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ИЗВЕСТИЯ

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ГЕОЛОГИЯ ЖӘНЕ ТЕХНИКАЛЫҚ ҒЫЛЫМДАР СЕРИЯСЫ

♦

СЕРИЯ ГЕОЛОГИИ И ТЕХНИЧЕСКИХ НАУК

♦

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A. L. Shepetov[1], T. Kh. Sadykov[2], K. M. Mukashev[3], V. V. Zhukov[4], L. I. Vil'danova[4], N. M. Salikhov[5], A. D. Muradov[3], A. Kh. Argynova[2]

[1]P. N. Lebedev Physical Institute of the Russian Academy of Sciences (LPI), Moscow, Russia,
[2]Institute for Physics and Technology, Almaty, Kazakhstan,
[3]Al-Farabi Kazakh National University, Almaty, Kazakhstan,
[4]Tien-Shan Mountain Research Station. Kazakhstan, Almaty, Kazakhstan,
[5]Institute of Ionosphere JSC "National Centre Research and Technology", Almaty, Kazakhstan.

SEISMIC SIGNAL REGISTRATION WITH AN ACOUSTIC DETECTOR AT THE TIEN SHAN MOUNTAIN STATION

Abstract. The program of future development of the scientific detector complex at Tien Shan mountain cosmic ray station anticipates the creation of a system of high-sensitive microphones for registration of elastic disturbances of seismic origin in the acoustic frequency range. Synchronous operation of acoustic detector together with a widespread system of the cosmic rayparticles detectors permits to test the hypothesis on the possibility of microcrack creation in the deep seismic active regions of Earth's crustunder the influence of penetrative particles (the muons) which originateas a result of cosmic ray interaction with the atmosphere. The disturbance ofelastic oscillations which arise by the opening of microcrack propagatesas an acoustic wave within the mass of lithosphere and can be detectednear its surface as a momentary increase of acoustic noise. It is supposed that registration of such oscillations in correlation with passage moments of energetic cosmic ray particles can be a perspective earthquake forecast method in seismically active regions of the Earth. In this work, we discussthe design principles and possibilities of an acoustic detector which isbuilt on the basis of a high-sensitive microphone installed in a drilledhole, at the depth of 50 m from the surface, and is presently operating atTien Shan station. We present the results of the test acoustic signal registration which was held at the end of2017. The consideredinvestigation can be of a large importance for solving the problem of along-term earthquake forecast.

Key words: acoustic detector, cosmic rays, muon components, elastic seismic oscillations, synchronous recording.

Introduction. An actual problem of modern seismology is the long-term forecast of the level of seismic activity, in particular, of powerful earthquakes, in the seismically dangerous regions of the Earth. At present time the seismological science experiences a crisis which is connected both with the shortages of the existing theory of earthquake development and with the lack of any reliable method of earthquake forecast [1]. In fact, a multitude of methods which are applied now for prediction of the level of seismic activity such as the measurement of electric conductivity of the medium, the measurements of the deformation field and of the movement speed of different lithosphere regions, the measurements of the natural radioactivity level and the intensity of local neutron background, and the like [2, 3] are based on various physical phenomena which take place in the vicinity to the surface of the Earth's crust. Same shortages such as an extreme unreliability of the forecast and a poor reproducibility of the results gained are typical for the most part of these methods. These drawbacks are caused by the fact that the observable surface effects cannot be always unambiguously connected with an earthquake preparation in a certain region of the Earth.

Still, an open question of traditional seismology is the selection from an overwhelming information stream which comes from different seismological sensors of some distinctive signal on the approaching of a definite catastrophic earthquake with a strict forecast localization in the time and space. Usually, such a signal is lost irrecoverably against the steady background of small and non-dangerous earthquakes, and amongst the fluctuations of the large-scale geodynamics processes. Because of these obstacles, any plain signal of an earthquake preparation usually can be found only post factum.

In the late 1980s, the specialists of the P. N. Lebedev Physics Institute and the Institute of the Physics of the Earth in Russia have elaborated preliminary conception of the new perspective direction in the study of the earthquake forecast problem. Presumably, such a forecast can be based on registration of the signal from elastic waves in the acoustic frequency range which can be triggered in the depth of lithosphere under the influence of local ionization from propagation of the penetrative component of cosmic rays - the muons. Within an unstable medium like a largely stressed volume of the Earth's crust in a seismically active region any small disturbance like an elusive ionization increase can cause the momentary dissipation of elastic energy, and reveal itself as a macroscopic effect through generation of oscillations in the medium which propagate there as a sound wave [4-6].

In the case if such an approach could be realized, an effective probe of the Earth's crust with a beam of penetrative energetic muons originating from interaction of the high energy cosmic rays in atmosphere would be possible to test the inner condition of lithosphere up to the depth of 1-20 km which is close to typical formation depth of the earthquake centers. The monitoring of acoustic response on the influence of muon beam which can be made near the surface of the Earth is a unique method to reach relatively close vicinity of an earthquake center in comparison with other methods. Every separate measurement by muon monitoring is only a local one, but a set of such measurements made systematically and continuously during some period of time permit to control a large volume of the crust which depends on the sensitivity of acoustic sensors, on the level of seismic noise, and on the area of the muon detectors disposition.

