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On the use of the mutual correlation of cosmic rays penetrating the earth's crust with geoacoustic emission

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The elastic deformation energy accumulated at the edges of a fault in the earth's crust in a seismically active area can be released with a small external impact, causing vibrations that propagate in the form of a sound wave through the lithosphere and can be detected on its surface. As a trigger effect that causes such a vibration, an ionization can be used that is created in the deep lithosphere by particles of the penetrating component of cosmic rays. This idea was once proposed in the number of theoretical studies. An experiment to test this hypothesis was started at the cosmic ray facility at the Tien Shan Mining Scientific Station. As a result, short-term sporadic acoustic emission signals were recorded by highly sensitive microphone detectors of the station. Presumably, the origin of this emission can be associated with seismic processes occurring in the area of a deep earth fault, located directly under the station. A statistically significant temporal correlation has been found between acoustic emission and high-energy cosmic ray muon events up to 100 TeV. If the further research in this direction is confirmed, then the effect of stimulated acoustic emission from a seismically active region of the earth's crust may be of interest for solving the problem of short-term earthquake prediction.

Keywords: acoustic emission; cosmic rays; seismic activity; earthquake precursors

Introduction

To reduce material losses and avoid human casualties during earthquakes, the short-term and operational forecast must correspond to the realities in which rescuers can perform their duties in the best way and with minimal losses. A short-term and operational forecast is the basis for saving the life of the population with timely, systematic and panic-free evacuation. The primary task is to save the lives of children and adults. Of great importance is the timely shutdown of infrastructure, transport, enterprises and their transfer to a mode in which an earthquake (and a possible tsunami) will cause the least harm and destruction [1].

Due to the natural feature of the tectonic process, namely the movement of the earth's interior, the inaccessibility of direct observation of this movement and the impossibility of direct measurement of mechanical stresses in the earth's interior, the earthquake forecast is based on indirect precursors of the upcoming earthquake. These harbingers can be long-term, medium-term or short-term. That is, some precursors may appear for years, but do not carry information about the exact time of the earthquake, others appear hours and minutes before the main destructive shock, but often do not provide information about the strength and location. Such harbingers are generally difficult to use unless prior information from longer term harbingers is available.

The fundamental predictability of seismic catastrophes was beyond doubt for many years. Faith in the limitless predictive potential of science was supported by seemingly quite convincing arguments. Seismic events with the release of huge energy cannot occur in the bowels of the Earth without preparation. It should include certain changes of the structure and geophysical fields: the greater the changes, the more intense the expected earthquake. Manifestations of such rearrangements, i.e. anomalous changes in certain parameters of the geological environment are detected by methods of geological, geophysical and geodetic monitoring. The task, therefore, is to timely fix the occurrence and development of such anomalies, having the necessary methods and equipment at hand. However, it turned out that even in areas where continuous careful observations are carried out (in California, Japan), the strongest earthquakes happen every time unexpectedly. It is not possible to obtain a reliable and accurate forecast empirically. The reason for this was seen in the insufficient knowledge of the mechanism of the process under study.

The study and use of acoustic emission began a very long time ago, and one of the first were the authors of [2], where acoustic emission was proposed as a method for monitoring seismically active zones. Acoustic emission in the frequency range from a few to tens of thousands of hertz attracts special attention of researchers from different points of view. Firstly, this range is "working" for such developing areas as deep seismic sounding, registration of nearby earthquakes, the study of seismic effects of explosions, and the study of the impact on metrological systems. Secondly, the characteristic features of noise can be informative in a wide variety of application areas. For example, earthquakes in Alaska and Mexico in 1979 were studied using acoustic emission and seismic noise [3]. Naturally, after this, other methods of monitoring seismically active zones appeared, where acoustic emissions were used [4–6].

Scientists of the Physical Institute. In 1988, the P.N. Lebedeva Institute of the Russian Academy of Sciences (FIAN) theoretically substantiated the idea of a new method for predicting earthquakes – according to acoustic signals that are generated in a seismically active medium by cosmic ray muons penetrating the Earth's crust [7]. Thus, the concept of a completely new direction in the search for earthquake precursors was born, based on the registration of an anomalous acoustic response of the geological environment when exposed to penetrating particles of cosmic radiation.

