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The Tunka Radio Extension: Latest Analysis Results

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Abstract. Tunka-133 is an air-Cherenkov array placed in Siberia, near the southern tip of Lake Baikal, which registers air showers induced by cosmic rays from initial particles with energies of 10^{16} – 10^{18} eV. After several years of successful data collection, this array was extended by other detector arrays. One of them is the Tunka Radio Extension (Tunka-Rex): the radio array consists of presently 25 antenna stations connected to the data acquisition of Tunka-133. This combination provides hybrid measurements and the possibility for cross-calibration between the air-Cherenkov and radio measurement techniques. The main goal of Tunka-Rex is to determine the precision of the reconstruction of air-shower parameters using the radio detection technique. We present the latest results on the event reconstruction.

1. Introduction

Radio emission from extensive air showers was theoretically predicted [1, 2, 3, 4] and first detected [5, 6, 7] about 50 years ago. The radio detection techniques became popular in the last decade again, because standard detection methods are going to reach technological and economical limits, contrariwise, the digital processing of radio data became possible. Thus, a number of modern experiments [8, 9, 10, 11] aims at obtaining the main properties of extensive air showers using the radio detection technique.

Tunka-Rex, the radio experiment in the Tunka valley, is motivated by the well-developed infrastructure and unique possibility of hybrid air-Cherenkov and radio measurements. These conditions give a chance to show the prospects of a low-cost, scalable radio detector for cosmic rays. The main goal of Tunka-Rex is to determine the precision for the reconstruction of the primary energy, E_{pr} , and the atmospheric depth of the shower maximum, X_{max} , based on the cross-calibration with an air-Cherenkov detector.

The Tunka-133 air-Cherenkov detector [13] is taking data since 2009. In 2012 two new extensions were introduced: HiSCORE [14] and Tunka-Rex [15]. Moreover, the development of a new gamma-astronomy facility named TAIGA started [16]. This new facility will consist of



the existing Tunka-133 and HiSCORE detectors, additional imaging air-Cherenkov telescopes, and new particle detectors. TAIGA partly has started data acquisition in 2014.

Tunka-Rex currently consists of 25 antenna stations attached by cables to the cluster centers of the Tunka-133 photomultiplier array. Each antenna station consists of two orthogonally oriented SALLA antennas [17], aligned in magnetic North-East and North-West directions.

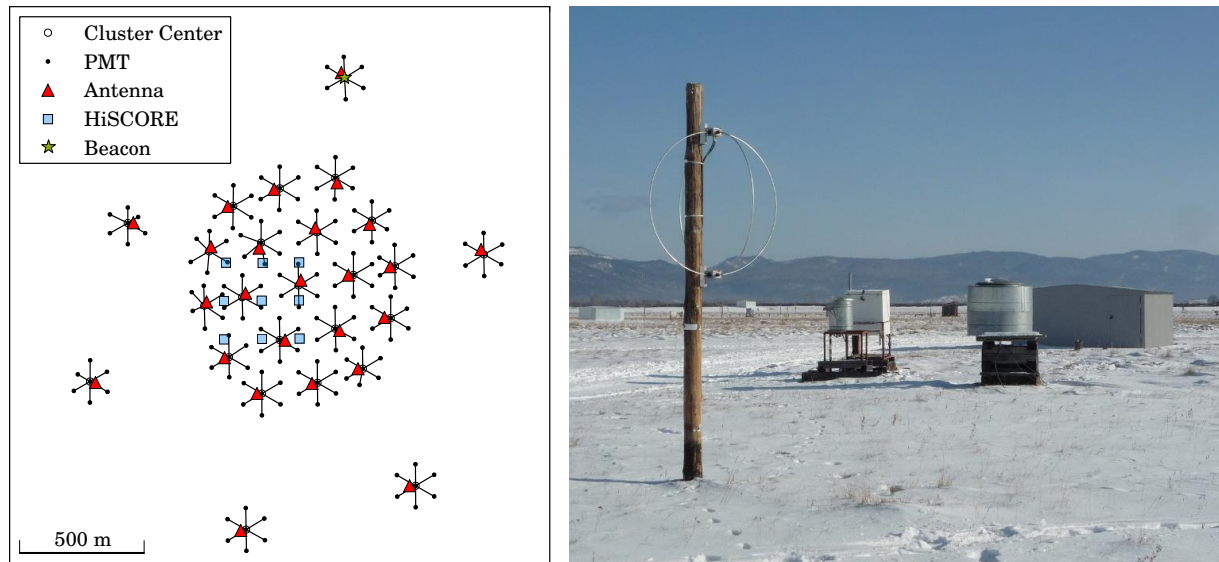


Figure 1. The Tunka facility.

