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Improving Signal Reconstruction with Matched Filters and Neural Networks for the Tunka-Rex Experiment

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Abstract—Tunka-Rex is an antenna array for the detection of radio emissions from extensive air showers generated by ultra—high energy cosmic rays. This emission has a broadband spectrum, which corresponds to pulses with durations of tens of nanoseconds and is measured in the band of 30 to 80 MHz. Matched filtering and artificial neural networks are used to improve signal processing at the Tunka-Rex facility. Matched filtering allows more accurate determination the signal peak time, but the best performance can only be achieved with white noise. Convolutional neural networks with autoencoder architecture are used to improve recognition of noise features in traces. These are implemented in Tunka-Rex signal processing and their performance is compared to that of standard means.

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INTRODUCTION

Tunka-Rex is an antenna array that solves the problems of detecting radio emissions from extensive air showers (EAS) initiated by cosmic rays with energies above 100 PeV. The experiment operates in the frequency range of 30 to 80 MHz and consists of 63 antenna stations located in the Tunka Valley, Buryatia [1].

The array requires an external trigger to operate, so Tunka-Rex works in conjunction with other detectors: the Tunka-133 Cherenkov detector [2] and the Tunka-Grande scintillation detector [3].

Typical signals recorded by the Tunka-Rex facility are coherent broadband pulses with durations of tens of nanoseconds. The amplitude and peak position of such a pulse are reconstructed by finding the maximum of the envelope [1]. This approach has proven itself well, but other means can also be used to improve the reconstruction of signal parameters, especially a matched filter and neural networks.

MATCHED FILTER

A matched filter is based on the correlation between a received signal and its template using convolution. The amplitude of each convolution point can be considered a measure of how closely the template matches the corresponding part of the incoming signal. The filter can be implemented using software. Starting from the beginning of the track, the template is multiplied in sequence with all values of the received signal. The results are summed, and the template is shifted by one step. The peak of the signal acquired as a result of these actions will correspond to the peak of the received signal.

For a matched filter to work, we must have a signal that is already known; in this work, we used a template of a 60-ns signal created by averaging several thousand EAS pulses simulated using the CoREAS software [4]. The length of this template is optimal in terms of speed and accuracy of the result, as can be seen on the left in Fig. 1.

To determine the response threshold of the matched filter, we constructed the distribution of square roots of the maxima of the template convolutions with a background noise window (i.e., with tracks that obviously contain no signal). A quantile corresponding to a 5% probability of detecting a false signal was determined for this distribution. As a result, we obtained a value of the convolution amplitude at

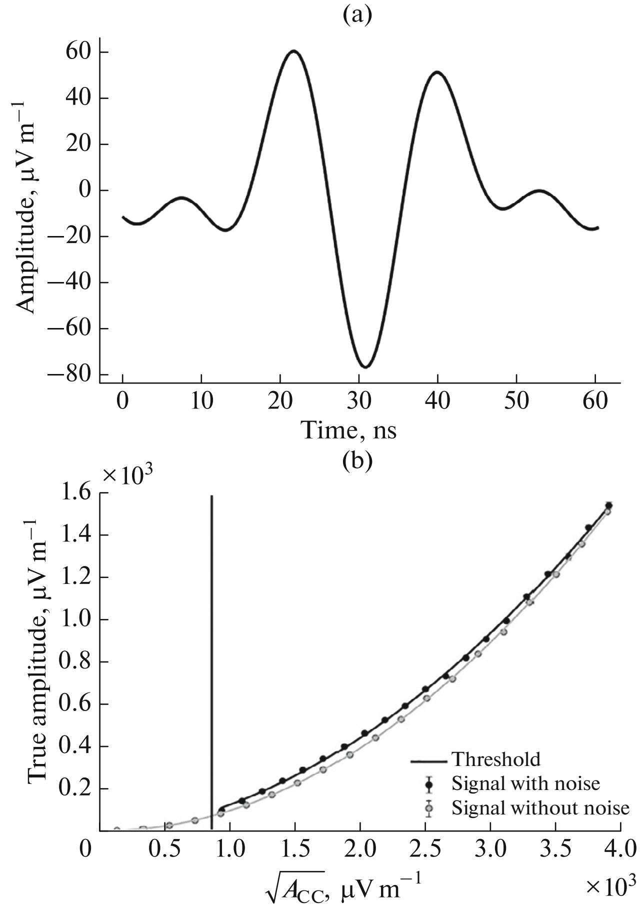

Fig. 1. (a) 60-ns signal template; (b) distributions of the true amplitude, relative to the square root of the maximum cross correlation.