The problem status

Destructive earthquakes in the recent past have shown that the problem of earthquake prediction does not currently have an effective solution. The system for registering the flux of cosmic radiation particles from an extensive air shower (EAS): neutron, electron-photon and penetrating (muons and neutrinos) components of cosmic radiation, followed by comparison with the movements of the earth's crust, will make it possible to find a connection between them. We get a unique opportunity to diagnose the seismic environment with a high spatial resolution of tens of meters. At the same time, the space accelerator constantly supplies us with cosmic particles to create muon rays at different points of the studied area of the geological fault.

The proposed new method for earthquake prediction used signals from elastic vibrations in the acoustic frequency range, which can be generated under the influence of local ionization formed at the time of the passage of penetrating particles of cosmic radiation (high-energy muons) through a seismically stressed medium in the deep layers of the earth's crust. If such a method were feasible, probing the Earth's crust with a beam of penetrating energetic muons, the constant source of which are high-energy cosmic rays, would allow direct monitoring of the internal state of the lithosphere at depths of up to 20 km, which is as close as possible to the zone of formation of earthquake sources. In combination with seismoacoustic monitoring of the response of the deep medium to the triggering action of the muon beam, such sounding is a unique method of direct penetration into the relatively close (compared to other methods) vicinity of the source zone. Each individual measurement in muon monitoring is local, and in aggregate, all measurements performed over a certain time interval make it possible to monitor a significant volume of the source zone, the value of which depends on the sensitivity of seismoacoustic receivers, the level of seismoacoustic noise, and the sensitive area of the means for detecting the muon flux. This method was quantitatively substantiated by numerical simulation, where the passage of muons with an energy of ≈ 10–100 TeV through the soil was studied. The obtained estimates of the multiplicity of muons in EASs with an energy of 10^{15}–10^{18} eV showed the depths of their penetration into the Earth's crust and the number of interactions (microcracks) that such muons can cause inside seismically stressed areas of the crust, depending on the muon energy and the stored energy of elastic deformation. The appearance of penetrating particles is associated with the development of extensive air showers in the atmosphere, and to distinguish acoustic emission against a background noise, one can use correlations between acoustic signals and signals about the passage of EAS, or signals from a muon detector [7–9].

In [10, 11], the process of interaction of a muon flux with a rock was simulated and it was shown that muons can reach great depths (up to 10 km) and interact with a seismically active medium in a metastable state. In addition, the minimum muon energy should be at least 3 GeV, and the energy of the primary particle in an EAS should be at least 10^{15} eV. This leads to an important conclusion that it is not necessary to detect muons specifically: it is sufficient to detect EASs with the energy of about 10^{15} eV, which greatly simplifies the entire process of recording and processing data.

Experimental and methodological support of research

Work in this direction is carried out at the Tien Shan Alpine Scientific Station (TSHVNS) of cosmic rays, located in a mountainous area at an altitude of 3340 meters above sea level directly in the zone of deep faults in the earth's crust, which is a convenient experimental platform for studying the possibilities of the cosmic geophysical method for predicting strong earthquakes. We emphasize once again that the method of seismic acoustic emission is based on the concept that anomalous high-frequency seismic noise is generated during the preparation of earthquakes. At the same time, in a seismically active medium, the muon contribution can increase by orders of magnitude compared to a conventional unstressed medium, and the corresponding technical means will be able to register the "anomalous acoustic response" of the medium to the impact of a muon.

The essence of the theory of "anomalous acoustic response" of a stressed medium under the action of muons on it is as follows. The interaction of muons with matter is accompanied by the formation of a nuclear-electromagnetic cascade, which leads to almost instantaneous energy dissipation in a small volume of rock, followed by the generation of acoustic and seismic waves. In this case, the elementary sources of acoustic noise will be opening cracks that appear inside the volume of the cascade.

Creation of a system of acoustic detectors for recording seismic acoustic emission with simultaneous continuous monitoring of the high-energy muon flux using a scientific experimental setup for recording extensive air showers (EAS) together with a time synchronization system for the operation of the entire complex will eventually make it possible to carry out a correlation analysis between the intensity of cosmic particles and the state seismically active environment.

