



OPEN Acoustic emission spectrum for mine hazards identification and prevention

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The article investigates the problems of mine hazard prevention, identification and control. Acoustic emission signals are one of the important signs of the appearance of deformations in rocks that can cause accidents in mines. Acoustic emission signals are quite broadband in nature. The article considers the task of the possibility of using broadband nature of acoustic emission signals to localize areas in which acoustic signals are generated for early warning of an emerging danger. The results of modeling of the process of localization of hazardous areas are presented. The proposed method is based on the frequency dependence of acoustic signal attenuation in rocks. Moving away from the signal source, not only changes its intensity, but also its spectrum. By measuring the intensity of acoustic signals in several spectral bands and knowing the frequency dependence of signal attenuation, it is possible to calculate at what distance from the receiving points the signal source should be located so that its spectral components would be changed as they are observed at the receiving points. This allows to localize the signal source. It is shown that four signal reception points and intensity measurements in two spectral frequency bands are sufficient to apply the method. It is shown that the proposed method allows not only to determine the coordinates of the local area of fracture formation, but also to restore the spectral characteristics of acoustic emission signals in the area of their occurrence, which can provide information about the mechanism of formation and development of processes of rock destruction.

Keywords Mine hazards, Monitoring and early warning, Acoustic emission, Damage localization, Coal/rock disasters, Coal and gas outburst, Prevention and control, Identification method, Earthquake precursor

Miner - one of the most dangerous professions in the world. Hundreds of people die in mines every year, and finding the ways to increase the safety of mining activities is an urgent task. The greatest danger is the collapse of rocks, leading to landslides, the release and explosion of flammable gases (methane), and collapses. Acoustic emission of rocks is one of the promising signs capable of detecting signs of impending collapse at an early stage. In the article¹, the authors conducted a review and analysis of publications on the use of acoustic emission in the coal industry from 2010 to 2020. The authors suggest that in the future the research focus will be on solving the principal problems of acoustic emission localization. In the field of coal mining, early warning of rock, coal and gas release technologies have not yet been developed. The authors of² note that effective monitoring and early warning methods are crucial for increasing safety and sustainability in deep coal mining. These methods make it possible to mitigate the effects of rock impacts caused by abrupt destruction of rock under conditions of high stress on the ground. The article³ also notes that in the development of deep underground mines, warning signals are crucial for predicting dynamic coal and mining disasters and will allow the coal industry to develop sustainably. In order to accurately identify the precursor signals of coal disasters, many samples of raw coal were tested. Acoustic emission was used as a signal accompanying the deformations and fractures of the coal samples.

Acoustic emission is the radiation of elastic waves that occurs during the restructuring of the internal structure of solids. Emission occurs during plastic deformation of solid materials, during the occurrence and development of defects in them, for example, during the formation of cracks. Acoustic emission has an “explosive”, pulsed character. The pulse duration can range from 10^{-8} to 10^{-4} seconds, and the energy of a single pulse can range from 10^{-9} to 10^{-5} Joules⁴. The frequency spectrum of the emission is very wide: it extends from the range of

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audible frequencies to tens and hundreds of MHz⁴. If the attenuation time of the signal and the time of transients in the sample are less than the time interval between the emitted pulses, the emission is perceived as a sequence of pulses and is called discrete or pulsed. If the interval between individual acts of radiation is shorter than the attenuation time, the emission has the character of continuous radiation, in the vast majority of cases non-stationary, and is called continuous.

Acoustic emission signals can provide the information needed to identify hazards and determine their locations. Monitoring and processing of these signals are promising for creating systems of early warning of hazards in mines.

The conditions of mining in deep mines differ significantly from the conditions of mining in mines of moderate depths due to the influence of a number of basic natural and mining-engineering factors. The depth of exploitation can vary from several hundred meters to several kilometers. In deep mines, among other, coal is mined. The main features of mining-geological and mining-engineering conditions in deep mines are associated with an increase of the harmful effects of rock pressure, an intense manifestation of the plastic properties of rocks, an increase in the temperature of rocks (at a depth of 1000 m to 36–40 degrees Celsius), an increase in the number and intensity of rock impacts, sudden coal, rocks and gas outbursts. This leads to the need of warning about sudden coal, rocks, gas outbursts, rock impacts. Conventionally, coal mines are considered to be deep with an initial depth of the ventilation horizon of more than 600 m in the exploitation of flat and inclined strata and 700 m – of steep. However, these depths are rough and subject to specification in particular conditions.