Left: Map of Tunka. One Tunka-Rex antenna station, consisting of two SALLAs [17], is attached to each cluster.

Right: A Tunka-Rex antenna station in front of a Tunka-133 cluster center box, the central PMT of the cluster and a house with scintillators.

2. Event selection and data analysis

In the season 2012/2013 (from October to April), Tunka-133 had 316 hours of effective measurement time. The Tunka-Rex data acquisition is triggered by the air-Cherenkov array, thus this is limiting its measurement time. For the first season we performed a non-blind analysis, i.e., we used the full reconstruction information from the Cherenkov detector as input for the radio analysis.

For analysis of the radio measurements, we use the radio extension of the Offline software framework developed by the Pierre Auger Collaboration [19, 20]. An example of a reconstructed event is presented in Fig. 2.

Since a full event reconstruction (i.e. reconstruction of E_{pr} and X_{max}) of Tunka-133 is available only for events with zenith angle less than 50° (will be explained below), we restrict the cross-calibration analysis to these events.

In the first step, we search for the signal in a defined time window. The time window is the same for every antenna because of the identical hardware configuration. The main uncertainty comes from hardware delays and shower geometry. A rough estimation can be found in Ref. [21]. Detailed study of traces has shown that the arrival times have relatively small uncertainties and that a window size of 300 ns is sufficient. Noise is defined as a RMS in special window, where the probability of false pulses is smallest. Thus, SNR (signal-to-noise ratio) is defined as a squared fraction between signal and noise. We apply two different SNR cuts on different reconstruction