One of directions in the development of the earthquake forecast methods is the analysis of temporal characteristics of the high-frequency seismic noise. In the work[7,8]it was suggested that the process of earthquake preparation causes an anomalous time behaviour of the intensity of such noises, and the role of trigger to provoke generation of elastic oscillations in acoustic frequency range can play the transient ionization increase from the passage of muons through the seismically stressed regions of lithosphere. An effective source of such muons can be the extensive air showers (EAS) – the cascades of a multitude of elementary particles which develop in the atmosphere after the hits of energetic cosmic rays which have the energy above 10^{16} eV.

Later on, the method discussed was proved quantitatively by numeric simulation of the passage of ~10-100 TeV muons through the ground which is described in the paper [9,10]. In this work concrete estimations were obtained for the muon multiplicity in the EAS with primary energy 10^{16} – 10^{18} eV, for the depth of muon penetration into lithosphere, and for the average number of macroscopic effects (micro-cracks) which the muons can cause within the seismically stretched crust in dependence on their energy. It was found that in a considerable part of events the creation of such micro-cracks can result in the generation of elastic sound oscillations in the acoustic frequency range of 1–2 kHz, and with an amplitude sufficient for their registration by a high-sensitive microphone near the surface of the Earth. Since the appearance of energetic muons is generally connected with extensive air shower development in the atmosphere, it was suggested in [9, 11] to use the correlation method based on the search for acoustic response signals temporally bound to the passage moments of the high-energy EAS.

A convenient experimental site to investigate the capabilities of considered method is the Tien Shan mountain cosmic ray station which, firstly, is located in mountain region above a deep lithosphere fault, and the widespread system of particle detectors of which, secondly, makes it possible to check directly the passage moments of the powerful EAS and connected energetic muons.

A preliminary search for a short-time emission of an acoustic signal by the group passage events of high energy muons has been made in a special experiment which was held at Tien Shan station in the year 2012. According to the data published in [12, 13] some transient increases of acoustic noise have been observed indeed in a short time neighbourhood (~10 s) after registration of a multiple muon event.

After completion of the complex modification of Tien Shan shower installation [14, 15] and the beginning of regular EAS studies there in 2015–2016, it is planned to continue such a type of experiment here in its advanced version, i.e. with taking into account any discrete information on the EAS (total amount of shower particles – the shower size, the type and energy of the primary cosmic ray particle, position of shower axes on the ground, and its arrival angles) which accompany the acoustic noise increase events. Accordingly, the modification program of shower installation anticipates the creation of a special system of acoustic receivers which should consist on a number of high-sensitive microphones distributed over the territory of Tien Shan station, with strict synchronization of recording process of acoustic signal with the moments of EAS passage.

At the beginning stage of this investigation program, one of such acoustic detectors has been installed in autumn 2017 and remains in continuous exploitation since that time. A microphone with a 20 mV/Pa sensitivity in acoustic frequency range, 500-10000 Hz, is placed within a hole drilled in the ground at the territory of Tien Shan station at a depth of 52 m under the surface. The distance between the hole and center of shower particles detector system is about 200 m.

A description of the microphone detector which is used now at Tien Shan mountain station for registration of the seismic noise signals, and an overview of preliminary results obtained by continuous operation of this detector during the winter season of 2017-2018 years are the subject of the present message.

Experimental equipment

The schematic of electronic equipment which is used for registration of seismic oscillations in acoustic frequency range is presented in figure 1. To obtain the necessary level of electromagnetic noise immunity, the transmission of electric signal from the microphone succeeds through a small-size transformer T1 which is connected to a long cable line made of a twisted pair of wires; both the microphone and transformer constitute a single compact construction unit which is dropped into the drilled hole. Besides, the ±3V direct current voltage for microphone powering is elaborated by a separate AC-DC power adapter which uses an independent transformer *T2* with ungrounded secondary winding. Up to the microphone this low-voltage direct current feeding comes over another twisted pair of wires. Hence, the microphone unit as a whole occurs to be isolated electrically and has not any direct contact with the grounding and external power feeding lines. This is necessary to prevent any influence on registered signal on the part of low-frequency electromagnetic interference, in particular of the 50 Hz sinusoidal noise from the power main.

Recording of acoustic signal is made indoors in a special cabin situated immediately at the top of the hole where other units of registration channels are placed: the differential amplifier and the selector of low-frequency envelope of microphone signal. The differential amplifier (the D1 element in the scheme of figure 1) is made on the basis of an integrated circuit chip of CA3130E type. This amplifier ensures the ~100^x amplification of useful signal with simultaneous ~70 dB suppression of any co-phased interferences which may arise on the long connection line between the microphone and amplifier input. At the output of amplifier, the bipolar sinusoidal signal is formed which belongs to acoustic frequency range, ~10-10^4 Hz, and is ready for digitization with a final amplitude-to-digital conversion (ADC) unit of the data acquisition channel. The low-frequency signal selector which consists of a pair of CA3130E *(D2)* and KA1458D *(D3)* operational amplifiers permits to pick out the slow modulating envelope of the seismic acoustic signal which is digitized by the second ADC channel.

Schematic of the small ADC system with a low power consumption which has been designed especially for registration of the signals from acoustic detector is shown in figure 2. This system is located just at the top of the hole together with all other electronics of preliminary signal shaping. The basis of ADC system is a single board microcomputer Raspberry Pi B+ [16] on a Broadcom BCM2835 type ARM microcontroller with the tact frequency of 700 MHz. By the means of its in-built general purpose input/output port (GPIO) the microcontroller is connected to a pair of AD7887 type integrated ADC chips [17,18]. The latter ensures digitization of the analogue signal level which is present temporarily at their inputs with a 12-bit resolution and with conversion speed of up to $1.25\cdot10^5$ samples per second.