Coal fields are characterized by an increased complexity of hydrogeological conditions. The highest water abundance is associated with coal strata with increased fracturing and water permeability. Almost all deposits of black and partially brown coals with a high degree of carbonification are characterized by methane content. Gas and dynamic phenomena (methane soufflers, its intense release during the destruction of a coal massif, sudden outbursts with coal or rock) make mining extremely difficult.

The most dangerous in mines is a sudden outburst^{5–12}, which is the spontaneous release of gas, solid minerals (coal, salt), or enclosing rock into an underground mine from a face or borehole zone of the massif. The duration of the sudden outburst is up to several seconds. As the depth of mining increases, the frequency and intensity of sudden outbursts increase, which often occur a few minutes after work stops in the face of the mine. The mine is filled with a fragmented mass of minerals or rock, natural gas. In this case, the borehole support and mining equipment often collapse. Precursors of a sudden outburst: a significant increase in the acoustic or seismoacoustic activity of the massif. The sudden outburst of coal and gas occurs mainly at a depth of over 250 m. Sudden outburst of rock and gas occurs mainly at a depth of more than 400 m (sandstones – more than 700 m)¹³.

Outburst danger is the probability of the appearance of outbursts mainly of coal or rock and gas (less often some sandstones from coal-bearing sediments and potash salts) during mining operations. The current forecast of outburst danger should be carried out continuously, based on the registration of outburst precursors (acoustic or seismoacoustic forecast) and should characterize the hazardous state of the exploiting stratum or rocks.

The article¹⁴ presents the results of investigation of the acoustic emission characteristics of coal and rock samples under load application. The results showed that the coal samples primarily exhibit plastic fracture and the corresponding acoustic emission exhibits the “rise-peak-fall” evolutionary characteristic. Rock samples primarily show brittle fracture, and the corresponding acoustic emission exhibits an evolutionary mode almost without stage of decay. In the article¹⁵, the results showed that the deformation and fracture of a coal sample containing methane under three-dimensional stress includes four stages: initial compression, elastic deformation, plastic deformation and fracture. In the article¹⁶, the authors carried out research on the study of the dependence of the development of rock damage from depth. The results showed that, under the influence of confinement pressure, the acoustic emission activity in the coal decreased with increasing depth. The article¹⁷ presented the results of an investigation on the detection of precursors of gas outburst in the form of microseismic and acoustic emission effects. The microseismic amplitude noticeably decreased before the explosion, the spectrum shifted significantly from extremely low frequencies to the high frequency band and changed from a “single peak type” with central frequency of 1.5–3.5 Hz to a “multiple peak type” with peak frequencies of 25, 50, 75 and 125 Hz, respectively. During the initial stage of the explosion, the microseismic spectrum showed a broadband distribution, and the predominant frequency was 20–35 Hz. The high-frequency part of the spectrum was generated by microcracks, and the low-frequency part corresponded to macro-fractures for the gas outburst channel. In the article¹⁸, the authors note that the efficiency of the acoustic emission system and the microseismic system is seriously reduced due to background noise and inaccurate determination of the location of the event. The authors demonstrate that the accuracy of determining the location of a source in mines can be significantly improved through the application of a comprehensive and highly effective approach to source localization. The approach includes digital filtering, phase matching, sensor array optimization, optimization method based on absolute value, advanced simplex localization algorithm, and reliability analysis.

Theoretical and experimental investigations on the destruction of rock samples, presented in numerous publications, show that acoustic emission signals are broadband^{19,20} and their spectrum differs depending on the type and stage of deformations^{21–23}, as well as on the depth and properties of mines^{24,25}. By obtaining spectral characteristic of acoustic emission signals, it is possible to obtain information about the type and stage of deformations. However, in order to warn of danger, it is necessary to know the coordinates of the signal source corresponding to these spectral characteristics.

Many investigations are devoted to determining the location (localization) of acoustic emission signals^{26,27}.

The article²⁶ provides an overview of methods for localization of acoustic emission sources in various dimensions. The main methods of localization of the acoustic emission source in two dimensions are considered, such as triangulation, beam forming, strain rosette technique, modal AE, artificial neural networks, optimization and time reversal technique, localization methods in isotropic and anisotropic structures, as well as localization

methods in complex structures in three dimensions. As one of the main directions for future research, the authors note the need to carry out research on the localization of the source in three-dimensional structures.

In the article²⁷, the authors also carried out a comparative review of well-known methods for localization of acoustic emission sources. Well-known methods of localization of acoustic emission sources were considered, such as modal acoustic emission, triangulation method, beamforming, time reversal and artificial neural network, multiple sources localization.

Modal acoustic emission method is based on measuring the arrival time of longitudinal and bending waves with a single sensor. If their respective propagation velocity is known, the distance can be measured. However, the difficulty lies in implementing the separation of longitudinal and bending waves in practice, since the distances are small and the waves overlap each other. This method is more often used to determine earthquake hypocenters.

