorist attacks or natural disasters. This processing can also be extended to locating persons in tunnels or persons digging tunnels.

4 SYSTEM ARCHITECTURE AND IMPLEMENTATION

This proposed new system, as depicted in Figure 1, can be viewed as comprised of two major subsystems. The first is related to the total process of acquiring and recording seismic data from geophones in the field. The second is related to the analysis of this data to enable the detection and localization of trapped personnel. The two subsystems are connected through a wireless network such as WiMax with over five-mile range.

The proposed new data acquisition subsystem consists of state of the art sensors, amplifiers and filters, transmitters and receivers, A/D's, computer related components, and system software components. This will allow one to reliably acquire broadband seismic data with very high signal to noise quality. As outlined herein, the new system will be capable of acquiring data from at least 16 geophone sub-arrays (pods) within a broader 10-400 Hz band and 24 bit amplitude resolution along with the additional GPS based self-survey capability of the geophone sensor subsystems.

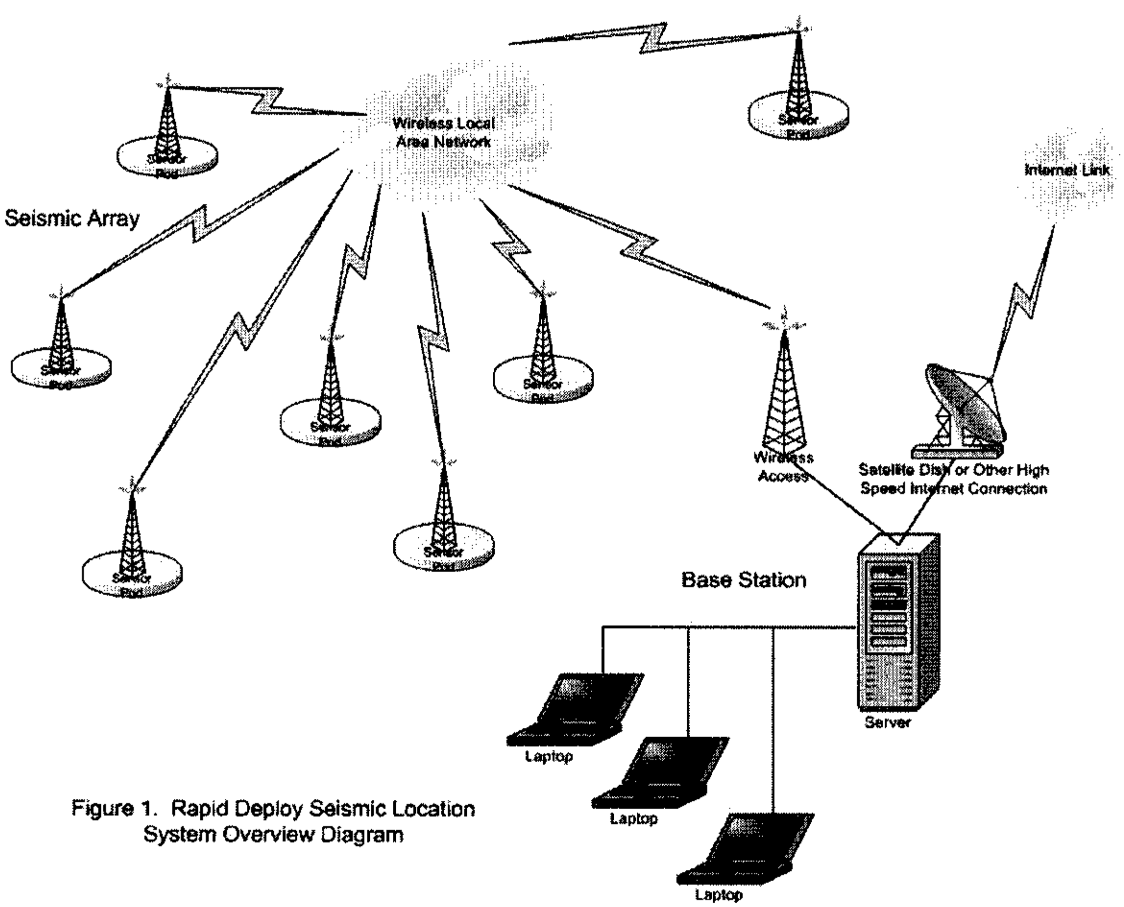

Figure 1. Rapid Deploy Seismic Location System Overview Diagram

5 TECHNICAL DISCUSSION

Creative Engineering Concepts, Inc. has designed a system architecture that takes advantage of technology developments and adds capabilities and options that do not currently exist in the present seismic location system. The most notable additions are the ability to use any of several techniques to remove noise and interference from the geophone signal before detection and localization processing. Also important is the small size of the system that allows for a rapid transport and deployment.

The new system employs high dynamic range precision front-end electronics to acquire and maintain signal quality from the geophones all the way to final results. Key to this is converting to digital format as early as possible in the signal processing chain. This prevents the degradation that can occur in analog signal processes such as filtering and signal transmission.

Taking full advantage of technological improvements will lead to a new system that is faster, more accurate, and capable of operating at longer range and greater depth. Moreover, the new seismic location system will be smaller, lighter, and will consume less power than the present system.

The new system is self-surveying using differential GPS to automatically determine geophone subarray placement to within approximately one meter. GPS also supports precise time synchronization of all elements in the sensor array.

Finally, a number of novel algorithms will be applied to improve the quality of detection and localization, including automated methods for suppressing the effects of refraction and reverberation. This will result in faster and more accurate location of trapped miners and others who are in similar distress. It is our hope and primary objective that this will ultimately save lives.

6 GEOPHONE SUB-ARRAY CONFIGURATION

One of the objectives of the hardware design is to increase the sensitivity and dynamic range of the remote sensors while rejecting as much noise and interference as possible at the front-end of the system. A digital data link coupled with a high resolution analog to digital converter will allow the delivery of precision signals to the processing base station. Figure 2 illustrates the major components of these remote subsystems.

