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Source location estimation using single three-component seismic station

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ABSTRACT: An experimental microseismic monitoring system composed of one three component station has been set up overlying the last iron mine in France. This experiment consisted of recording the seismic signals corresponding to the localised underground roof fall following the blasting of some small pillars 300 meters deep. The a priori knowledge of the position sources allows the application and validation of the seismic wave rotation technique to estimate the position of the microseismic events recorded at a single three component station. The method used is based on the calculation of the covariance matrix in a time window. However the length of this window significantly affects the precision of the calculations. The method used involves a new approach in which the length of the time window was optimised on the basis of the dominant frequency *in the seismic signal. This article describes the approach to optimise the convergence process* between numerical results and geometrical field assessment of experiment.

1 INTRODUCTION

The technique of seismic wave rotation can be used to determine the direction of polarisation of the seismic signal, in other words to calculate azimuth and incidence angle of the signal emerging at a three-component seismic station. Thus, the technique is used to estimate the position of a seismic event recorded at a single measuring station. The location will of course be cruder than those achievable with data from several stations surrounding the sources. However the seismic wave rotation technique is a big interest for microseismic systems monitoring areas that are affected by dynamic instabilities, and which are often limited initially to a single seismic measuring station.

The aim of this study was to test and validate the technique of seismic wave rotation for estimating the location of the seismic source from one three-component seismic station in the particular encountered field conditions.

A number of wave rotation techniques – whether in time or frequency domains - have been developed (Kanasewich 1981, Vidale 1986, Magotra et al. 1987, Jurkevics 1988, Christofferson et al 1988, Bataille et al. 1991). The method used in this study is based on calculating the covariance matrix in a given time window (Flin 1965). However the length of this window has a significant effect on the precision of the signal rotation (Roberts et al. 1989). This problem was examined by Cichowicz (1993) who proposed a new technique consisting in optimising the length of the time window on the basis of the dominant signal frequency.

In an experiment carried out in the last iron mine, the microseismic events from fracture and collapses caused deliberately at mine bottom were recorded using a single three-component station at the surface. Since the location of the seismic source was known, the data were used to validate the seismic wave rotation technique for estimating the location of the seismic source recorded by the single three-component seismic station. This article begins with a description of the experimental site, the microseismic monitoring system used, and the events recorded. We then give a summary of the literature on the wave rotation technique, a description of the microseismic events recorded during the experiment, and a sensitivity study of how different parameters influence the precision of the calculations. Finally we reach some conclusions about the validity of the technique and the prospects for its application.

2 PRESENTATION OF THE EXPERIMENT

2.1. The mine and the microseismic monitoring system

The microseismic monitoring technique was applied in an experiment carried out in the last working iron mine. The working method in these mines was to cut roadways to divide the deposit into panels, which were themselves cut into square or at least parallelepiped pillars with dimensions of the order of several metres. In the case of total extraction the size of these pillars was gradually reduced until they were finally blasted away with explosive. The experiment involved recording, at the surface, the microseismic events resulting from localised collapse deliberately caused at the mine bottom by destroying pillars with explosive (Senfaute 2000). Figure 1 shows the position of the microseismic monitoring station and the working units where the pillars were removed. Three working units carried out the pillar removal operations during the period of microseismic monitoring: unit 57 was located about 300 metres away from the vertical line passing through the microseismic monitoring station, unit 55 at a distance of about 890 metres and unit 58 at about 1250 metres.

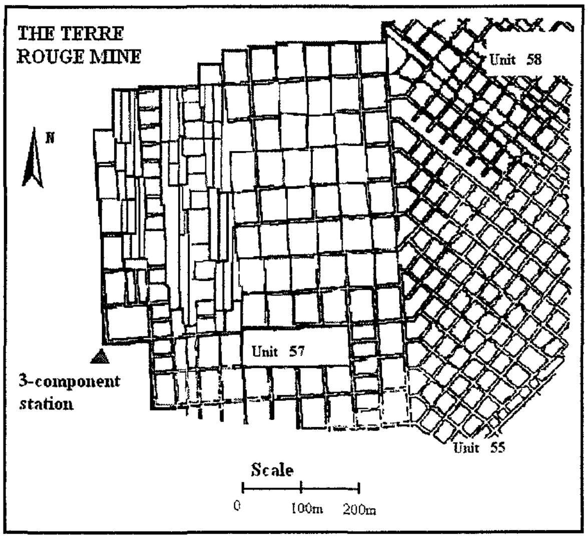

Figure 1 : Schematic delineation of the mining units and location of the microseismic monitoring station.