Triangulation method is based on accurate measurement of the arrival time and speed of the wave. There are variations of the method based on knowledge and on absence of knowledge of the wave propagation velocity. Various computational procedures have been developed to calculate the wave propagation velocity.

Beamforming is a signal processing method that uses a group (array) of antennas (sound receivers) to determine the direction of arrival of the wave. Since beamforming compares the shapes of signals, all sensors in the array must have the same amplitude and phase responses. The antennas should have a small aperture.

Time reversal and artificial neural network method is suitable for localization of the acoustic emission source in an anisotropic medium and the algorithm does not require knowledge of the wave propagation velocity. Since time reversal measures the phase of signals, identical conditions are required for forward and reverse propagation. However, the Artificial neural network method requires a large amount of data for deep learning^{28–32}.

Multiple sources localization method solves the issues of distinguishing between different signal sources, which is necessary for the practical implementation of many methods.

Methods for determining the source of acoustic emission are different and are divided, for example, by the feature of the placement of the registering sensors. Linear localization is used for rod-shaped structures, where the length of the structure is much greater than its width. To localize the acoustic emission source, it is necessary to know the difference in the time of arrival of a seismic wave to two sensors located on both sides of the rod and the speed of wave propagation in the material. Two-dimensional and three-dimensional spatial localization also uses the method of calculating the time difference of arrival of a wave (TDoA - Time Difference of Arrival) on various sensors and requires knowledge of acoustic waves propagation velocity in the medium. The error of the method depends on the influence of the anisotropy of the medium on the wave propagation velocity.

In the article³³, the authors note that TDoA-based methods can achieve good positioning results if the acoustic wave velocity is known with high accuracy. However, in complex and volatile environments, the speed of an acoustic wave may contain a certain degree of uncertainty or even be unknown, which significantly limits the use of traditional methods based on pre-measured speeds.

In the article³⁴, the authors note that the heterogeneity of the medium limits the accuracy of source localization algorithms. To overcome these disadvantages, it was proposed to use usual algorithm of acoustic emission localization in conjunction with travel time tomography by using the acoustic emission events as acoustic point sources.

In the article³⁵, the authors proposed to use traditional TDoA and beamforming methods together to localize acoustic emission sources.

This article considers the problem of determining the coordinates of an acoustic emission source. In contrast to the commonly used methods based on measuring the time of an acoustic emission signal registration by a group of sensors, the article proposes a method based on measuring the intensities of acoustic emission signals (RSS – received signal strength), which does not require the use of very precise time synchronization of sensors. Using of this method require the knowledge of the law of signal attenuation with distance and knowledge of the signal intensity in the source.

Acoustic absorption is one of the reasons for the dispersion of elastic wave velocities and distortion of pulse signals propagating in rocks. The attenuation coefficient α [m^{-1}] determines the change of the amplitude of the wave during propagation in rocks, at this value the amplitude of the wave decreases by a factor of e . Attenuation coefficient: for rocky undisturbed rock formations in the frequency range of 1–100 Hz is $10^{-6} - 10^{-3} \text{ m}^{-1}$, for frequencies of 1–10 kHz is $5 \cdot 10^{-2} - 1 \text{ m}^{-1}$, for loose rocks in the range of 1–100 Hz is $10^{-2} - 10^{-1} \text{ m}^{-1}$ ³⁶. Acoustic properties of rock are closely related to the physical and mechanical properties, thermodynamic state and structural features of the medium. For example, for rocks, the attenuation coefficient is approximately proportional to the first power of the frequency, for loose rocks – to its square³⁶. The attenuation coefficient decreases with depth³⁶. Acoustic properties also depend on temperature: as it increases, the attenuation coefficient increases³⁶.

We proposed a solution to the problem of using the RSS method without knowing the intensity of the acoustic emission signal in the source. Taking into account the broadband nature of the acoustic emission signal, a method for measuring the coordinates of the signal source based on the results of measuring signal intensities in two frequency bands was proposed. The corresponding equations for calculating coordinates were derived and the calculation results were verified by modeling in the Matlab system. Verification confirmed the operability of the method.

The development of the method is the result of the authors' research on the localization of foci of destruction in a rock massif during underground mining of minerals. The authors' previous results were aimed at improving the accuracy of determining the coordinates of foci of destruction in a rock massif to ensure industrial safety, as well as the completeness of mineral extraction in problem areas³⁷.

Materials and methods

Problem statement and its solution

When elastic waves propagate, in the medium mechanical deformations of compression and shear occur, which are transferred by the wave from one point of the medium to another. Elastic waves of only two types – longitudinal and shear – can propagate in a homogeneous isotropic infinitely extended solid medium. Longitudinal and shear waves of three types – plane, spherical and cylindrical – propagate in an infinite medium.

