Systematic uncertainties of the primary astroparticle energy estimation vs zenith angle distribution of EAS event rate measured with the surface array

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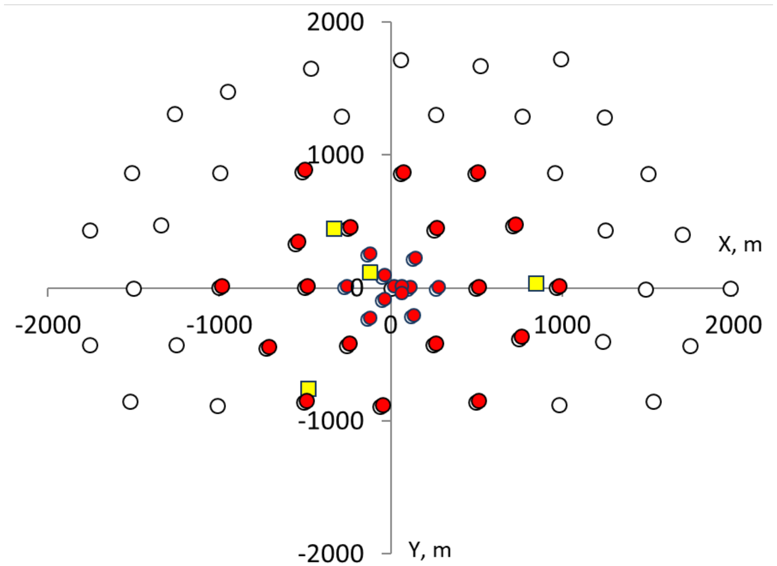
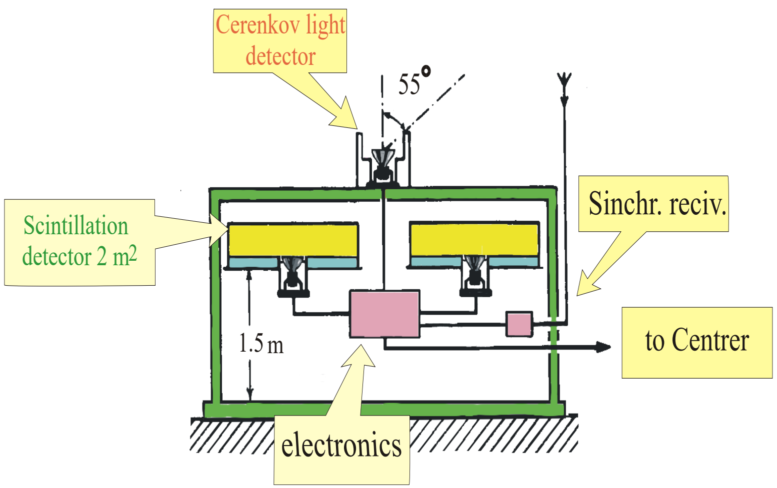
Measurement and parametrization of EAS with the Yakutsk array





The Yakutsk array studies cosmic rays in the energy range above 10 PeV.
The main parameter obtained from the measured data is S_{600} – the density of particles at the shower core distance 600 m.

Adding the Cherenkov radiation data and using the model simulation of EAS the relation of S_{600} to the energy of the primary astroparticle is derived.

