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Search for EAS radio-emission at the Tien-Shan shower installation at a height of 3340 m above sea level

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Abstract. The complex EAS installation of the Tien Shan mountain cosmic ray station which is situated at a height of 3340 m above sea level includes the scintillation and Cherenkov detectors of charged shower particles, an ionization calorimeter and a set of neutron detectors for registering the hadronic component of the shower, and a number of underground detectors of the penetrative EAS component. Now it is intended to expand this installation with a promising method for detecting the radio-emission generated by the particles of the developing shower. The facility for radio-emission detection consists of a three crossed dipole antennae, one being set vertically, and another two – mutually perpendicularly in a horizontal plane, all of them being connected to a three-channel radio-frequency amplifier of German production. By the passage of an extensive air shower, which is defined by a scintillation shower detector system, the output signal of antenna amplifier is digitized by a fast multichannel DT5720 ADC of Italian production, and kept within computer memory. The further analysis of the detected signal anticipates its operation according to a special algorithm and a search for the pulse of radio-emission from the shower. A functional test of the radio-installation is made with artificial signals which imitate those of the shower, and with the use of a N1996A type wave analyzer of Agilent Technologies production. We present preliminary results on the registration of extensive air shower emission at the Tien Shan installation which were collected during test measurements held in Summer 2016.

1. Introduction

The registration of radio-emission generated by particles of high-energy extensive air showers (EAS) has a number of advantages over other methods of primary cosmic ray investigation, both of which are based on direct registration of shower particles (a relative simple and cheap radio-detector system compared with wide-spread electronic detector systems, the large spatial volume of the space controlled by a single radio antenna, a sensitivity to the characteristics of longitudinal EAS development), and the methods connected with the registration of Cherenkov and fluorescent EAS emissions in ultraviolet and optic diapasons (an unrestricted duty cycle of radio installation which is independent of daytime and weather conditions). Because of these reasons, it is quite natural that the first registration attempts of radio-frequency (RF) signal from EAS were only tried in the 1960–1970 decades. These works were based on the results of theoretical studies of the possible generation mechanism of radio-emission by shower particles: the coherent electromagnetic radiation of negative charge excess which is present in developing EAS [1], and the model of a moving electric dipole which should arise because of the separation of the differently charged shower particles in a geomagnetic field [2]. As a result of these early investigations, the EAS signals were indeed found in the frequency range of 30–100 MHz, but the researchers met a number of difficulties in the interpretation of the registered signals which were connected with both insufficient qualities of those days' electronics and a bad reproducibility of the results because of electromagnetic interferences and weather conditions. A comprehensive review of previous studies on the detection of EAS radio signal can be found in [3].

The interest in the radio-method of EAS investigation reappeared in the early 2000 s when the experiments CODALEMA (France) [4] and LOPES (Germany) [5] started their work. The availability of this method was proved by the simplicity and low cost of radio devices built using modern electronic modules and perspective application of contemporary information technologies for analyzing the registered data, as well as its effectiveness for the study of EAS events caused by ultra-high energy cosmic ray particles (10^{19}–10^{20} eV) whose statistics remains rather scarce up to the present time.

A convenient place for the development of the radio-method of EAS particle registration is the Tien Shan mountain cosmic ray station (43°15′ N, 76°57′ E, 3340 m above sea level) whose installations for the complex EAS investigation in the range of primary energies of 10^{14}–10^{18} eV permit both a direct detection of the charged shower particles [6] at the station's level,