In any elastic medium, due to internal friction and thermal conductivity, the propagation of elastic waves is accompanied by its absorption. In many solids, at not very high frequencies, the sound absorption coefficient varies proportionally to the frequency. Numerous experimental investigations have shown that the sound absorption coefficient in dry soils and rocks linearly depends on the sound frequency in the range of 1–106 Hz, and the dispersion of the sound velocity in them is small³⁸.

Since the distances from the acoustic emission source to the receiving sensors are quite large compared to the acoustic wavelengths, and the sources themselves are local, then a spherical wave is formed in a solid medium, the intensity of which decreases with distance.

Problem statement

Suppose there are four acoustic signal receivers located at points with known coordinates (x_1, y_1, z_1) , (x_2, y_2, z_2) , (x_3, y_3, z_3) , (x_4, y_4, z_4) and an acoustic signal source located at the point (x_0, y_0, z_0) , whose coordinates are unknown. The intensity of the signal decreases as it propagates in space due to two factors: spatial wave divergence and energy loss due to its attenuation in the medium. In a spherical wave, due to the divergence, the intensity decreases with distance in proportion to r^{-2} . During attenuation due to scattering and absorption, the intensity decreases with distance according to the exponential law $e^{-\Delta r}$, where Δ is the attenuation coefficient. Accordingly, dependence of the intensity for a spherical acoustic wave on the distance can be described by the formula (1):

$$I = \frac{I_0}{r^2} e^{-\Delta r} \quad (1)$$

where I_0 – acoustic emission source intensity, r – distance from the measuring point to the acoustic emission source.

For direct application of the formula, it is necessary to know the intensity of the acoustic emission signal in the origin I_0 . However, the intensity of the acoustic wave signal in the origin is unknown. It is required to calculate the coordinates of the source when the intensity of the acoustic emission source is unknown.

In the general case, the spectrum of the acoustic emission signal is also unknown. The spectrum may be different for each type of damage. In the article³⁹, authors carried out an investigation of acoustic emission signals in the range of 50–600 kHz and compared them to four different types of damage. In our task, we proceed from the fact that the spectrum of the acoustic emission signal in its source is unknown to us, as well as its intensity, but when the signal propagates in the rock, the signal changes according to the same law and changes the more strongly the greater the distance from the signal source to the receiving sensors.

This example shows calculations for two frequency bands. Although the ratio of spectral components is unique for each specific event, the coordinates of the source are the same. This means that by measuring the intensity of the spectral components at several frequencies, it is possible to create a system of equations for each of the frequencies.

The sequence of problem solving

Form 4 equations for each of the frequencies by measuring the intensities of the acoustic emission signal at four different points at the frequencies f_1 and f_2 .

Equation (2) for frequency f_1 :

$$\begin{aligned} I_{11} &= \frac{I_{01}}{r_1^2} e^{-\Delta_1 r_1} \\ I_{21} &= \frac{I_{01}}{r_2^2} e^{-\Delta_1 r_2} \\ I_{31} &= \frac{I_{01}}{r_3^2} e^{-\Delta_1 r_3} \\ I_{41} &= \frac{I_{01}}{r_4^2} e^{-\Delta_1 r_4} \end{aligned} \quad (2)$$

where Δ_1 is the attenuation coefficient in the medium at frequency f_1 , I_{01} is the intensity of the emission signal at the source at frequency f_1 .

Calculate (3) the ratio of the intensities of acoustic emission signals measured at the frequency f_1 , for different reception points using Eq. (2):

$$\begin{aligned} \frac{I_{11}}{I_{21}} &= \frac{I_{01} e^{-\Delta_1 r_1}}{r_1^2} \frac{r_2^2}{I_{01} e^{-\Delta_1 r_2}} = \frac{r_2^2}{r_1^2} e^{\Delta_1 (r_2 - r_1)} = \alpha_1 \\ \frac{I_{11}}{I_{31}} &= \frac{I_{01} e^{-\Delta_1 r_1}}{r_1^2} \frac{r_3^2}{I_{01} e^{-\Delta_1 r_3}} = \frac{r_3^2}{r_1^2} e^{\Delta_1 (r_3 - r_1)} = \beta_1 \\ \frac{I_{11}}{I_{41}} &= \frac{I_{01} e^{-\Delta_1 r_1}}{r_1^2} \frac{r_4^2}{I_{01} e^{-\Delta_1 r_4}} = \frac{r_4^2}{r_1^2} e^{\Delta_1 (r_4 - r_1)} = \gamma_1 \end{aligned} \quad (3)$$

