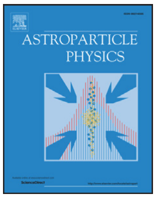
Astroparticle Physics 74 (2016) 79–86

Contents lists available at ScienceDirect

Astroparticle Physics

journal homepage: www.elsevier.com/locate/astropartphys



# Reconstruction of air-shower parameters for large-scale radio detectors using the lateral distribution

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## ARTICLE INFO

*Article history:*
Received 29 April 2015
Revised 4 September 2015
Accepted 15 October 2015
Available online 22 October 2015

*Keywords:*
Cosmic rays
Extensive air-showers
Radio detection
Lateral distribution

## ABSTRACT

We investigate features of the lateral distribution function (LDF) of the radio signal emitted by cosmic ray air-showers with primary energies $E_{\mathrm{pr}} > 0.1$ EeV and its connection to air-shower parameters such as energy and shower maximum using CoREAS simulations made for the configuration of the Tunka-Rex antenna array. Taking into account all significant contributions to the total radio emission, such as by the geomagnetic effect, the charge excess, and the atmospheric refraction we parameterize the radio LDF. This parameterization is two-dimensional and has several free parameters. The large number of free parameters is not suitable for experiments of sparse arrays operating at low SNR (signal-to-noise ratios). Thus, exploiting symmetries, we decrease the number of free parameters based on the shower geometry and reduce the LDF to a simple one-dimensional function. The remaining parameters can be fit with a small number of points, i.e. as few as the signal from three antennas above detection threshold. Finally, we present a method for the reconstruction of air-shower parameters, in particular, energy and $X_{\max}$ (shower maximum), which can be reached with a theoretical accuracy of better than 15% and 30 g/cm$^2$, respectively.

## 1. Introduction

The determination of the composition of the primary particles is one of the most interesting and complicated problems of experimental high-energy cosmic ray physics. Imaging instruments, particularly, fluorescence or Čerenkov detectors, detect cosmic ray air showers with high precision, but their duty cycle is only in the order of 10%. On the other hand, detectors with a full duty cycle, such as particle detectors, until now have poor sensitivity to the shower maximum and cannot provide accurate studies of the composition. A candidate to solve this dilemma is the radio detection of cosmic rays. It probably can reach a precision comparable with air-Čerenkov measurements. However, it still has a number of important open issues such as efficiency, systematic uncertainties and precision of the energy and shower maximum reconstruction, all also depending on the detector layout.

In the present paper we perform a detailed theoretical study based on a real large-scale detector layout. We performed about 300 simulations based on the reconstruction of measured high energy Tunka-Rex [1] and Tunka-133 [2] events. To simulate air showers we used CoREAS [3], software integrated in CORSIKA, which implements the end-point formalism for calculating radio emission from air showers. In comparison with previous work made for ideal detectors (see, for example, [4,5]), LOPES [6] and LOFAR [7], our investigations have several important differences. First, we reproduce detected events with small uncertainty, thus, our simulation could be compared with signals measured by Tunka-Rex, which, in turn, features an absolute amplitude calibration. Second, the geometry of the detector matches modern large-scale setups, i.e. the spacing between antennas is about 200 m. Finally, we transform the simulated signals applying the real hardware properties of Tunka-Rex (amplifiers, antennas, etc.), and check the sensitivity of selected antennas. That means, we do a statistical study which gives realistic upper limits for the precision of the reconstruction of air shower properties. “Upper limits” because we do not include noise and the precision will be slightly worse when taking into account realistic background (see Appendix). Therefore, this limit could be reached in the case of large signal-to-noise ratios (SNR).

The complication in describing the radio LDF originates from the interference of two completely different mechanisms of radio emission: emission due to geomagnetic deflection of charged particles, and the Askaryan (also known as charge-excess) effect. Adding these two effects causes an asymmetric two-dimensional lateral distribution function (LDF). There are two obvious approaches to describe this lateral distribution: to use a complex two-dimensional function, or to find some symmetries and rewrite the LDF invariantly. The first

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http://dx.doi.org/10.1016/j.astropartphys.2015.10.004
0927-6505/

approach was successfully tested in [7]. It was shown that the LDF can be described with good accuracy, but the method used in this approach requires a large number of points and, thus, a dense array. Because of that we used the second, customized approach. We found a transformation reducing the number of dimensions in the LDF representation to one, converting this function to an azimuthal-symmetric one. For this we estimate the strength of the asymmetry based on the shower geometry.

