Geotech Geol Eng (2009) 27:325–339
DOI 10.1007/s10706-008-9234-z

ORIGINAL PAPER

Microseismic Monitoring at a Limestone Mine

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Received: 19 March 2007 / Accepted: 17 June 2008 / Published online: 1 July 2008

Abstract Improving microseismic monitoring efficiency and accuracy at a mine requires an integrated effort. This article discusses a case study which demonstrates that the monitoring efficiency and accuracy can be drastically improved through optimally using the existing array, efficient techniques for signal processing and noise separation, and the advanced location algorithm which not only offers a robust search scheme, but also features the techniques for efficient data utilization and further error detection and minimization. The study is a collaborated research between Penn State and NIOSH researchers for the better use of microseismic technique for mine safety, ground control and roof fall prediction.

Keywords Microseismic monitoring · Sensor array · Source location · Rock burst · Mine safety

1 Introduction

The microseismic monitoring technique utilizes the signals generated by the material itself to study fracture/failure processes. It provides a unique opportunity for real time characterizations of fracture/failure processes in terms of event location, magnitude and source mechanisms. The technique is recognized as an ideal tool for studying mine seismicity and related ground control problems.

Since 2000, this technique has been used by NIOSH to investigate the ground control problems at the Springfield Pike Mine. The Springfield Pike Mine is an underground limestone mine near Connellsville, PA. The room-and-pillar mining method is used for ore extraction. The major ground control problem at the mine has been severe roof falls apparently caused by excessive horizontal stress (Iannacchione et al. 2001).

Since the installation of the microseismic monitoring system at the mine, a large amount of data was collected and used for improving mine safety and ground control (Iannacchione et al. 2003) and for studying the cause of roof fall problems (Gale et al. 2001).

In particular, the microseismic monitoring program at the mine was intended to solve two problems. The first one was to develop a roof fall prediction method and the second one was to verify the effectiveness of the new mining development strategy for alleviating the roof fall problem. In order to

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achieve these goals, the efficiency of the monitoring system, especially the event location accuracy and the associated data processing techniques, had to be improved. A research project aimed for this purpose was therefore set up at NIOSH and carried out by Penn State and NIOSH researchers.

2 Research Approach

As the microseismic system had been installed by NIOSH at the mine for almost 2 years at the beginning of the project and a large amount of data had been collected and analyzed, a logical step to start this investigation was to analyze the existing data. This would first allow an objective evaluation of the existing system and to pinpoint those significant problems. The data was also needed as a benchmark for calibration and evaluation of the potential solutions.

A block of the microseismic data was therefore selected by NIOSH researchers as the database for this investigation. The database consists of 157 microseismic events recorded during the period of March 6–15, 2002, when the mine experienced a severe ground control problem at its SE (southeast) corner area. A major roof fall took place at the beginning of this time period on March 8 (Fig. 1). Most of the events in this database are therefore related to the ground control problem in the area.

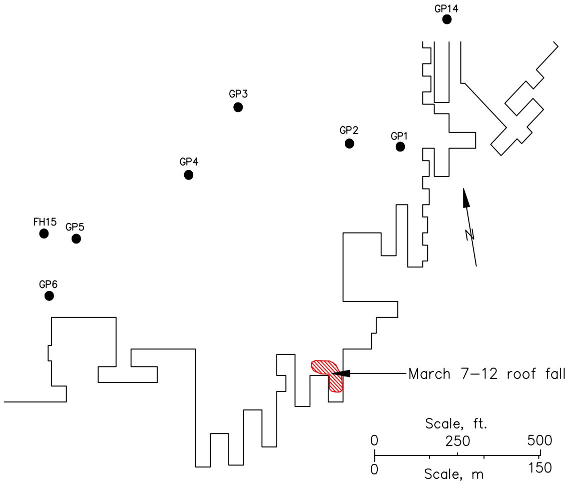

Fig. 1 Mine map and the location of the major roof fall on March 8, 2002

The database compiled by NIOSH researchers is ideal in many ways for this investigation. First, it provides the direct evidence on the locations of the recorded microseismic events so the source location accuracy could be evaluated objectively. Second, it contains a full spectrum of events, from small to large. This is not only essential for the research on magnitude, but also for various calibration studies required for source location. Third, because of the direct link of the data and the observed problems, the investigation result could be used directly for the study of roof fall prediction and mechanism at later stages.

The research was carried out in three stages. At the initial stage, the monitoring condition at the mine and the database forwarded by NIOSH were carefully examined. The main purpose was to set a solid foundation for the full scale source location study. The second stage involved a detailed analysis of the events originated from the SE corner area. In this process, the main problems were quantified and the potential solutions were evaluated and tested. The third stage was devoted for the further study of a number of special issues.

In this article, we first discuss the initial phase of this investigation, the work that set the stage for this investigation. We will then discuss several key techniques used in this investigation. Finally, we are going to discuss the improvement made by this research.

3 Assessment of Monitoring Condition and Event Database

Source location accuracy is affected by many factors. The most important ones are sensor array geometry, velocity model, arrival time and type, location algorithms, and background noise. For the mine environment, it is also the functions of many practical factors, such as mine layout, geology and various ground control problems. For a meaningful source location, these factors have to be carefully assessed.

The first task of our initial work was to understand those general issues related to the mine ground control and its microseismic monitoring system. In addition to the review of the previous work and the detailed discussion with NIOSH researchers, the authors visited the mine and gained first-hand information on the monitoring conditions at the mine.

Next, the waveforms for all 157 events were visually examined. This process was critical in many ways for this investigation. First, it provided the direct evidences for characterizations of microseismic signals and background noises. Second, it helped us to determine the triggering pattern for events originated from different regions, which provided immediate information on the sensor array geometry and allowed us to make a preliminary analysis on its potential impact on the location accuracy. Third, the knowledge of the triggering pattern as well as the characterizations of signals and background noises made it possible for a reliable assessment of the working condition for all sensors.

In this process, the general location of each event was estimated based on sensor triggering pattern, signal amplitude and arrival time differences. The potential location accuracy was assessed in terms of the accuracy of arrival times and sensor array geometry. A brief note was made for each event on its likely location, amplitude and signal characteristics. As a result of this general location the geographic distribution of 157 events was determined.

