Determination of EAS cores angular resolution in MAKET-ANI array

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The EAS incident angles estimation methods along with the angular resolution determination are described. Based on a data sample collected by the MAKET-ANI array, the angular resolution and it's dependence on the showers arrival direction are studied. It is shown that zenith angle accuracy is not worse than 1.6^o and azimuthal one not worse than $6.^o$.

1 Introduction

Precise determination of arrival direction of the incident Cosmic Ray (CR) gives possibility for:

1. More correct reconstruction of Extensive Air Shower (EAS) parameters (number of electrons, shower age parameter, shower core coordinates);
2. Splitting of differential spectra in small angular bins and therefore calculation of the showers and particles (in shower) attenuation lengths by one and the same installation;
3. Calculation of cosmic ray (CR) flux anisotropy.

The direction of Primary CR is assumed to coincide with the EAS incident angles, the last is usually derived from arrival time measurements applying the fast-timing technique. The angular resolution of an air shower array depends on details of the layout of the detecting system and the data processing. In Ref. [1] was suggested to introduce EAS as a thin disk around the shower core ($r < 100m$, where r is baseline of timing detectors).
In all EAS arrays [1-12] the zenith (θ) and azimuthal (φ) angles are defined by the following approximation:

$$c\Delta t_i = (x_i cos\varphi + y_i sin\varphi) sin\theta + z_i cos\theta, \quad (i = 1, M) \tag{1}$$

where $c(m/ns)$ is the light speed, Δt_i is relative i-th detector time-delay compared with detector positioned in the center of coordinates, x_i, y_i, z_i are the space coordinates of detectors, M is the number of timing detectors. The least square method (LSM) or maximum likelihood method (MLM) are used to find θ and φ from system (1). The error in arrival time determination is mainly contributed by the arrival fluctuations of the shower particles (Linsley effect Ref. [2]) in the following way: $\sigma_t = \sigma_o(1 + r/30m)^b$, where σ_o and b are constants, which are changing in interval $1.6 \div 2.6$ and $1.5 \div 1.7$ accordingly, as defined in Ref. [3, 7, 10, 13]. In Ref. [3, 4, 10] the shower front curvature is also taken into account, which is changing in interval $600 \div 3000m$ depending on shower age. Ref. [10, 11] presented in details the algorithm used by MAKET-ANI group for finding the angular resolution, which is accepted to be preliminary because of poor statistics.
In this report we introduce different methods for measuring the angular resolution of MAKET-ANI array exploiting rich statistics obtained in $1997 \div 1999$ years.

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2 Experimental setup

The MAKET-ANI array timing system is described in details in Ref. [12]. We remind only that there are 19 detectors, one of which is in the center of coordinate and defines zero of the reference time. The central part of MAKET-ANI array is shown in Fig.1. The color squares are the timing and density detectors . The red and green squares are the two independent groups of the timing detectors (see below). The shower front measuring accuracy is $\sim 5ns$ [10, 12]. Timing detectors are located within $< 100m$ distance, therefore the shower front flat approximation is valid.

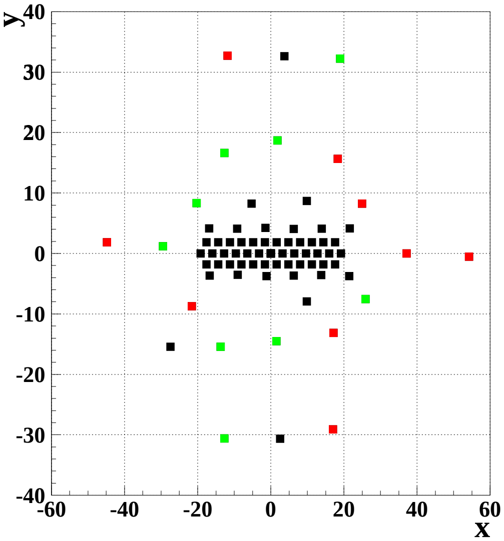

Figure 1: *The central part of MAKET-ANI array. Color squares are the timing and density detectors.*