Form another 4 equations, identical to Eq. (2), for signal intensities at four points at the frequency f_2 (4):

$$\begin{aligned}
 I_{12} &= \frac{I_{02}}{r_1^2} e^{-\Delta_2 r_1} \\
 I_{22} &= \frac{I_{02}}{r_2^2} e^{-\Delta_2 r_2} \\
 I_{32} &= \frac{I_{02}}{r_3^2} e^{-\Delta_2 r_3} \\
 I_{42} &= \frac{I_{02}}{r_4^2} e^{-\Delta_2 r_4}
 \end{aligned} \quad (4)$$

where Δ_2 is the attenuation coefficient in the medium at frequency f_2 , I_{02} is the intensity of the emission signal at the source at frequency f_2 .

Calculate (5) the ratio of the intensities of acoustic emission signals measured at the frequency f_2 , for different reception points identical to Eq. (3):

$$\begin{aligned}
 \frac{I_{12}}{I_{22}} &= \frac{I_{02} e^{-\Delta_2 r_1}}{r_1^2} \frac{r_2^2}{I_{02} e^{-\Delta_2 r_2}} = \frac{r_2^2}{r_1^2} e^{\Delta_2 (r_2 - r_1)} = \alpha_2 \\
 \frac{I_{12}}{I_{32}} &= \frac{I_{02} e^{-\Delta_2 r_1}}{r_1^2} \frac{r_3^2}{I_{02} e^{-\Delta_2 r_3}} = \frac{r_3^2}{r_1^2} e^{\Delta_2 (r_3 - r_1)} = \beta_2 \\
 \frac{I_{12}}{I_{42}} &= \frac{I_{02} e^{-\Delta_2 r_1}}{r_1^2} \frac{r_4^2}{I_{02} e^{-\Delta_2 r_4}} = \frac{r_4^2}{r_1^2} e^{\Delta_2 (r_4 - r_1)} = \gamma_2
 \end{aligned} \quad (5)$$

Calculate (6) the distance from sensor 2 to emission source using ratio of α_1 to α_2 :

$$\begin{aligned}
 \frac{\alpha_1}{\alpha_2} &= \frac{r_2^2 e^{\Delta_1 (r_2 - r_1)}}{r_1^2} \frac{r_1^2}{r_2^2 e^{\Delta_2 (r_2 - r_1)}} = e^{(\Delta_1 - \Delta_2)(r_2 - r_1)} \\
 \ln \frac{\alpha_1}{\alpha_2} &= (\Delta_1 - \Delta_2)(r_2 - r_1) \\
 (r_2 - r_1) &= \frac{1}{(\Delta_1 - \Delta_2)} \ln \frac{\alpha_1}{\alpha_2} = \alpha_{12} \\
 r_2 &= r_1 + \alpha_{12}
 \end{aligned} \quad (6)$$

Calculate (7) the distance from sensor 3 to emission source using ratio of β_1 to β_2 :

$$\begin{aligned}
 \frac{\beta_1}{\beta_2} &= \frac{r_3^2 e^{\Delta_1 (r_3 - r_1)}}{r_1^2} \frac{r_1^2}{r_3^2 e^{\Delta_2 (r_3 - r_1)}} = e^{(\Delta_1 - \Delta_2)(r_3 - r_1)} \\
 \ln \frac{\beta_1}{\beta_2} &= (\Delta_1 - \Delta_2)(r_3 - r_1) \\
 (r_3 - r_1) &= \frac{1}{(\Delta_1 - \Delta_2)} \ln \frac{\beta_1}{\beta_2} = \beta_{12} \\
 r_3 &= r_1 + \beta_{12}
 \end{aligned} \quad (7)$$

Calculate (8) the distance from sensor 4 to emission source using ratio of γ_1 to γ_2 :

$$\begin{aligned}
 \frac{\gamma_1}{\gamma_2} &= \frac{r_4^2 e^{\Delta_1 (r_4 - r_1)}}{r_1^2} \frac{r_1^2}{r_4^2 e^{\Delta_2 (r_4 - r_1)}} = e^{(\Delta_1 - \Delta_2)(r_4 - r_1)} \\
 \ln \frac{\gamma_1}{\gamma_2} &= (\Delta_1 - \Delta_2)(r_4 - r_1) \\
 (r_4 - r_1) &= \frac{1}{(\Delta_1 - \Delta_2)} \ln \frac{\gamma_1}{\gamma_2} = \gamma_{12} \\
 r_4 &= r_1 + \gamma_{12}
 \end{aligned} \quad (8)$$