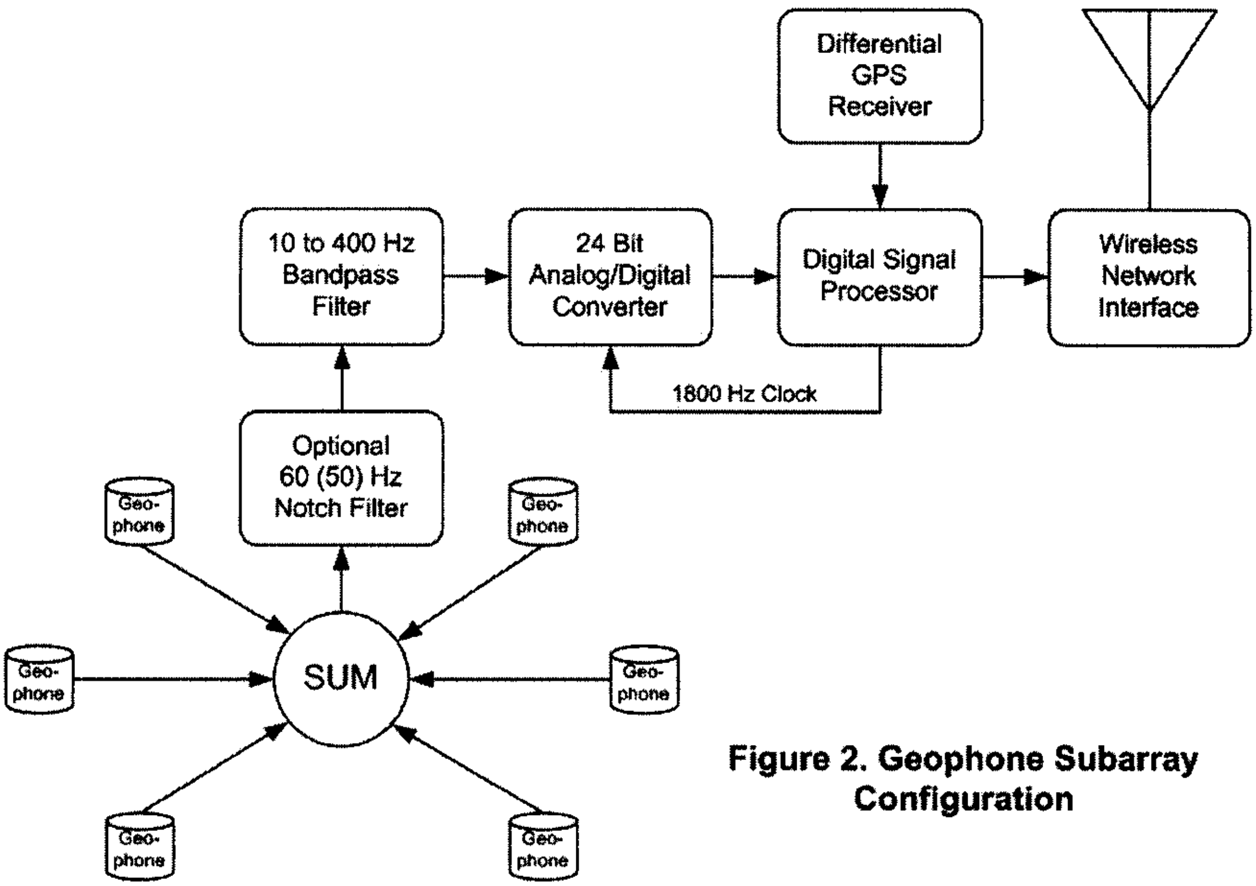

Figure 2. Geophone Subarray Configuration

As is commonly done, a set of geophones arranged in a circle is summed to increase the reliability of the geophone coupling to earth and reduce the effects of wind induced vibration, surface waves, and thermal noise. An optional power line frequency notch filter may also be used to remove the fundamental at 50 or 60 Hz. This filter may not be required because the system will have enough dynamic range to carry both the signal and power interference that can be more accurately removed digitally.

Prior to digitizing the geophone signal, it is bandlimited to a range of 10 to 400 Hz. This extends the frequency range one octave below and one octave above the current MSHA system. The output of this filter is connected to a precision 24-bit analog to digital converter. Although a 24-bit converter is theoretically capable of about 144 dB of dynamic range, practical monolithic A/D converters provide about 120 dB.

A floating point digital signal processor (DSP) serves several purposes in preparing the geophone signal for transmission to the processing base station. First, the DSP generates an 1800 Hz sample clock for the A/D converter. Using a relatively high sample rate relative to the signal bandwidth has several advantages. The fundamental and second and third harmonics of 50 Hz or 60 Hz power line interference are integrally related to 1800 Hz. This allows precise removal of these components without damaging underlying signal structure by using synchronous digital filters. The high sample rate also provides better time resolution and potentially more accurate source location. The DSP is also used to format the digitized geophone signal and to construct telemetry data packets for digital transmission.

Included in the geophone sub-array instrumentation package is a differential GPS receiver. Differential corrections are obtained from the satellite broadcast Wide Area Augmentation System. This provides the capability to locate the sensors to within about three meters absolute or less than one meter relative to the other sub-arrays. Additionally, the GPS receiver provides a time reference signal that is accurate to within one microsecond. The 1800 Hz A/D converter sample clock is synchronized to this reference, resulting in all geophone instrumentation packages being precisely time synchronized. The GPS derived position and time and 1800 sensor samples (one second) are formatted into telemetry data packets for transmission over the wireless network using a commercial off-the-shelf WiMax wireless network interface.

7 BASE STATION CONFIGURATION

Geophone sub-arrays are placed in a number of locations surrounding the area where miners are believed to be trapped in a geometric configuration that enhances the location solution. Geophone signals from each remote site are forwarded via the local wireless WiMax network to a central location for processing, typically a mobile van or local building. The recommended hardware configuration is illustrated in figure 3 below.