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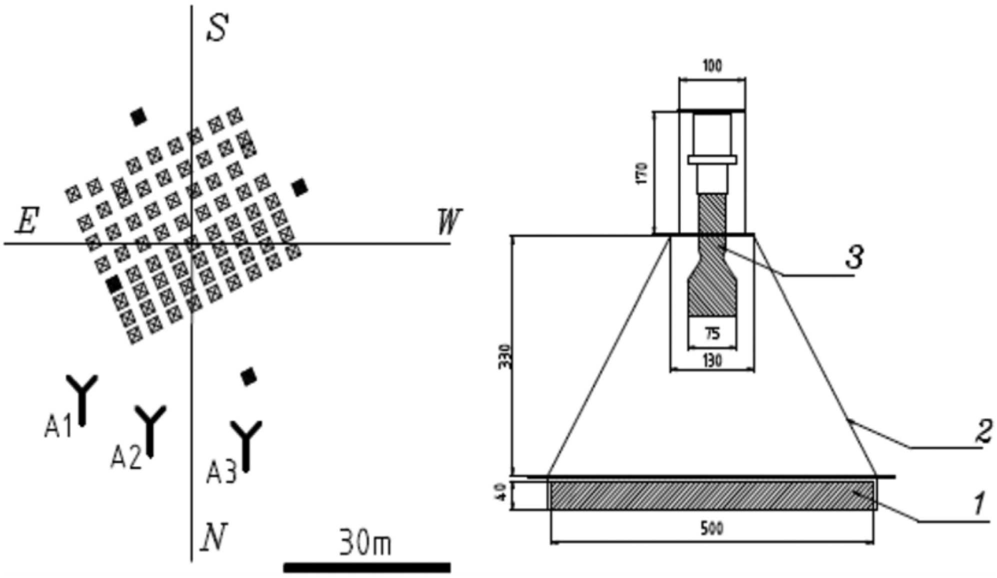

Figure 1. Left: the particle detector disposition scheme in the center part of the Tien Shan shower installation. Squares – the scintillation detectors of the central carpet, A1 – A3-the positions of the radio-antennae. Right: the internal arrangement of a scintillation detector (1–a $500 \times 500 \times 40\,\mathrm{mm}^3$ plastic scintillator, 2–the pyramid-shaped reflector of scintillation light, 3–PMT; dimensions are shown in mm).

and registration of Cherenkov light emitted above in atmosphere [7]. Inclusion of a system for registering EAS electromagnetic radiation in the RF range into this complex gives a possibility of mutual calibration of all three EAS investigation methods, and permits to set accuracy limits on EAS parameters definition procedures based on their simultaneous employment. Later on, with the development of experimental techniques and enlargement of the detector system the study of EAS up to 10^{19} eV primary energy should be possible. This opens up the possibility of studying many yet unclear problems, such as the primary composition, anisotropy, sources of ultrahigh energy cosmic ray particles, specific features of their interaction with matter etc, which stay before the contemporary cosmic ray physics.

With the help of the Karlsruhe Institute of Technology, Germany which donated the necessary apparatus, activity started in Summer 2016 at the Tien Shan station to register EAS RF signals in the 25–85 MHz frequency range. The description of the experimental installation and preliminary results of the test measurements are the subject of this paper.

2. Experimental set-up

The wide-spread shower installation used for the registration of EAS charged particles at Tien Shan is built on the basis of plain polystyrene scintillators with $0.5 \times 0.5 \times 0.05\,m^3$ size. For collection homogeneity of scintillation light, the scintillators are placed within a pyramid-shaped light reflector casing and viewed by photomultiplier tubes (PMT) of types FEU49, FEU84, FEU115. A pair of electric pulse signals taken from the PMT anode with different electronic amplification ($a \sim 30\times$ amplification high-sensitive signal, and a $1\times$ low-sensitive one) are transmitted in parallel and in analogue form to the data collection and acquisition center; simultaneous registration of the signals of two amplitude diapasons ensures the whole dynamic range about $\sim$(5–7) $\times\, 10^4$ of scintillation amplitudes measured linearly and without noticeable saturation effects.

In the data acquisition center, the scintillation amplitudes which were present at the PMT outputs at the time of an EAS passage are digitized by a special multichannel amplitude-to-digital conversion (ADC) system which gives the momentary distribution profile of the density of charged shower particles over the installation plane. The ADC system of the Tien Shan station is built on the basis of 12-bit ADC chips of AD7888 type [8] and permits simultaneous digitizing of up to some thousands of analogue signals for the time that does not exceed 0.5 ms.

The central part of the shower detector system which operated together with the EAS radio-emission registration facility in Summer 2016 is a carpet of 72 scintillation detectors placed nearly equidistantly in the nodes of a net with $4\,\mathrm{m} \times 3\,\mathrm{m}$ spatial step in the shape of an elongated rectangle with a total area of about $900\,\mathrm{m}^2$. The EAS selection algorithm which was applied at that time ensures a 100% registration probability for showers with primary energy $E_0 > (5-7) \times 10^{14}$ eV whose axes pass through the central scintillation carpet; in every case of EAS registration a special control pulse signal, the shower trigger, was generated to synchronize any detector subsystems which were working simultaneously with the shower installation.