The microseismic monitoring station was installed at the surface in a borehole 30 metres deep. The monitoring station is a three-component station with sensors of the accelerometer type with pass band 2 to 2300 Hz and a sensitivity of 500 mV/g before post amplification. For signal acquisition a local computer was used with a sampling frequency of 8 kHz par channel (Figure 2).

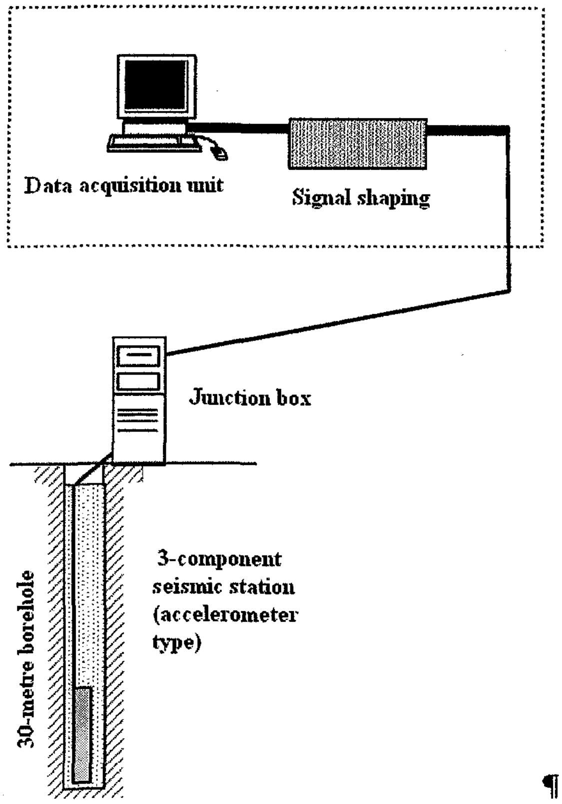

Figure 2: Microseismic monitoring system.

2.2. Microseismic events recorded during the experiment

During the experiment, 265 microseismic events were recorded. They were subdivided into three categories:

- class 1: events directly associated with blasting;
- class 2: events associated with immediate roof fractures, during the collapse process,

class 3: events associated with rock fractures not connected with roof collapse.

The events in class 1 were identified by noting the precise time at which the shot was fired and were contemporaneous with the explosions. The events in class 2 are defined as concomitant with localised roof collapses (limited caving) consecutive to the blasting of the pillars. The third class of event corresponds to isolated incidents, i.e., those occurring at different times than those of shotfiring and roof collapse. The table 1 shows the distribution of events throughout the period of microseismic monitoring.

Table 1: Classification of microseismic events recorded during the monitoring period

Seismic events concomitant with shotfiring	Seismic events concomitant with collapse phenomena	Seismic events recorded at times other than those of roof collapse and shotfiring
31	66	168

2.3. *Microseismic events associated with blasting*

From an initial spectral analysis of the recordings associated with the shotfiring it was possible to separate the blasting signals into two groups. One group of events was associated with shotfiring at unit 57. This unit at a distance of about 300 metres was the closest to the seismic station. The frequency band of these events is fairly broad, between 200 and 400 Hz (Figure 3).