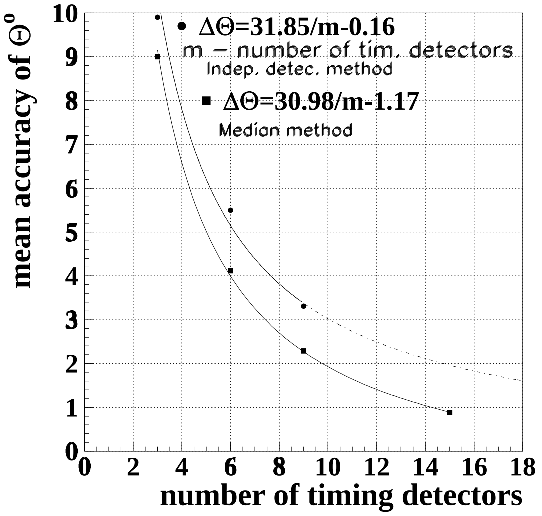

Figure 2: *Zenith angle accuracy obtained by the median and subgroups methods vs. number of timing detectors.*

3 Method of analysis

To find the angular resolution we apply the following methods:

1. 18 timing detectors have been divided into 2, 3 and 6 groups, each containing consequently 9, 6 and 3 detectors. These subgroups are arranged symmetrically in array and θ_i, φ_i are defined for each subgroup separately. Approximately the same method is used in [4, 5]. If we take 2 independent groups after estimating θ_1 and θ_2 we can calculate $\Delta\theta \simeq \theta_1 - \theta_2$ (Fig.1). If we assume that both groups provide equal resolutions, then from distribution of $\Delta\theta$ we readily can obtain the angular resolution of array containing 9 timing detectors ($\sigma_\theta = \sigma_{\Delta\theta}/\sqrt{2}$).

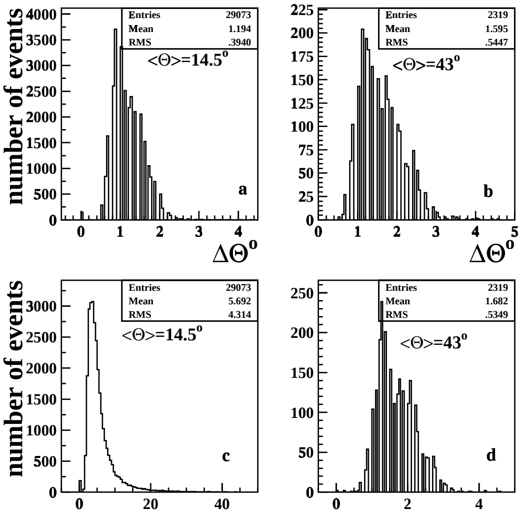

Figure 3: *Distribution of the zenith and azimuth angles resolution for different zenith angle bins.*

If we take 3 independent groups formed by 6 detectors in the same way and find θ_i by each subgroup, then calculate $\Delta\theta_{ij} = \theta_i - \theta_j$ (i≢j; i=1,2; j=2,3);

2. The median method [14]. We take C^n_{18} combinations of timing detectors with n=6,9,15 and θ, φ are defined for each combination. These values are arranged in increasing sequence (ordered statistics) and median value is taken as angle estimate. θ and φ resolution is defined by interquartile difference so that $\sigma_\theta = (l(3/4) - l(1/4))/1.35$, where l is the ordered statistic. Approximately the same method is used in [6];
3. Use angular resolution given by reconstruction programs; CERN FUMILI [15] and MINUIT [16] packages.

4 Results

The zenith angular resolutions for the different number of detectors introduced by the first two methods are given in Fig. 2. The approximation functions are given in the same figure. The dashed lines corresponds to extrapolations of the interpolated functions.
As expected, the resolution decreases inverse proportional to the number of used detectors.
In this and following figures the showers with $\theta < 45^o$ are taken into account, which correspond to elections given in Ref. [17].
The distributions of the zenith and azimuthal angles obtained by the third method are given in Fig.3. The angular interval $\theta < 45^o$ was divided into 5 uniforms (according to $sec\theta$) bins. The zenith angular resolution distributions for the first and fifth bins are posted in Fig.3(a,b). In Fig.3(c,d) the distributions of azimuth angular resolution for the same bins are presented. As one can see in Fig.3, the value for $\sigma_{\Delta\theta}$ is changing in the interval $1.2^o \div 1.6^o$ and for the $\sigma_{\Delta\varphi}$ is $1.5^o \div 6^o$.

