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ELECTROMAGNETIC MANIFESTATION OF GEOACOUSTIC EMISSION OF THE LITHOSPHERE

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A number of criteria was formulated in order to distinguish the radiation of a lithospheric origin from the atmospheric-lightning and magnetospheric-ionospheric natural radiation. Based on the determined criteria, a method was develop to record and to detect the electromagnetic signals of the lithosphere. A field experiment on simultaneous registration of signals from five different electromagnetic and one acoustic sensor was carried out in a seismically active region. Preliminary data analysis showed correlation of some pieces of data from acoustic and quadrupole channels. To reveal the connection between the acoustic and electromagnetic manifestations of lithospheric processes, the superposed epoch method was used.

Key words: VLF radiation, quadrupole antenna, superposed epoch method

Introduction

Acoustic and electromagnetic radiation of a solid body, occurring in the result of mechanical stress, is a powerful tool of investigation of solid body fault dynamics [1]-[4]. Thus, it is obvious to enrich these investigations by geophysics of lithospheric processes under conditions of natural occurrence.

Research of both acoustic and electromagnetic emission of the lithosphere has a great history. Many laboratory and field experiments has been realized. Theoretical models of both elementary and mesa-scale processes accompanying rock deformations has been constructed. Numerous studies of acoustic and electromagnetic emission of deformed rocks has been carried out in laboratory and field conditions, in wells and mines [5]-[9].

General principles of interaction of acoustic and electromagnetic disturbances in the Earth crust are clear; they are determined by atom interactions in a solid body. However, the character of relation between these disturbances is underinvestigated. This paper is aimed at detecting the connection of acoustic component with the components of natural electromagnetic field.

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Distinctive features of electromagnetic radiation of lithospheric origin

Natural electromagnetic field registered by an antenna on the Earth's surface is a mixture of fields of different origin. The most powerful component of it is associated with atmospheric-lightning activity. The component of magnetospheric-ionospheric origin manifests itself the most during magnetic storms. Lithospheric component is significant in the regions of increased seismic activity. Electromagnetic radiation of technical activity, especially in the range of industrial frequencies, is significant in the areas of dense population.

Investigations of electromagnetic radiation of the lithosphere should be based on the criteria which would allow us to distinguish this radiation from the natural electromagnetic field. To form these criteria, the following should be taken into consideration:

1. The expected level of electromagnetic manifestation of the lithosphere in usual conditions is significantly lower than the average level of the field of natural electromagnetic atmospheric-lightning and magnetospheric origin [7].

2. Natural electromagnetic field over the Earth's surface is the manifestation of relaxation processes of different nature having avalanche character. Thus, it is pulse radiation of random amplitude.

3. The times of occurrence, character and amplitudes of separate relaxation acts have random character.

4. During the electromagnetic radiation propagation in the Earth's crust, the losses are tens of dB/m [10]. Consequently, it is possible to register signals only from the closest lithospheric sources the distance to which is tens of meters which is significantly less than the wave length. Thus, they are located in the receiver near-field zone.

5. A great number of sources of atmospheric-lightning origin are located in the Asian, African and American centers of world lightning activity where 100 – 300 lightning stokes occur every second. Radiation of lightning origin propagates mainly in a waveguide between the Earth's surface and the ionosphere where the losses are from fractions to units of decibel per a kilometer [11]. Therefore, for ELF-SLF waves, the sources of the world lightning centers are in the far-field (wave) zone.

Thus, most significant difference in the parameters of electromagnetic radiation of lightning and lighospheric sources is associated with the zone of source location relatively a detector. Just these circumstances are important to choose a method for detection and registration of radiation from lithospheric sources.

Synthesis of the method

Realization of the criteria for detection of the radiation of lithospheric origin from natural radiation is carried out by technical realization of the criteria in the form of algorithms, software and devices which process signals carrying the data which are a receiver and data processing software.

When analyzing the field, generated by the sources of natural electromagnetic radiation, it is enough to consider emitters of minimal multipolarity, the dipole ones which have the longest typical propagation length.