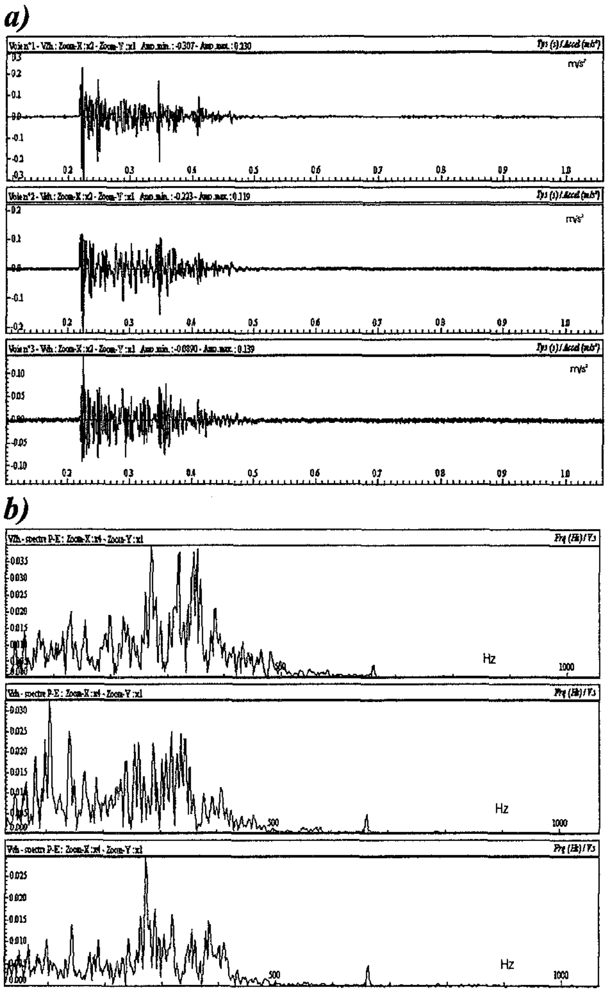

Figure 3 : Typical microseismic signals: a) seismograms along the directions X, Y and Z; b) frequency spectra recorded during a shot fired 300 metres from the seismic station on the surface (unit 57).

The second group of signals concerns the events resulting from shotfiring by a unit farther away than the previous one. The dominant frequency in these signals is therefore lower than that of the previous events. The frequency band of the signals is between 50 and 200 Hz (Figure 4), typically due to physical attenuation.

The first set of 31 microseismic events associated with the shotfiring operations were then processed using the seismic wave rotation technique because the source location was known precisely, and the signal/noise ratio of the signals was very good.

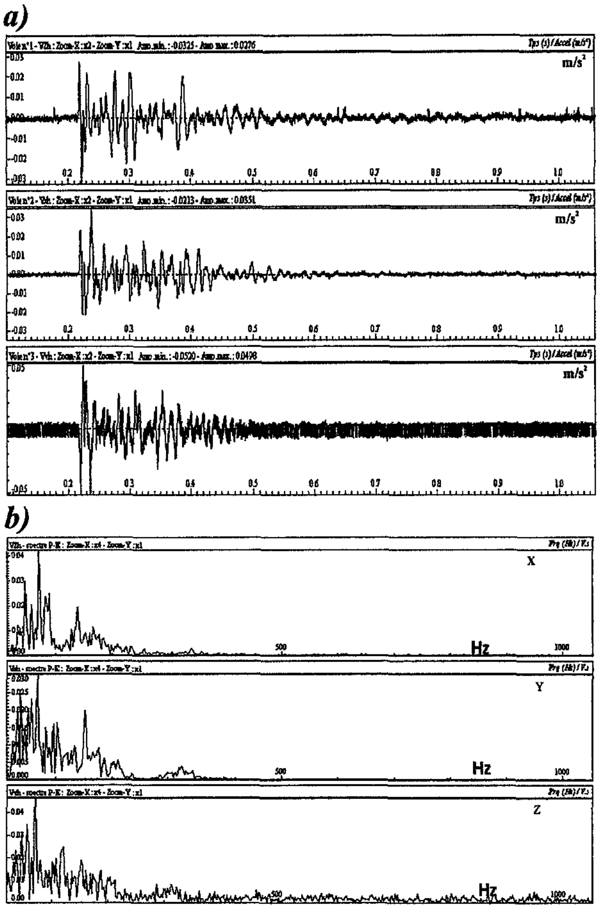

Figure 4 : Typical microseismic signals: a) seismograms along the directions X, Y and Z;
b) frequency spectra recorded during a shot fired some 890 metres from the seismic station at the surface (unit 55).

3 PRESENTATION OF THE SEISMIC WAVE ROTATION TECHNIQUE

The wave rotation method proposed by Cichowicz (1993) is based on the calculation of the covariance matrix in a given time window. According several authors, the length of the time window significantly affects the precision of the method used for rotating the signal. A link between the duration of the window and the errors committed has been demonstrated (Roberts et al. 1989). The new approach proposed by Cichowicz (1993) involves calculating the length of the time window on the basis of the dominant frequency in the seismic signal, which allows the different waves recorded to be processed separately. According to Cichowicz (1993), the length of the time window, denoted N_{filter} is given by the formula:

$Nfiltre = 1/(f_0 \, . \, \Delta t)$

f_o: dominant frequency

Δt: sampling interval

The method of Cichowicz (1993) involves several steps:

- Preliminary analysis of the signal to calculate the dominant frequency,
- Calculation of the covariance matrix during a time window of length N_{filter},
- Extraction of the parameters characterising the polarisation of the signal using eigenvalues and eigenvectors,
- Rotation of the signal to produce the seismogram in the new frame of reference,
- Pick up of the S wave arrival time.