Based on the result of the general location, 20 major events were selected for the further detailed analysis. This study was designed for a number of purposes. First, the source location algorithm to be used in this investigation had to be tested and evaluated. Second, the P-wave velocity and sensor coordinates forwarded by NIOSH researchers had to be further checked. The idea was that, if the source location was accurate for those large events, the associated velocity and the sensor coordinates must be accurate. The large events referred to those consisting of at least seven or eight channels with clear arrival times. Third a quantitative assessment was needed on the geometry of the SE corner array as well as the achievable location accuracy in the area.

The following is a summary of the main conclusions based on our initial assessment of the event database and the monitoring condition at the mine.

3.1 Geographic Distribution of Database Events

Based on the result of the general location as well as the detailed study for 20 main events, the geographic distribution for 157 events contained in the database was determined as given in Table 1.

Table 1 Distribution of geographic locations of 157 events

Area	Number of events
SE (Southeast)	115
NE (Northeast)	11
Inside mine	2
Others	3
Low frequency events	24

Among the 157 events, 115 were classified as SE corner events. There were three typical locations for these events, which were all located at the major roof fall areas. Most of them were in the vicinity of March 7–12, 2002, roof fall. Another group was centered at February 20, 2002 roof fall area. The third group, consisted of several major events occurred on March 6, were tightly clustered at the tip of 10/99 roof fall area.

The low frequency events were determined to have not originated from this mine. They were most likely associated with the operations of the nearby mines and quarries, indicated by very low and consistent frequency across the mine area.

3.2 Sensor Working Condition

The efficiency of a monitoring system is significantly affected by the sensor condition as it has a direct impact on the array geometry as well as the number of sensors which could be used for source location. The detailed analysis of waveforms and triggering patterns allowed us to make a full assessment on the working conditions for all sensors. As the result of this assessment, sensors were classified into three groups: good, malfunctioned, and severely affected by background noises. Good refers to those which were frequently triggered with low background noises. Malfunctioned refers to the ones which should have been triggered but never recorded anything or sensors with a constant system noise. Sensors 1–6, which were frequently used in this investigation, were in good condition.

3.3 Accuracy of Velocity Data

The P-wave velocity as determined by NIOSH for the mine site is 5,030 m/s (16,500 ft./s). We evaluated this velocity by two methods. First, it was tested by the location of several large and reliable events. The accurate location results implied that it was highly unlikely that an inaccurate velocity data was used. Second, we compared these events with different velocities and found that the velocity of 5,030 m/s (16,500 ft./s) would yield the best result in general.

3.4 Sensor Coordinates

Sensor coordinates, especially those located in the vicinity of the SE corner region, were carefully checked through various means, including triggering pattern, analysis of arrival time difference, amplitude information, and a detailed source location study for several large events. There were no suspicious signs being detected.

3.5 Sensor Array Geometry

Sensor array geometry is probably the most important factor for accurate source location as it determines in which degree the location result would be affected by initial errors. As such, special attention was paid to this factor. For the location of the SE corner events, there were two questions needed to be answered. The first question was if the whole array or just the SE corner array should be used. The second question was how good the SE corner array was. While detailed analysis of these problems will be given in a later section, the brief answer is that the local array should be used and it provides a reasonable coverage for the area.

3.6 Factors Affecting Arrival Time Accuracy

The accuracy of arrival times here refers to the one that can be manually determined based on visual inspection of waveforms. Accuracy under this definition depends on two factors: digitizing speed, which determines the achievable or the best resolution, and the clearness of signals, which is a combined effect of the level of background noise and the characteristics of microseismic signals.

The digitizing speed used by the system at the mine is 1,929 sample/s, which is equivalent to a resolution of 0.518 ms. If we consider the P-wave velocity of 5,030 m/s (16,500 ft./s) as used in this investigation, this resolution would yield a travel distance error of 2.4 m (8 ft.). How this reading error affects the location accuracy depends primarily on the sensor array geometry. For the events located inside the array, the effect should be limited and the actual location error could be much less than 2.4 m (8 ft.). For those outside the array, this initial reading error may be magnified many folds to location errors.

The accuracy of arrival times is strongly correlated with the distance between sensors and event locations. For those SE corner events, sensors 1–4 usually have very clear arrival times. In contrast, the signals at sensors 5 and 6 are normally fuzzier because of the larger distance. The arrival time signals of the SE corner events at other sensor locations are in general very weak and often mixed with high background noises. The mine system utilized all available signals. As such, large timing errors often occurred at those remote sensors, which appeared to be a main reason for the poor location accuracy for the mine system.

3.7 Source Location Strategy for SE Corner Events

After the initial assessment of the main microseismic activity during the period of March 6–15, 2002, the sensor array geometry, and the signal and noise characteristics, it was decided to use sensors 1–6 as the primary array for the location of the events originated from the SE corner area. This would allow the best use of the array already installed at the mine and, meanwhile, ensure the quality of arrival time data.

4 Sensor Array Analysis and Optimization

Sensor array geometry refers to the configuration of the sensors to be used for event location. The fundamental importance of the sensor array geometry lies in the fact that it determines the stability of the source location system, or in other words, it determines the impact of initial errors on the location result. A good array will effectively minimize the impact of initial errors, while a poor one will maximize it. If we consider the fact that errors are inevitable for input data, such as arrival times, velocity and sensor coordinates, and the source location accuracy depends greatly on the efficiency to reduce the impact of these initial errors, the sensor array geometry is probably the most important factor affecting the location accuracy.

As the sensor array was already in place for this investigation, the objective of our array analysis was to determine how the existing array could be most efficiently used.

The 23-channel monitoring array deployed at the mine practically forms three sub-arrays: SW corner array, NE corner array and SE corner array, because of the special monitoring needs in these areas. The microseismic data to be analyzed in this investigation, on the other hand, primarily originated from the SE corner area (Fig. 1). A question initially faced by this investigation was: should all sensors that detect the event or only those local ones be used? To answer this question, we have to step back briefly and to review a basic effect of the sensor array geometry.

Source location accuracy is strongly affected by the relative location of the event under study and the sensor array. In general, if sensors are placed on an arc, the location accuracy will be best in the foci area and decreases as sources move away. It is very difficult to locate events which are behind the arc. This array effect is demonstrated in Fig. 2 by the density of the hyperbolic field associated with a three-sensor array. According to location theory, the density of the hyperbolic field is an indication of the relative location accuracy for the array (Ge 1988). It is clear from the figure that we have the best location accuracy at the center of the array and have almost no confidence for the area outside of the array.