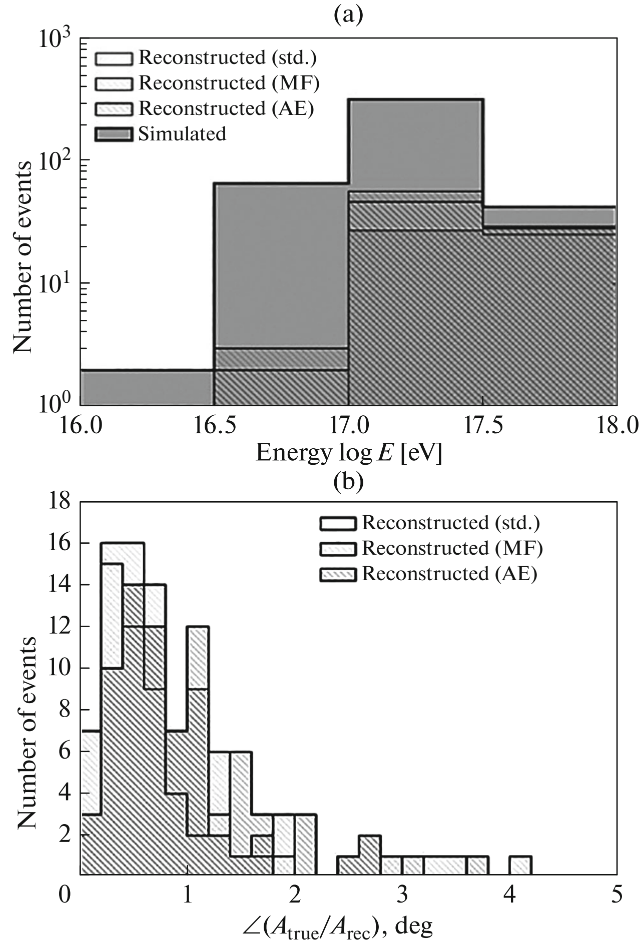

Fig. 2. (a) Distribution of reconstructed energies; (b) distribution of deviations in the direction of arrival.

which the reconstruction of the peak and position of the signal could still be performed (854 $\mu V\ m^{-1}$).

The right-hand part of Fig. 1 shows the result from using the matched filter to reconstruct the amplitudes of a set of model signals with and without noise, along with one using the threshold to distribute the true amplitude relative to the square root of the maximum cross-correlation.

The matched filter was included in the Offline software environment [5] and tested on a set of simulated events. It was shown that the filter is capable of reconstructing pulses with lower amplitudes, and the angle-of-arrival resolution is similar to the one in the standard approach.

NEURAL NETWORKS

Another means used in this work was an autoencoder, i.e., a neural network based on one-dimensional ultra-precise layers with a straightened linear unit and maximum unification after the ultra-precise layer. Binary cross-entropy is in this case used as a loss function. In contrast to matched filtering, an autoencoder is intended for isolating and eliminating noise features.

Two metrics were used to evaluate the quality of networks: efficiency N_{rec}/N_{tot}, which corresponds to the part of the events that cross the threshold, and purity N_{hit}/N_{rec}, denoting the reconstructed events for which a peak is reconstructed with the condition $|t_{rec} - t_{true}| < 5$ ns. Here, N_{rec}, N_{tot}, and N_{hit} are the number of reconstructed events, the total number of events, and the number of reconstructed events, the peak of which hits the interval $|t_{rec} - t_{true}| < 5$ ns, respectively; t_{rec} and t_{true} are the reconstructed and true positions of the signal peak in time.

As with a matched filter, an autoencoder is able to recover signals with lower energy than in the standard approach, and its angular resolution remains at the same level. This can be seen in Fig. 2.

CONCLUSIONS

Signal reconstruction was improved with both a matched filter and an autoencoder. Both approaches showed similar efficiency higher than that of the standard technique. Software that includes these procedures is ready to be implemented in the standard processing of the Tunka-Rex experiment. Work is also under way to improve the efficiency of these means by creating a library of templates for the matched filter and optimizing the architecture of the autoencoder.

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