Form Eq. (9) of 4 spheres with centers at different reception points:

$$\begin{aligned}
 (x_0 - x_1)^2 + (y_0 - y_1)^2 + (z_0 - z_1)^2 &= r_1^2 \\
 (x_0 - x_2)^2 + (y_0 - y_2)^2 + (z_0 - z_2)^2 &= r_2^2 = (r_1 + \alpha_{12})^2 \\
 (x_0 - x_3)^2 + (y_0 - y_3)^2 + (z_0 - z_3)^2 &= r_3^2 = (r_1 + \beta_{12})^2 \\
 (x_0 - x_4)^2 + (y_0 - y_4)^2 + (z_0 - z_4)^2 &= r_4^2 = (r_1 + \gamma_{12})^2
 \end{aligned} \quad (9)$$

and transform them into a system of 3 equations (10) with three unknowns (x_0, y_0, z_0) that need to be solved:

$$\begin{aligned}
 \sqrt{[(x_0 - x_1)^2 + (y_0 - y_1)^2 + (z_0 - z_1)^2]} &= \sqrt{(x_0 - x_2)^2 + (y_0 - y_2)^2 + (z_0 - z_2)^2} - \alpha_{12} \\
 \sqrt{[(x_0 - x_1)^2 + (y_0 - y_1)^2 + (z_0 - z_1)^2]} &= \sqrt{(x_0 - x_3)^2 + (y_0 - y_3)^2 + (z_0 - z_3)^2} - \beta_{12} \\
 \sqrt{[(x_0 - x_1)^2 + (y_0 - y_1)^2 + (z_0 - z_1)^2]} &= \sqrt{(x_0 - x_4)^2 + (y_0 - y_4)^2 + (z_0 - z_4)^2} - \gamma_{12}
 \end{aligned} \quad (10)$$

Results

To verify the developed problem-solving method, set the initial data for checking the algorithm for determining the coordinates of the acoustic emission source. The input data for solving the problem will be:

- (1) Coordinates of the receivers at four different points (x_1, y_1, z_1) , (x_2, y_2, z_2) , (x_3, y_3, z_3) and (x_4, y_4, z_4) ;
- (2) Attenuation coefficients Δ_1 and Δ_2 for two different reception frequencies f_1 and f_2 ;
- (3) Measured intensity values at four different reception points I_1 , I_2 , I_3 and I_4 for two frequency bands.

Check the operation of the algorithm on accurate, pre-known input and output values.

Set the coordinates of the receivers (in meters) at four different points:

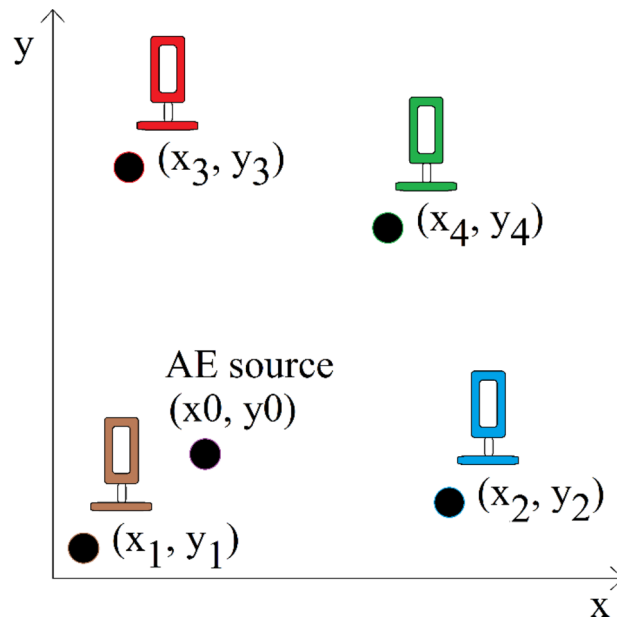


Fig. 1. Coordinates of the four receivers and the acoustic emission signal source on the (x, y) plane.

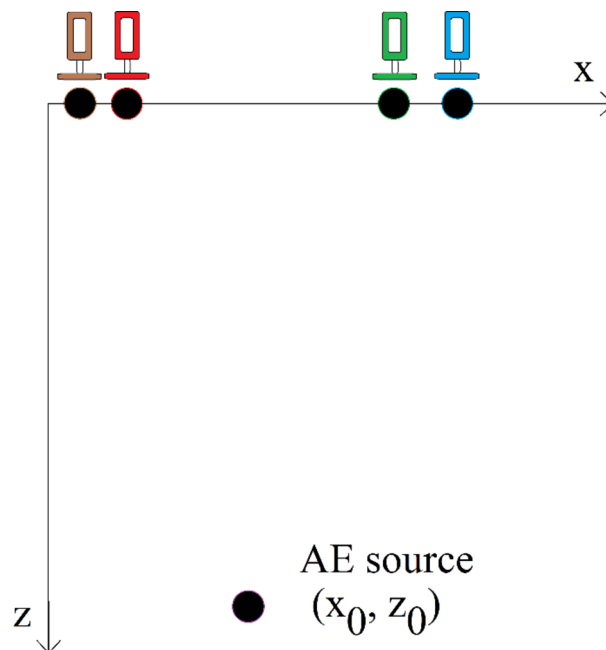


Fig. 2. Coordinates of the four receivers and the acoustic emission signal source on the (x, z) plane.