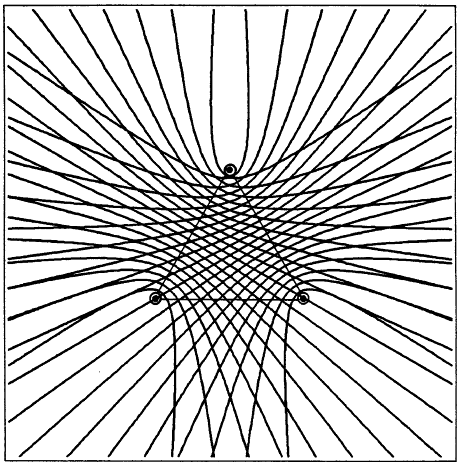

Fig. 2 The Hyperbolic field associated with a triangular sensor array, where circulars denote sensor locations (after Ge 1988)

It is understood from this effect that whether to use all available sensors depends on the potential event locations. If the events come from the mined area surrounded by the three local arrays, especially the central region of the mine, all available sensors should be used. However, for the SE corner area which is located outside of the arc formed by the mine wide array, using the sensors from other sub-arrays may not be helpful. Furthermore, signals received by the sensors at the other sub-arrays are in general very weak and the offset times are often poorly defined, which was identified as a main problem for the mine system at the initial evaluation stage.

The local array that covers the SE corner area primarily consists of channels 1–6 (Fig. 1), which provides a reasonable coverage for the events from that area. This is evident that the potential locations are at the foci of the arc formed by this local array. An added advantage for this local array is the quality of arrival time data. In general, the sensors of this local array have much better data quality than the sensors from other sub-arrays.

Of course, this local array is by no means an ideal one. A large portion of the monitoring area is left open and a good part of the monitoring area is below the area. This deficiency would inevitably affect source location accuracy, especially in the north–south direction.

The weakness of the array is due to the limited accessible locations for sensor installation and should not be interpreted as a design deficiency. The challenge for this investigation was how to get the best under the given condition. With this in mind, particular attention was paid to make channels 5 and 6 "alive". Because of distance, the signals received by these two sensors were often very weak. If they had been simply ignored, the array geometry could have been severely damaged. Therefore, the key to keeping this local array at its best shape was to preserve the data from these two channels. The arrival time picking techniques which played a major role in this regard will be discussed in Sect. 6.

5 Waveform Based Visual Inspection of Event Locations

For any microseismic monitoring project, it is always desirable that the event locations can be cross-checked by other physical evidence, and this is especially true at the beginning of a project. In this investigation, the complete event waveforms provided an opportunity for this purpose.

An important observation made from these waveforms is the rapid decay of the microseismic signals with their travel distances. This observation, together with the information of relative arrival times, allows an immediate delineation of the locations of the associated events. The following is a demonstration of the method.

On March 6, 2002, three major events took place within 3 min from 8:58 to 9:01. The events were recorded by all sensors located at the east part of the mine. The waveforms of these three events exhibit similar characteristics. The following are the waveforms for the first two events: event NI030620 and event NI030621 (Figs. 3, 4).

It is seen from both figures that the amplitudes at channels 2 and 3 are very high while they are drastically lower at channels 1 and 4. If we consider the locations of these four channels as shown in Fig. 5, the only potential event location that is able to create the pattern of the contrast shown in these figures is somewhere in the middle of channels 2 and 3.

The above conclusion can be further confirmed by the identical arrival times for channels 2 and 3 and for channels 1 and 4. The identical arrival time means that the source must be at the central line between two sensors. As such the intersection of two central lines is the location of the AE source, which is at the tip of a previous roof fall area (Fig. 5).

The waveform based visual solutions were confirmed by the PSU analytical solution procedure, which shows that these three events are closely clustered within a range of 4.6 m (15 ft.). The actual coordinates of these three events are given in Table 2.

The example given here demonstrates several key points for this investigation. First the source location code used for this investigation has the ability to produce very accurate solutions. This is shown by the very small residuals for all PSU solutions which have almost identical locations (within 4.6 m). In contrast, the original solutions are widely scattered.

Second these analytical solutions are independently verified by the graphical solution which is based on the amplitude, a different type of physical data, and identical arrival times. This independent verification gives us a full confidence of the analytical solutions presented in Table 2.

Third the location of the first event is calculated based on the arrival times from 12 sensors from two sub-arrays, SE corner array and NE array. With the consideration of the high accuracy of the solution and the large number of sensors involved (and therefore the large area covered by the sensors), it can be concluded that the P-wave velocity used for this

