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Determination of angular accuracy of the MAKET ANI surface array

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Abstract. The methods of EAS incident angles estimation along with the angular resolution determination are described. Based on a data sample collected by the MAKET-ANI array, the angular resolution and its dependence on the showers arrival direction is studied. We use classical methods of Moon and Sun shadow detection as well as new software methods for experimental determination of MAKET ANI angular resolution. It is shown that zenith and azimuthal angles' accuracy is approximately 1.5^o and 5^o respectively.

1 Introduction

Precise determination of arrival direction of the incident Cosmic Ray (CR) flux particles provides opportunity for:

1. Correct reconstruction of Extensive Air Shower (EAS) size and core coordinates;

2. Measurement of size spectra for different angles of incidence allowing calculation of the showers and particles (in the shower) attenuation lengths by one and the same installation;

3. Measurement of CR flux anisotropy;

4. Investigation of the Sun magnetic field and its changes during solar activity cycle.

The direction of Primary CR is assumed to coincide with the EAS incident angles. The latter 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 algorithms. In (Bassi et al., 1953) it was suggested to describe EAS as a thin disk around the shower core ($r < 100m$, where r is baseline of timing detectors). In EAS arrays usually the zenith (θ) and azimuthal (φ) angles are determined by the following approximation [1-12]:

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

where $c(m/ns)$ is the light speed, Δt_i is relative time-delay compared with detector positioned in the center of coordinates, x_i, y_i, z_i are the coordinates of detectors, M is the number of detectors. The least square method (LSM) or maximum likelihood method (MLM) are used to find θ and φ from (1). The error in arrival time determination is mainly contributed by the arrival fluctuations of the shower particles (Linsley effect (Linsley, 1985)) 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 (Alexeenko et al., 1990; Sinha et al., 1990; Kabanova et al., 1990; Xiaoyu et al., 1991). In (Alexeenko et al., 1990; Newport et al., 1990; Kabanova et al., 1990) the shower front curvature, which is changing in interval of $600 \div 3000m$ depending on shower age, is also taken into account. In (Kabanova et al., 1990; Avakian et al., 1989) the algorithm used by MAKET-ANI group for finding the angular resolution (considered tentative due to poor statistics) was presented in details.

In 1957 Clark (Clark, 1957) suggested that because the Sun and the Moon must cast a shadow in the high- energy CR flux observation, their obscuration might supply new information about the magnetic field of these bodies. In further analysis the method of discovering the shadow effects of the Sun and the Moon has been used for the independent test of angular resolution of the EAS arrays [17-21]. Also the average mass composition for energies more than $10^{14}eV$ could be determined by observing the rigidity dependence of the onset of the Sun's shadow due to traversal through the solar magnetic field (Lloyd-Evans, 1985).

In this report we introduce different methods for measuring the angular resolution of MAKET-ANI array exploiting statistics obtained in $1997 \div 2000$ and as an independent test, study the shadowing of CR by the Sun and the Moon.

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2 Method of analysis

The MAKET-ANI array timing system is described in details in (Bazarov et al., 1986). We remind only that there are 19 detectors, one of which is located at the center of coordinate system and defines zero of the reference time. The detectors are located within $< 100m$ distance, therefore the flat approximation of shower front is valid.

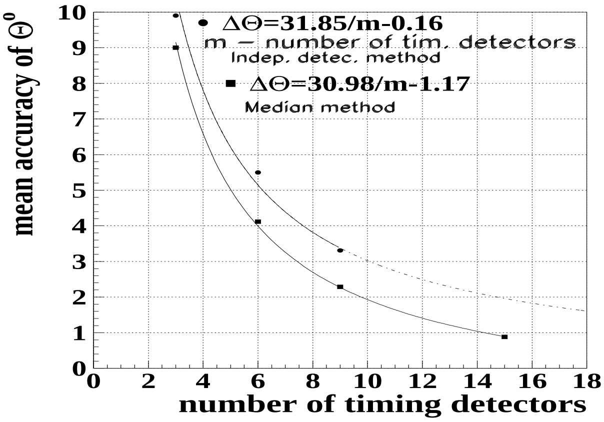

Fig. 1. *Zenith angle accuracy ($\sigma_{\Delta\theta}$) obtained by the median and subgroups methods vs. number of timing detectors used.*

