Experimental results of radio observations at the Yakutsk EAS in 2009-2011

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Abstract. Results of radio emission measurements at 30−34 MHz from extensive air shower particles with primary energy above $10^{17}$ eV are presented. The data recorded at the Yakutsk EAS for the period 2009 – 2011 years with energies above $10^{17}$ eV, zenith angles less than 60 degree, the axes of which were within a large EAS. The shape of the spatial distribution has a different slope, depending on the distance to the shower axis. At large distances $R > 500$ m from the shower radio emission is small and almost constant up to a distance of 800 m. The primary energy of EAS and the amplitude of the peak radio pulse are correlated.

1. Introduction

To measure radio signals from extensive air shower (EAS) it is vital to choose optimal frequency at which the best signal to noise ratio is expected. This choice comes from the analysis of background noise from the field of electrical interference $E$ in the frequency range 1−200 MHz by [1]. In this work it was concluded that for twenty four- hour observations with account of ionospheres interferences it is reasonable to choose operational frequency above 20 MHz. Galactic noises reduce with frequency growth and amount to 1−2 $\mu$V m$^{-1}$ MHz$^{-1}$ at 30 MHz [2], while antenna-induced thermal noises increase. According [3], there is also a limitation towards higher frequencies. So, as most friendly for EAS radio signal registering, a rather narrow window of 30−40 MHz is considered, where the best signal-to-noise ratio is expected. For this reason the equipment in the experiment was suited for 32 MHz. In model calculations [3, 4], after considering various mechanisms for EAS radio emission generation, a frequency spectrum of emission was analyzed and an attempt was made to connect its intensity to shower parameters. It followed from those computations that for fixed $x_{\text{max}}$, the strength of electric field had its maximum at small distances from shower core within 20−80 MHz range. For fixed frequency 30 MHz the shape of electric field strength lateral distribution significantly depends on $x_{\text{max}}$ — the altitude of maximum in shower development.

This makes possible estimation of $x_{\text{max}}$ by measuring EAS radio emission which is an alternative to optical methods. It is possible to test these calculations at the Yakutsk EAS array where, besides measuring the flux of charged particles, also Cherenkov radiation generated by EAS is measured. In prospect, joint correlation of radio signal and Cherenkov light measurements provides an opportunity to select preferable mechanism of EAS radio emission generation. Experiments on radio emissions measurement at 32 MHz have been conducted during 1987 - 1989 period. Emission was registered from showers of various energies and first results demonstrated the possibility of using the radio
emission for EAS detection and studying. At the present day we are reconstructing the system for EAS radio emission measurement at this frequency.

2. Experimental setup for radio emission registration
To check the “purity” of chosen wavelength band for Yakutsk array, a spectrum of noise field was recorded in 10 - 50 MHz range. It was discovered that the smallest amount of noise falls to 32 MHz. Also this frequency region lacks the interference associated with human activities. In 1987 - 1989 and 2009 - 2011, a setup was mounted to register EAS radio emission at frequency 32 MHz. It consisted of receiving antennas and peripheral registering device. Half-wave dipoles were used to register signals, which were East-West aligned (maximal sensitivity of direction diagram was at North-South) and at North-South. The dipole setup at 1/4 height provides maximum of direction diagram for downward-directed emission. Bandwidth radio pass at the level 0.7 equals to 4 MHz, sensitivity 10 μV (2 μVm⁻¹MHz⁻¹), dynamic range 50. Receiving channels were based on the principle of direct signal amplification with subsequent detection. Preliminary low-noise amplifiers were put into special thermo-stabilizing containers and placed near antennas. Main amplifying circuits were built according to a cascade scheme with out-of-alignment circuits. From output of the detecting unit the signals were transferred to ADC where they were digitized in continuous mode and were stored in the buffer memory.

All ADC worked from one clock generator. Additional synchronization with shower arriving time was provided via separate channel reserved for receiver of synchronization pulses from the array. Unit for registration control, data collecting and data storage is based on industrial computer with 19 PCI slots. Recording of radio signal is synchronized with “master” signal from EAS array, selecting showers with energies 10¹⁵ - 10²⁰ eV. The data is recorded to hard disk drive and is displayed on the monitor at the same time. Antennas and ADC numbers, date, time, number of shower and ADC technical info are recorded to a frame. AD conversion is realized on the base of LAN-4 unit. It is 8-digit with peak digitization rate 250 MHz and maximal capacity of buffer storing unit 4 Mb. Continuous operation of parallel converter together with BSU constructed according to ring principle provide registering the “pre-history” of event, i.e. the state of radio channels prior to “master-signal” arrival. Sampling rate, period of “pre-history” and transfer ratio of input divider are software controlled. Sampling period was set to 4 ns, period of “pre-history” - to 13.8 μs.

3. Results and discussion
During the period of 1987 - 1989 the radio setup has registered signals in 6250 showers with energy above 10¹⁷ eV including several events with E₀ = 10¹⁹ eV. Radio emission from the most powerful event registered at the Yakutsk array was detected, with zenith angle about 60° and estimated energy above 10¹⁹ eV. Considered core distance range was 70 - 1000 m, since at small core distances the amplitude of signal might significantly exceed ADC dynamic range which would lead to ADC saturation.