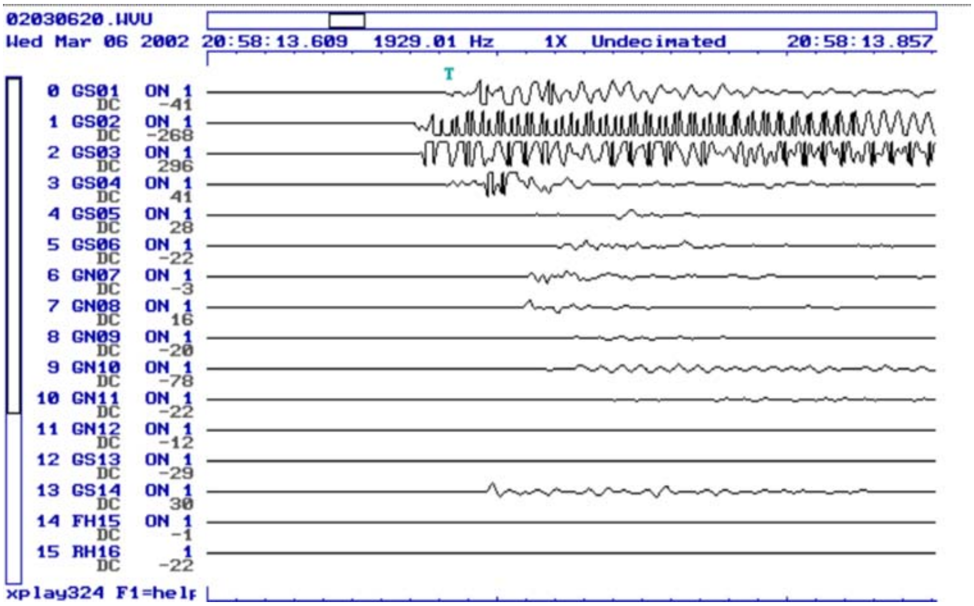

Fig. 3 Full waveform for event NI060320

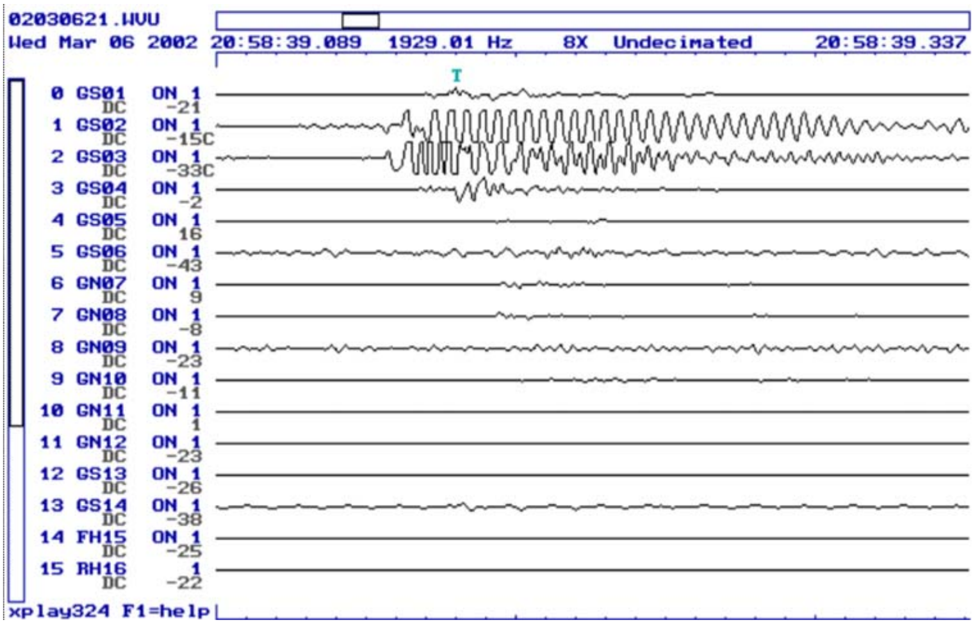

Fig. 4 Full waveform for event NI060321

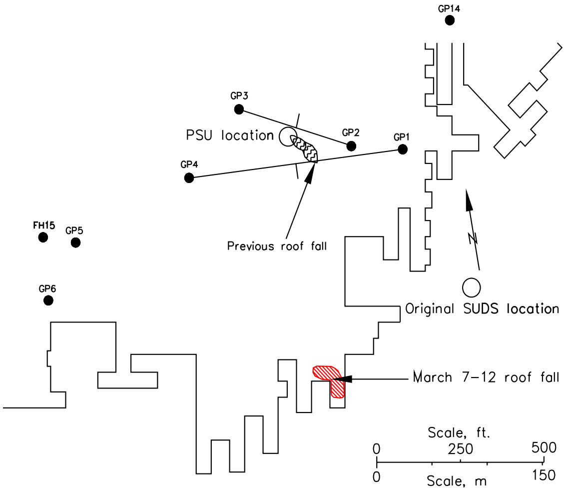

Fig. 5 Locations of event NI030620, NI030621 and NI030622 and the surrounding sensors (The triangles represent the locations originally given by the system at the mine and the circle represents three PSU locations)

Table 2 A comparison of the location results for three major events occurred on March 6, 2002 at the tip of 10/99 roof fall area

Event number	Original location (m)		PSU location (m)		
	X	Y	X	Y	Residual
NI0620	1,649	430	1,668	470	0.76 ms
NI0621	1,690	496	1,665	467	0.28 ms
NI0622	1,880	353	1,667	467	0.23 ms

investigation (5,030 m/s) and the coordinates for the sensors involved are accurate. Mathematically, it is very unlikely to have any major errors associated with velocity or coordinate data if the residual is very small and the number of sensors involved is large.

Because of its reliability and fair accuracy, this method was used extensively in this investigation as an independent means for verification of event locations.

6 Techniques for Data Processing and Arrival Time Picking

A major problem encountered by the mine monitoring system as well as faced by this investigation was arrival time picking. This is not a surprise as arrival time picking under the mining environment is an inherent difficult task because of the high background noise level and weak signals.

For this investigation, we manually inspected all arrivals. Although manual inspection is considered the most reliable approach to determine arrivals, many of them in our case still could not be resolved.

There were two major problems. First, arrivals were mixed with or even buried by background noise. Second, it was often difficult to separate signal arrivals from noise "arrivals" when signals were weak. Several techniques were used to solve these problems, which are discussed as follows.

6.1 Frequency Analysis and Data Filtering

A method that could significantly improve the signal-to-noise ratio, and hence improve the capability of the detection of first arrivals is to filter out background noise. Our study has shown that this is a very effective means to separate microseismic signals from high background noise and should be utilized as a principal tool to deal with this problem at the mine. The following is a brief discussion how the technique was used for this investigation.

The separation of microseismic signals from background noise by filtering requires that the frequency range for signals is different from that of noise. Therefore, the first step to use the technique is to determine the frequency domains for both microseismic signals and background noise.

For a reliable assessment of the frequency range associated with microseismic signals and background noise, three types of signals were analyzed: signals with very low noise level, signals with very high noise level, and pure noise. All these analyses consistently showed that the dominant frequencies for microseismic signals were typically below 200 Hz with a concentration in the range of 0–130 Hz while the frequencies for noise were typically above 200 Hz. This is demonstrated in Fig. 6.

There are four parts in the figure. Part a contains the original signal and Part c is the corresponding