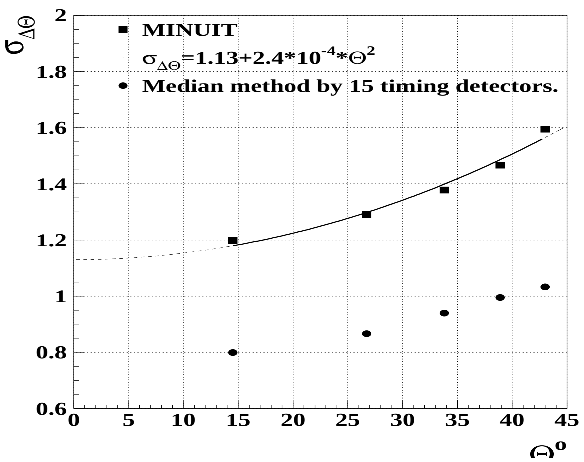

Fig. 2. *Dependence of the zenith angular resolutions on the arrival direction of EAS.*

To estimate the angular resolution we apply the following procedures:

1. 18 timing detectors are divided into 2, 3 and 6 groups, each containing respectively 9, 6 and 3 detectors. These subgroups are arranged symmetrically in array and θ, φ angles for specially selected data file of events are defined for each subgroup separately. The showers selection conditions which have been presented in (Gharagyozyan et al., 1998, 2000).Approximately the same method is used in (Newport et al., 1990; Bloomer et al., 1990).
   If we take 2 independent groups of detectors, after estimating θ_1 and θ_2 we can calculate $\Delta\theta = \theta_1 - \theta_2$. If we assume that both groups provide equal resolutions, then

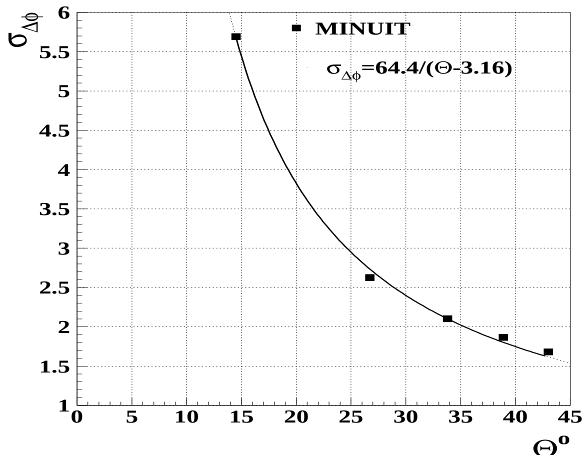

Fig. 3. *Dependence of the azimuth angular resolutions on the arrival direction of EAS cores.*

   from distribution of $\Delta\theta$ we readily can obtain the angular resolution of array containing 9 timing detectors ($\sigma_\theta = \sigma_{\Delta\theta}/\sqrt{2}$).
   For 3 independent groups formed by 6 detectors in the same way we can estimate angles of incidence by each subgroup, then calculate $\Delta\theta_{ij} = \theta_i - \theta_j$ (i=1,2; j=2,3);

2. The median method (Jonson, Leone, 1980). 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 ascending (or descending) 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 statistics. Approximately the same method, but only for four detectors, is used in (Luorui, 1990);