The location of the microseismic events is estimated from the azimuth and incidence angle of the seismic signal. These angles are determined from the eigenvector associated with the P wave using the following formulae:

$\text{Azimuth} = \arctan (u_{21}/u_{31})$

$\text{incidence} = \arccos | \, u_{11} \, |$

u_{11} : vertical component of the eigenvector associated with the P wave;

u_{21} and u_{31}: horizontal components of the eigenvector (figure 5).

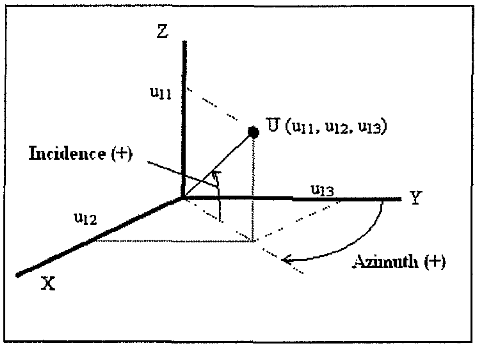

Figure 5 : Azimuth and incidence angle calculated from the eigenvector associated with the wave P.

In order to qualify the calculated angles, we determine the degree of rectangularity from the eigenvalues of the covariance matrix using the formula of Jurkevics (1988):

$$\text{Rectangularity} = 1 - ((\lambda_2 - \lambda_3) / 2\lambda_1)$$

where λ_1, λ_2 and λ_3 are the eigenvalues of the covariance matrix. These eigenvalues are usually in the following order: $\lambda_1 \geq \lambda_2 \geq \lambda_3$. The degree of rectangularity is an important parameter that characterises the polarisation of the ground motion. It takes the value "1" if the ground motion is completely polarised or, in other words, linear. In this case the specific value λ_1 associated with the P wave is dominant.

4 APPLICATION OF THE SEISMIC WAVE ROTATION TECHNIQUE

Comparison between the azimuth and incidence angle calculated from the wave rotation technique and those measured at the known source location makes possible to test, to validate and to determine the precision of the technique in the field context.

4.1 Presentation of results

The seismic wave rotation were applied to the 31 selected microseismic events. Applying the rotation technique for each event allowed the determination of the angles (azimuth and incidence) of the seismic signal. These results were used to classify the events into two groups :

- group 1: events with a mean azimuth N 81° and a standard deviation of 11.7°; a mean incidence of 54° and a standard deviation of 8.5°;
- group 2: events with a mean azimuth N 110° and a standard deviation of 7.7°; a mean incidence of 27° and a standard deviation of 6.9°.

The calculations of azimuth and incidence angle assume that the wave is propagated following a straight line in a homogeneous, isotropic medium.

The two groups of events classified by the wave rotation technique correspond to the events resulting from the blasting operations by units 57 and 55 (see Figure 1). Table 2 shows the comparison of the expected theoretical angles (azimuth and incidence angels) and the mean values of the angles calculated using the wave rotation technique.

Tableau 2 : Comparison of the azimuth and incidence angles calculated by the signal rotation technique and those expected theoretical angles

	Expected angles		Calculated angles by rotation technique	
	Azimuth	incidence	Azimuth	incidence
Groupe 1	N 81°	51°	N 81° ± 11.7°	54° ± 8.5°
Groupe 2	N 108°	22°	N 110° ± 7.7°	27° ± 6.9°

The events in group 1 are clearly associated with the operations of unit 57 (see Figure 1). The shots fired from that unit are located some 300 metres from the seismic station at the surface. As a result, the error in locating these events is of the order of 30 metres in the vertical plane and 40 metres in the horizontal plane. This error is determined by converting the standard deviations of the angles (incidence and azimuth) into the distances. Finally, the estimated resultant error is of about 50 metres. Figure 5 shows the azimuth and incidence angle for all the events associated with the shots fired by unit 57.

The shots 12 and 13 (see Figure 6) show fairly large differences between the calculated and measured azimuth values. This error was due to substantial saturation of these signals. We observed that the strongest events that gave substantial saturation of the signals generated significant bias in the calculation of wave rotation.

