Methods for spatial direction finding of geoacoustic signals at Mikizha Lake in Kamchatka

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Abstract. In the framework of the work, a spatial analysis of geoacoustic emissions properties recorded by a hydroacoustic receiver in a shallow Mikizha Lake, Kamchatkskiy kray, is carried out. The features of geoacoustic pulse registration are considered, methods to determine the directions of their arrival and to locate the sources are proposed. Examples of geoacoustic signals during background periods and seismic event preparation periods are presented.

1 Introduction

Long-term observations of geoacoustic emission in Kamchatka allowed us to detect high-frequency acoustic emission effect which consists in the increase of geoacoustic radiation intensity and its directivity anisotropy change during rock mass deformation rate increase [1]. This is determined by rock deformations at observation sites and manifests the most at kilohertz frequency range 1–3 days before earthquakes at the distances of first hundreds of kilometers from their epicenters [2, 3]. The data of the direction to geoacoustic signal sources and the distances to them may be applied to determine the stress-deformed state of rocks at an observation site.

In the investigations [1–3] the task of determination of sound wave arrival direction is solved applying combined receivers and vector-phase methods, the concept of which is based on the hydrodynamic rule that one vector and two scalar characteristic are necessary to make a complete description of wave motion in a medium [4]. Three mutually orthogonal projections of pressure gradient are recorded as the vector value, and acoustic pressure and signal propagation medium density are used as scalar values.

A combined receiver (CR), produced by ZAO «Geoakustika» at FGUP VNIIFTRI, is applied to record these signals. The device is capable of measuring simultaneously the acoustic pressure and three mutually orthogonal components of pressure gradient $\nabla P_x(t)$, $\nabla P_y(t)$, $\nabla P_z(t)$, which are projections of pressure gradient vector on the corresponding coordinate axes. When processing these four signals, we can find the vectors of oscillating rate, shift and acoustic radiation power density [4].

The receiver is installed in Mikizha Lake at the distance of 35 cm from its bottom. The depth of the lake at the point of measurements is about 3 m in summer time and the distance from the bottom to the ice lower edge is about 1 m in winter time. The horizontal dimensions of the lake are about 200×700 m [2].

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2 Methods for analysis of geoacoustic emission directivity properties

We consider a three-dimensional structure of the graph of geoacoustic pulse acoustic pressure gradient recorded by the combined receiver. It is clear from figure 1 that the presented geoacoustic pulse has a clearly defined elliptical form which can be used to determine the direction to its source. To solve this problem on a horizontal plane, we successfully apply the amplitude method described in the paper [4] and realized in hardware-software complex [5].

Figure 1. Example of geoacoustic pulse (a) and acoustic pressure gradient graph reflected in three-dimensional coordinates with projections on coordinate planes (b). In the figure, N , W and V are the axes North-South, West-East and the vertical direction, respectively.

At the first stage of the method, we plot an ellipse describing an area of pulse point group projected on a horizontal plane (figure 2a). The ellipse semi-major axis is directed along the “receiver – signal source” axis. The semi-minor axis corresponds roughly to the noise level.

Figure 2. Determination of the direction to a signal source. Plotting a describing ellipse and determination of noise level $\vec{r}$ (a), elimination of the ambiguity of point directions (b) and calculation of mass center and determination of the azimuth φ to a signal source (c).

After that, we eliminate the ambiguity of directions for all the points in a pulse by analyzing the phase difference of the signals recorded by vector channels and acoustic pressure channel [4]. In the result of this operation, the majority of points with amplitudes, exceeding the background value, are grouped in one half of a describing ellipse along its semi-major axis (figure 2b). The detection of the direction to a signal source is reduced to the calculation of the direction to a mass center M crosshatched region of the describing ellipse (figure 2c):

$$\tan \varphi = \frac{M_y}{M_x}, \quad (1)$$

where: φ is the azimuth, M_x , M_y mass center projections on x and y axes.

The mass of each point participating in the determination of mass center is different and is calculated by the formula $m = r/\bar{r}$, where r is radius-vector, $\bar{r}$ is the describing ellipse semi-minor axis value. Introduction of unequal mass for the points allows us to give the priority to the points with the largest amplitudes which carry the main information of the direction to a pulse source.