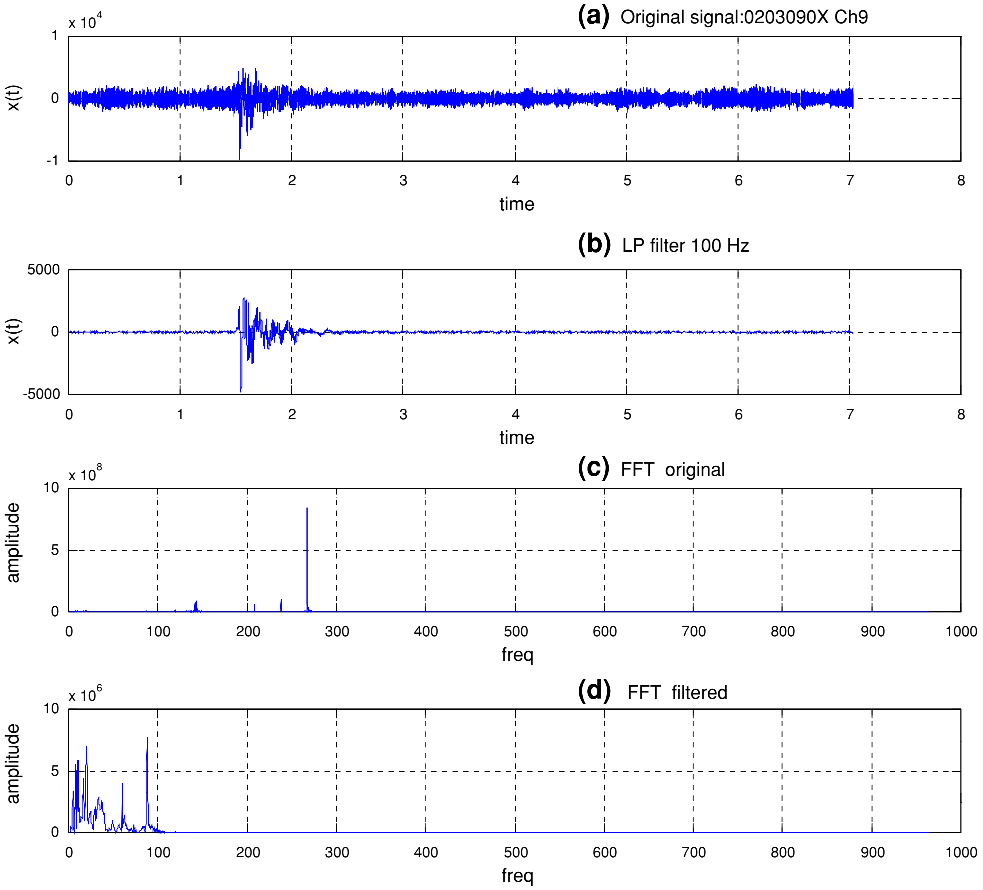

Fig. 6 An AE signal with a high noise level filtered by a 100 Hz low pass filter: (**a**) original AE signal of event 0203090x detected at channel 9, (**b**) filtered signal by a 100 Hz low pass filter, (**c**) frequency spectrum of the original signal, (**d**) frequency spectrum of the filtered signal

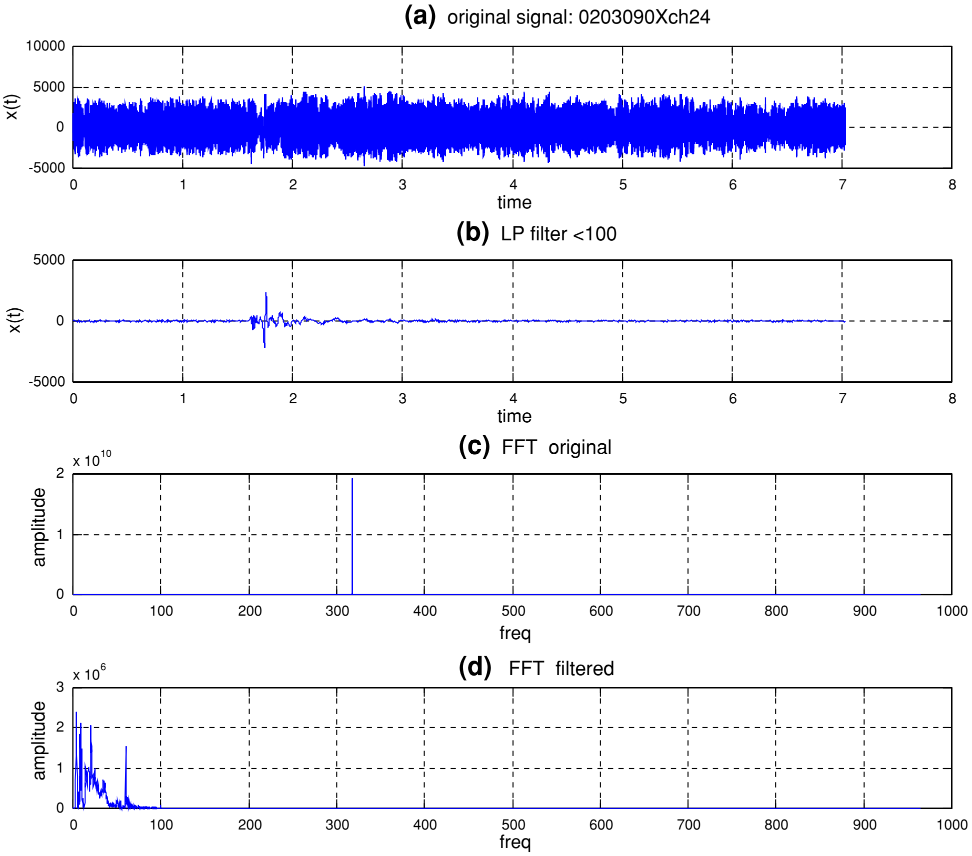

Fig. 7 Recovering an AE signal buried in the background noise: (**a**) background noise at channel 24, which contains the AE signal of event 0203090x, (**b**) filtered signal by a 100 Hz low pass filter, (**c**) frequency spectrum of the original signal, (**d**) frequency spectrum of the filtered signal

frequency distribution. It is not difficult to tell from Part c that the dominant frequency for the background noise is somewhere near 270 Hz. Part a also shows the presence of a microseismic signal. However, its arrival cannot be determined. Part b is the signal after applying a low pass filter (<100 Hz). The filtered signal is clean and its arrival is ready to be picked up.

A more drastic effect of this filtering technique is shown in Fig. 7. In this case, no recognizable microseismic signals can be observed from Part a. However, a very clear one, as shown in Part b, emerged from this high noise channel after a 100 Hz low pass filter is applied.

6.2 Arrival Time Difference Analysis and Residual Analysis

A problem that was frequently encountered in our analysis was the identification of true first arrivals, especially when signals were weak. Such an example is shown in Fig. 4. It is seen from the figure that the signal on channel 5 is very weak. The most likely location of the first arrival would be the one marked by "initial guess". Is this the right pick?

The waveform here offers little help. In order to answer this question we have to turn to the arrival time difference analysis and the residual analysis. The arrival time difference analysis and the residual analysis are two different techniques used for identifying the physical status of AE arrivals. A complete discussion on the subjects was given by Ge and Kaiser (1990). Here we just give a very brief discussion.