The events in group 2 are associated with the shots fired by unit 55. This unit is located about 890 metres from the seismic station. As a result, the error made in locating the shots is of the order of 100 metres in the vertical plane and 115 metres in the horizontal plane. The resultant error is of the order of 150 metres. Figure 7 shows the variations in the calculated angles of azimuth and incidence for the events associated with the shots fired by unit 55.

3.2 Influence of the length of the time window

We carried out a sensitivity study to determine the influence of the length of the time window on the precision of the calculated azimuth and incidence of the seismic signal. We showed that there is a relation between the dominant frequency in the signal, from which the length of the time window is determined, and the precision of the angles of azimuth and incidents calculated by signal rotation.

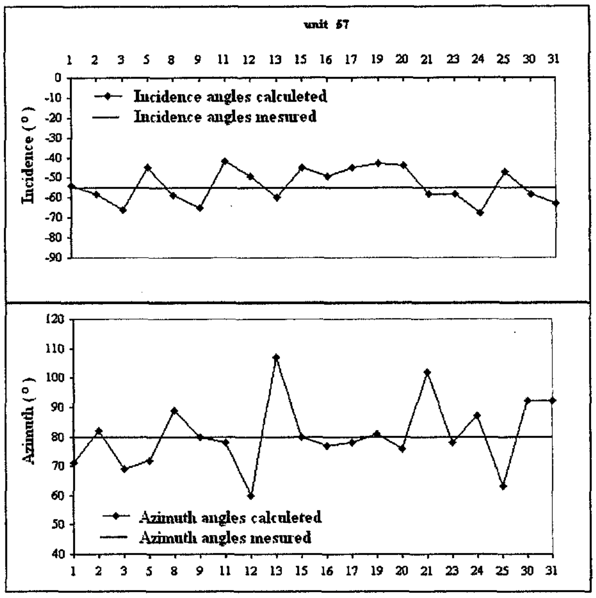

Figure 6 : Variations in incidence and azimuth of events associated with the shots fired by unit 57. The horizontal line shows the expected incidence and azimuth values.

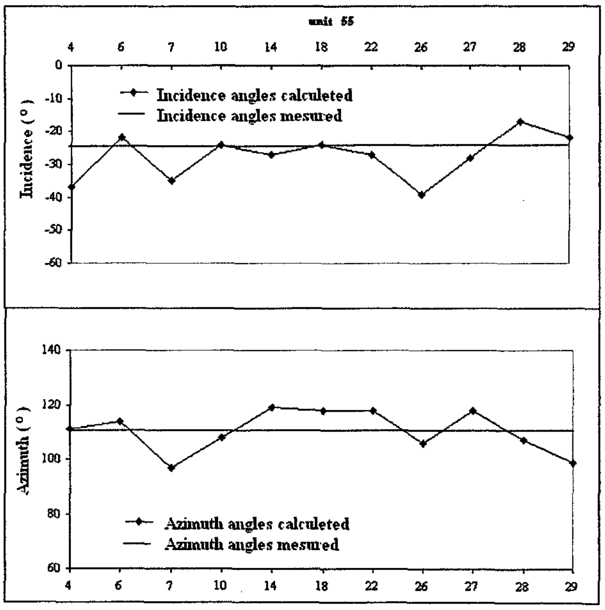

Figure 7 : Variations in the incidence and azimuth of the shots fired by unit 55. The horizontal line shows the expected incidence and azimuth values

For the shots fired by unit 57, about 300 metres from the monitoring station, the events show a principal frequency band between 200 and 400 Hz (see Figure 3b).

Figure 8 shows the variations in the angles of azimuth and incidence as a function of the frequency from which the length of the time window is calculated. Equation 1 gives the relationship between the length of the time window and the dominant frequency. The results show that the precision of the calculated angles depends on the length of the time window and on the associated dominant frequency. The precision of the results is considerably worsened for frequencies above 600 Hz and below 200 Hz – entirely outside the frequency range of the events – are used (Figure 8).

