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Zenith angle distribution of extensive air showers by TBS array (GELATICA experiment)

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Abstract: The GELATICA experiment in Georgia (GEorgian Large-area Angle and Time Coincidence Array) is devoted both to the Primary Cosmic Ray (PCR) energy spectrum investigation at very high energies and possible correlations in the arrival times and directions of separate Extensive Air Showers (EAS) over large distances. The angular distribution of EAS arrival directions for the showers within a wide range of a number of charged particles is derived using the experimental data obtained with the EAS 4–detector array in Tbilisi (TBS). It is shown that the distribution function with the exponential absorption of the showers' flux provides a good approximation of the angular distribution despite the existing azimuth anisotropy. The dependence of the EAS absorption path on the angular measure cutoff boundary is studied.

Keywords: extensive air showers, angular distribution, sequential estimation.

1 Introduction

The process of EAS development with an accompaniment absorption in the atmosphere manifests itself in the distribution of zenith angle θ of the shower arrival direction. That is why some interest to such investigations permanently exists [1, 2, 3, 4, 5, 6].

The results obtained by some previous investigations have shown a low sensitivity of the distribution to the energy of PCR particles [6]. So, it is possible to investigate the subject even by small installations, incapable of EAS energy direct measurement. The data discussed hereafter is obtained by small 4–detector installation (EAS goniometer TBS) placed in the roof space of second building of Andronikashvili Institute of Physics in Tbilisi [7, 8, 9].

Detectors are arranged in the corners of a square with $10m$ sides; they are surrounded by concrete walls and are covered with a concrete roof. The room is oblong in the East–West direction. This surrounding is taken into account in the following analysis.

The TBS installation is located at the altitude of $500m$ approximately. So the estimation $d_{\text{TBS}} = (976.6 \pm 0.5) g/cm^2$ of the installation depth in the atmosphere is used for the EAS absorption path Λ_{abs} calculations.

2 The considered form of distribution

2.1 Physical and geometric factors' account

We shall assume that all EASs', developing in the atmosphere, are absorbing in accordance with the usual exponential low. Therefore let us accept that the flux of EAS observed in the unit solid angle by the installation located under the atmospheric layer of depth d is proportional to the expression $\exp\{-(d/\Lambda_{\text{abs}}) \cdot \sec(\theta)\}$. Here Λ_{abs} is the EAS absorption path required. The dependence assumed is applicable in the framework of a flat atmosphere model, i.e. in the interval $0 \leq \theta \leq 60^\circ \ldots 70^\circ$ of zenith angles. Now, taking into consideration that the TBS goniometer is currently employing the flat detectors located in the horizontal plane, let us integrate the observed flux expression by the azimuth to get a distribution in the form of

$$f_\theta(\theta) \sim \sin(\theta)\cos(\theta) \cdot \exp\{-(d/\Lambda_{\text{abs}}) \cdot \sec(\theta)\} \qquad (1)$$

Unfortunately, the planar goniometers are capable of straight estimation of two components of EAS arrival direction ort only, i.e. n_x, n_y , being parallel to the detectors' location plane [10]. That is why the immediate variable, measuring the event distance from the zenith direction and independent of any additional assumption, is the estimated "radius" of the ort projection onto the detectors' plane:

$$\alpha = \sqrt{n_x^2 + n_y^2} = \sin(\theta), \qquad 0 \leq \alpha \leq 1$$

The variable estimates usual zenith angle indirectly. The distribution of EAS arrival directions (1) expressed in the terms of this variable proves to be proportional to the function

$$f_\alpha(\alpha \mid q) \sim \alpha \cdot \exp\left\{-\left(q/\sqrt{1-\alpha^2}\right)\right\}. \qquad (2)$$

Here $q = d/\Lambda_{\text{abs}}$ measures the EAS vertical path range. The theoretic distribution function (2) has to be corrected for account of distortions by the surrounding matter anisotropy and installation's resolution function.

2.2 Anisotropy account

We attempt to account for the influence of the azimuth-anisotropic surroundings (i.e. the room walls etc.) by adding to the exponent index in (2) of the expression

$$\frac{-P(\alpha)}{\sqrt{1-\alpha^2}} \cdot \cos 2(\varphi - \varphi_0(\alpha)), \qquad (3)$$

which is proportional to the fundamental harmonic of existing anisotropy. Here the function $P(\alpha)$ allows for the additional matter of the surroundings reduced to the horizontal layer. The anisotropy existing is shown on the figure 1.