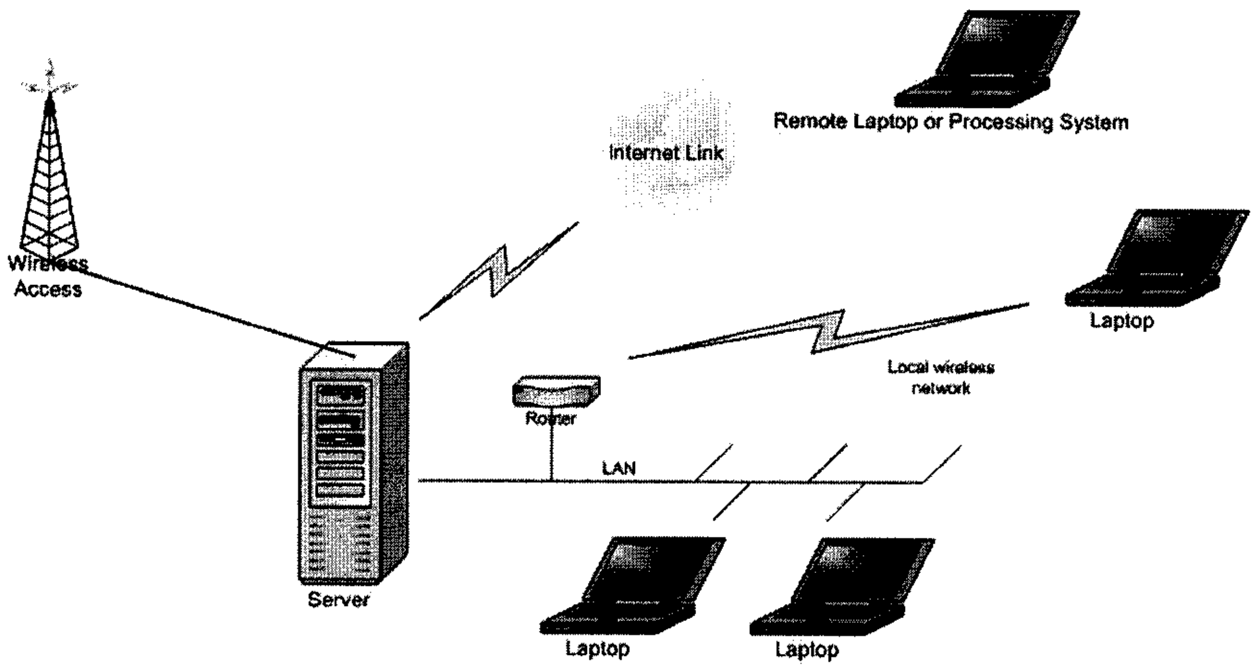

Figure 3. Rapid Deploy Seismic Location Base Station Overview

WiMAX is a wireless network standard (802.16) designed to support high speed data transmission and internet connectivity over significantly greater distances than the WiFi (802.11) standard commonly used for wireless local area networks. The intent of this standard is to provide coverage over a metropolitan area or in rural areas that lack the necessary wired infrastructure for other access methods. Terminal equipment is small and relatively easy to connect. In our application, the base station will serve as the central access point, receiving seismic data packets from all of the seismic sensors. However, the TCP/IP protocol allows the remote sensors to forward or relay data from nodes that may be out of range or obstructed from communicating directly to the base station.

The data acquisition system is a high performance industrial grade (ruggedized) computer/server system selected for high computing speed and large disk capacity. Collected data received from the geophone subarrays will be reformatted into composite files containing data from all sensors and written to the disk. Assuming that a maximum of sixteen sensor channels are active, this results in a storage requirement of about 115 kbytes/sec or 414 Mbytes/hour. Typical large capacity disk drives are available at over 160 Gbytes, resulting in continuous storage for over 16 days. The system will also include a portable hard disk or recordable DVD drive for data archives.

Additional computers or laptops will be connected to the same network to perform the signal analysis of the data. The signal analysis PC's/laptops will access stored data files on the data acquisition system over the local area network. Note that network access to these files will be on a read-only basis to assure that they are not inadvertently deleted or damaged.

7.1 Process Control and Display

System startup may be performed from any system on the local area network. User preferences and password accounts will be defined to allow specific user access. A system control screen with status and control displays will be available showing scanning array status, location information, voltages, sensors/pod status, dropped data indicator, time, and storage statistics. Software tools will be available on each laptop that will allow the user to graphically display a spatial map of the area of interest with an overlay of the sensor placement. Noise sources will be identified as "hot spots" on the display with corresponding location information. Correlation functions and spectrum graphics will show suspect regions relating to the respective sensor pods.