Evaluation of the energy of the primary particle initiating EAS

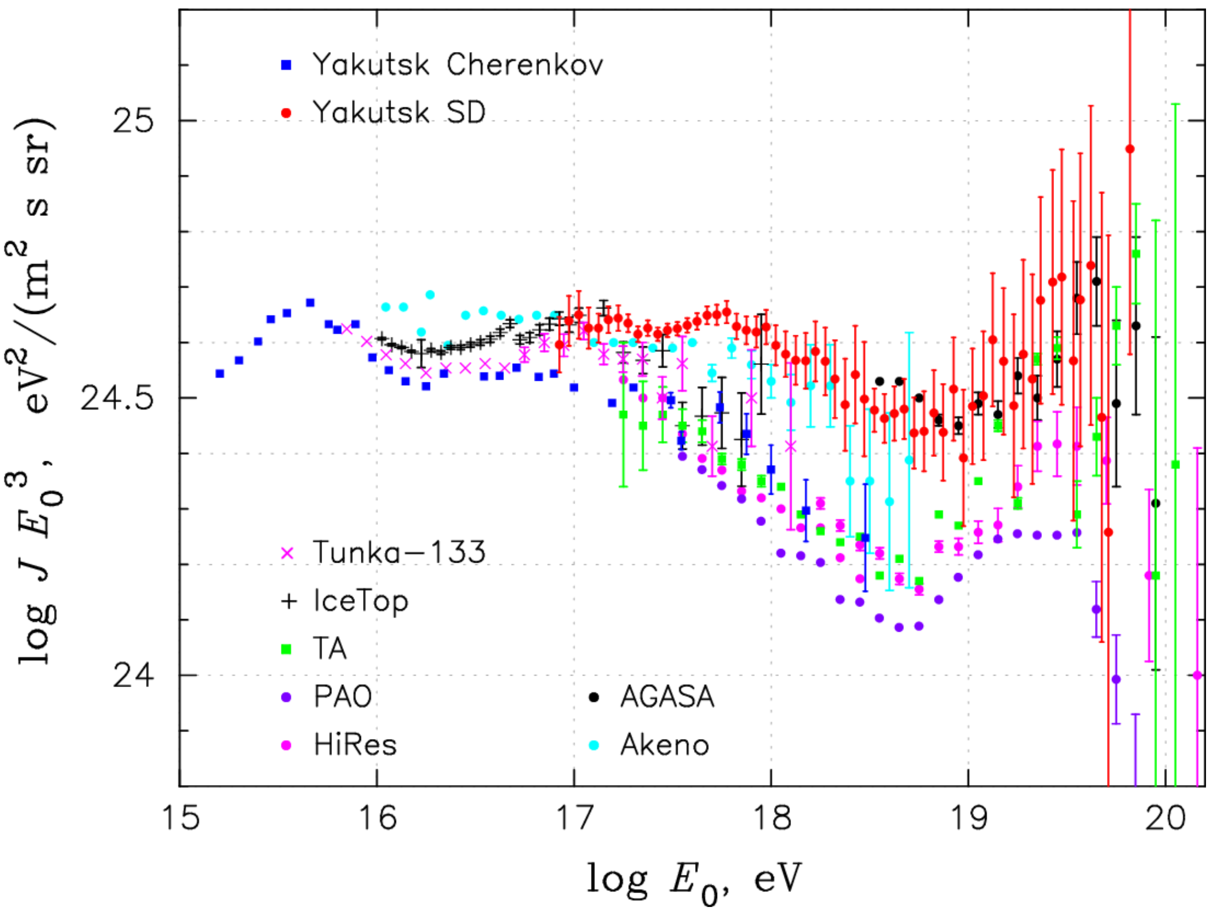
We have considered three methods of E_0 evaluation used to be in use in the Yakutsk array group. They all are based on the measurement of the total flux of the Cherenkov radiation from EAS as well as on scintillator's data and model simulation results of the shower development parameters.

Method 1. (A.V. Glushkov et al., Izv. AN SSSR ser. fiz. **55** (1991) 713)
$E_0 = (4.8 \pm 1.4) \times 10^{17}(S_{600}(0))^{1.0\pm0.02}$, where $S_{600}(0) = S_{600}(\vartheta)\exp((\sec\vartheta - 1)L_0/L)$, m⁻2,
$L = (460 \pm 50) + (32 \pm 15)\ln(S_{600}(0))$, g/cm^2.

Method 2. (M.I. Pravdin et.al., Bull. Russ. Acad. Sci.: Phys. **71** (2007) 445)
$E_0 = (4.6 \pm 1.2) \times 10^{17}(S_{600}(0))^{0.98\pm0.02}$, where
$S_{600}(\vartheta) = S_{600}(0)((1 - \beta)\exp((1 - \sec\vartheta)L_0/L_e) + \beta \exp((1 - \sec\vartheta)L_0/L_\mu))$, m⁻2,
$\beta = (0.39 \pm 0.04)(S_{600}(0))^{-0.12\pm0.03}$; $L_e = 250$ g/cm^2;$L_\mu = 2500$ g/cm^2.

Method 3. (A.V. Glushkov et al., Phys. Atom. Nucl. **81** (2018) 474)
$E_0 = (3.76 \pm 0.3) \times 10^{17}(S_{600}(0))^{1.02\pm0.02}$, where $S_{600}(0) = S_{600}(\vartheta)\exp((\sec\vartheta - 1)L_0/L)$, m⁻2,
$L = (450 \pm 44) + (32 \pm 15)\ln(S_{600}(0))$, g/cm^2 [6].