The theoretical background for the arrival time difference analysis is that there exists a theoretical limit of the arrival time difference for each pair of sensor locations. For instance, if we assume the arrivals at both sensors are due to P-waves, the observed arrival time difference shall not exceed the theoretical limit of P-wave arrival time difference. The theoretical limit of P-wave arrivals is simply the distance between two sensors divided by the P-wave velocity. For instance, the theoretical limit will be 0.25 s if the distance is 500 m and the P-wave velocity is 2,000 m/s. In practice, the theoretical limit may be slightly relaxed, say 10% to account for velocity variation. In any case, it would signal a non-P-wave arrival for the second one or non-P-wave arrivals for both if the limit is exceeded.

The residual analysis is a theory on the distribution of station residuals. Station residual, r_i, here is defined as the difference between the observed arrival time, t_{oi}, and the calculated time, t_{ci}, that is:

$$r_i = t_{oi} - t_{ci}$$

According to the theory (Ge and Kaiser 1990), the sign and the magnitude of those relatively large residuals may be used to interpret the physical status of the associated arrivals if the minimization procedure is meaningfully carried out. For instance, if the residual is not statistically insignificant and it has a positive sign, it implies that the observed arrival time is later by $|r_i|$ units.

To demonstrate how arrival time difference analysis and residual analysis were used in this investigation, let us go back to Fig. 4, which contains the waveforms for event NI030621. As it has been discussed earlier, this is a relatively large event shown by very high amplitudes at channels 3 and 4. The signal, however, weakens rapidly with distance. The combined effect of the weak signal and the high background noise make it undetectable at sensor 6. For sensor 5, the signal is barely seen. The apparent arrival would be the one marked with “initial pick”. Is this a right pick?

To determine whether this is the right pick, let’s analyze the problem by the theory of the arrival time difference analysis. According to the theory, the observed arrival time differences between sensor 5 and the earlier triggered ones should not exceed their theoretical limits. It is seen, however, from Table 3 that three out of four observed arrival time differences grossly exceeded their limits. The “initial pick”, therefore, by no means could be a P-wave arrival. As a comparison, the arrival time differences corresponding to the correct pick shown in the figure by “Final pick” are also given in the table. In this case most of them are well below the theoretical limits. The only exception is sensor 3. But the exceeding amount is very small, within the velocity fluctuation range.

Table 3 Comparison of the observed arrival time differences (ms) between sensor 5 and four earlier triggered sensors and their theoretical limits of P-wave arrival time differences (ms)

Sensors triggered earlier	1	2	3	4
Theoretical limit (P-arrival)	52.60	37.69	23.75	61.44
Observed arrival time difference (without errors)	32.47	32.47	24.11	24.11
Observed arrival time difference (with an error at sensor 5)	67.25	67.25	58.89	58.89

Table 4 A comparison of the event location results

Solution	Coordinate (m)		Residual (ms)
	X	Y	
Solution without errors	1,665	467	0.28
Solution with wrong pick at sensor 5	1,666	470	17.61

Table 5 A comparison of channels residuals (ms)

Sensor no.	1	2	3	4	5
Solution without errors	0	0	−0.44	−0.09	0.02
Solution with wrong pick at sensor 5	0	0	−0.85	0.00	34.36

The residual analysis yields the same conclusion. The comparisons between the solutions for the correct and incorrect picks are given in the following two tables. Table 4 is a comparison of the event locations and location errors (in terms of the total residual). It is seen from the table that the location coordinates are actually very similar, but the total residuals are very different. In Table 5, channel residuals are compared. For the solution with the correct arrival times, channel residuals are extremely small while for the one with a wrong pick, channel residual for sensor 5 reaches to 34.36 ms. This distribution of channel residuals demonstrates two important points. First, the “initial pick” was indeed an erroneous pick indicated by the very large residual associated with the channel. Secondly, the error due to the pick is contained at this channel and does not propagate to the other ones. As the result this wrong pick does not affect the final source location result.

6.3 A Further Discussion on Data Processing

One of the most important challenges in microseismic monitoring is how to improve the signal-to-noise ratio. Although the methods discussed in this session are important, they are only part of the solution for this complex problem. Fundamentally, the problem has to be addressed from three positions.

First, it is essential to understand the basic characteristics for both the expected signals and the potential noises. In order to acquire this information, a very detailed analysis of the seismic data is necessary. It is also important to identify the origins of noises to assist in noise reduction and data processing. Noises at a mine site can be initiated by a variety of causes, including electrical power, mining operations and interference of microseismic events under the burst condition. Therefore, a thorough site investigation is imperative.

The second aspect consists of the utilization of suitable hardware, including both the sensors and the data acquisition system. Using appropriate sensors is the single most important method to improve the signal-to-noise ratio. A suitable sensor here means that it will provide the best frequency response for the expected signals. The other important method in managing noisy data is to use large channel systems. When an event is recorded by many channels, the analysis of the event is much easier and much more reliable than when an event is recorded by few channels.

The third aspect is the data analysis. There are three types of problems to be solved in the analysis of the microseismic data. The first one is the background noise. This problem can be solved by using suitable filters based on the detailed analysis of the data. The second type of problem is the identification of “outliers”, which are either channels triggered by mining operations or those due to the interference of other seismic events. In this case, arrival time deference analysis and residual analysis may be used to identify these outliers. A detailed analysis of this approach was provided by Ge and Kaiser (1990). If a channel is constantly triggered due to the mining operation, it may be turned off temporarily. The third type of problem is the identification of P- and S-wave arrivals. The method discussed in this paper provides a robust and easy means to deal with this problem.

7 Advanced Location Algorithm

In addition to the measures for the high quality arrival time data and the best use of the existing sensor array, another important measure being taken for this investigation is the use of an advanced location algorithm, which includes not only an enhanced search algorithm, but also a number of important features which are essential for accurate source location. We now briefly discuss several major features and their importance for this investigation.

7.1 Robust Convergence Character

In our code, the searching scheme is based on the Simplex algorithm. The Simplex method is a relatively new method developed by Nelder and Mead (1965). It searches the minimums of mathematical functions through function comparison. The method was introduced for the source location purpose in late 1980s by Prugger and Gendzwill (1989) and Gendzwill and Prugger (1989). The mathematical procedures and related concepts in error estimation for this method were further discussed by Ge (1995).

