Investigation of acoustic phenomena from extensive atmospheric showers

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Abstract. The experiment on search of acoustic phenomena from EAS was carried out in the scheme of the trigger start from the scintillation installation. Two methods were developed for search of weak ultrasonic pulses from showers: method of peak and noncoincidences and method of small peaks. The results (obtained from different hydrophones) at very different noises and geometries point at the registration of acoustic effects from showers.

1. Introduction

In the process of evolution the Extensive Atmospheric Showers (EAS) reach the surface of the Earth and further development and propagation of electromagnetic and hadronic-electromagnetic cascades will be in the dense medium. In the presented experiment the EAS were registrated by means the scintillation installation placed on the Baikal ice. At the instant of registration the scintillation installation produced the trigger signal, which started the acoustic recording in the under-ice water by means the hydrophones.

The shower propagation and absorption goes with heat release that results in generation of ultrasonic waves. The mechanism of sonic waves generation from high energy particles is thermoradiational one. The sonic waves generation originating due to local rapid heating and creation of microcavities along particle tracks were considered by G A Askariyan and the method for acoustic registration of high energy particle was proposed [1,2].

The thermoradiational mechanisms (also called as thermoacoustic, thermoelastic one) of sonic waves generation from high energy particles is the most investigated at the accelerator and lasers experiments [3-9]. Acoustic waves generation in the water from proton beam (\(E_p = 125\) and 200 MeV) with duration of the beam spill-out of 70 ns was investigated at the ITEP synchrotron, that confirmed the prelevant yield of thermoradiational mechanism to sound arising. But at the 4 °C of water temperature the coefficient of thermal expansion vanishes and the thermoradiational mechanism does not work. For investigation of sonic waves generation close to the temperature point 4 °C it was carried out the last ITEP hydroacoustic experiment: the water temperature was on-line controlled by ten electronic detectors (along the beam trajectory) with precision of 0.1 °C in order to observe the another possible mechanisms of sound generation that is especially important for cold water areas as the Baikal.

The hydroacoustic experiment in the Baikal is carried out in tight cooperation of ITEP and BAIKAL Collaboration [10]. The experiment is directed to search of ultrasonic phenomena from EAS.
2. Experimental setup. Geometry
The experimental installation is based on two main parts: the scintillation installation (from Skobeltsyn Institute of Nuclear Physics, Moscow State University) and the hydroacoustic signal path (of ITEP). Six scintillation detectors were placed on the ice in vertexes of the regular hexagon, the seventh detector was situated in the center. The hexagon radius was equal to 50 m (in 2002 and 2003 year) and 70 m in 2001 (see figure 1).

Figure 1. The geometry of the acoustic experiment for EAS registration in 2001-2003 years.

Now the hydroacoustic signal path allows to attach up to 12 hydrophones (and can be extended) with embedded preamplifiers, signal cables, differential amplifiers, special trigger with function of storage and time filter to prevent the possible overflow of signal queue and digitization failures, electronic board for digitization of analog signal and computer. For registration we use the single hydrophones and hydroacoustic antenna of four hydrophones with 7 m step between hydrophones (in 2001) and 5 m step (in 2002 and 2003). The antenna hydrophones were deployed at the depth of 3, 10, 17 and 24 m (in 2001), 3, 8, 13 and 18 m (in 2002) and 4, 9, 14, 19 m (in 2003). For the single hydrophone the deployment was fixed at the depth of the upper antenna hydrophone. One of the single hydrophone was frozen into the ice with purpose for search of EAS sound propagation in the Baikal ice. The analog signals from hydrophones were digitized by means the LCard-783 board at the frequencies (per channel): 250 kHz (in 2001), 250 or 400 kHz (in 2002) and 238 kHz (in 2003). The recording of the acoustic files was made with duration: 0.2 s (in 2001) and 0.1 s (in 2002, 2003).