A highly sensitive microphone with a sensitivity of 20 mV/Pa in the acoustic frequency range of 500–10.000 Hz is placed in a well 100 meters deep from the earth's surface, drilled in rocky soil [12]. Figure 1 shows the location of the monitoring system microphones in the well and the functional diagram for recording, amplifying, processing and accumulating acoustic signals from the microphones. The distance between the well and the system of rain detectors is approximately 200 meters. Acoustic signals from microphones (M1 and M2) installed at a depth of 40 meters and 96 meters are fed by cable to differential amplifiers (1 and 2), high-pass filters (3 and 6) with a cutoff frequency of 1.5 kHz and an envelope detector (4 and 5). Further, the signal envelope is digitized by a twelve-bit analog-to-digital converter (ADC, 11) and accumulated in the computer memory. Simultaneously with the signal envelope, signals from the microphones are recorded after high-frequency filters (3 and 6) and amplified with amplifiers 8 and 9. To record the integral noise of the well at a depth of 100 meters, a special channel is organized where the signal envelope is fed to the low-frequency filter (7), amplified by the amplifier (10) and digitized by the ADC. Subsequently, with the help of the Wi-Fi radio modem (13), the registration and processing data from the computer (12) are sent to the TSHVNS database. The complex has the possibility of time synchronization with the experimental setup for recording EAS using the GPS system. Synchronization of the current time of the control computer with the world time was carried out using the NTP protocol through a local network with a gateway to the Internet.

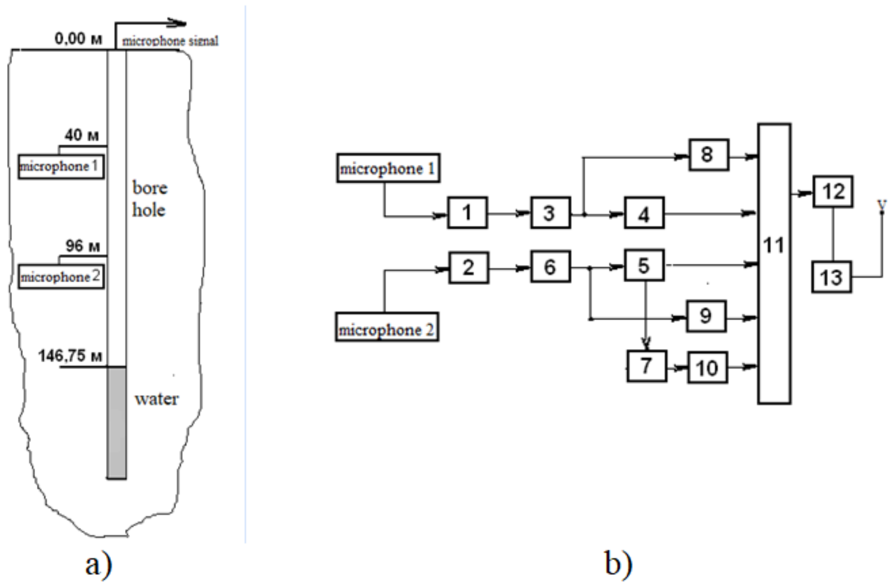

Figure 1. Scheme of placement of microphone sensors in the well (a) and registration and processing of acoustic signals from microphones (b).

It was shown in [11, 13] that in a seismically active medium, the muon contribution can increase by orders of magnitude compared to a conventional unstressed medium, and the corresponding technical means will be able to register the "anomalous acoustic response" of the medium to the impact of a muon. The essence of the theory of "anomalous acoustic response" of a stressed medium under the action of muons on it is as follows. The interaction of muons with matter is accompanied by the formation of a nuclear-electromagnetic cascade, which leads to almost instantaneous energy dissipation in a small volume of rock, followed by the generation of acoustic and seismic waves. In this case, the elementary sources of acoustic noise will be opening cracks that appear inside the volume of the cascade. Creation of a system of acoustic detectors for registration of seismic acoustic emission, continuous monitoring of the flux of high-energy muons using a scientific experimental facility for registration of EAS, as well as a time synchronization system will eventually make it possible to carry out a correlation analysis between the intensity of cosmic particles and the state of a seismically active medium.

Based on the results of measurements, it is possible to obtain information about the sound pressure level in the specified frequency band, which corresponds to the region of seismic frequencies of acoustic emission, exponentially averaged sound levels with time characteristics fast, slow, and other equally important parameters associated with the registration of acoustic emission.

In addition, the additional hardware stations for monitoring geoacoustic signals correlated in time with the flux of high-energy cosmic ray muons produced in extensive air showers, which operate at the Tien Shan high-mountain scientific station on the territory of the Almaty seismically active region, are a unique experimental site for collecting statistical material on the influence of the flux of cosmic ray muons on a seismically active medium. Figure 2 shows an example of test registration of geoacoustic emission at the TSHVNS, where the X-axis shows the time in seconds from the beginning of the day, and the Y-axis shows the ADC levels. The results of test measurements of geoacoustic emission were obtained in the frequency range from 1.5 to 10 kHz.

