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Precise Reconstruction of a Shower Maximum in the Tunka Radio Extension Experiment

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Abstract—Tunka-Rex is an antenna array located in the Tunka Valley that measures the radio emissions of cosmic ray air showers with energies of up to 100 PeV. In this work, a precise technique for reconstructing a shower maximum from Tunka-Rex data is presented. A model is developed for calculating detector efficiency that considers different parameters: primary particle energy and mass ranges, shower geometry, and detector configuration. The systematic error introduced by the atmosphere in reconstructing a shower's maximum depth is estimated, and the distribution of the mean shower maximum versus energy is determined.

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INTRODUCTION

Tunka-Rex is an antenna array that measures the radio emissions of extensive air showers (EASes) initiated by high-energy cosmic rays (CRs). The measurements are made by optical (Tunka-133 [2]) and scintillation (Tunka-Grande [3]) detectors in the 30–80 MHz range. Compared to classical optical techniques, EAS radio emissions are of special interest, since they do not dependent of the weather conditions or time of day.

Tunka-Rex currently consists of 63 antenna stations that cover an area of around 3 km^2. Each antenna station consists of two perpendicular SALLA (Short Aperiodic Loaded Loop Antenna) ring antennas [4] with diameters of 120 cm, mounted on masts 2.5 m high. In the upper part of the antenna station, the antennas are connected to a low-noise amplifier and then to the ADC of the Tunka-133 or Tunka-Grande facility (sampling frequency, 200 MHz; dynamic range, 12 bits; track length, 1024 values).

CALCULATING EFFICIENCY

EAS radio emissions are due to two main effects. The first of these is geomagnetic [5] and consists of a change in the direction of charged shower component motion under the action of the geomagnetic field. It depends on the direction of shower arrival (the smaller the angle to the geomagnetic field vector, the lower the amplitude of the recorded radio emission) and makes the main contribution to the final pattern. The second is the Askar'yan effect [6], which is a change in the shower charge due to atmospheric ionization and pos-

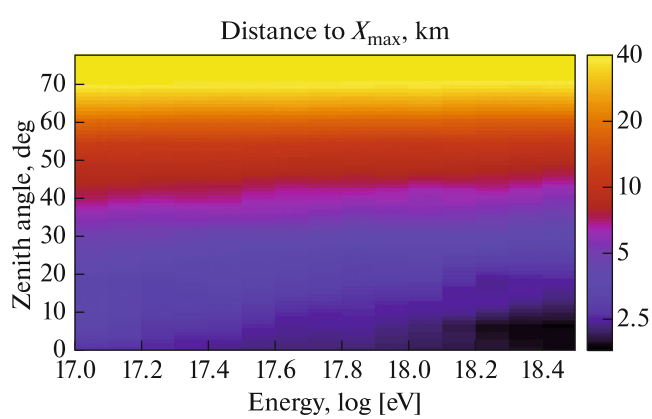

Fig. 1. Mean distance to a shower maximum versus the zenith angle and primary particle energy, according to modeling data.

Table 1. Model efficiency for different seasons, compared to Tunka-Rex reconstruction results

Generation of antenna	Year	Number of antennas	Expected events	Recorded events	Efficiency
1a	2012/13	18	23	20	0.85
1b	2013/14	25	28	27	0.96
2	2015/16	44	14	14	1.00
3	2016/17	63	17	16	0.94
		Total	82	77	0.94

itron annihilation. The contribution from this effect is small (about 10%) compared to the geomagnetic effect, but it remains appreciable and should be considered during data processing and interpreting results [7]. There is thus a dependence of the recording efficiency on the direction of arrival of primary particles for a large number of events.

To calculate the efficiency of recording EAS radio emissions under Tunka-Rex conditions, a Monte Carlo model was developed on the basis of CoREAS simulation data and detector parameters. In the model, a shower's track (the area on the detector's surface inside which the amplitude of radio emissions exceeds the threshold) was calculated, sampling over the number of antennas was performed, and the efficiency of event recording was calculated, depending on the energy and direction of arrival. The model results were compared to actual Tunka-Rex reconstruction data. The data from the host detector for 2012–2017 events was taken as the input, and the efficiency of recording was calculated for each event. The events for which the calculated efficiency of recording was higher than 90% were then selected and compared to actual recorded events (filtered, sampled, and with successfully reconstructed shower parameters). The test showed good agreement between the model and the data of the host experiment (see Table 1).

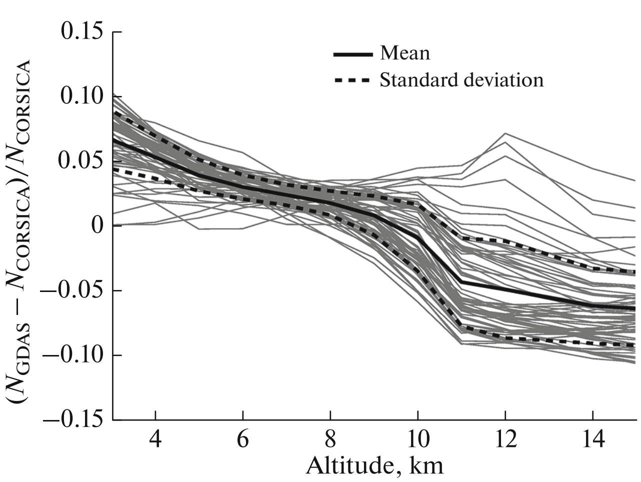

Fig. 2. Altitude dependence of the deviation of the refractive index from the refractive index used in the CORSIKA modeling, according to GDAS data.

TEMPLATE FITTING

We used the following approach to increase the accuracy of shower maximum reconstruction. A series of radio emission showers was modeled for preliminarily processed Tunka-Rex events (the primary particle mass and a shower's maximum depth are free parameters for each individual event in the series). Signal tracks were obtained from the modeling. Their envelopes were compared to ones reconstructed from real data. A minimum of χ^2 between the simulated and real signals was calculated, and the position of the shower's maximum depth was thus related to the corresponding model. For more detail, see [8].

ATMOSPHERIC REFRACTIVE INDEX EFFECT

The effect the atmospheric refractive index has on the reconstruction of EAS parameters was studied in [9]. Data from the GDAS satellite atmosphere observation system [10] were used to calculate the refractive index, including the air density, humidity, and temperature distribution over altitude with a temporal resolution of 3 h and a spatial resolution of 1°. A comparison was made between GDAS data and data from the atmospheric model included in the CORSIKA software [11] and used for processing Tunka-Rex data. Profiles of the refractive index were constructed (Fig. 2) and served as the basis for calculating the systemic error in the shower maximum at Tunka-Rex. The estimated fluctuation of the shower maximum due to changes in atmospheric conditions was negligible.

CONCLUSIONS

The approach described in this work allowed us to increase the accuracy of energy reconstruction to 10% and that of reconstructing a shower maximum to 25–35 g/cm^2 in the tunka-Rex experiment. A model for calculating the efficiency of recording EAS radio emissions was developed and tested. It allows us to calculate the detector aperture and exposure and thus to obtain better accuracy in reconstructing the CR energy spectrum and mass composition. More detailed calibration and systematization are planned for the future, and we shall then proceed to reconstructing mass composition using combined measurements made with the radio and scintillation detectors.

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