3. Method of peaks and noncoincidences. Search of acoustic effects from EAS
Acoustic signals is recorded in the digitized form. The digital representation of signals results in the cases of coincidences and noncoincidences of signal peaks from different hydrophones (different signal channels): during some time counts (i.e., time step of digitization $\Delta f$) the local maxima or the local minima occur for both hydrophones simultaneously [11]. The figure 2 illustrates this for two hydrophone channels. We will use the “peak coincidences” term for the cases when in the time count $i$ the local maxima occur in the both channels or in the count $i$ the local minima appear in the both hydrophone channels. Let us introduce the “peak noncoincidences” term if in the time count $i$: 1) the local peak (local maximum or local minimum) is detected only in one channel, or 2) the local maximum exists in one channel, and in the other channel the local minimum appears simultaneously.
Let us make the mental experiment [11]: let a short-time sound source arises in the water (see the figure 3 for the typical geometry: the position of two upper-antenna-hydrophones with respect to the possible simplified sonic source from EAS). When the sonic signal of this source will reach the top hydrophone, it will cause (in common case) some change in the peak positions (for the top hydrophone) compare to the non-arising of this short-time sound source. So, appearing of the short-time sound source will change the coincidences and noncoincidences for peaks of the hydrophone #1 compare to the peaks of the hydrophone #2. We can expect, that the short sonic source originating from EAS will cause change in the distribution of coincidences, noncoincidences and peaks too.

It is necessary to consider the variation of noncoincidence numbers depending on the peak frequency. We will assume that in the time interval $T_S$ the signals in channels are noncorrelated. Let us consider the peaks to be the local maxima. Under this assumption, the probability of peak detection for the hydrophone #1 in the time count $i$ is:

$$W_{i#1} = \frac{\Delta t_d}{T_{i#1}} = \frac{f_{i#1}}{f_d},$$

where $\Delta t_d$, $f_d$ - time step and frequency of digitization; $T_{i#1}$, $f_{i#1}$ - time interval (to which the count $i$ belongs to) between peaks and corresponding frequency. In the same way, the probability of peak absence for the hydrophone #2 in the count $i$ is:

$$\overline{W_{i#2}} = 1 - \frac{f_{i#2}}{f_d}.$$  

The conditional probability of peak noncoincidences for two hydrophones in the count $i$ is:

$$P_{i, \overline{W_{i#1}}|\overline{W_{i#2}}} = \frac{f_{i#1}}{f_d} \left(1 - \frac{f_{i#2}}{f_d}\right).$$

Number of noncoincidences for two hydrophones in the time interval $T_S$ is:

$$N = \sum_{i=1}^{T_S/\Delta t_d} P_{i, \overline{W_{i#1}}|\overline{W_{i#2}}} = \sum_{i=1}^{T_S/\Delta t_d} \frac{f_{i#1}}{f_d} \left(1 - \frac{f_{i#2}}{f_d}\right).$$

If to take into account the peaks both of local maxima and local minimum the value of noncoincidence numbers $N$ will be doubled.

As the upper hydrophone #1 (see figure 3) will register a source wave (which will have an influence on the value $f_{i#1}$ and will change it) $\Delta l/V$ early compare to the hydrophone #2 (here $V$ – is the sound velocity in the water), then we can conclude that the number of peak noncoincidences $N$ (here we take into account the upper hydrophone peaks, which do not coincide with the peaks of the more distant hydrophone #2) is sensitive to a frequency variation of a source especially during the time interval $\Delta l/V$.

All the presented here distribution of peaks and noncoincidence numbers were obtained namely for the top hydrophone relative to the more lower hydrophone (as illustrated in the figure 3).
The desired acoustic phenomena from EAS are small. So, the search of acoustic effects from showers was realized statistically, i.e. by means the accumulation of effects in the sound files of the experimental statistics. For this type of statistical searching the each file is centred relative to the instant of time \( t = 0 \), when the expected sonic signal from EAS will reach the considered hydrophone. The every file is divided into 2 ms time steps, which are numbered with respect to the zero-time-step (the time step with the instant \( t = 0 \) at the centre). The procedure of centering is shown in the figure 4.