The dependence of dipole radiation transverse component amplitude on distance r to a source, when propagating in a free space, has the form

$$A = A^0 \frac{\exp(-i\,f\,r/a)}{r} \left(\left(\frac{a}{f\,r} \right)^2 + i \frac{a}{f\,r} - 1 \right) \sin(\theta). \tag{1}$$

Here $a = \dfrac{c}{2\pi\sqrt{\varepsilon\mu}} \approx 5\cdot 10^9$m/s is the constant, c, ε, μ is the light speed, electrical and magnetic susceptibility of a medium, A^0 is a parameter depending on the dipole moment, medium parameters and radiation frequency, θ is the angle between the direction of radiation propagation and the dipole moment, f, r are frequency and distance, respectively.

It is clear from expression (1) that in the near-field zone the amplitude of the field is asymptotically described by the expression $A_{r\to 0} \to r^{-3}$, and in the far-field zone it is described by the expression $A_{r\to\infty} \to r^{-1}$.

The natural field in a seismically active zone may approximately be considered as a sum of atmospheric-lightning $E_L = \dfrac{E_L^0\, a^2}{f^2 r_L^3}$ and lithospheric $E_G = \dfrac{E_G^0}{r_G}$ feilds

$$E = E_L + E_G \approx \frac{E_L^0 a^2}{f^2 r_L^3} + \frac{E_G^0}{r_G} \tag{2}$$

Here E_L^0, E_G^0 are effective amplitudes from lightning and lithospheric sources at the places of their occurrence, r_L, r_G are the distances from lightning and lithospheric sources to a detector.

It should be taken into account that field intensity in the area of generation of lightning sources is much greater than that of lighospheric sources $E_L^0 >> E_G^0$.

The same may be applied to field amplitudes at an observation point $E_L >> E_G$. Moreover, the distance to lightning sources is much greater than that to lithospheric ones $r_L >> r_G$.

It is every indication that direct measurements of the field will not allow us to distinguish signals of ordinary lithospheric events.

Thus, development of a method for distinguishing of signals from lithospheric sources is reduced to the search of such a procedure of measurement of field parameters $F(*)$ which allows us to distinguish and to record weak sources of the near-field zone E_G at the background of strong atmospheric events E_L.

For the further analysis to be correct, it is necessary to introduce an additional distance in the vicinity of a detector $x \sim r_G$.

Then the condition for detection of a signal from a closely located weak source at the background of a prevailing signal from a remote source may be written as follows:

$$F\left\{\frac{E_L^0\, a^2}{f^2 (r_L + x)^3}\right\} < F\left\{\frac{E_G^0}{r_G + x}\right\}. \tag{3}$$

It is clear from the relation that the arguments of the right and the left parts of the inequality have different powers x. It is not difficult to understand that that we can use the x–derivative as such a function, and it is simply realized in the form of a measurement procedure. Using this function, we rewrite the expression (3) as follows:

$$\left|\frac{d}{dx}\frac{E_L^0\, a^2}{f^2 (r_L + x)^3}\right| < \left|\frac{d}{dx}\left\{\frac{E_G^0}{r_G + x}\right\}\right|. \tag{4}$$

Taking into account $x \sim r_G$, equation (4) may be modified into

$$1 < \frac{r_L^2 f}{a\, r_G}\sqrt{\frac{E_G^0}{3E_L^0}}. \tag{5}$$

We estimate to what extent this condition is fulfilled for the frequency range of $f\,\mathrm{dim}\, 10 \div 10^3$ Hz.

The distance to the centers of lightning activity is tens of megameters and to the lithospheric source is tens of meters.

Voltage amplitude in the time of a lighting stroke is estimated as a value equal in order to air breakdown voltage of $\dim 10^6$ V/m.

According to different data, the field strength induced by dislocation motion is $\dim 10^{-10} \div 10^{-7}$ V/m [3, 4].

Substituting these data into expression (5) we see that the inequality is fulfilled

$$10^2 \leq \frac{r_L^2 f}{a\, r_G}\sqrt{\frac{E_G^0}{3E_L^0}} \leq 10^6.$$

The fulfillment of relation (5) means that in the frequency range of $10 \div 10^3$ Hz, the signal from a lithospheric source can be reliably registered and distinguished from strong noise of atmospheric-lightning origin applying an electromagnetic sensor based on registration of electromagnetic field spatial derivative.