8 SIGNAL PROCESSING OPERATIONS

The proposed signal processing components can be considered as grouped into three different classes depending on their function. The first class consists of those software components which are basically simply adaptations of standard signal processing and analysis algorithms. However, these analyses can be accomplished much faster in the environment of the proposed system. The second class of signal processing modules consists of new or improved algorithms which support the current analysis methods, but make them more effective. For example, the use of modern deconvolution filters will more accurately and easily measure time delays of the target signal of interest. Finally, the third class of software modules consists of proprietary specially designed multichannel adaptive filters which more effectively isolate and analyze the target signal. For example, an adaptive filter will automatically remove interfering seismic noise from a nearby pump or generator at the site.

8.1 Algorithm Processing Discussion

The following discussion gives a brief overview of the signal processing operations to be used for locating trapped miners or searching for people using underground acoustic methods. Some of the operations are new; others are improvements over procedures previously or presently used. Figure 4 below describes these operations.

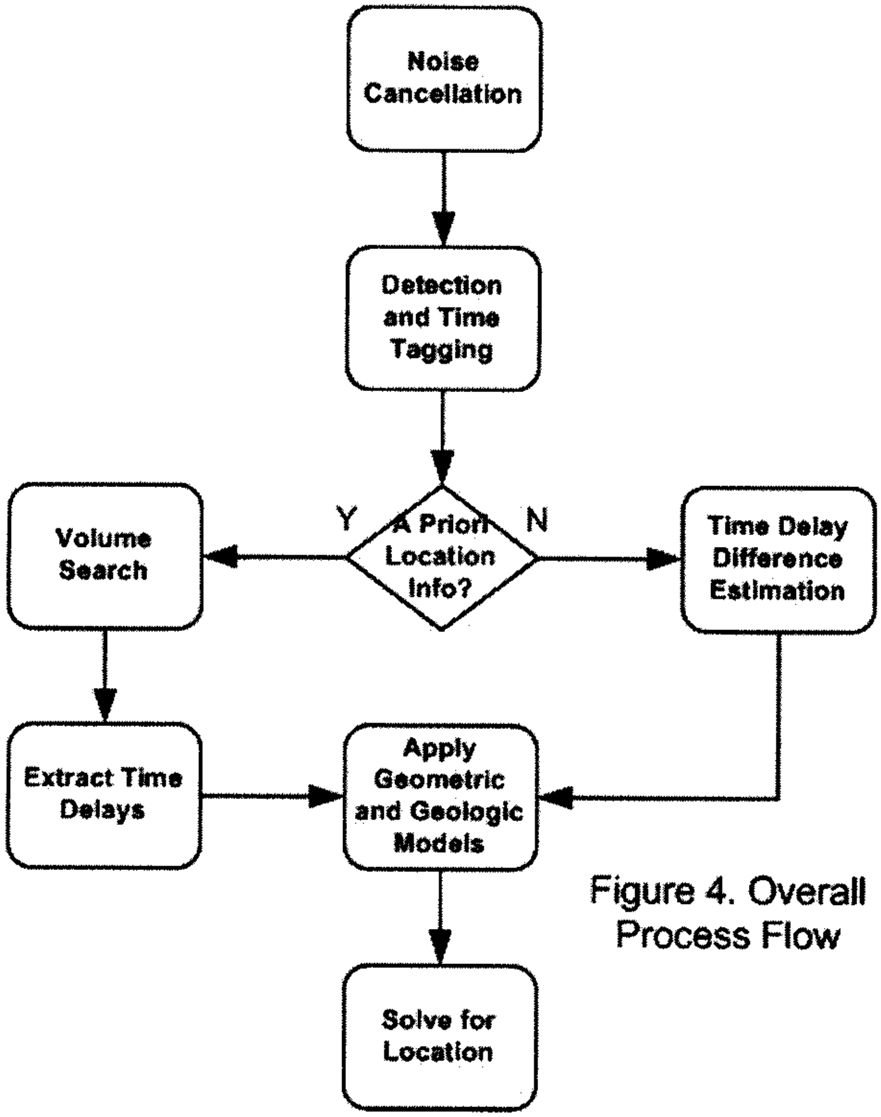

Figure 4. Overall Process Flow

8.1.1 Noise Cancellation

Noise cancellation is an important new step that can significantly improve the ability to locate the miners' signals. One of several methods will be applied to this problem depending on the noise source. The first involves using the array to project nulls in the direction of noise sources. Another uses sensors placed on or near machinery that produces noise and interference. It is then possible to determine the component of the noise signals received by each geophone and then coherently remove it from each geophone.