At the same time EAS radio pulses were discovered at large distances from antennas. For example, in inclined shower registered in February 21 1988 (energy above 10¹⁹ eV) two antennas operated at distances 1030 m and 950 m. In addition signal induced in each antenna exceeded 100 μV. To compare with, shower from 09.03.88 (E₀ = 9×10¹⁷ eV) at core distance 790 m had signal only slightly above 20 μV. Joint analysis of EAS characteristics and EAS radio pulses gave lateral distribution of electric field strength at small and large core distances and connected the magnitude of radio signal with shower arrival direction, its energy and the depth of its development maximum.

For the analysis we selected 300 events of EAS (2009 - 2010) with energies above 5 x 10¹⁶ eV, whose axis lies within the perimeter of the installation, and zenith angle no more than 60°. In figure 1 shows the dependence of the ratio of amplitudes in different directions in the antenna operating frequency. Preliminary analysis of the arrival of EAS events in the azimuthally angle, showed that there is a preferred direction of the maximum signal - E-W. The amplitude of the signal with the antenna oriented in the E-W was greater than the signal recorded antennas oriented N-S, that is, the
dependence of the observed signal on the azimuthally angle. This phenomenon can occur only in the case of the charged particles in the Earth's magnetic field and the ratio of amplitudes in this case reflects the polarizing effect of radio emission from EAS.

Figure 1. The ratio of the amplitude of radio signals recorded antennas oriented in E-W and N-S.

Figure 2. The distribution of EAS events axis.

Figure 2 shows a cloud of points corresponds to the distribution of EAS events axes in the plane of the installation. Showers were selected in the energy range $5 \times 10^{16} - 5 \times 10^{18}$ eV and zenith angles from 0° to 60°, followed by radio waves exceeded the detection threshold and registered two or more antennas. These showers are used to construct a function of spatial distribution.

In figure 3 shows the average spatial distribution of the electric field $E_\nu$ obtained from the events of EAS with the energy above $10^{17}$ eV. The magnitude of the field $E_\nu$ in this case is obtained based on the normalization of the azimuth, zenith angles and reduced to the zenith angle 35° and equal to the energy above $10^{17}$ eV. It is made the correction for the polarization effect observed in the latter experiment. Averaging carried out at intervals by the distance from the center of showers.

The normalization of the corners of the shower arrival made the assumption that the main contribution to the radio emission from EAS geomagnetic mechanism of radio emission. Reducing the scatter in the values of the normalization speaks in favor of the formation mechanism of radio emission. With the normalization of the energy it was used the linear dependence of the amplitude of the pulse from the shower energy. In the analysis of the selected showers with axes, were within the perimeter of a large set of EAS, and the signal induced on the antenna, was five times or more greater than the average radio noise.

Figure 3 shows that the signal changes only slightly over distances of 50 - 200 m and the distance from the antennas to the shower axis above 300 m, the signal is significantly attenuated in the showers with energies $10^{17}$ eV. The index in the power spectrum slope approaching at a distance of 100 meters is $0.71 \pm 0.13$, at a distance of 100 to 700 m of $0.97 \pm 0.10$ m and more than 700 index is $0.84 \pm 0.16$. Data on the magnitude of the slope parameter in good agreement with the results obtained in [1]. The powerful showers produced by particles with energies above $10^{18}$ eV signal at large distances from the axis has a value of 100 - 1000 mV and the recording equipment with confidence. It should be noted that at small distances from the shower axis there is considerable variation recorded amplitudes. Most likely this is due to the contribution of different mechanisms of generation of radio emission.

Figure 4 shows the dependence of the amplitude of the radio signal from energy, as defined by the flow of EAS Cherenkov light at a distance of 400 m from the shower axis. Most of the showers, registered in the season 2009 - 2010 years. Showers with a maximum recorded energy above $10^{19}$ eV are taken from observations as in the seasons 1988 - 1989.
The good correlation of the two characteristics of the shower are observed, despite the different methods of obtaining the energy. The preliminary approximation of these data gives the following formula to estimate the energy of the EAS in the amplitude 32 MHz.

$$\varepsilon_{EW} /[\mu V/m/MHz] \propto (0.7 \pm 0.3)(E_0 / 10^{17} \text{eV})^{(0.95 \pm 0.04)}$$

**Figure 3.** The average spatial distribution of the amplitude of the radio signal.

**Figure 4.** The amplitude of the signal from the primary particle energy.

Thus, the registration of a radio signal from EAS can serve as another model-independent method for estimating the interaction energy of the shower.

4. **Conclusion**

The analysis of experimental data showed: a) the main mechanism responsible for the radio emission of EAS is geomagnetic because observed dependence of the signal from the arrival direction of EAS events, that is on the azimuthally angle, and this indicates the polarization of the EAS disk. The contribution of other mechanisms in the generation of radiation from EAS requires a more careful study and further analysis of experimental data, b) the spatial distribution of radio emission from EAS has a complex shape (varies with the distance to the shower axis), which shows the dependence of the characteristics of the height of the maximum bulk of the birth of the charged particles and can be used to determine the maximum development of EAS in the future to evaluate the mass composition of ultrahigh energy cosmic rays.

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