$$(x_1, y_1, z_1) = (100, 100, 0) \quad (x_2, y_2, z_2) = (1300, 250, 0) \quad (x_3, y_3, z_3) = (250, 1350, 0) \\ (x_4, y_4, z_4) = (1100, 1150, 0)$$

Set the coordinates of the acoustic emission source (in meters):

$$(x_0, y_0, z_0) = (500, 400, 1600)$$

Figures 1 and 2 show the coordinates of the four receivers and the acoustic emission signal source on the (x, y) and (x, z) planes with the specified values for verifying the algorithm.

Calculated distances from the four receivers to the source (in meters), using formulas (9), will be equal (rounded to 1 m):

$$r_1 = 1676 \quad r_2 = 1795 \quad r_3 = 1877$$

$$r_4 = 1866$$

Set the values of the attenuation coefficients Δ_1 and Δ_2 for two different reception frequencies f_1 and f_2 equal:

$$\Delta_1 = 0.001 \quad \Delta_2 = 0.002$$

The attenuation coefficients used for calculations are conditional. The actual values of attenuation coefficients can be empirically measured or taken from tables of dependences of attenuation coefficients, taking into account the frequency of the signal and the types of rocks.

Using Eqs. (2–9) find the required parameters for calculations α_{12} , β_{12} and γ_{12} :

$$\begin{aligned} \alpha_1 &= \frac{I_{11}}{I_{21}} = \frac{r_2^2}{r_1^2} e^{\Delta_1(r_2-r_1)} = 1.2915 & \alpha_2 &= \frac{I_{12}}{I_{22}} = \frac{r_2^2}{r_1^2} e^{\Delta_2(r_2-r_1)} = 1.4544 \\ \beta_1 &= \frac{I_{11}}{I_{31}} = \frac{r_3^2}{r_1^2} e^{\Delta_1(r_3-r_1)} = 1.5340 & \beta_2 &= \frac{I_{12}}{I_{32}} = \frac{r_3^2}{r_1^2} e^{\Delta_2(r_3-r_1)} = 1.8759 \\ \gamma_1 &= \frac{I_{11}}{I_{41}} = \frac{r_4^2}{r_1^2} e^{\Delta_1(r_4-r_1)} = 1.4984 & \gamma_2 &= \frac{I_{12}}{I_{42}} = \frac{r_4^2}{r_1^2} e^{\Delta_2(r_4-r_1)} = 1.8117 \\ \alpha_{12} &= \frac{1}{(\Delta_1 - \Delta_2)} \ln \frac{\alpha_1}{\alpha_2} = 118.7891 & \beta_{12} &= \frac{1}{(\Delta_1 - \Delta_2)} \ln \frac{\beta_1}{\beta_2} = 201.2098 \\ \gamma_{12} &= \frac{1}{(\Delta_1 - \Delta_2)} \ln \frac{\gamma_1}{\gamma_2} = 189.8678 \end{aligned}$$

Using equations (10), create three equations with three unknown desired source coordinates (x_0, y_0, z_0) , that need to be solved:

$$\begin{aligned} \sqrt{[(x_0 - 100)^2 + (y_0 - 100)^2 + (z_0 - 0)^2]} &= \sqrt{(x_0 - 1300)^2 + (y_0 - 250)^2 + (z_0 - 0)^2} - 118.7891 \\ \sqrt{[(x_0 - 100)^2 + (y_0 - 100)^2 + (z_0 - 0)^2]} &= \sqrt{(x_0 - 250)^2 + (y_0 - 1350)^2 + (z_0 - 0)^2} - 201.2098 \\ \sqrt{[(x_0 - 100)^2 + (y_0 - 100)^2 + (z_0 - 0)^2]} &= \sqrt{(x_0 - 1100)^2 + (y_0 - 1150)^2 + (z_0 - 0)^2} - 189.8678 \end{aligned}$$