Several multi-channel digital signal processing techniques are available which reduce or cancel interfering noise in our seismic signals. The resulting signals, with an improved signal-to-noise ratio, will more readily yield higher quality data for detecting and locating targets of interest.

The program will then proceed to draw a map of the positions of all seismic sources, noise sources and target source, within the volume of interest. If the target source is expected to consist of a series of taps then this condition can be added to the mapping so as to exclude seismic sources that do not meet this condition. We note that this automated method does not rely on estimates of time delays as an intermediate step and because of this property is extremely simple to use.

Also, if any of the sources are not stationary in the sense of either spatially moving or in the sense of varying in intensity the software adaptively corrects for these variations. The result is that the source map is not fixed or constant in time, but changes over time. If such changes are not allowed for the true target then these sources can also be eliminated from the final map.

8.1.2 Detection and Time Tagging

We view the overall problem as a search in both time and space. It is important to identify the times when miners are signaling so that their signals can be isolated for use in location. Presently, detection is performed manually by examining the time-series waveforms from each of the sensors. Individual transients from a particular channel are manually time aligned and then stacked to improve the signal to noise ratio. The new system will automate these procedures, using autocorrelation to align individual transients and deconvolution to identify the underlying impulse sequence from the miners' signaling.

Presently the stacked transients from the various sensors are manually measured to determine the time delay differences needed for localization. We have identified two new complementary approaches to performing the spatial search based on automated digital signal processing and coherent array processing.

8.1.2.1 Volume Search and Time Extraction

The geophone array can be used to search specific underground regions by focusing the array on volumes of interest. This is done by inserting time delays in the signal path from each geophone that will cause signals from a certain location to add coherently. Significant energy from a location represents a "hot spot" that may be due to signaling miners. Since the sensor data have been stored in disk files, they can be processed iteratively to form a three dimensional map of underground seismic/acoustic energy. Suspected locations can be further searched by perturbing the time delays slightly to maximize the recovered signal power.

When the volume search indicates one or more hot spots, we can simply extract the time delay sets that maximized the signal power. Each time delay set represents a steering vector to the suspected location. Of course we must still convert from time delays to a physical location.

8.1.2.2 Time Delay Difference Estimation

A second approach is to directly solve for the time delay differences using cross-correlation functions. In this approach we search within the time window where signals have been found during the detection process. Correlation functions are computed for all sensor pairs. Correlation peaks that occur within plausible time delay differences are matched using a procedure that demands that the sum of time delay differences around any closed loop be near zero. This constraint is used to resolve ambiguities when multiple correlation peaks appear between sensor pairs.

8.1.3 Apply Velocity and Geologic Models

Once time delay differences have been found between signal observations at the various sensors, we need to use the array geometry and a geologic model of propagation velocities to convert from a time delay solution to a spatial solution. We expect that the locations of the sensors in the array will be well known. However, propagation velocities in a stratified geological model may be significantly misestimated. We believe that given knowledge such as mine depth and comparing solutions based on subsets of the array, it is possible to improve our initial model and produce more consistent measurements.

In order to localize the target source of interest it is necessary to make certain assumptions regarding the propagation velocity of seismic waves in the regions of interest.