Two digital tact sequences, C (clock), and *CS* (chip select) which are necessary for ADC chips operation are elaborated at corresponding GPIO pins by the special low-level driver program which runs at the microcontroller unit. Same program accepts the binary conversion results which are set in sequential code at the *DO* pins of both ADC chips and converts them into two byte long data words. All microcontroller signals are connected to ADC pins through additional resistor dividers and through the buffer SN7404 type TTL- gates which are necessary for proper matching of their logical levels.

Permanent recording of acoustic signal data is made with a high-level program which operates at the same Raspberry Pi B+ microcomputer together with ADC system driver. Both the current level of the microphone output signal and its low-frequency envelope are registered uninterruptedly with a 2 ms temporal resolution which corresponds to the total rate of information income about 4 Mb/s. The whole

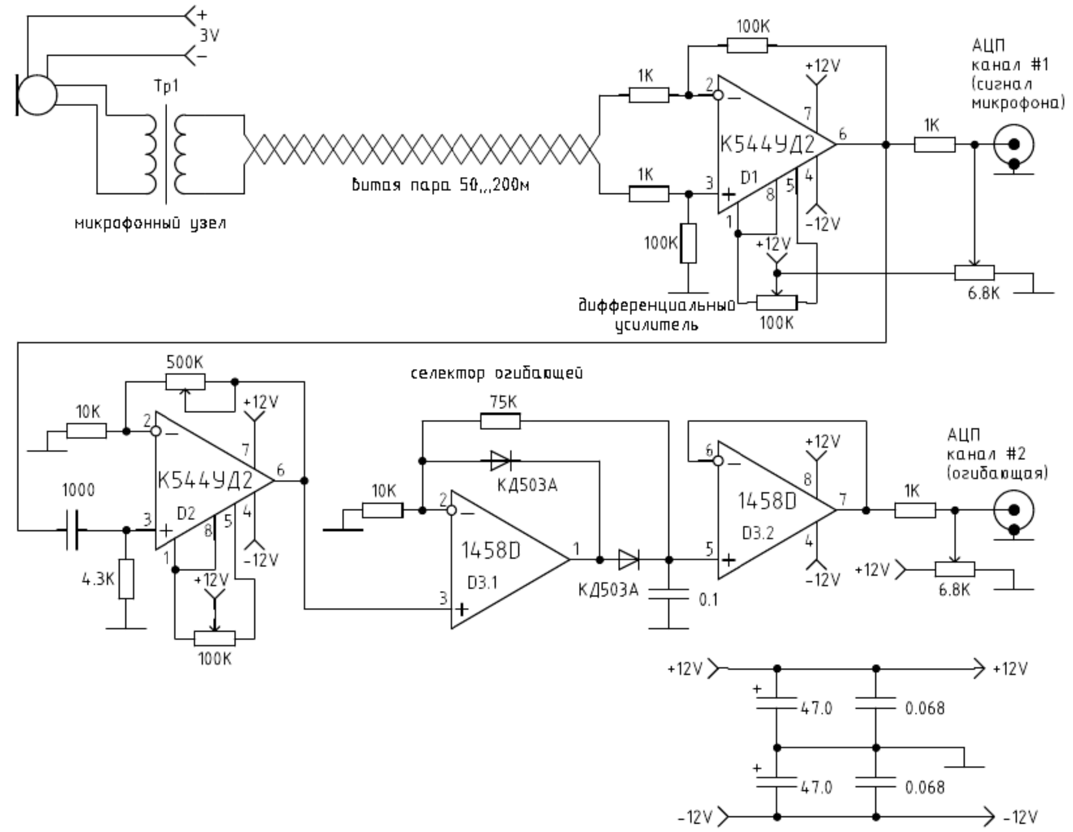

Figure 1 – Schematic of the high-sensitive microphone connection

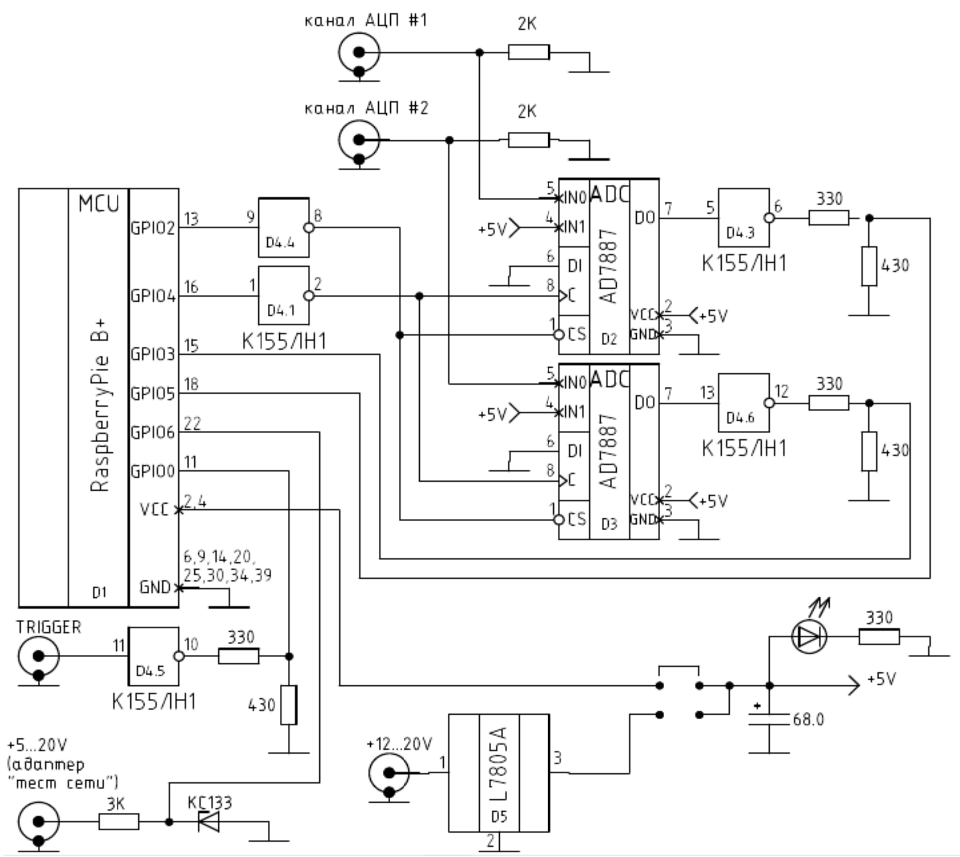

Figure 2 – Small ADC system on the basis of Raspberry Pie microcontroller

data stream of measurement information is kept completely in a compressed archive file which is created by registration program on a local hard disk connected to microcomputer through an USB interface plug.

In turn, the information kept within initial archive files is used by another high-level program to calculate periodically the mean characteristics of acoustic signal which have been observed in succeeding 1 min long averaging periods: the root-mean-square ADC codes of microphone signal and of its envelope, and minutely amounts of the events when the envelope amplitude was exceeding a number of predefined ADC code thresholds: 300, 500, and 1000. The resulting set of average characteristics comes into general database of the Tien Shan mountain station and can be seen in real time at the corresponding page of the station's web-site [19].