The Matlab software environment was used to solve the problem. Entering of the following command in the command line solve the equations:

```
syms x0 y0 z0
[x0,y0,z0]=solve...
(((x0-100)^2+(y0-100)^2+(z0-0)^2)^0.5==...
((x0-1300)^2+(y0-250)^2+(z0-0)^2)^0.5-118.7891,...
((x0-100)^2+(y0-100)^2+(z0-0)^2)^0.5==...
((x0-250)^2+(y0-1350)^2+(z0-0)^2)^0.5-201.2098,...
((x0-100)^2+(y0-100)^2+(z0-0)^2)^0.5==...
((x0-1100)^2+(y0-1150)^2+(z0-0)^2)^0.5-189.8678)
```

The Matlab software environment calculates the coordinates of the source (in meters) and provides two solutions, the second of which cannot be a source of acoustic emission of rocks, since it is located above ground level:

$$(x_0, y_0, z_0) = (499.93, 399.73, 1601.72) \quad (x_0, y_0, z_0) = (499.93, 399.73, -1601.72)$$

Verification confirms the algorithm's performance. The calculation error was 1.7 m.

Discussion

People have known for a long time that different attenuation dependences of sound waves can be used to determine the range. Each person, subconsciously, can roughly estimate the range of acoustic events, such as the sound of a gunshot or the noise of a locomotive. There are special studies devoted to this issue⁴⁰. Advances in the development of artificial intelligence suggest that the accuracy of determining the distance to the sound source can be significantly improved. In this paper, we have shown that the use of a two-frequency intensity measurement method and the presence of at least four receiving sensors makes it possible to solve the problem of determining the coordinates of the signal source. The errors in determining coordinates obtained during modeling are probably related to errors that occur due to rounding decimal numbers during calculations.

The example used in the modeling with the location of the receiving sensors on the same plane (on the earth's surface) is not a requirement. The resulting system of equations is solved in a general way and does not depend on the specific geometry of the locations of the sensors themselves.

Multipath propagation of the signal is the main disadvantage of the RSSI method, which reduces the accuracy of measuring the amplitude of the signals due to possible interference during their re-reflections from inhomogeneities in the ground. The solution to this problem was proposed in the article⁴¹ using multi-frequency averaging to reduce interference when signal sources used are narrow-band. In the case described in this paper, the signal source is broadband in nature and interference may not be as significant. Although, the frequency band in which it is required to measure the spectrum to reduce interference errors requires additional study.

We considered the case with only two frequency bands, although there are significantly more of these frequency bands that can be selected (and used for analysis). Increasing the number of receiving sensors will also reduce measurement errors and increase the reliability of collapse warning systems in practice.

The exact values of the signal attenuation coefficients at different frequencies can be determined empirically in advance, which makes it possible to apply the method to localize foci of destruction in a rock mass during

underground mining³⁷. To do this, it is enough to apply a calibrated signal source, placing it in different control sections of the mine.

The proposed method can also be used to determine the coordinates of hypocenters of strong earthquakes. In⁴², 1–2 days before an earthquake with a magnitude of 5 at a distance of 200 km from the future hypocenter a case of registering of broadband acoustic emission signals in the frequency range from 200 Hz to 11 kHz was described. It was shown in⁴³ that acoustic emission associated with fracturing of rocks is most informative in the frequency band of 4–11 kHz. This frequency band allows to allocate 4 frequency bands with a width of 1/3 octave each.

Conclusions

Investigation of the possibility of using broadband nature of acoustic emission signals to localize areas in which acoustic signals are generated for early warning of an emerging danger was approved.

The paper demonstrated the fundamental possibility of determining the coordinates of an acoustic emission signal source propagating in a dissipating medium with a priori unknown source signal intensity and spectrum of this signal, just with condition that it is broadband, which is typical for random pulse signals of any nature. The derivation of the equations and their solution showed the validity of the algorithm.

The proposed method does not require absolutely strict synchronization of receiving devices, unlike widespread location determination methods such as TDoA and beamforming.

Proposed algorithm is applicable in systems of mine hazards identification and prevention. In addition, an assumption was suggested about possible promising application of the proposed method for determining the coordinates of hypocenters of dangerous earthquakes in their forecast.

Data availability

Necessary data is available from correspondence author by request.

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Author Contributions: Conceptualization, I.V.; methodology, Zh.M.; software, Zh.M.; validation, B.I., Sh.A., K.I., N.I. and G.M.; formal analysis, I.V.; investigation, I.V. and Zh.M.; resources, Sh.A.; data curation, Sh.A.; writing—original draft preparation, Zh.M.; writing—review and editing, I.V.; visualization, Zh.M.; supervision, Sh.A.; project administration, Sh.A.; funding acquisition, Sh.A. All authors have read and agreed to the published version of the manuscript.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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