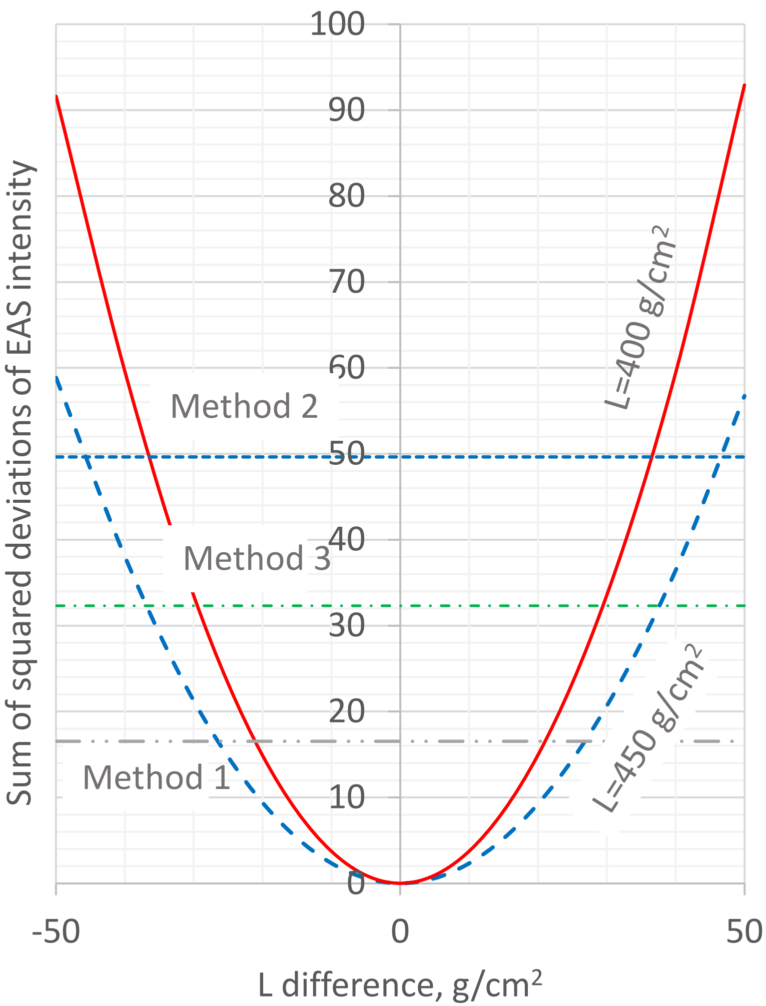
Energy spectra of UHECRs measured by different EAS arrays



The measured spectra demonstrate some discrepancy in intensity/energy. One of the possible sources of the discrepancy may be systematic uncertainties of the primary astroparticle energy estimation algorithm. In the Yakutsk array case, the energy estimation divergence is up to 13%.

Glushkov A.V., Pravdin, M.I. Saburov A.V. JETP, 2019. 128 415.
Method 3 is implemented in SD data.