The results of the test detector exploitation

Test recording of the level of acoustic detector signal in accordance with the algorithm described in the previous section was initiated at Tien Shan station in November 2017, and since that time it is continuing there uninterruptedly. Since it was not known in advance any characteristic behaviour of microphone signal which should be expected in response to the events of seismic activity, during all the period of detector operation digitization of its output signal is made continuously with the time resolution of 2 ms, and the whole data set is kept completely for its further off-line operation. Some of the results gained in such postponed operation are considered in the present section.

A sample of acoustic events of the type which is most frequently met and is presumably connected with development and subsequent fast decay of micro-cracks in the seismically stretched medium is presented in figure 3. Among microphone signal records such an event manifests itself as a sharp but quickly fading increase of oscillation amplitude with typical duration of 10-20 ms, like the ones which are visible in upper graphs of figure 3. Momentary increase of the microphone signal is accompanied usually with a short-time outburst of the amplitude of its envelope, which can be seen also in the discussed figure. From a statistical point of view the reliability of these effects is beyond any doubts; hence, in the case of figure 3 the signal/noise ration is not worse than 5-7 times for the direct microphone channel, and ~30 times for envelope. The observed intensity of such a type of events does vary irregularly during the time, but usually, it remains within the limits of 1-5 events/day (for the threshold ADC code of 1000).

During the period of acoustic detector operation it was registered a noticeable seismic event – an earthquake with a magnitude of M = 4.9, and with epicenter distance about ~130 km apart from the Tien Shan station. The earthquake has occurred at the time moment of 16 November 2017, 01:42:58 UT [20].