In practice, the sensor is a quadupole antenna, a system made of two equally spaced dipole antennas with oppositely oriented dipole moments. This approach is described in detail in [12, 13].

Expreimental set up

Field experiment on synchronous registration of electromagnetic and acoustic fields was carried out at an observation site of IKIR FEB RAS in the valley of Karymshina river (South Kamchatka) (fig. **??**).

It is located in the area of intersection of regional faults of Malko-Petropavlovskaya zone by the bottom of blister cone of Goryachaya mountain. This region is characterized by high level of microseismisity an low level of industrial noise.

Several kinds of sensors were used. Each of them corresponded to a certain information channel during the registration (fig. 2).

1. Quadrupole magnetic antenna is a construction with two opposite magnetic frames. Q-channel is used further for the channel of data registration of a quadrupole antenna.

The sensitivity is $\dim 10^{-15}$ T Hz$^{-0.5}$.

2. Three mutually perpendicular-oriented frame magnetic antennas.

The plane of one of the frames is arranged horizontally (Z-channel), and the planes of other two frames are arranged vertically and according to the cardinal points (WE- and NS-channels).

The sensitivity of WE and NS-channels is $\dim 10^{-16}$ T Hz$^{-0.5}$, that of Z-channel is $\dim 10^{-15}$T Hz$^{-0.5}$.

3. Electric rod vertical antenna had the sensitivity of $\dim 10^{-8}$A m Hz$^{-0.5}$ (E-channel).

4. The acoustic sensor of soil vibrations (A-channel). This sensor is a hydrophone placed in an artificial water reservoir, where water acted as immersion minimizing acoustic boundary acoustic resistance with geological medium.

Antenna amplifiers are mounted near the antennas to minimize noises. Signals from these amplifiers arrive at the registering unit (PC) via screened twisted pairs.

The experiment was carried out in dry weather conditions and included two sessions of continuous synchronous registration of the data from these sensors. The total time of observation was 49 hours. The sampling frequency was 44100 Hz. The distance from the registration site to the acoustic sensor was 20 m, to Q и Z – sensors – 35 m, to WE, NS and E sensors – 180 m. We may neglect the time difference of signal propagation from different sensors since the time interval between adjacent samples ($2 \cdot 10^{-5}$c) significantly exceeded the time of signal propagation along the cable from the sensors to the recorder ($10^{-7} \div 10^{-6}$s). The typical size of the spatial zone of an acoustic sensor sensitivity is several meters due to the strong sound attenuation in soil [6]. Thus we can roughly consider that the location of an acoustic radiation source coincides with the location of the acoustic sensor. The time of propagation of an electromagnetic signal in soil for typical conductivity values from the vicinity of the acoustic sensor is not more than

Fig. 1. Dislocation of the experiment

$4 \cdot 10^{-7}$s, i.e. it is significantly less than the sampling period. All these means that signal delay in the time of electromagnetic disturbance propagation in soil should not affect the moment of signal arrival at a recording device. The effect of construction peculiarities of pre-amplifiers on the difference of registration time of various channels is quite possible.

Analysis of the results

Preliminary visual analysis showed significant difference in the character of data of different channels.

More detailed analysis of wave forms of the channels allowed us to discover coordinated variation of signals in acoustic and quadrupole channels around the extreme values of the acoustic signal. The illustrated example (fig. **??**) confirms this fact.

As long as the flow of acoustic events is significantly less than the flow of electromagnetic data, it is reasonable to be restricted to the analysis of electromagnetic events occurred close to the times of acoustic events when detecting acoustic-electromagnetic relations.

To do that we chose acoustic channel record fragments containing strong bursts of a signal, outbursts exceeding the average value by not less than 10 times in amplitude. The duration of the fragment also exceeded the characteristic duration of a peak by not less than 10 times. Such