In additional to the simulation reproducing real Tunka-133 events, we also performed an “ideal” simulation using a symmetrical geometry and a three-dimensional dense detector. In contrast to the other simulations this is not for a statistical study of air-showers with different $X_{\max}$, but for performing a tomographic study of a mean air-shower (the description of this study is given in Section 2.2). In this way, we obtained evidence of a new feature of the radio emission, and found new connections of the parameters of the radio emission with the shower maximum.

### 1.1. Geomagnetic coordinate system

To perform our calculations and later the reconstruction in an invariant way, we will use the so-called geomagnetic coordinate system, a special version of shower coordinates. The outstanding feature of this system is that the electrical field vector has only two non-zero projections to the axes, the third projection is always close to zero. The basis of this coordinate system takes the form

$$\hat{\boldsymbol{e}}_x = \hat{\boldsymbol{V}} \times \hat{\boldsymbol{B}}, \tag{1}$$

$$\hat{\boldsymbol{e}}_y = \hat{\boldsymbol{V}} \times (\hat{\boldsymbol{V}} \times \hat{\boldsymbol{B}}), \tag{2}$$

$$\hat{\boldsymbol{e}}_z = \hat{\boldsymbol{V}}, \tag{3}$$

where $\boldsymbol{V}$ and $\boldsymbol{B}$ are the shower axis and the Earth’s magnetic field (hat over vector means normalization, e.g. $\hat{\boldsymbol{B}} = \boldsymbol{B}/|\boldsymbol{B}|$), respectively. Let us also define useful angles: the geomagnetic angle $\alpha_g = \angle(\boldsymbol{V}, \boldsymbol{B})$ and the geomagnetic azimuth $\phi_g = \angle(\hat{\boldsymbol{e}}_x, \hat{\boldsymbol{e}}_y)$.

### 1.2. Simulation sets

All simulations used in the present paper, have been produced with CoREAS [3]. As the hadronic interaction model we selected QGSJET-II. As the detector layout we used the setup of the Tunka-Rex experiment, which is located at an altitude of 675 m. The strength of the geomagnetic field was set to $\approx 60\ \mu$T, with inclination and declination of about 72° and $-3^\circ$, respectively. For the incoming direction and energy we used measured Tunka-133 events from 2012/2013. We selected events satisfying the condition $E_{\mathrm{pr}} \sin\alpha_g > 0.05$ EeV. Tunka-133 reconstructs only air-showers with zenith angles $\theta < 50^\circ$ due to design restrictions. That way, as initial parameters we used the energy of the primary particle $E_{\mathrm{pr}}$, the arrival direction $(\theta, \phi)$, and the core coordinates $(x, y)$ on the detector plane. As the primary particle we used the two possible extreme cases for these energies: protons and iron nuclei. Due to the high resolution of the Tunka-133 instrument, we can reproduce real events with high accuracy. The most important unknown parameter in the simulation is the depth of the shower maximum. Using different random seeds and primary particles (proton and iron) we try to limit the deviation between the shower maximum in the simulations and the measurement by Tunka-133 to less than 30 g/cm$^2$, as this is the precision of Tunka-133 [2]. For the present work we selected about 300 simulated events of each primary particle, using for each event the simulated shower with the smallest deviation between simulated and real $X_{\max}$.

Signal transformation and event selection on the detector level are made with the Auger Offline software framework [8]. We used the pattern of the Tunka-Rex antenna type, which is in first order close to a dipole. The frequency range is 30 – 80 MHz. The event reconstruction pipeline is similar to Tunka-Rex, except for the SNR cuts: we do not add noise to the simulations[1]; thus, we put only a threshold on the signal amplitude to reduce the digital noise.

All plots, except Fig. 2, are obtained with the Tunka-Rex layout and Tunka-133 event set. For Fig. 2, we performed a different simulation, as explained in Section 2.2.