The positions of the detectors within the central part of the Tien Shan shower installation and the basic scintillation detectors are shown in Fig. 1. A detailed description of the whole detector complex and the data operation algorithms of the Tien Shan mountain station, as well as a report on the results of calibration measurements made there in 2014–2015, can be found in [6].

The zenith and azimuth angles of EAS arrivals are estimated by the mutual time delays between scintillation signals in two detector pairs placed symmetrically at opposite sides of the central carpet (these detectors are

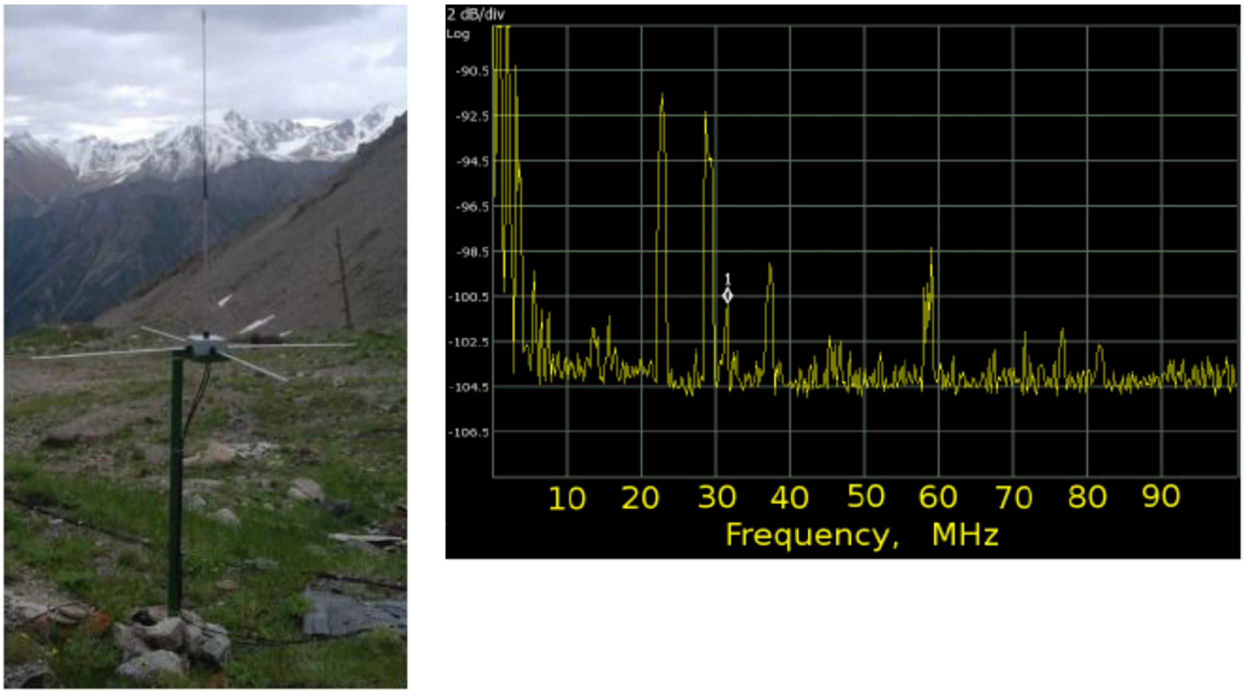

Figure 2. Three dipole antennae set installed at point A1 at the Tien Shan mountain station (left), and the spectrum of background radio-emission measured with the Agilent Technologies N1996A wave analyzer (right).

shown as black squares in Fig. 1). These delays are measured automatically for every registered EAS event using a 4-channel Tektronix TDS 2014 digital oscilloscope which operates with a 4 ns granularity for the time axis.

A shortcoming of the Tien Shan shower installation in its current state of Summer 2016 was the absence of any operational detectors in its periphery. This limited the range of registered events with satisfactorily defined shower characteristics for only EAS whose axes came within the central scintillation carpet. To overcome this, additional scintillation detectors are now being installed at various points at distances of 20, 40, and 70 m from the carpet's center.