At the analyses of distributions of peaks and noncoincidences it was paid attention on the increasing and decreasing of these values relative to the instant of time \( t = 0 \). For the each file we will interest in increasing and decreasing of the values compare to the considered mean value, which is recalculated for the every file. Let us describe step-by-step how to obtain the distributions for the case of noncoincidences decreasing. This procedure is illustrated in the figure 5 by the example of two files statistics (file 1 and file 2): a) in the interval of equal statistics (it is the interval of the maximum statistics - see figure 4) we will find the noncoincidence numbers for the each time steps (see step 1 in figure 5; the mean values level of noncoincidences are marked by dotted lines for the both files ); b) for the each file we obtain the distribution of noncoincidences, which is below the mean level of the current file in the interval of equal statistics (in other word these distributions are positive differences between the mean level of noncoincidences for the current files and noncoincidences in the time steps; see step 2 in figure 5); the extreme values are marked; c) the distributions for every files (results of step 2) are summarized and statistically averaged.

The procedure for the case of noncoincidence increasing (when for some time steps the noncoincidence numbers is above the mean level of noncoincidences for the given file) is completely similar to the described steps.

The distributions of the peaks and noncoincidence numbers for the top antenna hydrophone are shown for the data of 2002 and 2003 year in the figure 6. The minimum as for peaks as for noncoincidence numbers appears in the two experiments close to the \( t = 0 \) (the instant of time for expected signal from EAS): in the interval \( t = (-2 \div 0) \) ms.

The found tendency to lowering of frequencies close to the EAS instant of time is also confirmed by results on probability to registrate the noncoincidence numbers below the mean level of noncoincidences. This distribution of probability density (obtained on the data of 2001, 2002 and 2003 years) is presented in the figure 7. The maximal probability appears close to the EAS instant at \( t = -2 \) ms. This tendency was derived from data of “water” hydrophone.

One of the single hydrophone was frozen in the ice for search of the acoustic effects from showers. The data processing was realized under the assumption that the sound speed in the ice is about 3900 m/s. For processing the method of peaks and noncoincidences was modified: the peaks in the current time step are considered as registrated by the lower hydrophone, but the signals in the previous time step were used as received from the top hydrophone; In the other words, the method of quasi-noncoincidence was applied to fill the absence of the second hydrophone in the geometry of the figure 3. This analyses indicated on the tendency of increasing for the peak frequency.
Figure 5. Steps of the procedure for obtaining of the noncoincidence distributions in the case of noncoincidence decrease relative to the mean level. EAS instant of time is marked by the vertical arrow at the time $t = 0$. The procedure for the case of noncoincidence increase is completely similar.

Figure 6. Distributions of peak numbers (see curves with points and left axes of ordinates) and noncoincidence numbers (see curves with cross marks and right axes of ordinates) relative to the EAS instant of time. The distributions are derived from the Baikal experiments in 2002 and 2003. EAS instant of time is marked by the vertical dotted line with arrow at the time $t = 0$. The horizontal arrowheads show radial distances, which correspond to the time intervals of distributions.

Figure 7. Probability density of noncoincidence numbers to be below than the mean value of noncoincidences per 2 ms time step. The distribution (obtained on the data of 2001, 2002 and 2003 years) is drawn relative the EAS instant of time $t = 0$. The horizontal arrowheads show radial distances, which correspond to the time intervals of distributions.

Figure 8. Distributions for the hydrophone frozen in the ice: 1) increase of noncoincidence numbers relative to EAS instant of time (see the curve with points and left axis of ordinates); 2) probability of the extreme noncoincidence relative to EAS instant of time (see the cross marks curve and right axis of ordinates). EAS instant of time $t = 0$ is marked by the vertical dotted line with arrow.
It was derived the noncoincidence distribution for the case of increasing according to the steps a) ÷ c) of the above discussed procedure (see figure 8). The maximum appears close to EAS instant of time \( t = 0 \): at \( t = 2 \) ms (see upper curve and left axis of ordinates). The lower curve (see the right axis of ordinates) shows probability of extreme values for the interval \( t = [-7, 73] \) ms and has also the highest level in the same moment \( t = 2 \) ms (illustration of extremes is presented in the step 2 of figure 4). Taking into account the sound velocity in the ice, the time interval of the distribution corresponds to signal registration in 312 m radius from the hydrophone frozen into the ice.