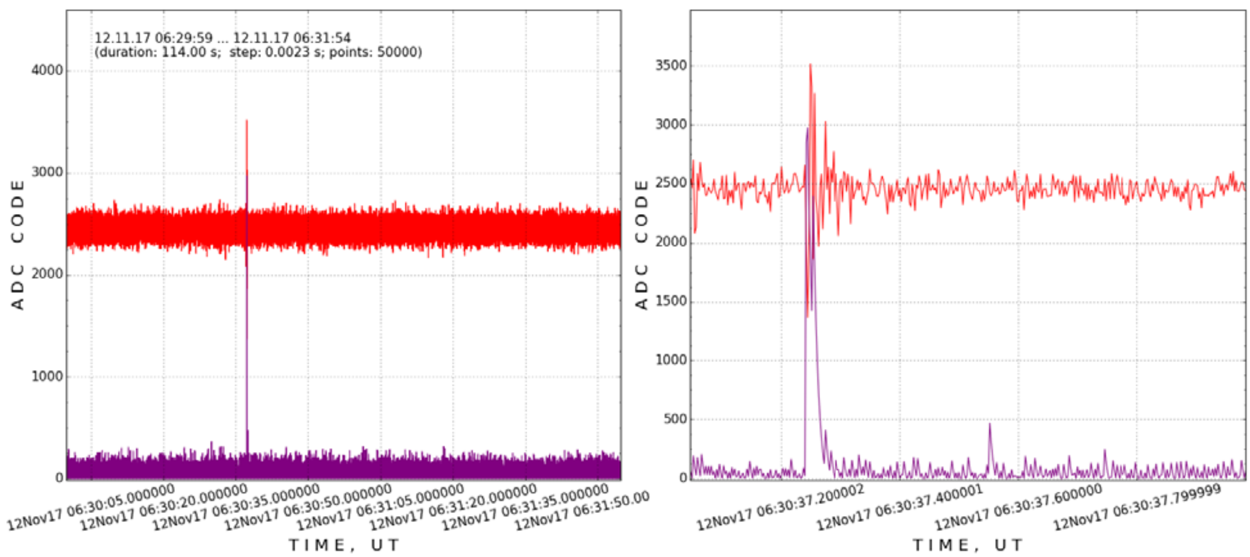

Figure 3 – Typical seismic event signal in the data records of acoustic detector.
Upper graphs in the plots correspond to the microphone signal, the lower ones – to its low-frequency envelope.
The time axes of the right plot are stretched around the moment of transient amplitude increase due to transient seismic noise.
Vertical axes are graduated in the values of the 12-bit ADC code

In the vicinity of Tien Shan station, this event was felt as a weak earthquake with local magnitude about 2. As shown in figure 4, in spite of general weakness at the observation point, the effect of this event can be seen prominently in average parameters of acoustic signal. Disturbances from the remote earthquake have influenced both the records of root-mean-square values of microphone signal, and the multiplicity of transient outbursts of the envelope amplitude.

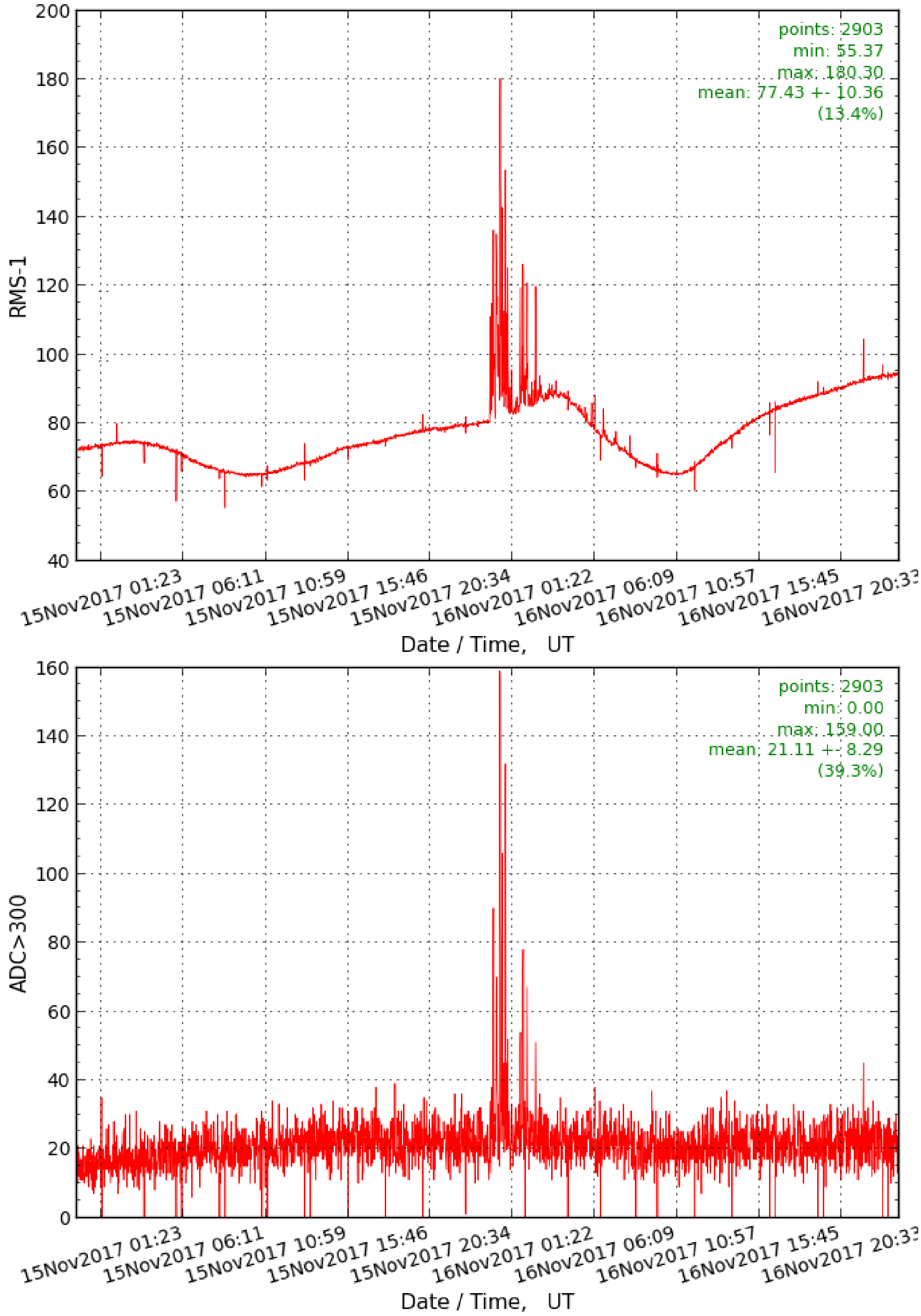

Figure 4 – Average data gained over a 2 days long period of continuous operation of acoustic detector:
the minutely values of the root-mean-square ADC code in microphone channel (above),
and the number, per one minute, of the events when the envelope amplitude code was exceeding the threshold of 300 (below).
Time moment of 16 November 2017, 01:42:58 UT corresponds to a M = 4.9 magnitude earthquake
with epicenter distance about 130 km apart from Tien Shan station