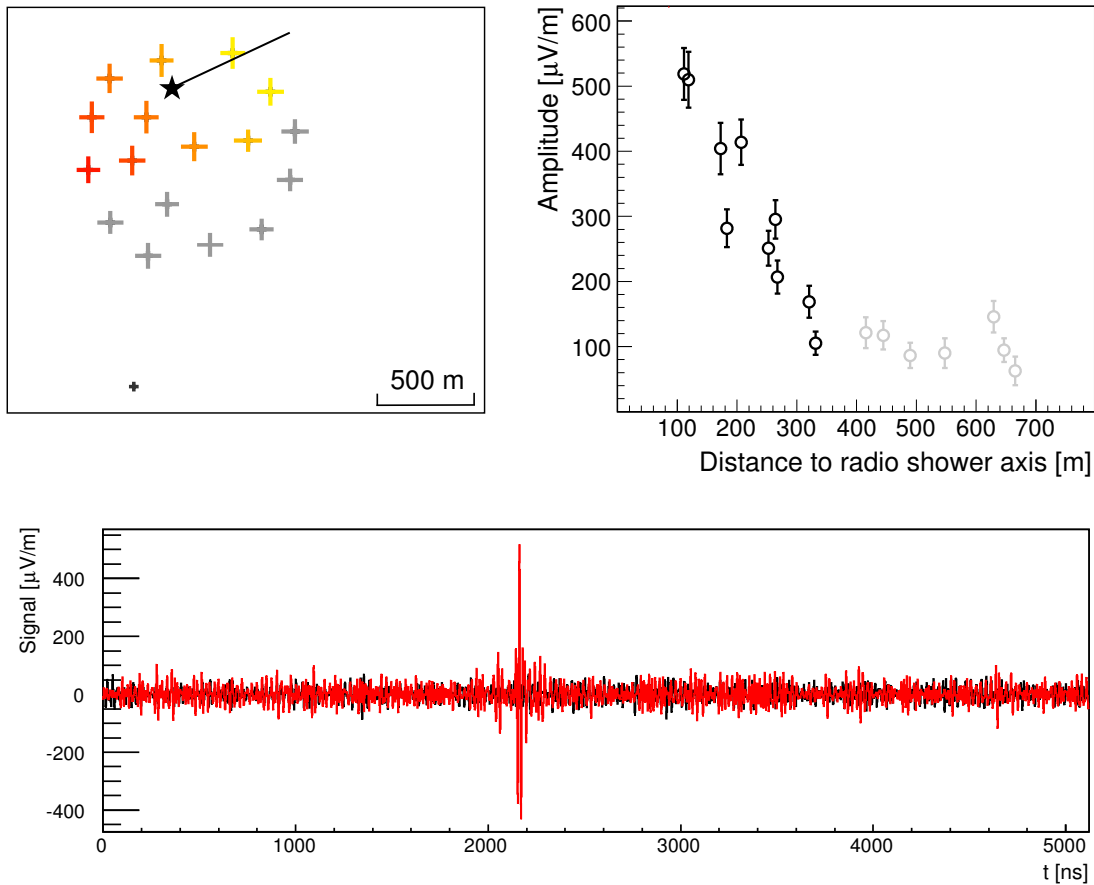


Figure 2. Example for a Tunka-Rex event.

Top left: footprint of the event, where the size of the crosses indicates the signal strength, the color code the arrival time, and the line and the star the direction and shower core, respectively.
Top right: lateral distribution of reconstructed signals. As in the footprint, grey points indicate signals which did not pass the SNR (signal-to-noise ratio) cut.

Bottom: example trace of the reconstructed electric-field strength, we expect the radio pulse around 2000 ns.

levels: the SNR must be larger than 9 in both channels and the SNR must be larger than 6 on the station level (reconstructed electrical field vector). After these cuts we found 117 events, which contain 3 or more antennas with signal.

For the next quality cut we compare the arrival direction obtained from the Cherenkov and radio detectors. We set an upper limit for the reconstruction difference to 5° and compare the values obtained from a plane fit of the radio shower front with the values from Cherenkov reconstruction. After this cut 65 events remain, where the other events likely are contaminated by disturbances.

In the third step we apply a final quality cut: after removing clear outliers in the signal strength from the lateral distribution, we set a limit for the LDF (lateral distribution function, described later) fitting quality of $\chi^2/\text{NDF} < 8.0$. This number was chosen arbitrarily in order to select events, for which an exponential LDF provides a sufficient approximation. In a detailed theoretical study [22], it is shown, that the exponential function can not give a good description for every case, and a detailed analysis taking this into account is in preparation. Assuming that

the theoretical limit for the energy precision is about 10% [22], thus, to obtain a resolution of order 20%, it is sufficient to remove events with fitting uncertainty larger than 20%. Under the assumption, that the geomagnetic effect dominates, one event with small geomagnetic angle ($\alpha_g < 0.3$ rad) is also removed¹. Finally, 54 events remain (quality cuts from third step removed 11 events).

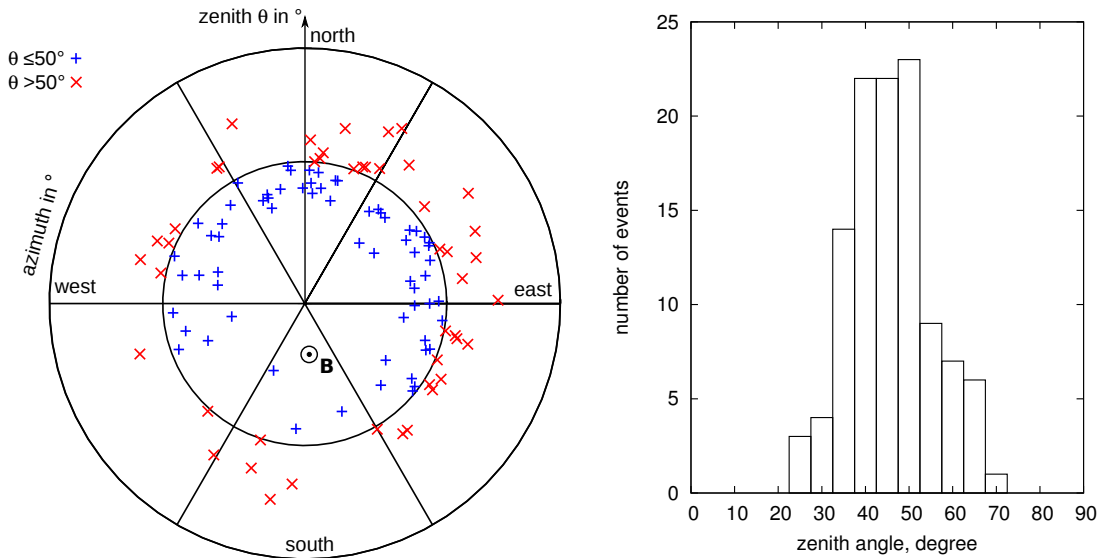


Figure 3. Distribution of the arrival directions of the Tunka-Rex events passing the quality cuts.