It has managed to approximate the anisotropy amplitude with a function of the form

$$P(\alpha) = p \cdot \left(\mathrm{e}^{-k\alpha} - 1\right) \tag{4}$$

shown on the same figure, too

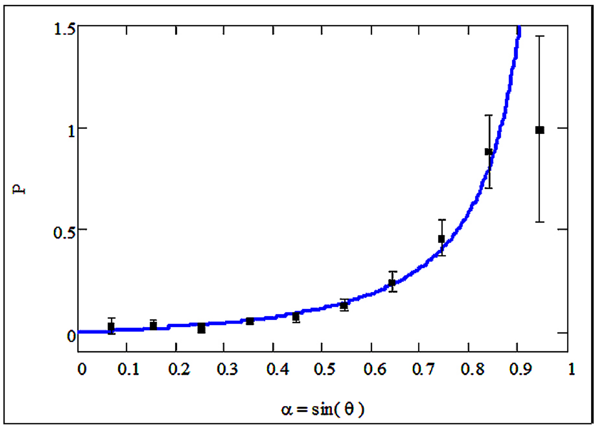

Fig. 1: The amplitude $P(\alpha)$ of existing azimuth anisotropy

The necessary azimuth integration of the corrected (with use of the (3, 4) functions) initial distribution (2) leads up to the anisotropy-fitted form of the distribution

$$\bar{f}(\alpha) = \frac{\alpha \cdot \exp\left\{-\left(q/\sqrt{1-\alpha^2}\right)\right\}}{\bar{N}(q,p,k)} \cdot \mathrm{I}_0\left(\frac{p\cdot(\mathrm{e}^{-k\alpha}-1)}{\sqrt{1-\alpha^2}}\right) \tag{5}$$

Here the dependence on the initial phase $\varphi_0(\alpha)$ is dropped out due to full period integration. The normalization factor $\bar{N}$ is defined by means of a usual integral. The free parameters q, p, k have to be obtained out by means of the distribution comparison with observations' data.

2.3 Resolution function

Detectors of TBS installation are located symmetrically at the vertices of the square. The estimations of components of EAS arrival directing ort are uncorrelated, with equal dispersions in this case [10]. The estimations are obtained by means of linear transformation of directly measured delays of signals' from the detectors. Therefore it is possible to assume that the simultaneous distribution of n_x, n_y components' estimations can be approximated by the normal one with the dispersion matrix proportional to identity. Consequently the distribution of α variable, measuring the "spacing" of EAS events from the Zenith point, can be obtained by the averaging by azimuth of the normal distribution mentioned, with account of $0 \le \alpha \le 1$ constraint. This consideration allows us to define the resolution function as

$$R(\alpha \mid \alpha_0, \sigma) = \frac{\alpha \cdot \mathrm{e}^{-\frac{(\alpha-\alpha_0)^2}{2\sigma^2}} \cdot \mathrm{I}_0^*(\alpha\alpha_0/\sigma^2)}{\int_0^1 \mathrm{e}^{-\frac{(\alpha-\alpha_0)^2}{2\sigma^2}} \cdot \mathrm{I}_0^*(\alpha\alpha_0/\sigma^2)\, \alpha d\alpha} \tag{6}$$

Here the variable α is a measured estimation of the event's spacing from Zenith, the variable α_0 is a true (unknown) value of the estimated one, while σ is a standard deviation of the estimation. The normalized modified Bessel function is defined as $\mathrm{I}_0^*(x) = \mathrm{e}^{-x}\mathrm{I}_0(\mathrm{x})$.

The data observed allows determination of the standard deviations' dependence on the event's spacing from Zenith. The data on standard deviations' are shown on the figure 2. This data allows the approximation by the function

$$\Sigma(\alpha) = a_\Sigma + b_\Sigma \cdot / \sqrt{1-\alpha^2}$$
$$a_\Sigma = 2.82 \cdot 10^{-2}, \qquad b_\Sigma = 6.11 \cdot 10^{-3};$$

or, in other terms, by

$$\Sigma(\theta) = a_\Sigma + b_\Sigma \cdot \sec(\theta).$$

This function is shown on the figure 2 , as well.

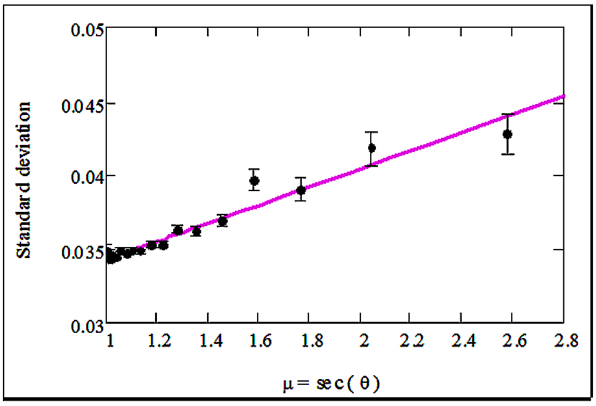

Fig. 2: The standard deviations of α variable estimations

The definitions (5), (6) allow to construct the final distribution density function of the event's spacing from Zenith observation probability:

$$\hat{f}(\alpha \mid q,p,k) = \int_0^1 R(\alpha \mid \alpha_0, \Sigma(\alpha_0)) \cdot \bar{f}(\alpha_0 \mid q,p,k)\, d\alpha_0 \tag{7}$$

This "distorted" distribution density function is just the one which has to be compared with the TBS observations' data to estimate both the apparatus-specific parameters p, k and the EAS absorption path required.