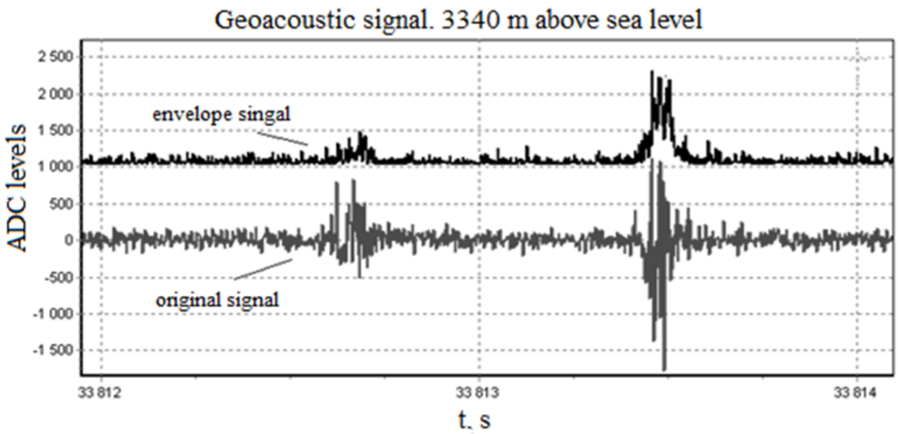

Figure 2. An example of test registration of geoacoustic emission on TSHVNS. (abscissa–time in seconds from the beginning of the day, ordinate–ADC levels).

Figure 3 shows an example of variations in the geoacoustic signal in a well at TSHVNS, where the X-axis is the time in seconds from the beginning of the day.

In this case, the microphone and the intermediate small-sized transformer serving for signal transmission are a single structural unit, which is completely lowered into the well. DC voltage ± 3V to power the microphone is generated by an independent power source, which is built on the basis of a separate transformer with an ungrounded secondary winding and has no direct electrical contact with either the rest of the electronic circuit or with the power lines of the external electrical network. From the power source to the microphone, this voltage is supplied through the second pair of twisted wires. Thus, the microphone unit of the measuring system is electrically isolated from all common grounding

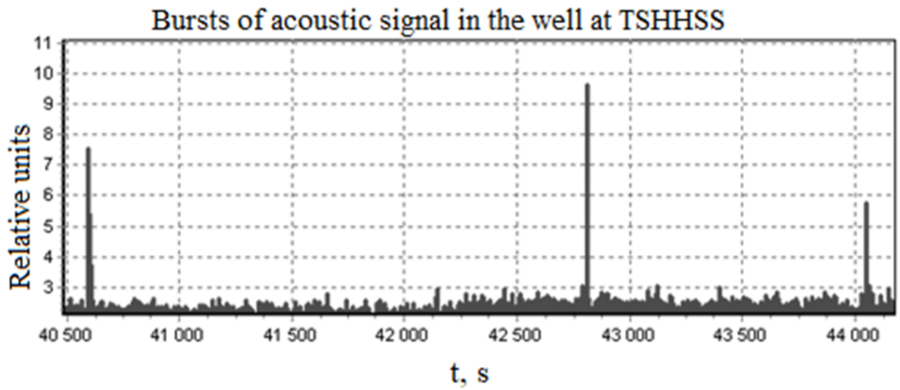

Figure 3. An example of acoustic signal variation.

and power supply lines to electronic circuits, which may contain significant electromagnetic interference and noise, in particular, a sinusoidal interference with a frequency of 50 Hz from an external AC network.

Signals are recorded continuously with a period of 2 ms, which corresponds to the total rate of data arrival via two information channels ≈ 4 Mb/s. The resulting data is accumulated for subsequent offline analysis in a file on a local disk. To work with acoustic detector data, a k09007 visualization program has been developed, which, when launched in a graphical mode of operation, allows viewing in its window the measurement results stored in these files in the form of interactive graphs (Figure 4). The program loads the average parameters of the acoustic signal into a table of the same name database specially designed for them. The information stored in this table can be requested by a web server to be displayed in text or graphic form on the web page of the Tien Shan station [14] in the form shown in Figure 4, which shows the root mean square value of the amplitude of the acoustic signal for two days.