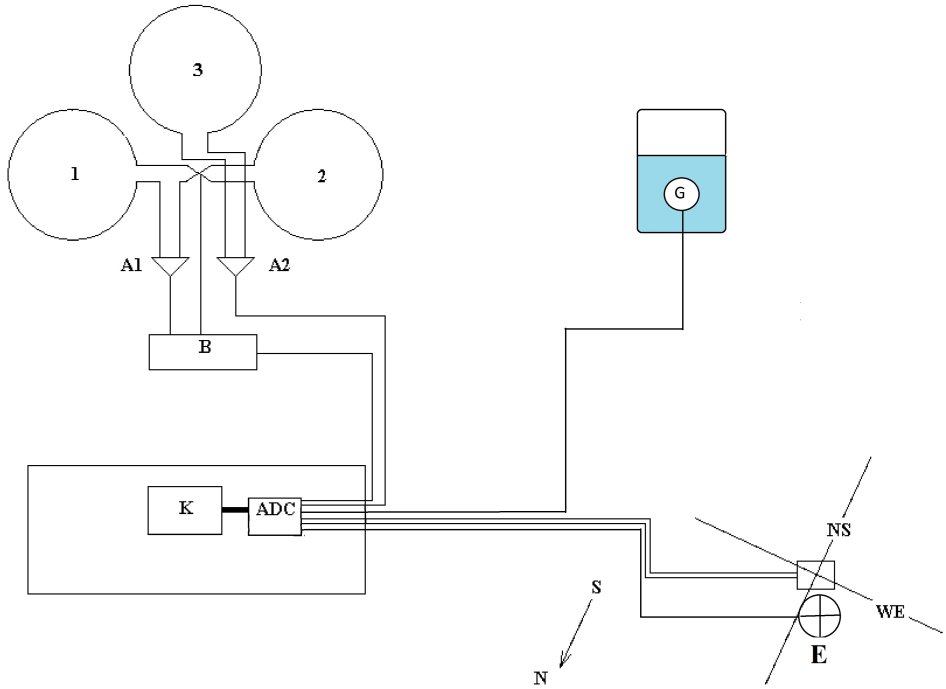

Fig. 2. Scheme of the experiment. 1 and 2 are quadrupole antenna arms, 3 is Z-antenna, A1, A2 are antenna amplifiers of Q and Z channels, B is a symmetrizing unit of the quadrupole antenna, G is an acoustic sensor, NS, WE are north-south and east-west antennas with antenna amplifiers, E is an electric antenna with an amplifier

a choice allowed us to distinguish electromagnetic signals of lithospheric origin with a high degree of certainty. In all, about 400 000 such events were analyzed.

We should note that the density of events in the acoustic channel is significantly less (by 10-100 times) than in electromagnetic channels. However, it turned out that application of cross-correlation function apparatus to time series having similar wave form of different processes with substantially different densities of event flows is ineffective. The superposed epoch method that we used refers to the number of methods insensitive to the difference of event flux densities.

Superposed epoch method

As it was mentioned above, a flux of events of atmospheric-lightning origin significantly exceeds the lithospheric flux of events. Therefore, to detect the relation between different channels, a superposed epoch method is used. It allows us to average sample fragments of a signal relatively a reference event of a reference channel. A reference event is characterized by the features which distinguish it from other events, for example, defined time interval between such events when searching for hidden periodicity or quite large amplitude in comparison to the background allowing us to consider it as a burst.

The superposed epoch method is the following procedure. Two data samples received in different channels, in a reference one I_r and in the one under investigation I_s, are used. The character of the connection between the processes in the channels is suggested to be determined by the coupling function $K(I_r, \tau_r, \tau_s)$, depending on the difference of event moments in a reference and investigated channels $\Delta\tau_{rs} = \tau_s - \tau_r$ steadily increasing function of a reference signal $I_s \dim I_r$:

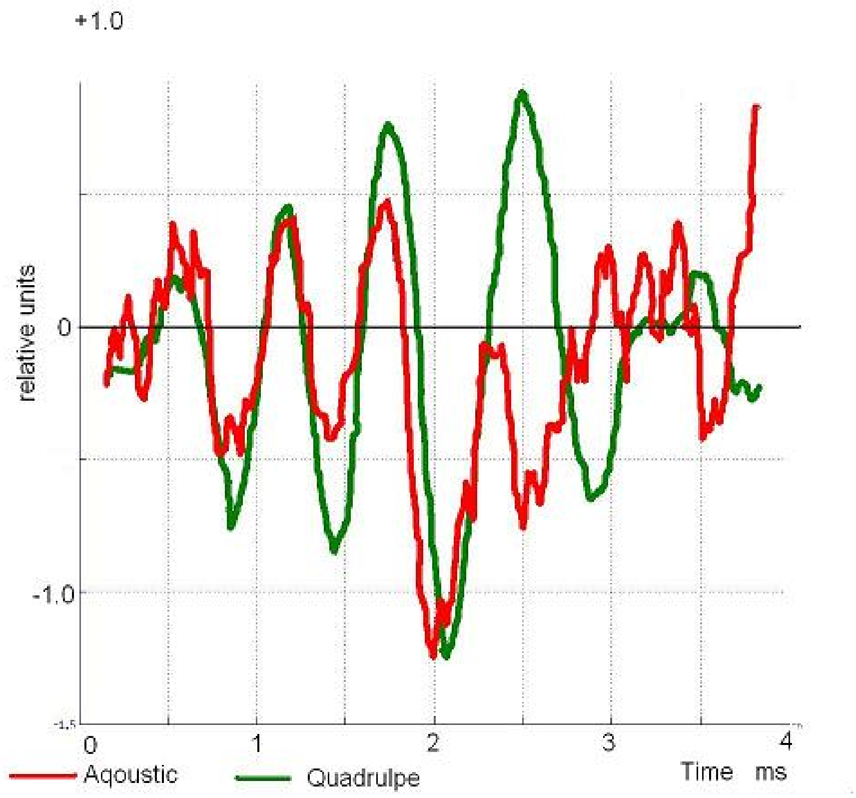

Fig. 3. Example of a strong signal in acoustic and quadrupole channels

$$I_s(\tau_s) = \int_{-\infty}^{\infty} K(I_r, \tau_s - \tau_r)\, I_s(\tau_r)\, d\tau_r.$$

If we choose data fragments in the vicinity of a strong maximum in which the values adjacent to the maximum are close to the background values

$$I_r(\tau) >> I_r(\tau + \Delta\tau);\ I_r(\tau) >> I_r(\tau - \Delta\tau),$$

the relation in this interval may be approximately written as follows:

$$I_s(\tau_s) \approx K(I_r, \tau_s - \tau_r)\, I_r(\tau_r).$$

If we now average over all the possible values of the times of maximums of a reference signal satisfying conditions (6):

$$\overline{I_s(\tau_s)} = \sum_r K(I_r, \Delta\tau_{sr})\, I_r(\tau_r) = K(I_r, \tau_s - \tau_r)\, \overline{I_r(\tau_r)}, \tag{6}$$

and center the averaged sample timing relatively the time of a reference signal maximum assuming that $\tau_r = 0$, we obtain

$$\overline{I_s(\tau_s)} = K(I_r, \tau_s)\, \overline{I_r(0)}.$$

Here τ_s now has the sense of time interval between the maxima of an averaged reference signal and the channel under investigation. In other words, anticipation of the reference signal by the signal under investigation corresponds to negative values of τ_s, and lagging of the investigated signal in relation to the reference one corresponds to the positive values of τ_s. Actually, the superposed epoch method is the recovery of a function of coupling of two processes. One of the processes (reference) is used to form a sequence of reference moments. In this case, the coupling function may be determined as follows:

$$K(I_r, \tau_s) = \frac{\overline{I_s(\tau_s)}}{I_r(0)}.$$

An example of such an approach was used in [14].

Application of periodically arranged references allows us to detect hidden periodicities of arbitrary shape, for example, the shape of pulsar light curve. In our case, the superposed epoch method was used to determine the relation between acoustic and electromagnetic channels.

In order to check the efficiency of this method, the coupling functions of different channels in relation to the reference channel were calculated (Fig. 4).