Left: sky map of the arrival directions. We present events passing the direction cut and do not apply additional quality cuts for this distribution. Due to the geomagnetic effect, the radio signal is expected to be on average stronger for events coming from North, which explains the asymmetry in the detection efficiency: 46 of the 65 events are in the northern half, and 19 in the southern half.

Right: Zenith angle distribution of detected radio events. The maximum efficiency is reached at the Tunka-133 reconstruction threshold of $\theta \approx 50^\circ$. The statistics at smaller angles is mainly suppressed by the steeply falling lateral distribution of the radio signal, the statistics at larger angles is suppressed by trigger detection capabilities of the air-Cherenkov detector.

The distribution of the arrival directions is shown in Fig. 3. The upper limit for direct Cherenkov light detection is a zenith angle less than 50° , but the zenith angle for triggering can be extended up to 70° due to indirect detection of reflected light. The total number of all inclined events is only about 5% of all Tunka-133 high energy events, since the sensitivity of trigger to big zenith angle decreases rapidly. This means that the detection of inclined events is suppressed by trigger design, and the detection of events with small zenith angles is suppressed

¹ The asymmetry given by the charge excess phenomena is proportional to

$$\frac{\varepsilon \sin \alpha_g}{\sin^2 \alpha_g + \varepsilon^2} \cos \phi, \quad (1)$$

where ε is a contribution of charge excess effect to total signal strength, α_g is a geomagnetic angle, ϕ is an azimuth in geomagnetic coordinate system [22]. E.g., if the contribution of charge excess is 10% and geomagnetic angle is about 0.3 rad, the asymmetry can be up to 30% depending on the azimuth of the antenna station with respect to the shower axis. This can be crucial when the number of antennas is small.

by the geometry of the detector (the spacing between antennas is about 200 m, thus shower need a high energy to illuminate at least three antennas at small zenith angles).

In Fig. 3 we divided events into two groups: vertical (“+” symbol) and horizontal (“×” symbol). For horizontal events the air-Cherenkov detector can reconstruct only the direction, but neither the energy nor the shower maximum. Therefore, we use only the vertical events for cross-calibration.

It is worth mentioning that we also see a North-South asymmetry in the arrival direction as is predicted by the geomagnetic effect. The number of vertical events coming from the Northern and Southern hemispheres of the sky is 46 and 19, respectively.

To explain the features of the lateral distribution one can use the following exponential description of the LDF

$$\mathcal{E}(d) = \mathcal{E}_{d_0} \sin \alpha_g \exp[f_\eta(d - d_0)], \quad f_\eta(x) = \sum_{k=1}^n a_k x^k, \quad (2)$$

where $\mathcal{E}(d)$ is the strength of the electrical field at the distance d from the shower axis, a_k are parameters describing the shape of the lateral distribution; d_0 is usually selected in a way to degenerate the dependence on the shower maximum of $\mathcal{E}_{d_0}$, i.e. $\mathcal{E}_{d_0}(E_{\text{pr}}, X_{\text{max}}) \approx \mathcal{E}_{d_0}(E_{\text{pr}})$. The geomagnetic angle α_g is defined as the angle between the shower axis $\mathbf{A}$ and the geomagnetic field $\mathbf{B}$: $|\mathbf{A} \times \mathbf{B}| = |\mathbf{A}| \cdot |\mathbf{B}| \sin \alpha_g$. The shower parameters such as energy and shower maximum mostly depend on the properties of LDF $\mathcal{E}(d)$: $E_{\text{pr}} = E_{\text{pr}}(\mathcal{E}_{d_0})$ and $X_{\text{max}} = X_{\text{max}}(a_k)$. A rough description of the lateral distribution can already be obtained by setting $n = 1$

$$\mathcal{E}(d) = \mathcal{E}_{d_0} \sin \alpha_g \exp[-\eta(d - d_0)] \quad (3)$$

where $\eta \equiv a_1$ is an exponential slope parameter [23]. Traditionally we chose $d_0 = 100$ m [24]. After normalizing by the sine of the geomagnetic angle, we check for the correlation between the reconstructed electrical field $\mathcal{E}_{d_0}$ obtained fitting the LDF and the energy of primary particle reconstructed by Tunka-133 (see Fig. 4). The relative deviation between the energy reconstructed by both detectors is about 20%. Thus, we conclude that the two parameter exponential LDF is sufficient the energy estimation with that precision. The uncertainty of the energy reconstruction is mainly defined by the parameter fitting uncertainty. A more sophisticated analysis taking into account the Askaryan effect, and aiming at a better energy precision is in preparation.