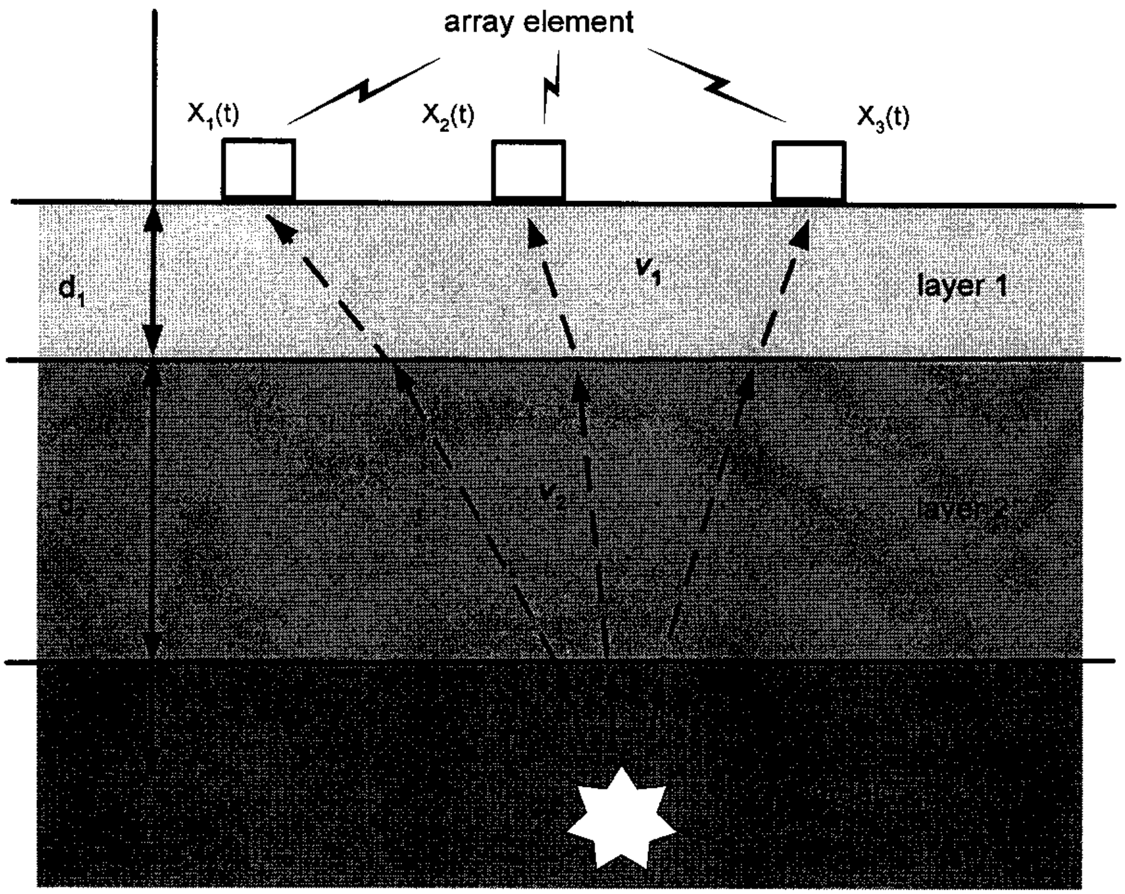

Figure 5. Velocity Profile

Another approach to the use of this velocity model for detection and localization may be by directly incorporating the model in the volume searching method. In this approach we assume a volume cell of interest and use the velocity model to calculate all the time delays of the sensor locations. These delays are inserted into the beam forming procedure that will directly yield signal amplitude estimates for that cell. In this approach the detection and localization are folded in directly with the earth model.

8.1.4 Power

The power task involves the design and development of power supplies for both the geophone sensor subsystems and the base station equipment. Of particular concern is the battery life of the remote sensors. We believe that this equipment should be capable of operating for about a week without changing batteries. Once the power consumption has been determined we will specify the appropriate battery capacity and type. We will also select appropriate battery chargers that are capable of charging a complete set of batteries in a reasonable amount of time.

The base station may not always have access to commercial power. Therefore the power system will include a power inverter/charger to allow the base station to operate from 120 Volt AC lines or from 12 Volt DC power from vehicle batteries. In addition, we will select a portable supplemental generator to support continuous operation while charging the batteries. This provides three ways of powering the base station equipment.

9 CORPORATE INFORMATION

Creative Engineering Concepts, Inc. was founded in 1990 as a research and development company in the fields of signal processing and pattern recognition. CECI also maintains a complete electronic development capability and laboratory for prototype development, manufacturing, and system integration.