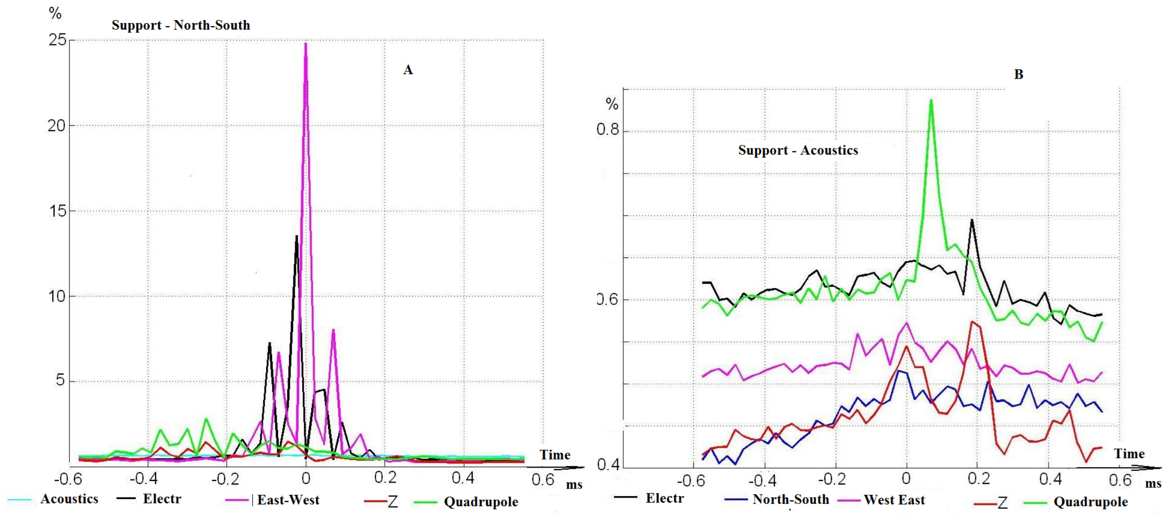

Fig. 4. Coupling functions between different channels. A – the reference signal is from a magnetic antenna with north-south orientation, B – the reference is the acoustic channel

In the example shown (Fig.4A), the channel of a magnetic antenna, the plane of which is oriented in the north-southern direction, is chosen as the reference channel. Good correlation of signals from the antennas of north-southern and west-eastern orientation is observed when comparing them visually. That is confirmed by application of the superposed epoch method which shows clearly defined maximum at the coincident point (0 shift). In other words, events in north-south and west-east are synchronous, and the frequency of their coincidence is 25%. The events in the north-south and electric channel also correlate quite well. However, in this case the events in electric channel anticipate the events of magnetic channel. It may be explained by the difference of the receiving and recording instrumentation in electric and magnetic channels.

Fig. 4B shows the values of acoustic-electromagnetic coupling functions in the vicinity of $(-0.8 \div 0.6)$ ms relatively the acoustic burst. The maximum of this curve indicates electromagnetic manifestation of acoustic disturbance which occurred at 0.1 ms after the acoustic one (green line in Fig. 3B). The observed value of shift of electromagnetic signal relatively the acoustic one may be explained by the effect of recording instrumentation. Weaker manifestations of acoustics were also observed in Z channel (black curve in Fig. 4B). On the curves of coupling functions of the acoustic channel with other channels, electromagnetic manifestations of acoustic disturbance were not observed. The strongest connection is detected between the acoustic and the quadrupole channels. The shift by about 0,7 ms may be explained by the effect of the receiving instrumentation. The frequency of manifestation of the acoustic channel in the quadrupole one is about 0.84%. Manifestation of the acoustics in the vertical component slightly exceeds the background noise, that is about 0.7% . Manifestation of the acoustic signal in other channels is at the background noise.

Discussion of the results and conclusions

The quadrupole antenna, which registers the horizontal spatial derivative of the magnetic field vertical component, turned to be the most sensitive to the signals of relaxation events of the lithosphere.

Absence of the relation of horizontal magnetic components with the acoustic field means that the magnetic component of the electric field of lightospheric origin has mainly subvertical direction. In its turn, it indicates the horizontal polarization of the electric component of this field.

Manifestation of the acoustic radiation in the quadrupole channel indicates the longest distance to the source of this radiation.

The conducting ionosphere over the Earth's conducting surface result in the formation of a slab resonator for vertically distributing waves with horizontal electric component. The characteristic size of the coherence area and the characteristic region of radiation propagation from a source are comparable with the radiation wave length. These circumstances allow us to hope for the detection of electromagnetic manifestations of seismic events occurring within the period of earthquake preparation by a long base quadrupole magnetic antenna with horizontal arrangement of the plane.

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