3. Conclusion

Tunka-Rex has shown the feasibility of the present implementation of hybrid air-Cherenkov and radio measurements of cosmic rays. Our measurements are compatible with the picture predicted by theoretical description and latest results given by other experiments. The next step in the analysis will be the reconstruction of the shower maximum and unblinding the air-Cherenkov data of the season 2013/2014 for cross-check and analysis with high statistics.

The local infrastructure allows to extend the radio detector and perform super-hybrid measurements of the different components of air-showers: air-Cherenkov, particles on ground and radio. In 2014, 19 new antenna stations were attached to future stations of the scintillator extension and three antenna stations were attached to HiSCORE stations for technical tests. The new scintillator triggered radio extension can increase the duty cycle of Tunka-Rex up to 100%, and, consequently, increase the statistics by one order of magnitude. Consistent with the amplitude calibration it helps to check radio emission models and the shower universality hypothesis.

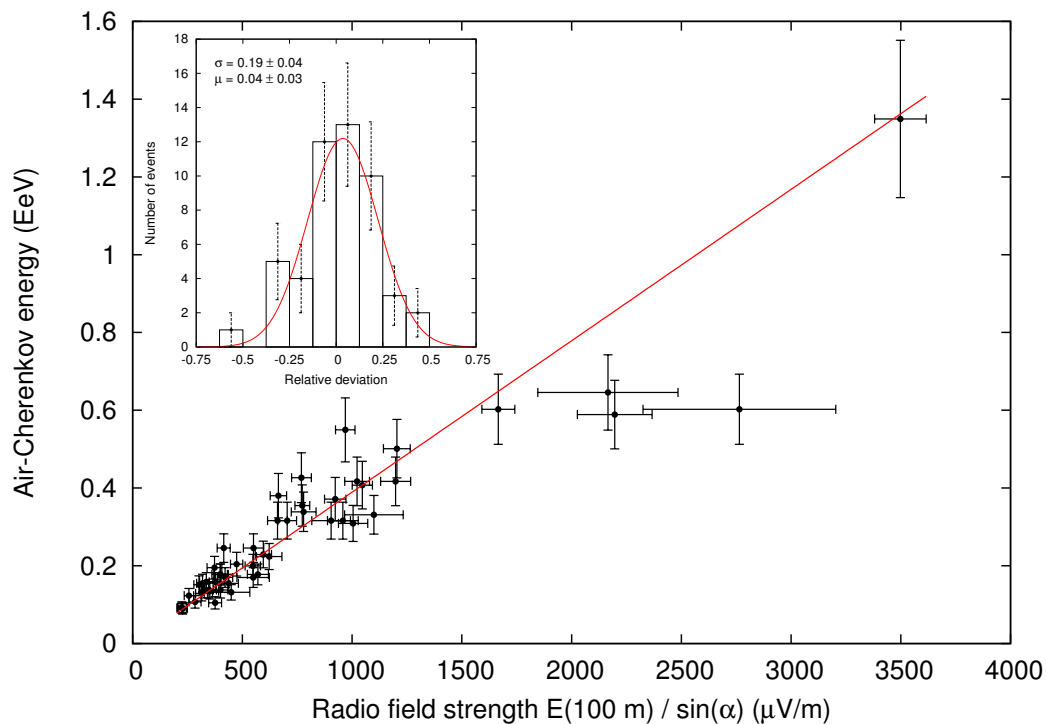


Figure 4. Correlation between the radio field strength at 100 m $\mathcal{E}_{d_0}$ normalized by the sine of the geomagnetic angle and the energy reconstructed with the air-Cherenkov measurements. The uncertainties of the electrical field are from the LDF fit, the uncertainties of the Tunka-133 energy reconstruction are 15%. The histogram shows the scatter between the energy reconstructed by Cherenkov and radio.

Acknowledgments

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