The most important advantage of this iterative algorithm over the other popularly used iterative algorithms, such as Geiger’s method (Geiger 1910, 1912), is its robust convergence character. Divergence is recognized as the most serious problem for iterative algorithms as it may cause an abrupt interruption of the calculation process. For mine microseismic monitoring, the daily rate is often in the order of hundreds and it would be a disaster if the problem occurs. In contrast, divergence is essentially a non issue for the Simplex algorithm because of its robust convergence character. This character offers the basic insurance for smoothly carrying out the source location analysis.

7.2 Data Processing Capability

A unique advantage of the algorithm is its built-in data processor which automatically identifies P- and S-wave arrivals as well as outliers (or arrivals with large errors). In this investigation, all of the calculated events were first screened by this processor and the results were then manually checked. With this process, large and systematical errors were prevented, which ensured the quality of the arrival time data used for source location.

7.3 Flexibility on the Use of Different Arrival Types

One of the advantages of the algorithm used in this investigation is its flexibility on the use of different arrival types. For instance, users can simultaneously use P- and S-wave arrivals from either different channels or the same channels or a combination of both.

In this investigation, signals for channels 5 and 6 are generally weak because of the larger distances. Sometimes only S-waves can be observed from these two channels. If the USBM method were used, we would be forced to exclude these two sensors from our calculation, which would seriously damage the sensor array geometry. In order to keep these two sensors "alive", algorithms which are capable of dealing with multiple arrival types are essential and the algorithm used in this investigation fulfills this requirement. The USBM method (Leighton and Blake 1970; Leighton and Duvall 1972) is a dominant mine oriented algorithm, which can only use a single velocity for an event location.

7.4 Choice of Optimization Methods

Accurate source location depends greatly on our ability to limit the impact of initial errors. In addition to array optimization, an adequate statistical analysis is also essential. The least squares method has been used almost exclusively for this purpose.

For microseismic source location, the least squares method, however, may not necessarily be the best choice. This is because the method assumes a Gauss distribution for errors, and this condition is often difficult to meet in the case of microseismic source location. For instance, the number of sensors used in this investigation is typically six or even less. If there is just one relatively large error, the assumption will not be fulfilled. The consequence for the situation is that the method will be overly sensitive to large errors and lose its balance. A more robust method for the situation is the absolute value method.

Our location algorithm includes both the least squares method and the absolute value method so that a choice can be made based on error characteristics. In this investigation, the absolute value method was used, which played a major role for improving location accuracy. The following is an example.

Table 6 Comparison of location results by the absolute value method and the least squares method with an error pick at channel 5

Optimization method	Coordinate (m)		Location error (m)
	X	Y	
Absolute value method	1,666	470	2.7
Least squares method	1,699	519	59.5

Table 7 Comparison of channel residuals (ms) for the solutions by the absolute value method and the least squares method with an error pick at channel 5

Sensor no.	1	2	3	4	5
Absolute value method	0.08	0.00	−0.85	0.00	34.36
Least squares method	−3.22	−8.01	−12.98	1.98	22.22

In the earlier discussion of event NI0621, it was noticed that location accuracy was still good even with a wrong arrival time picking at sensor 5. This is not a surprise if we examine the channel residuals for the absolute value method. The error was quarantined at the channel and did not spread out. If the least squares method had been used instead, the result would have been very different. As it can be seen from Table 6, the location error would be 200 ft. in this case. The cause of this large location error is evident from Table 7. If we compare the channel residuals for these two methods, a large amount of errors has been transferred to other channels.

7.5 Reliability Analysis

The code also has a built-in reliability analysis system. With this system, the accuracy and reliability of each located source are examined from three different perspectives: residual, sensitivity and hit sequence.

Residual analysis concerns the constitution of channel residuals: their size, sign and distribution. With residual analysis the physical status of each channel can be examined and studied. The information from this analysis is also important for system evaluation. Residual analysis, as discussed earlier, is one of the principal tool used for arrival time picking.

Sensitivity analysis is used to assess the stability of the event location system. The index of sensitivity is a strong indication of the potential influence of initial errors. An important usage of this parameter is to determine the direction that is most sensitive to initial errors. Since the impact of the initial errors is largely governed by sensor array geometry, it is also an indication of the suitability of the sensor array. Sensitivity analysis is a basic tool that we utilized to study the effect of the SE corner array as well as how to improve this array.

Hit sequence analysis studies the patterns of observed hit sequences and compares them with calculated sequences. Since the observed hit sequence delineates the feasible region for the recorded events, a comparison of two sequences provides intuitive information on the reliability and feasibility of the calculated result.

8 Summary of the Location Result

In this investigation, a detailed source location study was carried out for 133 events from the 157 event database compiled by NIOSH researchers. The events that were not included in this analysis are mostly very low frequency events, which, according to our analysis, were not related to this mine. They were most likely due to blasts from the adjacent mines and quarries.

The 133 event locations as determined by this investigation are presented in Fig. 8. As a comparison, the corresponding event locations as originally determined by the mine system are given in Fig. 9. Our locations are mostly clustered within a narrow band, approximately 61 m (200 ft.) wide and 244 m (800 ft.) long. It is noted there are a number of events at the NE corner of the mine. These are not miscalculated locations. They do belong to that area according to the analysis of sensor triggering sequence.

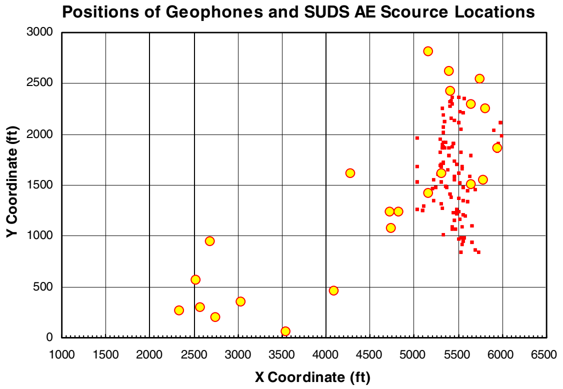

Fig. 8 The AE event locations as determined by the SUDS system used at the mine site (the yellow circles represent geophone locations, and the red squares denote the event location by SUDS)

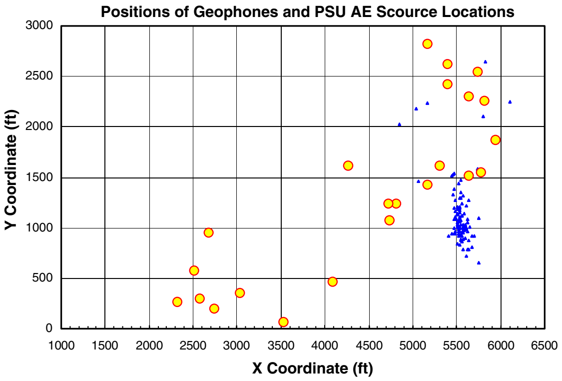

Fig. 9 The AE event locations as determined by the Penn State approach (the yellow circles represent geophone locations, and the blue triangles denote the event location by PSU)

The average location accuracy based on our assessment is about 7.6 m (25 ft.) and it can be higher for many major events. This accuracy assessment is based on the analysis of residual (the difference between the observed and calculated arrival time), sensitivity (the potential location error due to the inaccurate input data), hit sequence (feasible region delineated by the triggering sequence) and the physical observations of the ground control problems.