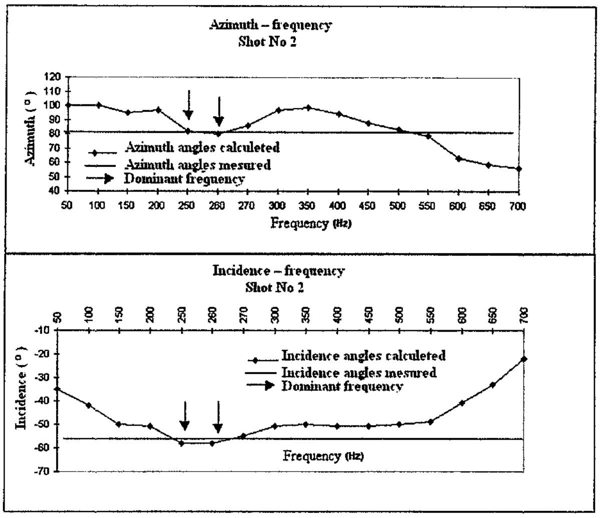

Figure 8 : Variations in azimuth and incidence as a function of frequency for the events at unit 55.

For the shots fired at unit 55, a mining unit that is farther from the seismic monitoring station than unit 57, the signals recorded show a predominant frequency between 50 and 200 Hz. Figure 8 shows an example of the variations in angles of azimuth and incidence as a function of frequency for the events associated with unit 55. The results show, as in the previous example, that above 500 Hz, which is completely outside the frequency range of the events, the precision of the calculations of azimuth and incidence is considerably degraded.

4.3 Consideration of unfavourable cases

Within the 31 microseismic events used in the wave rotation technique, 3 cases did not work out. Indeed, good precision of the calculation was not associated with the dominant frequency of the signals. For these cases, we noted that the signal was extremely complex and had several dominant frequencies. In addition, the precision of the calculation varies from one dominant frequency to another or is linked to none of them dominant. Figure 10 gives an example of an unfavourable case where the precision of the azimuth calculations is not related to any dominant frequency in the signal.

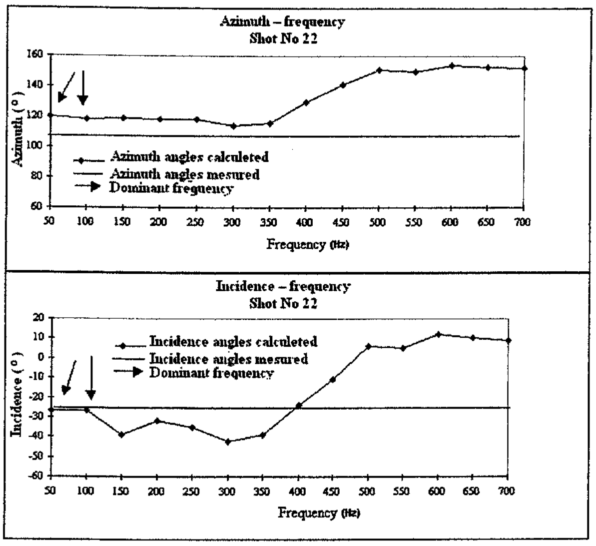

Figure 9 : Variations in incidence and azimuth as a function of frequency for the events of unit 55

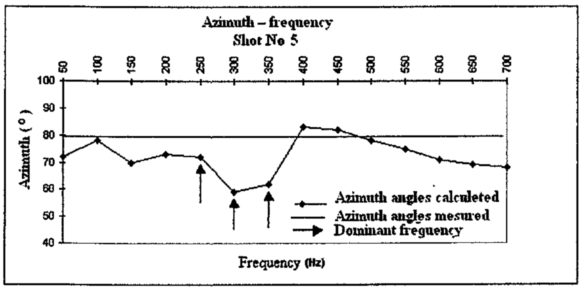

Figure 10 : Unfavourable case in which the azimuth is not associated with the dominant frequencies..

5 CONCLUSIONS

The microseismic events recorded during shotfiring operations in an underground mine were used to implement and validate the seismic wave rotation technique for estimating the location of the microseismic events recorded by a three-component station at the surface. The application of the seismic wave rotation technique to the 31 seismic events recorded produced the following results :

1. The covariance matrix method (Cichowicz 1993) used in this study gives good precision in estimating the incidence and azimuth angles of the seismic signal emerging at a three-component seismic station.

2. By applying the wave rotation technique it was possible to distinguish between two principal groups of microseismic events associated with the shots: one group of events represents the azimuth and incidence angle of unit 57 and one group represents the azimuth and incidence angle of unit 55. These results were compared

with expected theoretical azimuth and incidence values at the site which have been used to validate the application of the wave rotation technique in the specific field context.

3. The study permits to quantify the accuracy of the calculated azimuth and incidence angles related to the dominant frequency in the signal, from which the length of the time window used in the calculations is determined.

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