3 Parameters' estimations

At the first stage let us estimate the values of empiric parameters p, k which generally describe ((3), (4)) the properties of the matter surrounding the installation. The method of maximum likelihood has been used for this purpose, applied to the part of the data in the angles' interval $0 \le \theta \le 70°$, i.e. in the range of applicability of the flat atmosphere model. While provisionally disregarding the q value estimation, we get the parameters' estimations for the TBS surroundings description

$$\hat{p} = (14.5 \pm 0.5)10^{-3}, \qquad \hat{k} = 6.0 \pm 0.2 \tag{8}$$

This values have been fixed for the subsequent calculations. In order to estimate the required EAS absorption path Λ_{abs} let us investigate dependence of this value on the position of the upper trimming limit α_{trim} of the data subset used. (This is a case of sequential estimation method.) With repeating use of the same method of maximum likelihood to the sequentially expanding data subsets, the correspondent sequence of Λ_{abs} estimations is obtained and shown on the figure 3 . (All points in this sequence of estimations are mutually dependent!)

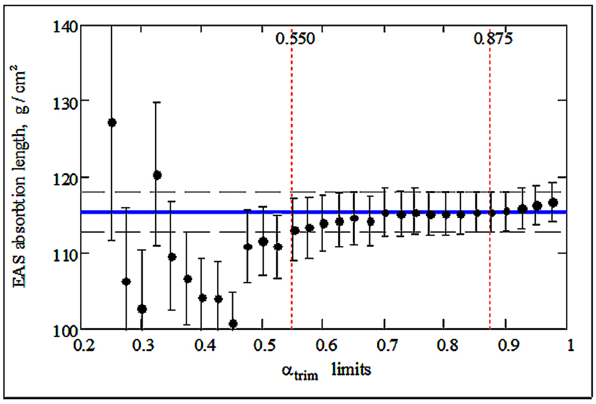

Fig. 3: Dependence of EAS absorption path estimation on the trimming limit of data

As it can be seen from the figure 3 , these estimations become stable within one standard deviation width for the trimming limits within the interval of

$$0.550 \le \alpha_{\text{trim}} \le 0.875.$$

That is why we adopt the final estimation of EAS absorption path

$$\hat{\Lambda}_{\text{abs}} = (115.4 \pm 2.6)g/cm^2$$

which is valid within the interval $0 \le \alpha \le 0.875$ of event's spacing from Zenith, at least.

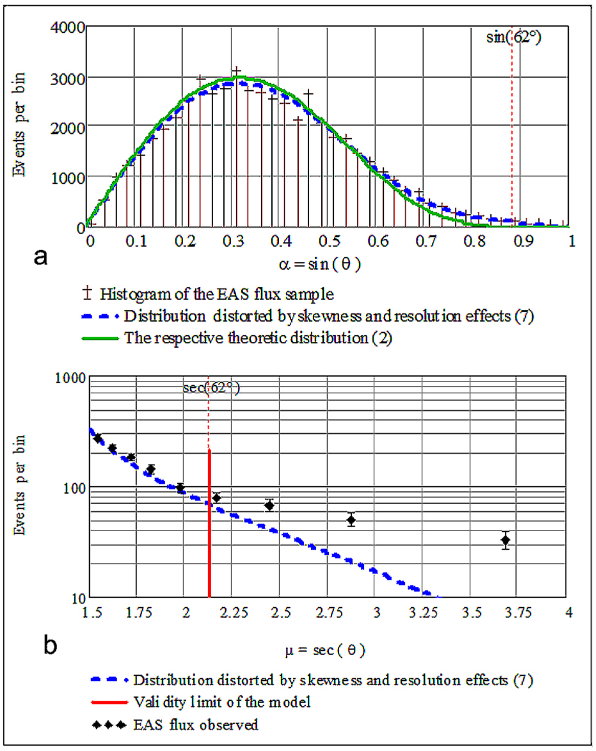

Fig. 4: Comparison of the observed data and distributions obtained

Take heed at last that the correspondence between the distribution (7) and existing data is sharply violated, indeed, beyond the domain of applicability of the flat atmosphere model. It can be seen from the figure 4b that the data points really deviate appreciably from the optimal distribution curve for zenith angles overriding the actual limit of the model validity range $\theta_{\text{lim}} = 62^\circ$, i.e. $\alpha_{\text{lim}} = 0.883$.

4 Conclusions

It has been established that the account for the resolution function and azimuth anisotropy of TBS installation surroundings makes it possible to employ the usual distribution (2) of event's spacing from Zenith $\alpha = \sin(\theta)$. This model of simple EAS absorption, in accordance with flat atmosphere model approximation, has proved to be valid for description of EAS absorption process within the interval $0 \le \alpha \le 0.883$ of event's spacing from Zenith, i.e. in the interval $0 \le \theta \le 62^\circ$ of zenith angle. The estimation value of EAS absorption path is actually stationary under the variation of data trim upper limits within the $0.550 \le \alpha_{\text{trim}} \le 0.875$ interval and is fixed at the value $\hat{\Lambda}_{\text{abs}} = (115.4 \pm 2.6)g/cm^2$. It would be remarked that any estimations of this value upon the sequence of more narrow intervals of α variable is unstable. Our $\hat{\Lambda}_{\text{abs}}$ estimation is in approximate accordance with previous estimations [1, 2, 5, 6] by installations located at low altitudes.

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