## 2. Asymmetry

Presently there are a number of mechanisms for air-shower radio emission suggested by theorists [5,9]. We will consider only two contributions, which have been proven experimentally and which are the most important and dominant ones: geomagnetically induced transverse currents [10] and the Askaryan effect [11]. The complexity of adding these two contributions arises from the different mechanisms of the emission. While the electrical field of the geomagnetic emission is obtained by integration of charged particles $N_e(h)$ over the height $h$ and lies along the $\mathbf{v} \times \mathbf{B}$ vector, the Askaryan emission is mostly defined by the derivative $N_e'(h) = \mathrm{d}N_e/\mathrm{d}h$ and polarized along $\mathbf{v} - \mathbf{V}$, where $\mathbf{v}$ is the velocity of the particle and $\mathbf{V}$ is the shower axis. In Ref. [12] good agreement between this simple model and measured data is shown. In our study we therefore assume that total polarization is a sum of two linear polarized contributions with unknown amplitudes. This leads to the known azimuthal asymmetry of the lateral distribution of the radio signal [12,13].

While in principle the asymmetry can be extracted from polarization measurements for individual events [14,15], in practice, this is difficult when the typical event has just three or four stations above the noise threshold. Therefore, we developed an approach to approximately correct for the asymmetry based on the event geometry only, since this is measurable with better accuracy for events with only a few antenna stations.

### 2.1. Origin of asymmetry

The total electrical field at an antenna at each distance $r$ and azimuth $\phi_g$ can be represented as vector.

$$\mathcal{E}(r) = \mathcal{E}_{\mathrm{g}}(r) + \mathcal{E}_{\mathrm{ce}}(r) + \mathcal{E}_{\mathrm{v}}(r)\,, \tag{4}$$

where $\mathcal{E}_{\mathrm{g}}$ is a dominantly linearly polarized geomagnetic contribution, $\mathcal{E}_{\mathrm{ce}}$ is a radially polarized (like a normal Čerenkov) contribution from the Askaryan effect and $\mathcal{E}_{\mathrm{v}} \approx 0$ is a vertical contribution to the signal. We neglect the contribution from the vertical component, since the angle between the shower plane and radio wavefront is only 1–2° [16]. As in Refs. [5,9], we assume that the amplitude of $\mathcal{E}_{\mathrm{g}}$ and $\mathcal{E}_{\mathrm{ce}}$ changes only with distance $r$, but is constant over $\phi_g$. For $\mathcal{E}_{\mathrm{g}}$ also, the orientation is constant. Thus, the signal has the following components in the introduced geomagnetic coordinate system:

$$\mathcal{E}_{\mathrm{g}} = (\mathcal{E}_{\mathrm{g}},\ 0,\ 0) = (\mathcal{E}_0 \sin\alpha_{\mathrm{g}},\ 0\,,0)\,, \tag{5}$$

$$\mathcal{E}_{\mathrm{ce}} = (\mathcal{E}_{\mathrm{ce}} \cos\phi_{\mathrm{g}},\ \mathcal{E}_{\mathrm{ce}} \sin\phi_{\mathrm{g}},\ 0)\,, \tag{6}$$

where $\mathcal{E}_{\mathrm{g}} = \mathcal{E}_0 \sin\alpha_{\mathrm{g}} \sim E_{\mathrm{pr}} \sin\alpha_{\mathrm{g}}$, and $\mathcal{E}_{\mathrm{ce}} \sim E_{\mathrm{pr}}$, and $E_{\mathrm{pr}}$ is the energy of the primary particle. We assume that the strength of the radio emission depends linearly on the energy of the electromagnetic component (and, consequently, on the total energy) of the air-shower. The squared amplitude has the form

$$\begin{aligned} \mathcal{E}^2 &= (\mathcal{E}_0 \sin\alpha_{\mathrm{g}} + \mathcal{E}_{\mathrm{ce}} \cos\phi_{\mathrm{g}})^2 + \mathcal{E}_{\mathrm{ce}}^2 \sin^2\phi_{\mathrm{g}} \\ &= \mathcal{E}_0^2\big((\sin\alpha_{\mathrm{g}} + \varepsilon\cos\phi_{\mathrm{g}})^2 + \varepsilon^2 \sin^2\phi_{\mathrm{g}}\big), \end{aligned} \tag{7}$$

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[1] This decision was motivated in order to avoid the study of the influence of noise on the signal, which is more appropriate in an analysis dealing with real measurements. Thus, the results we obtain here are a theoretical prediction for large SNR. For the influence of noise please see Appendix.