The pattern of the event locations obtained in this investigation is of interest. First, the narrow band as delineated by our event locations is closely correlated with the severe roof falls occurred in the area during the time period of March 6–15, 2002. Second, the major fall that occurred on March 7–12, 2002 during this period is located right at the center of this narrow band. Third, a number of major events took place at the tips of two previous major falls. One occurred on February 20, 2002, just 16 days before, and the other was in October, 1999.

In contrast to the locations determined by this investigation, the original solutions as given by the mine's system, however, painted a different picture. These events were more scattered over a larger section of the mine.

9 Conclusions

The much improved source location accuracy achieved in this investigation is due to a number of factors.

First, the monitoring condition at the mine and its relation with the database events were carefully evaluated. This allowed us to set the right location strategies, most notably, using sensors 1–6 as the primary array for locating the SE corner events. The initial assessment also revealed the potential problems associated event location in the area and measures were therefore taken to address these problems. At this stage, the velocity model and sensor coordinates were verified and the sensor working condition was evaluated. The work at this stage set a solid foundation for the subsequent actual event location.

An integrated source location approach was used in the investigation. First, the sensor array geometry was assessed and the best array under the given conditions was determined. Next, the arrival time data were carefully screened and analyzed, which ensured the quality of the data used for source location. The advanced source location algorithm was then applied, which not only offered a robust and accurate location search process, but also provided several other important features for efficient data utilization and further error detection and minimization. Finally, the location result was cross-checked by other methods and the reliability for each event was assessed.

The event locations determined in this investigation accurately delineated the area with severe roof falls during the same time period. Three typical locations were identified, which were all found at the major roof fall areas. Most of them were in the vicinity of March 7–12, 2002 roof fall. Another group was centered at a previous roof fall area. The third group, consisting of several major events that occurred on March 6, were tightly clustered at the tip of another previous roof fall area.

This investigation demonstrates that the monitoring efficiency and accuracy at the mine site can be improved substantially by optimally using the sensor array, the data processing techniques demonstrated in this investigation and the advanced source location algorithm. For the SE corner area, the source location accuracy and reliability can be greatly improved if additional sensor(s) can be installed at the boundary of the southeast corner area.

An extremely promising future of the microseismic monitoring technique at the Springfield Pike Mine is the roof fall prediction. The microseismic activity at the mine reflects fracture processes taking place in the thin limestone roof due to the high horizontal stress. Unlike geological structures bedded in massive hard rockmass where it is always uncertain if small recorded microseismic events are the precursors of a major rupture, the fractures developed in the thin roof have an immediate impact on its strength. If microseismic activity is intense at a particular location, the chances are that the roof will be broken at some point.

This hypothesis was confirmed by a recent study carried out by the NIOSH scientists (Iannacchione et al. 2004). The study shows that there exists a strong correlation between microseismic activity and roof convergency rate prior to major roof falls: the convergency rate accelerates before major roof falls, but the acceleration of the convergency lags in days behind the microseismic activity. A roof fall prediction approach was therefore proposed by the NIOSH scientists for the Springfield Pike Mine: using the location data of microseismic events to determine where the convergency station should be installed and predicting roof fall timing by the convergency acceleration rate.

9.1 A Note on Instrumentation

From a technical point of view, microseismic monitoring has four major aspects: instrumentation, sensor array planning, data processing and source location. With the case study presented in the paper, we demonstrated the importance of the last three aspects. However, we did not discuss instrumentation because the focus of the paper was to improve the source location accuracy with the existing data. For the sake of completion, we now provide a brief discussion on instrumentation.

Instrumentation covers a large array of issues. A detailed discussion of the subject is beyond the scope of this paper. There are, however, several factors which are important to practitioners and have to be carefully evaluated at the planning stage. These factors are system capacity, sensor type, and sampling rate. The following is a brief discussion of these factors.

System capacity here refers to the number of data acquisition channels. The number of channels required for a monitoring project depends on several variables. The most important ones are the size of the area to be covered, the location accuracy required, the signal level expected, and types of rock formations. An initial estimation may be made with the reference to existing mines with similar conditions. Both theoretical study and practical monitoring experience have shown that using a relatively large channel system is the most efficient means to improve the monitoring efficiency (Ge 2005). For the purpose of daily monitoring in mines, the system capacity typically ranges from 32 to 128 channels.

Using suitable sensors is critical for an efficient monitoring program. The most important consideration in the sensor selection process is the compatibility of the expected signal frequency and the frequency response of the sensors. Geophones and accelerometers are two types of sensors commonly used for mine microseismic monitoring. The choice between these two sensor types is a function of the signal frequency range. If the expected signal frequency range is relatively low, less than 200 Hz, geophones may be used. However, if the frequencies of the expected signals extend over a much wider range, from few to several hundred or even several thousand Hz, then accelerometers are the sensors of choice. Another important consideration in sensor selection is the sensitivity. When the expected signals are remote and weak, sensors with high sensitivity should be considered.

Seismic signals are preserved in digital form. The sampling rate is the number of times an analogue waveform is measured or sampled per second to convert it to digital. A higher sampling rate provides a better quality reproduction than a lower sampling rate. However, a higher sampling rate also requires much more storage space. The sampling rate should be at least twice the highest frequency of the expected signals.

Acknowledgements We thank NIOSH researchers for preparing the database used in this investigation, and. Mr. Hongliang Wang, a graduate assistant at Penn State, for helping to process the data. We thank an anonymous reviewer for this comments and suggestions to improve the manuscript. The work was supported by NIOSH (Service Order No.: 0000258690).

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