Besides this approach, in order to determine the direction to a signal source in a horizontal plane, we can also apply the projections of acoustic power flux $\mathbf{W}$ [4]:

$$\tan \varphi = \frac{W_y}{W_x}, \quad (2)$$

$$W_i = \frac{1}{T} \int_0^T I_i(t) dt, \quad (3)$$

where: T is the averaging interval which should be multiple of the oscillation period or exceed it significantly, $I_i = P(t)V_i(t)$ is the Umov's vector projection, $V_i(t)$ is the projection of oscillatory speed on the axis i , $i = x, y$.

When using this method, the question on the ambiguity of detection of the direction to a signal source does not occur as long as the required information is already contained in the sign of acoustic power flux.

As a rule, to realize the method, we need to know the data of oscillatory speed $\mathbf{V}(t)$ of medium particles. The applied receiver measures sound pressure gradient which is associated with oscillatory speed by the ratio [6]

$$\mathbf{V}(t) \sim \int \nabla P(t) dt. \quad (4)$$

To determine the oscillatory speed $\mathbf{V}(t)$ vector, it is necessary to integrate the signals recorded by pressure gradient channels. As a rule, this operation is performed after Fourier transform, however, due to the short duration of geoacoustic signals, this method is not practically applied. In such cases, it is simpler to realize a shift signal pressure phase $P(t)$ by 90° using its numerical differentiation. In this case, the obtained signal direction coincides with Umov's vector but calculated energy characteristics of pulses will depend on filling frequency. Owing to this fact, we should compare these measures for different pulses carefully.

The described methods may be applicable to estimate the directivity properties in a three-dimensional space. It is realized the most easily for the approach with calculation of acoustic power flux $\mathbf{W}$ vector direction. In order to do that, formula (2) is supplemented by an expression for elevation angle θ

$$\tan \theta = \frac{\sqrt{W_x^2 + W_y^2}}{W_z}. \quad (5)$$

To realize the method for estimation of the direction on a signal source by describing ellipses, it is necessary to perform such operation for signal projections both on a horizontal plane and on both mutually orthogonal vertical planes. After that, it will be possible to calculate three-dimensional coordinates of mass M center and to determine the direction to it.

3 Method for detection of the distance to signal source

In the conditions of location of the combined receiver by the bottom of a shallow lake, significant reflections of the signal from the water surface or ice lower edge are unavoidable. It is due to the fact that the CR referring to the devices of co-oscillating type records superposition of acoustic waves simultaneously propagating in its vicinity. Thus, when analyzing the obtained signals, it is almost impossible to separate different waves from each other and to determine their eigen properties. As a result, the CR may effectively be used to determine the direction to a signal source only in horizontal plane as long as, owing to the broad width of the lake, the signals reflected from the shores arrive with a delay, which exceeds geoacoustic pulse duration multiply, and with significant damping. In such conditions, the vertical channel is affected by the signals reflected from the water surface.

Under certain conditions of signal propagation and recording, we can distinguish characteristic change in medium particle motion which is determined by the impact of a wave reflected from the surface (figure 3). It is clear from the example that during the initial phase of the recorded pulse, reciprocal motion of the receiver along the axis, directed to the signal source, is observed. About 0.5 ms after it, significant change of the graph is observed. It is caused by the overlapping of the signal reflected vertical component on the main signal. These features of the recorded signal may be used to determine the distance to its source.

Figure 3. Example of geoacoustic pulse recorded together with the reflected signal (a) and its reflection in a vertical plane parallel to the North-South axis (b). In figure 3a the gray area is a signal fragment formed by the direct and reflected waves. In figure 3b the same part is marked by a solid line.

To do that, we consider the simplest case when, according to the scheme in figure 4, the receiver records two waves, the direct and the reflected from the water surface or the ice lower edge.

Figure 4. Scheme of direct wave (**SV**) and reflected wave (**OV**) propagation. $S(x_0, y_0)$ is the source, $O(x_1, y_1)$ is the incidence point, $V(x_2, y_2)$ is the receiver.