Modeling the energy evaluation of EAS primaries

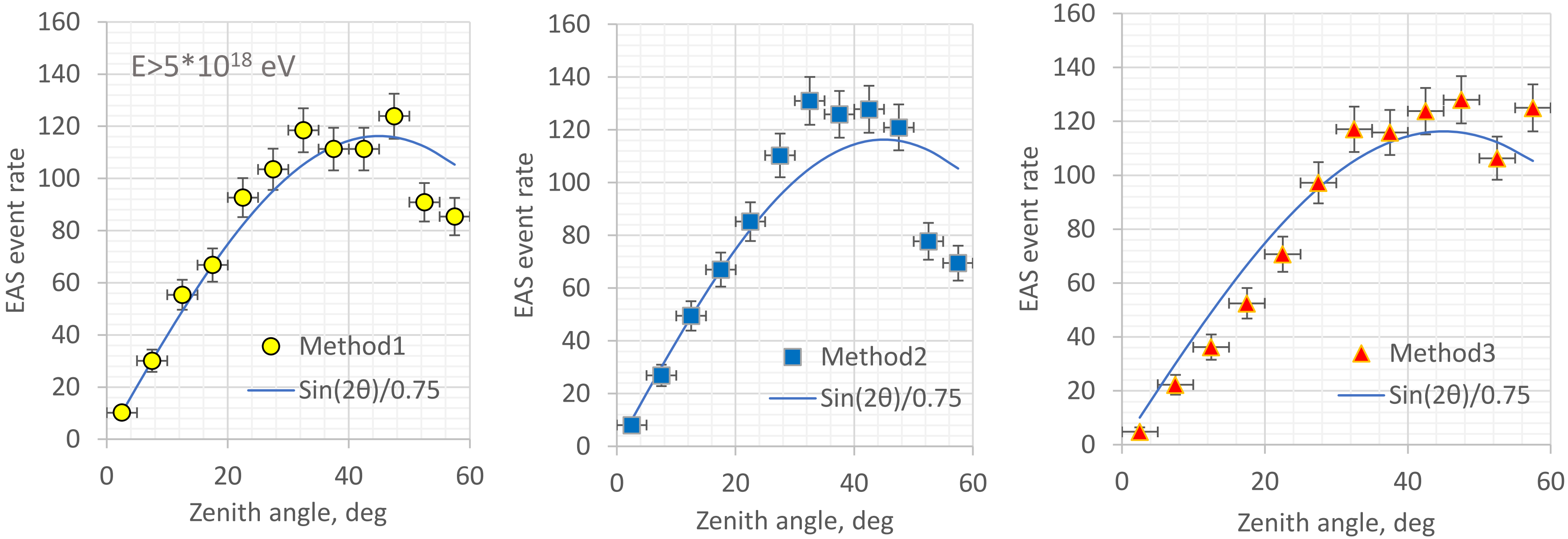


We have found the observed zenith angle distribution of EAS event rate to be sensitive to systematic uncertainties of the energy. The energy evaluation of EAS primaries is modeled implementing Monte Carlo simulation in the vicinity of $E_0 = 5 \times 10^{18}$ eV, where arrival directions distribution is supposed isotropic, therefore, expected zenith angle distribution of EAS event rate is sin(2θ).

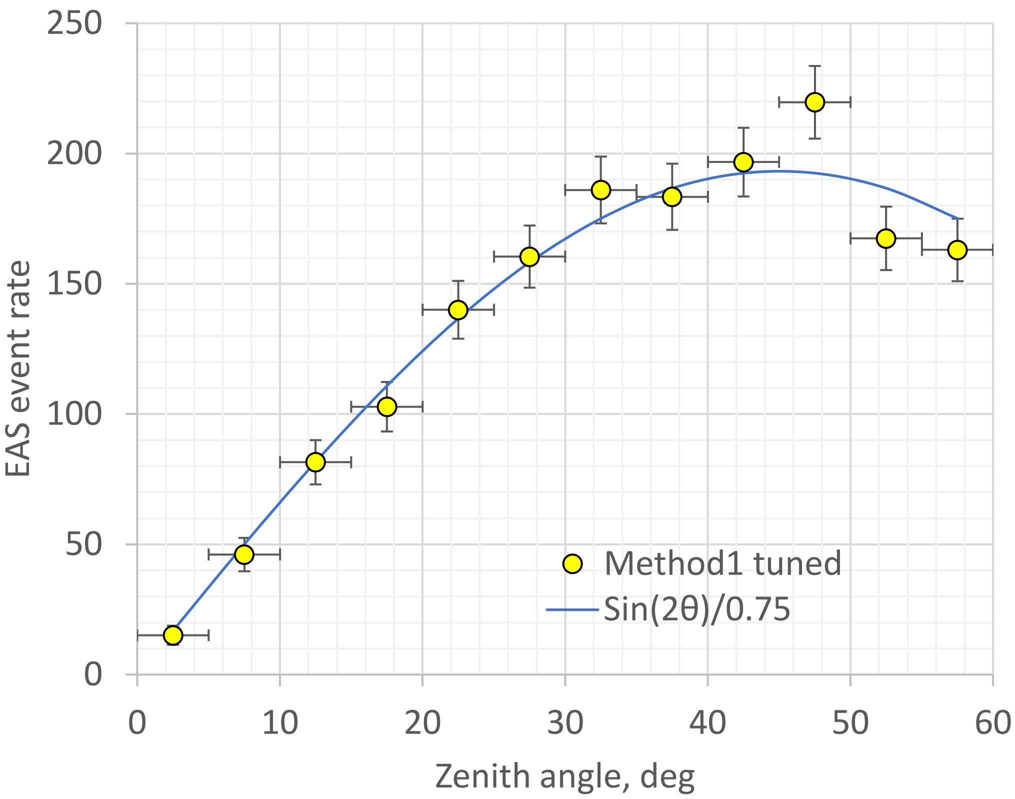
For three methods of E_0 evaluation given above, a sum of squared deviations of observed zenith angle distributions from expected one is calculated. It turned out that the oldest algorithm is the best in terms of systematic error size.

Comparing the energy estimation algorithms used by the Yakutsk array group

Each model may have hidden systematic uncertainties, for identification of which the deviation of inherent zenith angle distribution of EAS event rate from that expected for isotropic CR flux is a valuable model-independent test. Here, three methods of energy evaluation are visualized with respect to observed EAS event rate vs expected.



The model independent fit of the energy estimation parameters and the confidence interval



The sum of the squared deviations is used as a measure of the proximity. The parameters are varied in order to minimize the measure. The resultant parameters are found to be
α=1; L=415 g/cm^2.

The estimated confidence intervals are:
L in (400,430) g/cm^2,
α in (0.995,1.005).
ΔE ~ 30% which is larger than the energy estimation divergence in the energy spectra.

Summary

- We have demonstrated that the observed zenith angle distribution of EAS event rate is in close connection with the primary energy estimation algorithm used in data processing for the flat surface array.
- The basic hypothesis engaged in modeling of the phenomenon is isotropic arrival directions of cosmic rays.
- The connection found provides the possibility to test the energy estimation methods, and to find the optimized parameters in the model-independent way.