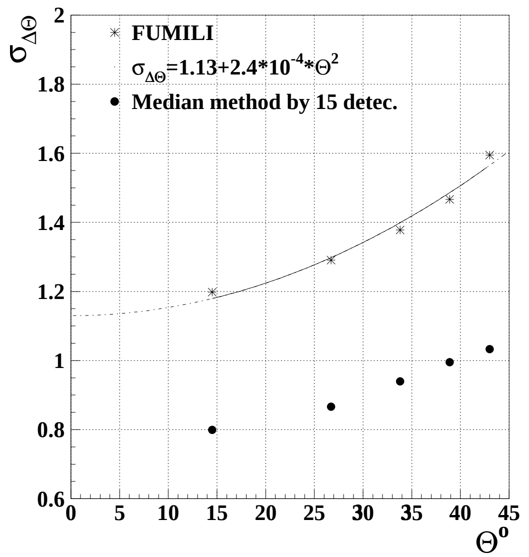

Figure 4: *Dependence of the zenith angular resolutions vs. arrival direction of EAS. Curve is the approximation function.*

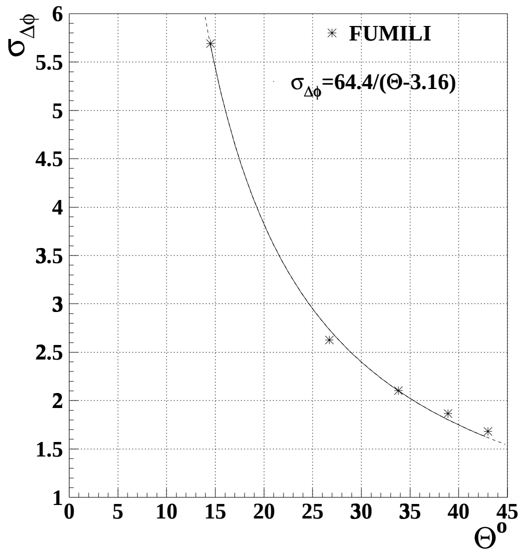

Figure 5: *Dependence of the azimuth angular resolutions vs. arrival direction of EAS cores. Curve is the approximation function.*

In Fig.4 the zenith angular dependence of accuracies is presented. Comparing the interpolations for independent detectors (Fig.2) with Fig.4 we can see that angular resolutions approximately are the same for the subgroups and FUMILI methods.

In Fig.5 the azimuth angle resolutions for the third method according to zenith angles of EAS cores and the approximation curve are presented.

As one can see in Fig.4,5, the zenith and azimuth angular accuracy is not worse than 1.6^o and 6^o respectively, which allow to solve the problems pointed in introduction. FUMILI and MINUIT give identical results.

Comparing the results from the FUMILI and median methods in Fig.4 one can see that median method provides about 1.5 times better accuracy, i.e. not conventional methods give better results and in future these methods will probably be widespread in CR investigations.

The angular accuracies does not depend on N_e in interval $10^5 \div 10^7$, which coincides with results of Ref. [4, 8]. The angular accuracy for more "young" showers ($s < 0.5$) is $\simeq 15\%$ worse than for the other showers, also confirmed in Ref. [13].

5 Concluding Remarks

- The MAKET-ANI timing system provide angular accuracy not worse than 1.6^o for zenith angle and $< 6^o$ for azimuthal one for all the showers with $\theta < 45^o$.
- Approximation functions for θ and φ resolutions vs. θ, are the following:

$$\sigma_{\Delta\theta} = 1.13 + 2.4 * 10^{-4} * \theta^2,$$
$$\sigma_{\Delta\varphi} = 64.4/(\theta - 3.16).$$

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