The distance to a source corresponds to the vector **SV** length

$$|\overline{SV}| = \sqrt{(x_0 - x_2)^2 + (y_0 - y_2)^2}. \quad (6)$$

Thus, the problem is reduced to the finding of signal source coordinates. To do that, according to the scheme (figure 4), we can compose a system of equations.

$$\begin{cases} \sqrt{(x_0 - x_1)^2 + (y_0 - y_1)^2} + \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} - \sqrt{(x_0 - x_2)^2 + (y_0 - y_2)^2} - v \cdot \Delta t = 0, \\ y_0 - x_0 \cdot \tan(90^\circ - \theta) - y_2 = 0, \\ x_1 = \frac{x_0 \cdot y_2}{y_0 + y_2}. \end{cases} \quad (7)$$

where: v is the sound wave propagation velocity in water, Δt is the delay between the times of recording of the direct and reflected waves, θ is the elevation angle.

The first equation in the system takes into account the difference Δt , the second one describes a line with a directing vector **SV**, the third one follows from the reflection law based on which the elevation and reflection β angles as well as their tangents are equal.

The solution of this equation system is the signal source coordinates. It is necessary to substitute the determined coordinates into (6) to determine the distance to a source. Table 1 illustrates several examples of location of geoacoustic pulse sources. The signals were recorded in winter time. The distance from the receiver to the ice lower edge was estimated to be from 0.75 to 0.9 m.

We should note that the obtained values are the lower estimates of real distances since the sound wave refraction effects at the medium boundary are not taken into consideration at this stage of investigation.

Table 1. Examples of location of geoacoustic pulse sources.

Data, time	Azimuth, degrees	Elevation angle, degrees	Delay Δt , s	Distance to source, m
2014.12.08 00:12:03	48	136	0.001031	0.77
2014.12.08 00:23:38	49	136	0.000906	3.83
2014.12.08 00:32:37	49	136	0.000979	1.49
2014.12.08 00:32:37	90	142	0.000844	3.41
2014.12.08 00:34:25	90	142	0.00101	1.7
2015.02.07 14:43:25	155	108	0.000781	1.17

4 Results of geoacoustic pulse investigations in three-dimensional coordinates

The methods described above to determine the direction to geoacoustic emission source were realized in special software which allowed us to compare the results of both approaches. Figure 5 shows the geoacoustic pulse azimuthal distribution from 06:53 on 01.09.2015 till 02:48 on 02.09.2015 UT in the vicinity of an earthquake recorded on 01.09.2015 at 15:51 UT (energy class $Ks = 9.4$, azimuth $Az = 47^\circ$, epicentral distance $D = 99$ km, depth $H = 142$ km).

It is clear from figure 5 that the periods of seismic event preparation and occurrences are characterized by inequality of azimuthal distribution of signal arrival directions that agrees with the works which had been carried out before [7]. We can see the areas from which both direct and the corresponding reflected signals were recorded.

Figure 5. Distribution of directions to geoacoustic pulse sources before the earthquake on 01.09.2015 at 15:51 UT. Dashed line indicates the horizon.

Now we consider an example of pulse direction distribution during a seismically calm period from 08:00 on 26.07.2015 till 08:00 on 27.08.2015 UT (figure [6]). It is clear from the figure that the pulses were mainly recorded in the upper semi-plane. Evidently, these signals are associated only with the noises of the lake surface or the space under the lake. This fact is unlikely to be the result of re-reflection of geoacoustic pulses from the lake surface as long as in such a case we do not observe the areas from which a direct signal from the lower semi-plane is recorded.

The illustrated diagrams show that spatial analysis of geoacoustic signal directivity anisotropy opens great opportunities for further investigations in this direction.

In context of this paper, it is also interesting that the estimate of acoustic power flux vector direction evidently gives more accurate result. It may be confirmed that the diagrams obtained by the analysis of point distribution in a describing ellipse are significantly noisier than those which were obtained in the result of acoustic power flux calculations. In this case we should take into account the fact that the method of acoustic power vector estimate, in the form which we realized, has two significant limitations. Firstly, the method cannot be applied to

Figure 6. Distribution of directions to geoacoustic pulse sources during a seismically calm period from 08:00 on 26.07.2015 till 08:00 on 27.08.2015 UT. Dashed line shows the horizon.

compare different pulse energy properties. Secondly, the method imposes limitations on the duration and filling frequency of the pulses under investigation. Thus, pulse duration should significantly exceed the signal oscillation period. As a result, it is interesting to develop an algorithm joining the two proposed ways of spatial estimate of geoacoustic signal directivity estimate.

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