During the test measurements searching for EAS connected radio-signals at Tien Shan three radio-antennae sets placed along the northern side of scintillation carpet were used, as shown by A1-A3 in Fig. 1. Three dipole antennae were placed in each of these points; one of them being set vertically, and other two-mutually perpendicularly in the horizontal plane with their axes oriented in parallel to meridional and latitudinal directions (see the left panel of Fig. 2). The RF-signals from these antennae after detection in 3-channel receiver devices designed by Karlsruhe Institute of Technology and placed immediately at the antennae positions were transmitted through matched 50 Ω cable lines to the data collection center.

The frequency spectrum of background radio-emission accepted by the antennae system after its installation at the operation place (with no connection to any external trigger signal) is shown in the right panel of Fig. 2. According to the position of the spectrum density peaks it is seen that the considered antennae system is sensitive mostly in the 25–85 MHz frequency range. A high level of electromagnetic interference was also found to be temporarily present at these frequencies, in particular during the night time, which practically cancels any attempt of EAS signal registration by masking it between intensive high frequency noise. The problem of interference control must be one of the most important in the definitive design of the EAS radio system at Tien Shan.

A fast ADC system consisting of a pair of 4-channel CAEN DT5720 electronic modules of Italian production [9] was used to register the detected signal from radio-antennae set in the experiment.

This system ensures digitizing the analogue input signals with a 4 ns time resolution and keeps in its internal memory continuous records of the time history of the input signal stored for some tens of microseconds as a minimum. Presently, the outputs of all three antennae dipoles of the A1 point, and two horizontal dipoles of the point A2 are connected to these ADC modules.

Following the arrival of an EAS trigger signal generated by the scintillation shower system, the whole data set kept within the internal ADC memory is transmitted to a special program of the main control computer, and the latter in turn sends this information to the general Tien Shan database. Simultaneously, the spatial distribution of the EAS particle density measured with the central scintillation carpet detector system are also loaded in the same database; these distributions can be used later for determining the parameters of the corresponding shower: the position of the shower core in the plane of the shower installation, zenith and azimuth directional angles of the shower axis, the parameters of shower age and size (the size has a physical meaning of the total number of particles in the shower. It is proportional to the primary energy of a cosmic ray particle, E_0, which caused the event, and can be used, with some assumptions, for its immediate estimation). All records in the Tien Shan database are supplied with a time stamp which marks the moment of EAS registration with an accuracy of