Personnel at CECI have developed digital signal process methods and acquisition systems in such diverse fields as:

- medical electronics (EKG, EEG, MEG, ultrasonics),
- geophysical exploration (seismic, magneto telluric induced polarization),
- speech and audio analysis and synthesis,
- machine vibration (electrical, torsional, radar arrays and active noise cancellation)

Many of the signal processing techniques and concepts described in this effort have been proven in other applications and developments. Some examples are discussed as follows:

Detection of Concealed Persons via Geophone Signals

Research studies for the U.S. Department of Justice showed that the small seismic signals generated by a person hiding in a large truck could be detected by (1) a geophone placed in the truck exterior plus (2) advanced signal processing for isolating the heartbeat signal from other background noise. Based on these studies, a system called "MicroSearch" (reference 10) has been developed and is being used to search vehicles at correctional facilities, border inspection points and entries to military facilities.

Wiener Filtering for Speech Noise Masking

Research studies for the FBI has proven that it is possible to build Wiener filters for removing background interfering car radio signals from human speech recordings. An electrical signal representative of the radio interference was used to construct Wiener filters for automobile acoustics so that the speech signals from the inhabitants of the automobile were basically noise free.

Seismic Geothermal Mapping

Studies of the seismic signals generated by active geothermal fields in California were conducted. Arrays of geophones were used to collect seismic signals covering a large area of the earth's surface. Advanced signal processing and cross-correlations techniques allowed one to build 3-D maps indicating the intensity of the geothermal sources in the region.

Signal Identification

CECI has also developed coherent noise cancellation algorithms and systems that automatically identify broadcast music. Our expertise spans the fields of analysis and algorithm development to implementation of hardware and software systems for signal processing.

10 SUMMARY

Creative Engineering Concepts, Inc. proposes the development of a Rapid Deployment Seismic Location System. The system components are designed to be easily transported in a car, SUV, or as airline baggage. The geophone subarray pods are transportable by standard backpacks. The search and analysis computers are implemented as high performance laptops that are carried in standard laptop computer cases. The base station components consist of a network server that stores data from the geophone sensor array and distributes it to the search computers. The base station contains a wireless network access point for communication with the sensor pods, and a portable power system. All of these components plus the cabling and network distribution equipment can be packed in several portable shipping cases.

Once the system has been deployed on site, the GPS based self-survey will automatically locate all geophone sensor pods that are able to receive the satellite signals. Others will employ a computer assisted survey technique using measured bearing angles from GPS located sensor pods. After locating all sensor pods in the array, surface charges and signal processing algorithms on the base station computer will be used to measure the velocity of seismic waves at the site. This information is needed to convert time delays to distances in the search.

The search for trapped miners is based on the detection and location of seismic signals from miners pounding on the walls or ceiling of the mine. The system continuously records signals from an array of seismic sensors placed at known locations above the area where miners are believed to be trapped. Noise from machinery is first removed using coherent signal processing algorithms that operate from a vibration reference channel or by projecting "nulls" in the direction of noise sources. The recorded sensor data are then scanned to detect the times that miners are signaling. Signal processing algorithms are then applied to determine the arrival time differences from the miners to each of the sensors. This allows the system to focus the sensor array on the source and to solve for the location of the trapped miners.

The use of multiple networked portable computers provides the capability for simultaneous search by several operators. In addition, a second network access port supports connecting the server to the internet using a hard-wired connection or a satellite data link. The intensity of the search can be increased by making the recorded sensor data on the server available to many other remote operators using the same search software. The search software includes a graphical user interface that supports geographic displays and overlays of the structure of the mine. The location of the sensors and noise sources can also be displayed. Finally, the location of underground signal sources can be displayed both visually and in terms of geographic coordinates. This information can then be used to direct rescue efforts to the proper location.

Additional systems can be constructed for substantially lower cost to permanently instrument mines or to support search operations in collapsed buildings. If a mine is permanently instrumented the system can be calibrated. This is done by pounding on the mine surfaces at known locations while the system collects the signals. This allows the system to correct for geological anomalies; improving the accuracy of search operations should an accident occur. An additional application of the system is the detection of tunneling and illicit underground activity.

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