Time variation of the low-frequency envelope of acoustic signal within the temporal neighborhood of the 16 November 2017 earthquake is shown in figure 5. This plot was obtained by low-pass filtering of the original envelope record which consists of its 30-point decimation with multiple application of the moving average filter to remaining data, each time with compensation of the resulting temporal shift. The arrival moment of longitudinal seismic wave from the earthquake epicenter into the region of Tien Shan station is marked with a vertical line in the figure 5. This moment was calculated over the data of a three-component seismic station of the National Nuclear Center of Kazakhstan Republic KNDC [21]. As it is seen in the figure, just after arrival of seismic wave the acoustic detector starts to register a characteristic sequence of quasiperiodic oscillations with sum duration of 2.1 s and with the mean period of 0.55 s. This sequence can be considered as modulation result of the local seismic noises by the seismic wave in vicinity of the Tien Shan station.

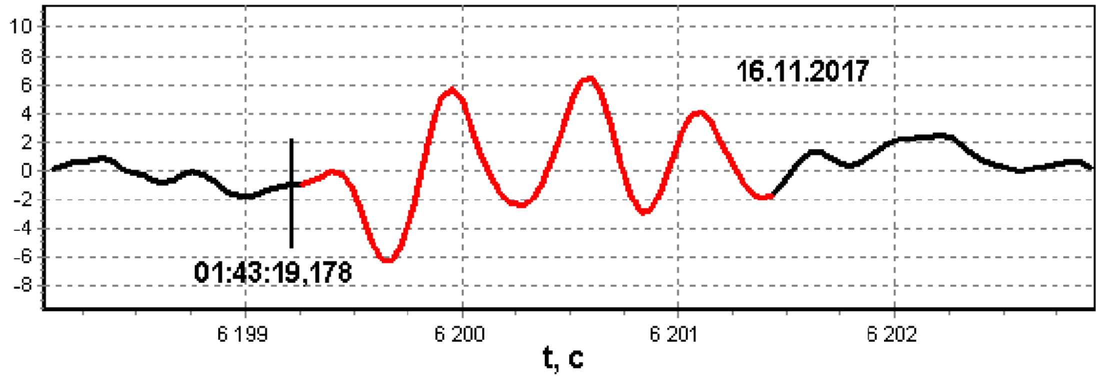

Figure 5 – An imprint of longitudinal seismic wave which has reached the Tien Shan station after the earthquake of 16 November 2017 on the record of microphone signal. Time axes is graduated in the seconds since the beginning of the day 16 November 2017, 00:00 UT

Hence, a conclusion can be made on the basis of experimental results presented in this section that registration of the acoustic detector signal which is currently on at the Tien Shan mountain station does indeed provide the necessary sensitivity level to seismic processes which take place deeply in the Earth. This result permits to consider the applicability of the described measurements technique to practical search of acoustic signals which could accompany the passage of the high-energy extensive air showers, including the intensive muon beams in the core region of the latter. Any realization of this task anticipates continuous recording of acoustic signal, together with strict registration of the shower passage moments and determination of EAS parameters accordingly to the data of the wide-spread shower particles detectors system, as well as mutual comparison of both data sets further on. The final goal of this study should be an answer to the question if some statistically significant excess of EAS events does exist which precede systematically the moments of transient increase of acoustic signal, and what are the mean characteristics of these showers (such as their size, primary energy, core distance to location point of acoustic detector and the like).

Preliminary data which have been obtained in a such type of measurements are illustrated by the figure 6. Sample events with characteristic short-time imprint of seismic effect in the records of microphone signal and of its envelope are presented here together with the data of the shower particles detector system. The latter are two-dimensional spatial distributions of the charged particles density (mostly, electrons) taken in a number of showers which have been preceding the moments of acoustic envelope outburst up to the time of 30 s, and the muonic component of which could serve as a trigger to initiate elastic oscillation deeply underground.

Making an approximation of these experimental distributions with the standard particle density distribution function of the particles cascade development theory, one can obtain a number of estimations for the basic shower parameters [8]. In particular, one can define the size of the shower, i.e. the sum amount of constituting charged particles which is connected with its primary energy and multiplicity of the muons. For the cases shown in figure 6 the EAS size is in the limits of 10^5–10^7 particles, which corresponds to the primary energy of ~ $3\cdot10^{14}$–10^{16} eV, and to the multiplicity of high energy muons of the order of 1-10 per a shower.