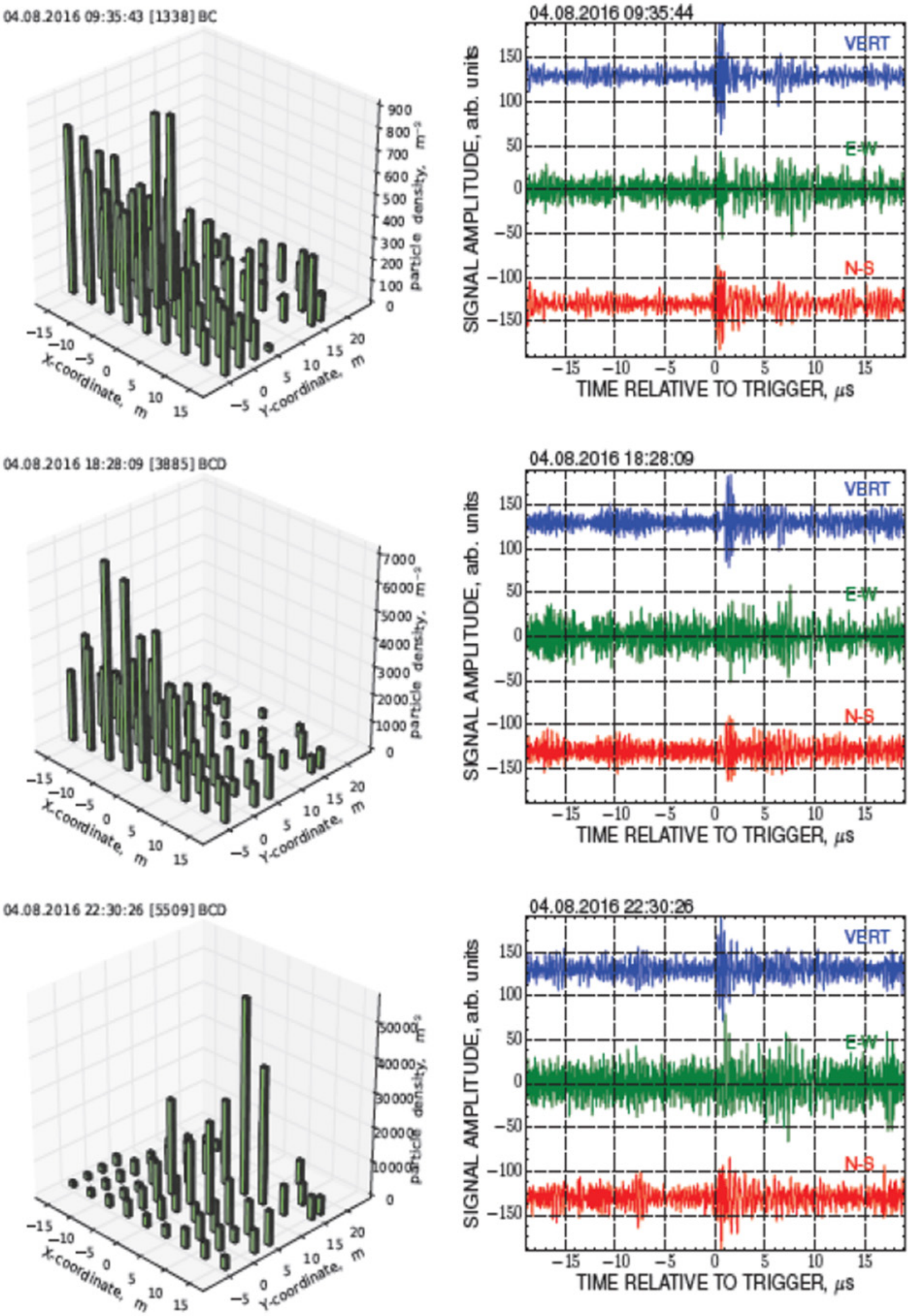

Figure 3. Sample events with a noticeable radio-signal from EAS. Left panels: 2D distribution of the density of charged shower particles in the plane of the central scintillation carpet; right panels: time series of the detected radio-signal amplitude from the vertical and two horizontal (East-West and North-South) antennae dipoles of the A1 point. Zero point of time axis in the right panel plots corresponds to the arrival time of the shower trigger.

1 s (in the UT time zone); the clock of the local data registration system is verified continuously according to external Internet and GPS time servers.

3. Experimental results

The test experiment on the simultaneous registration of the data from the shower and radio systems of the Tien Shan station was held during four days in August 2016, the total life-time of the installation's operation was 70 h. The purpose of this experiment was to clarify the real operational conditions for the registration of radio-signals at Tien Shan and to check the whole complex of hardware and software tools necessary for synchronous recording of the data from both detector system types. All records of radio-signal time series written in this period were looked over visually, and the signs of the presence of radio-emission signal above the usual fluctuation level in the $\pm 10\,\mu$s vicinity of shower trigger moment were searched for in every registered radio-event. The total amount of examined radio-records is about 30000, of which 400 candidate events were selected which have an indication of a noticeable radio pulse shortly after EAS arrival time. Characteristic examples of such event type are presented in the plots of Fig. 3.

For each of the events in Fig. 3 the spatial 2D distribution of the density of EAS charged particles is shown in the plots of the left column, while the right column plots demonstrate the time distributions of detected radio-signal intensity obtained from three dipoles of antennae at point A1 (antennae signals at point A2 are quite similar to those shown in the figure). Every one of the shown distributions is registered with a 4 ns temporal resolution and consists of 10000 sequential measurements of signal intensity which correspond to the full duration of the measured time series of $40\,\mu$s. All distributions are centered relative to the arrival time of the EAS trigger which came from the scintillation shower system; hence, the leading $20\,\mu$s in every time series corresponds to the 'prehistory' of the radio-signal which precedes the EAS time, and the next $20\,\mu$s describe the time behaviour of the radio-signal after the passage of the shower front through the antennae system.