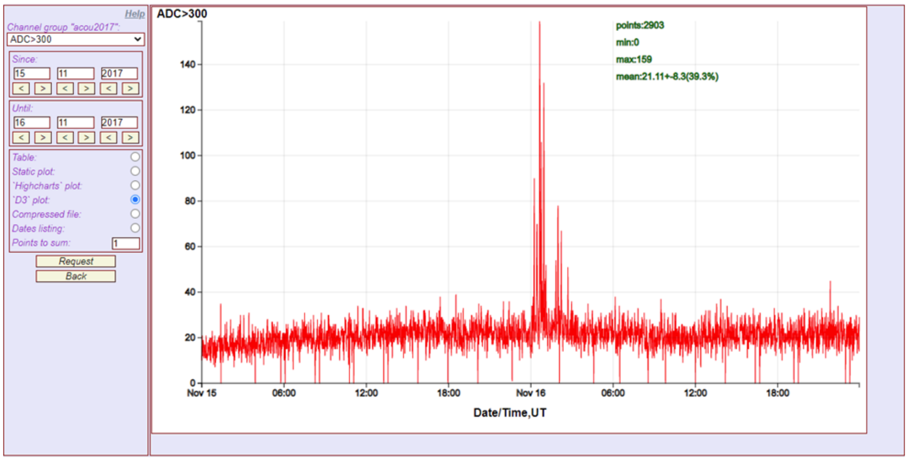

Figure 4. RMS amplitude of the acoustic signal, measured over two days. The acoustic signal intensity recording 2 ms.

Cosmic rays were recorded using the Hadron-55 complex setup [15]. The Hadron-55 installation is a unique structure located on the territory of the Tien Shan Alpine Scientific Station at an altitude of 3340 meters above sea level. The complex installation consists of a 2-tier coordinate ionization calorimeter with an area of 55 m^2 with a total absorber thickness of 1200 g/cm^2, as well as a central shower installation of thirty scintillation detectors located in the laboratory building and peripheral scintillation detectors outside the building at distances of 40 and 100 meters from center of the ionization calorimeter.

The calorimeter consists of two blocks-tiers spaced 2.2 meters apart. The upper tier, called the gamma block, contains 2 layers of ionization chambers located in mutually perpendicular directions and a layer of lead absorber of 22 cm thick. 30 scintillation detectors are installed on the gamma block and around it. The gamma block contains 100 ionization chambers in the first row and 138 chambers in the second, separated by lead with a total thickness of 26 cm or 310 g/cm^2. This block is used to measure the energy of the neutral and charged components of cosmic radiation, as well as to determine the trajectory of particles.

The lower tier, called the hadron block, contains 8 rows of ionization chambers, 144 chambers in each row, located in mutually perpendicular directions. Modules with neutron and Geiger counters are installed in the hadron unit. This unit is used to measure the energy of various components of cosmic radiation and determine the trajectory of particles. All data is automatically saved on the computer connected to the installation. The technique for determining the EAS energy is described in [16].

The discussion of the results

It is known [13, 17] that one of the conditions for the occurrence of acoustic emission in the Earth's crust is the threshold energy of muons, which is 3 GeV. Muons of such energies arise under the condition that the energy of primary particles reaches 10^{15} eV. For this reason, it is sufficient to register an EAS with the energy of the primary particle of at least 10^{15} eV. This data can then be compared with geoacoustic data obtained from the well. At the moment, experimental data have been collected and processed on the registration of cosmic rays at the "Hadron-55" facility (Figure 5), where the energy is 10^{12} eV, geoacoustic data from an underground well (Figure 6) and seismic data from the website of the Kazakhstan National Data Center [18]. Comparing them with each other, 9 matches were identified in the period from October 1 to 31, 2018 (Table 1).

Table 1.
Comparative matching results.