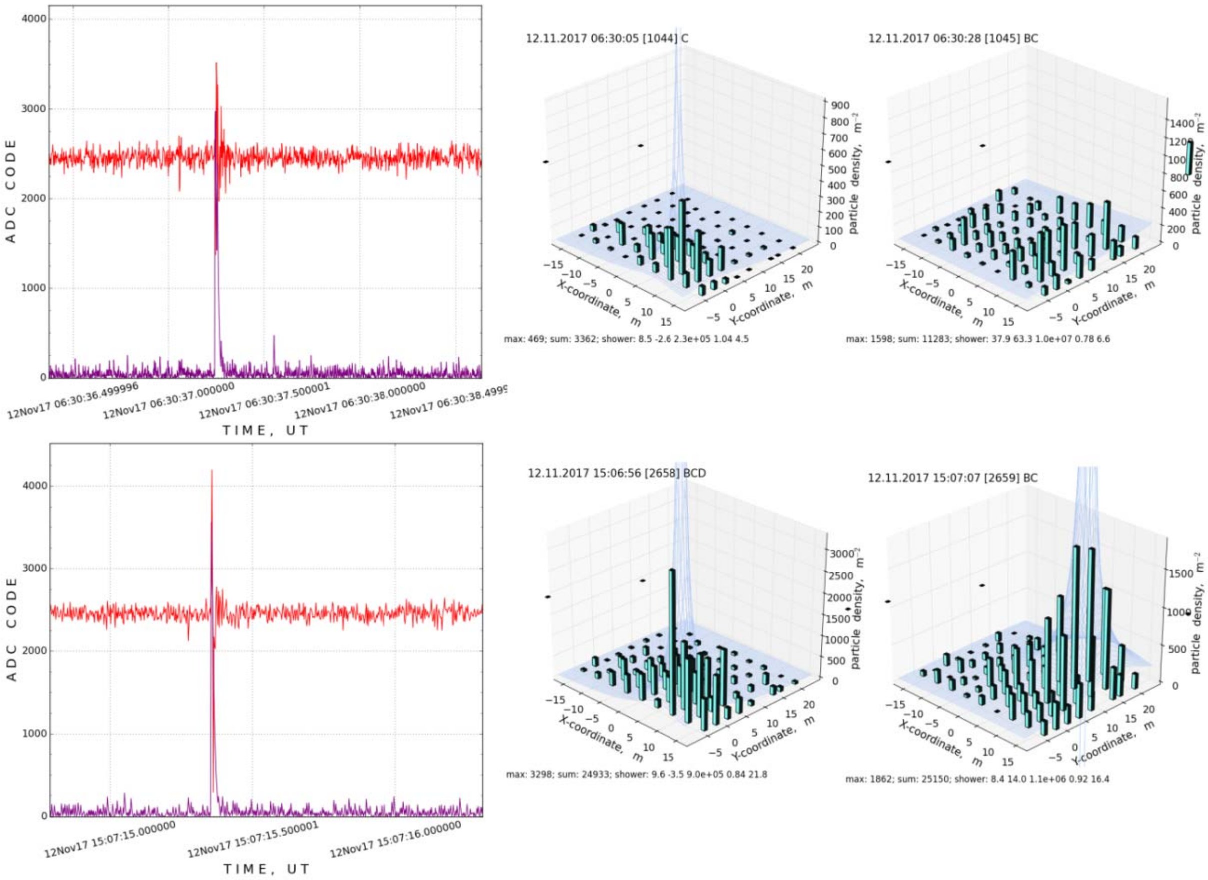

Figure 6 – Short time events with characteristic amplitude increase of acoustic signal and the two-dimensional distribution of the charged particles density amongst the shower detector system of the Tien Shan station in a number of preceding EAS (columns-original density measurements, smooth distributions-their approximation with a standard two-dimensional function of the particles cascade theory)

Conclusion. At the Tien Shan mountain cosmic ray station it is started the realization of the planned system of high-sensitive microphone detectors aimed at the search of elastic oscillations in acoustic frequency range which are connected with seismic processes in the depth of lithosphere. Up to the present time, the design of acoustic signal detector, of the necessary electronic equipment, and of the software complex have been elaborated, as well as operation technique of the incoming measurement information. According to the experience of practical exploitation of the test acoustic detector which has been taken place at the end of 2017, the detector of considered type does ensure indeed the necessary sensitivity level for registration of the signal from seismic processes. Synchronous operation of the acoustic detector system with EAS particles detector installation of the Tien Shan mountain cosmic ray station permits to check the practical applicability of proposed probing technique of seismic conditions deeply underground which is based on registration of the elastic oscillations signal originated in the seismically stretched lithosphere regions under the influence of penetrative cosmic ray particles. This study is of interest for the problem of long-term earthquake forecast.

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А. Л. Щепетов[1], Т. Х. Садыков[2], Қ. М. Мұқашев[3], Л. И. Вильданова[4], В. В. Жуков[4], Н. М. Салихов[5], А. Д. Мурадов[3], А. Х. Арғынова[2]

[1]П. Н.Лебедев атындағыФизика иституты, РҒА, Мәскеу, Ресей,
[2]Физика-техникалық институты, Алматы, Қазақстан,
[3]әл-Фараби атындағы Қазақ ұлттық университеті, Алматы, Қазақстан,
[4]Биік таулы Тянь-Шань ғарыш сәулелерінің ғылыми станциясы, Алматы, Қазақстан,
[5]ЖШЕС «Ионосфера институты», «ҒЗТҰО» АҚ, Алматы, Қазақстан