A noticeable radio-signal pulse with amplitude significantly above the mean level of stochastic fluctuations is present in all events of Fig. 3, and this pulse always arrives with a constant time delay of 1–3 μs duration relative to the trigger. At the same time, it is seen from the particle density distributions in the left column that the axis of corresponding shower has evidently come somewhat northward of the central scintillation carpet, i.e. at the side of the radio-antennae location, at least in the events of 09:35:43 UT and 18:28:09 UT. Such an asymmetric disposition of EAS core is typical for the greater part of the events selected by the presence of a visible radio-signal just after the shower trigger, which is evidence that the observation of both signal types (i.e. an EAS and a radio-pulse delayed for a constant small time) in these events cannot simply be a random coincidence.

Because of the side location of EAS core in selected events relative to the central scintillation carpet and the absence of peripheral particle detectors in the operational state during the considered measurements run any strict determination of shower parameters in the presented events is impossible. If it is supposed that the shower axis of the 09:35:43 UT and 18:28:09 UT events is somewhere around the region of the radio-antennae sets, i.e. at a $\sim$30–40 m distance from the center of the scintillation carpet, then according to the registered distributions of the particle density one can state that the primary EAS energy, E_0, in these events must be, correspondingly, at least $(2–3)\cdot 10^{16}$ eV and 10^{17} eV respectively (these estimations should be taken in the sense of lower limits). As for the 22:30:26 UT event, its maximum registered particle density of the order of 40000 particles/m^2 corresponds to a primary energy $E_0 > (3–5)\cdot 10^{17}$ eV. Considerable E_0 estimations which result, again, for the most part of the events selected by the presence of a radio-pulse in the vicinity of their shower front is another confirmation that this coincidence is non-random. Remembering that the threshold of the shower trigger during the measurements was about $E_0 > (5–7)\cdot 10^{14}$ eV, and the overwhelming part of registered shower events have, indeed, energies around 10^{14}–10^{15} eV (since the intensity of the primary cosmic ray flux decreases roughly with increasing energy), then the high E_0 values which result at once in all selected events cannot be fully accidental. It should also be noted that according to both modern experiments [4] and [5] the lower threshold of EAS radio-emission registration in 10–100 MHz diapason is of the order of $5\cdot 10^{16}$ eV which satisfactorily agrees with present estimations for E_0 in the events with a feasible radio-signal observation.

Besides the comparatively prominent radio-signal maximum within the closest 1–3 μs vicinity of EAS triggers frequently there is another secondary weak pulse which can often be seen in the time series of radio-intensity in selected candidate events, and usually follows the primary one at a fixed time of 5–7 μs after the trigger. Such a secondary pulse can be observed in the time distributions of Fig. 3, in particular in the 09:35:43 UT event. The characteristic 5–7 μs time delay of the secondary pulse corresponds to a linear distance of about 1.5–2 km, and this estimation, in its turn, to the distance to the nearest mountain slopes surrounding the Tien Shan station together with its antennae system sets. Hence, the secondary radio-pulse observed in time distributions of selected events can be interpreted as an echo signal resulting from the reflection of EAS radio-emission from the local relief details of Tien Shan station.

It is supposed that, in future, events with an appreciable EAS signal like the ones manually selected in the test experiment should serve as a prototype for the elaboration of an automatic recognition algorithm of the events with EAS radio-emission which is necessary for the final version of the corresponding software complex and any strict statistical investigations.

4. Conclusion

Setting up a radio-signal registration system mostly sensitive in the 25–85 MHz RF range is now in progress at the Tien Shan mountain cosmic ray station. This system is aimed for simultaneous operation with the EAS particle density and Cherenkov radiation detectors which are present at the station, and will permit a mutual calibration of all these independent methods of EAS investigation. Later on, with the use of an EAS radio-emission registration method, an enlargement of the energy range of primary cosmic ray investigation at Tien Shan up to $E_0 \sim 10^{19}$ is anticipated.

As a result of the preliminary test experiment, which was made using a newly installed dipole radio-antennae set, some candidate events were selected which demonstrate the presence of a noticeable radio-signal pulse in closest 1–3 μs vicinity of EAS arrival time. Specific features of particle density distribution in these events permit to state that most of them have a rather high primary energy $E_0 >$ (2–5) $\cdot 10^{16}$ eV and a close location of their shower cores near to the radio-antennae set, so the time coincidence of the observed radio-pulse with the shower front arrival time in these events cannot be fully accidental. Hence, the radio-antennae system installed at Tien Shan together with a designed program complex for registration of its signal do indeed ensure an effective selection of radio-emission from EAS particles, and further work in this direction should be seriously considered.

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