Date	EAS	Acoustics	Earthquake
01.10.2018	21:58:18	21:59:29	22:18:18
06.10.2018	05:07:53	05:09:31	07:22:14
16.10.2018	03:40:17	03:41:45	05:48:39
18.10.2018	01:24:28	01:26:05	03:50:02
23.10.2018	20:24:02	20:25:39	22:13:26
27.10.2018	08:31:29	08:33:01	10:43:11
30.10.2018	18:25:17	18:26:55	19:39:19
31.10.2018	14:32:55	14:34:27	16:32:33
31.10.2018	16:33:49	16:35:31	18:47:49

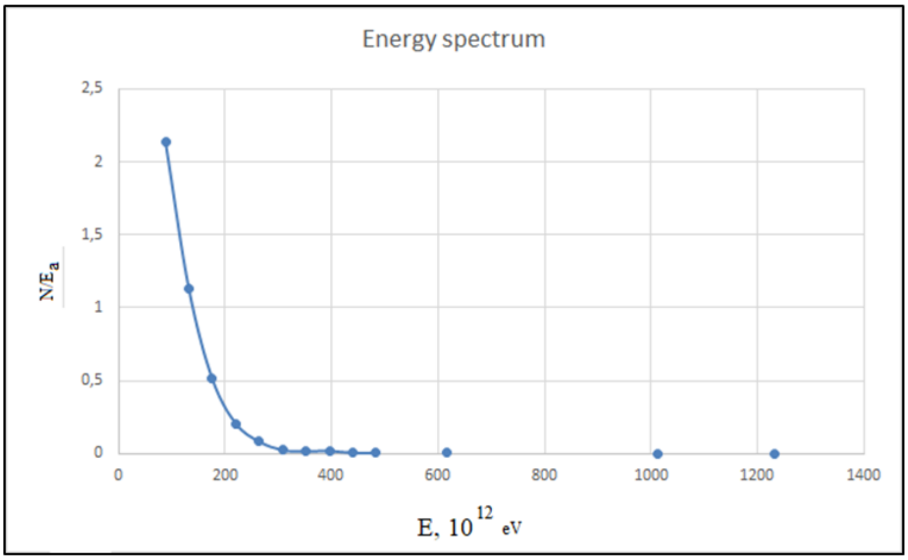

Figure 5. Energy spectrum of cosmic rays obtained at the Hadron 55 installation from 1.10.2018 to 31.10.2018.

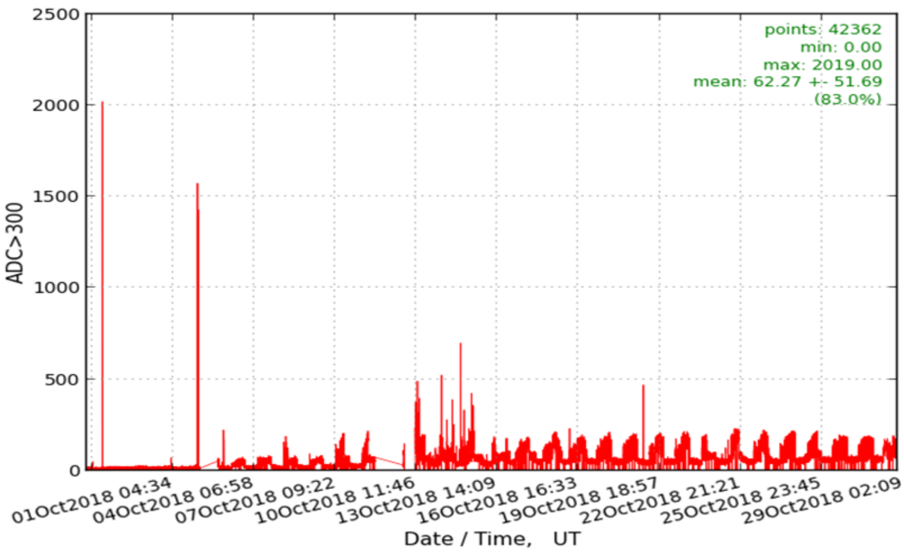

Figure 6. Variation of acoustic emission from 01.10.2018 to 31.10.2018.

According to the data given in Table 1, it is not difficult to establish that approximately 1–1.5 minutes after EAS registration, acoustic signals coming from the installation located in the well are recorded. Further, after about 1–2 hours, processes can be observed that indicate the occurrence of seismic activity in the earth's crust in this region.

Conclusion

In general, it can be concluded that the Tien Shan station, located in a mountainous area directly in the zone of deep faults in the earth's crust, together with a system of shower detectors that provides the ability to monitor in real time the moments of passage of powerful EASs and associated beams of energetic muons, is a convenient experimental platform for studying the possibilities of the cosmic geophysical method for predicting strong earthquakes. The developed system of devices that record acoustic emissions provides an acceptable level of sensitivity to the acoustic signal correlated with the penetrating cosmic ray muon flux, which allows us to raise the question of searching for seismic signals that arise after the passage of extensive air showers.

Acknowledgments

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