БИІК ТАУЛЫ ТЯНЬ-ШАНЬ СТАНЦИЯСЫНЫҢ АКУСТИКАЛЫҚ ДЕТЕКТОРЫМЕН СЕЙСМИКАЛЫҚ СИГНАЛДАРДЫ ТІРКЕУ

Аннотация. Биік таулы Тянь-Шань ғылыми станциясының құрамындағы ғылыми жабдықтарды дамыту бағдарламасы бойынша сейсмикалық серпімді тербелістерді тіркеуге арналған, сезімталдығы жоғары дыбыстық диапазондағысейсмикалық серпімдітербелістерді тіркеуге арналғанакустикалық детекторларды жобалау және станция аймағында құру жоспарланған. Акустикалық детектордың ғарыш сәулелерінің детекторларымен синхронды жұмыс істеуі сол ғарыш сәулелерінің жер атмосферасымен әсерлесуі барысында туындайтын, өтімділігі жоғары құраушыларының (мюондар) әсерімен литосфералық тереңдікте орналасқан сейсмикалық бөлшектену кеңістігіндемикро сызаттарды туғызу туралы гипотезаны тексеруге мүмкіндік береді. Сондай сызаттардың пайда болуы нәтижесінде туындайтын серпімді тербелістер жер қыртысы арқылы дыбыс толқындары түрінде таралады және жердің беттік қабатында қысқа мерзімдік акутикалық шу түрінде тіркеледі. Осы тербелістерді жоғары энергиялық ғарыштық сәулелердің өтуімен қатар тіркеу мәселесін шешу ісі сейсмикалық белсенді аймақтарда жер сілкінісін болжаудың болашағы зор тәсілдерінің қатарына қосылуы мүмкін. Мақалада сол үшін арналған және бүгінгі күні станция аумағында жұмыс істеп тұрған, жер бетінен 50 м тереңдікте скважинада орналасқан, сезімталдығы айрықша жоғары микрофон негізінде жасалған акустикалық детекторды құру принципі мен пайдалану мүмкіндігі баяндалады. Сонымен қатар, 2017 ж. соңына қарай осы жүйені тестілік тексеруден өткізу барысында қол жеткен нәтижелер де келтіріледі. Зерттеу жұмыстарының нәтижелері жер сілкінісі туралы алдын-ала ұзақ мерзімділік болжау мәселесін шешу үшін айрықша маңызды.

Түйін сөздер: акустикалық детектор, ғарыш сәулелері, мюондық құраушылар, серпімді сейсмикалық тербелістер, синхронды тіркеу.

А. Л. Щепетов[1], Т. Х. Садыков[2], К. М. Мукашев[3], Л. И. Вильданова[4], В. В. Жуков[4], Н. М. Салихов[5], А. Д. Мурадов[3], А. Х. Аргынова[2]

[1]Физический институт им. П. Н. Лебедева РАН, Москва, Россия,
[2]Физико-технический институт, Алматы, Казахстан,
[3]Казахский национальный университет им. аль-Фараби, Алматы, Казахстан,
[4)]Тянь-Шаньская высокогорная научная станция космических лучей, Алматы, Казахстан,
[5]ДТОО «Институт ионосферы» АО «НЦКИТ», Алматы, Казахстан

РЕГИСТРАЦИЯ СЕЙСМИЧЕСКИХ СИГНАЛОВ АКУСТИЧЕСКИМ ДЕТЕКТОРОМ ТЯНЬ-ШАНЬСКОЙ ВЫСОКОГОРНОЙ СТАНЦИИ

Аннотация. Программа развития комплекса научной аппаратуры Тянь-Шаньской высокогорной научной станции предусматривает разработку и размещение на ней системы чувствительных акустических детекторов для регистрации упругих колебаний сейсмического происхождения в звуковом диапазоне частот. Синхронная работа акустического детектора с расположенной на станции распределенной системой детекторов частиц позволяет проверить гипотезу об образовании микротрещин в зоне глубинных сейсмических разломов под воздействием частиц проникающей компоненты космических лучей (мюонов),которые рождаются в результате взаимодействия энергичных частиц космического происхождения с веществом земной атмосферы. Возмущение от упругих колебаний, которые генерируются при образовании таких микротрещин, распространяется в массе земной коры как звуковая волна и может регистрироваться вблизи поверхности земли в виде кратковременного всплеска акустических шумов. Предполагается, что регистрация таких колебаний в корреляции с регистрацией моментов прохождения космических лучей высокой энергии, может представлять собой перспективный метод прогноза землетрясений в сейсмически активных районах. В работе обсуждаются принцип построения и возможности действующего в настоящее время на станции детектора, который построен на основе чувствительного микрофона, установленного в пробуренной скважине, на глубине 50 м от поверхности земли Вместе с описанием акустического детектора представлены результаты измерений, которые проводились во время его тестовой эксплуатации в конце 2017 года. Результаты этих исследований имеют важное значение для решения проблемы долгосрочного прогноза землетрясений.

Ключевые слова: акустический детектор, космические лучи, мюонные компоненты, упругие сейсмические колебания, синхронная регистрация.

Information about authors:

Shepetov A. L. – PhD in Physics and Mathematics, leading researcher, P. N. Lebedev Physical Institute of the Russian Academy of Sciences (LPI),

Sadykov T. Kh. – Grand in PhD Physics and Mathematics, professor, Institute for Physics and Technology,

Mukashev K. M. – Grand PhD in Physics and Mathematics, professor, Al-Farabi Kazakh National University,

Salikhov N. M. – PhD in Physics and Mathematics, leading researcher, Institute of Ionosphere JSC "National Centre Research and Technology", Kamenskoe Plato, Almaty, Kazakhstan.

Vil'danova. L. I. – PhD in Physics and Mathematics, leading researcher, Tian-Shan mountain research station. Kazakhstan,

Zhukov V. V. – PhD in Physics and Mathematics, leading researcher, Tian-Shan mountain research station. Kazakhstan,

Muradov A. D. – Grand PhD in Physics and Mathematics, professor,

Argynova A. Kh. – researcher, Institute for Physics and Technology.

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