4. Search of acoustic effects from EAS by means the method of small peaks

Let us carry out the mental experiment: let the weak bipolar sound pulse (origin from the shower in the EAS core) arise in the water. The bipolar pulse will cause the weak correction of the amplitude \( A \) of the registrated summary signal.

![Diagram](image)

Figure 9. Method of small peaks: illustration for creation of the local minimum at superposition of the weak bipolar pulse on the weakly changing noise (for visualization the bipolar pulse is multiplied by 20).

![Diagram](image)

Figure 10. Distribution of the local minima with respect to the instant of time \( t = 0 \), when expected acoustic signals from EAS will reach the considered hydrophone. Distributions are presented for amplitude changes \( \Delta = 1 \) (figure 10a) and \( \Delta \leq 2 \) (figure 10b). For amplitude changes \( \Delta = 1 \) the distribution of local minima are given also for different distances of the shower axis from the hydrophone: \( R = (31.6 \pm 46.4) \), \( 46.4 \pm 55.3 \) and \( 55.3 \pm 91.5 \) m (see figure 10c, 10d, 10e, respectively).
It is possible the cases when for two adjacent time counts \( (i-1) \) and \( i \) the amplitude change of the noise signal \( |A_i^{\text{noise}} - A_{i-1}^{\text{noise}}| \) is equal to several counts of the electronic card for digitization. Such weak changes of the noise are of interest: superposition of the weak bipolar pulse on the weakly changing noise (see figure 9) can create the local extremum in the summary digitized signal as well as to destroy the local extremum in the noise signal if \( |A_i^{\text{bipolar pulse}} - A_{i-1}^{\text{bipolar pulse}}| < |A_i^{\text{noise}} - A_{i-1}^{\text{noise}}| \).

The example for the such creation of the local minimum is shown in the right part of the figure 9. In the experimental data the search of local extremums was realized for the small amplitude changes of the registrated signals and additionally for this search we required the sign-changing tangent in the intervals \( [i-2, i-1] \), \( [i-1, i] \), \( [i, i+1] \) (see right part of the figure 9).

Basing on the 2003 year experiment it was obtained the distribution of such local minima \( N_{\text{min}} \) at \( \Delta = 1 \) (see figure 10a) and at \( \Delta \leq 2 \) (figure 10b). In the distribution the jump is clearly visible at the time \( t = 0 \) (instant of time when the expected signal from the shower reaches the hydrophone). The effect is pronounced stably at \( t = 0 \) and exists in the distributions for different distances of the shower axis from the hydrophone (see distributions of the local minima at \( \Delta = 1 \) for the intervals of the distance \( R = (31.6 - 46.4), (46.4 - 55.3) \) and \( (55.3 - 91.5) \) m in the figure 10c, 10d and 10e, respectively).

5. Conclusion

These experimental investigation (in cooperation of ITEP and BAIKAL Collaboration) is directed to seach of acoustic phenomena from extensive atmospheric showers. The experiment is realized in the scheme of the trigger start (trigger signal from the scintillation installation for EAS registration) for the hydroacoustic detectors.

It was developed two methods for search of weak acoustic effects: 1) the method of peaks and noncoincidences (amplitude-independent algorithm) and 2) the method of small peaks, which aimed at seaching of acoustic pulses close to the detection limit. The analyses of experimental data indicates on the acoustic effect close to the instant of time of the expected ultrasonic signal from showers in the water and ice. The acoustic phenomena display itself on the base of data from different hydrophones and from the hydrophone which was frozen in the ice.

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