3. Using the angular resolution given by minimization package MINUIT from CERN program library.

The zenith angular resolutions for the different number of detectors obtained by the first two methods are given in Fig. 1. The interpolation (solid lines) and extrapolation (dashed lines) functions are also posted in the same figure. As expected, the resolution decreases inverse proportionally to the number of detectors used. In Fig.2 the zenith angular dependence of accuracies is presented. Comparing the interpolations for independent detectors (Fig.1) with Fig.2 we can see that angular resolutions approximately are the same for the subgroups method and the MINUIT program. In Fig.3 the azimuth angle resolutions according to zenith angles of EAS cores and the approximation curve are presented. As one can see in Fig.2,3, the zenith and azimuth angular accuracy is not worse than 1.6^o and 6^o respectively, which allows to solve the problems mentioned in introduction.
Comparing the results from the MINUIT and median methods in Fig. 2 one can see that median method provides about 1.5 times better accuracy, i.e. non-conventional methods produce better results. The implementation of this method for MAKET-ANI data is now underway.

The angular accuracies does not depend on N_e in interval $10^5 \div 10^7$, which coincides with results from (Newport et al., 1990; Aglietta et al., 1990). The angular accuracy for "young" showers ($s < 0.5$) is $\simeq 15\%$ worse than for the other showers, also confirmed in (Xiaoyu et al., 1991).

3 The shadowing effect method

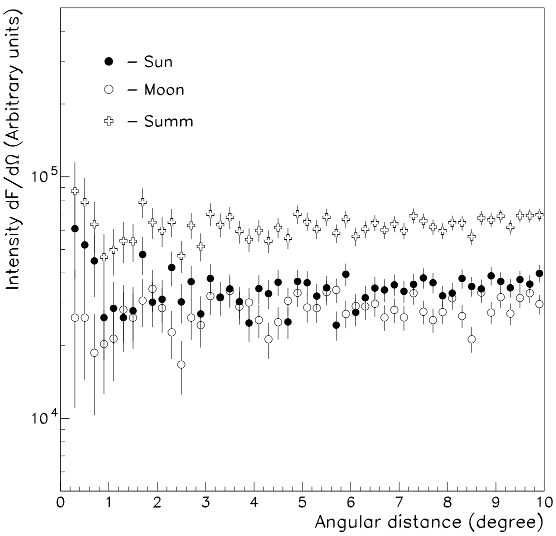

Fig. 4. *Events intensity arriving near the Sun (Moon).*

For all showers from MAKET-ANI data base the geocentric right ascension α and declination β of the events as well as of the Moon and the Sun were calculated by the TIME-SUB code (www.phys.washington.edu). Then the angular distance between the incident arrival direction and the Moon or the Sun were calculated. For further analysis the events hitting inside the rings with 10^o radius around the Sun (Moon) were selected. Taking into account that the Moon and the Sun each has an angular radius of approximately 0.26^o and because of poor statistics the shadowing effect was analysed using the statistics for both the Sun and the Moon. These events were distributed in concentric rings around the center of the Sun (Moon) with 0.2 width and were normalized on surface ($degree^2$) of proper ring. The intensity of those events vs the angular distance from the Sun (Moon) are shown in Fig. 4. The measured density between 5^o and 10^o from the Moon (Sun), where shadowing is negligible, is used to calculate the expected number of the events close to the Sun (Moon) (background).

The weight of the events deficit for each bin was calculated by the formula:

$$W_i = (E_i - B_i)/\sqrt{E_i}, \tag{2}$$

where E_i and B_i are the events and background densities in each bins respectively. The distribution of these weights are displayed in Fig. 5. The deficit was obtained from approximately 1.6^o, and at 0.8^o reach the maximal level (3.1σ). Then the distribution changed the behavior and in angular distance from 0.8^o to 0^o we observed the increase of CR intensity, which reached the maximal level 4.6σ in $0.2^o \div 0.4^o$ interval. The maximum events deficit shifting by the center of the Sun (Moon) was observed also by other groups (Alexandreas et al., 1991; Amenomori et al., 1991).

For the estimation of MAKET-ANI array angular resolution in the interval of $0^o \div 5^o$ χ^2 test was used. We develop special code for simulation of the Sun (Moon) shadowing effect taking into account finite angular resolution of the surface array. After generating several trials of data, corresponding to the number of preselected values of angular resolutions, we perform multiple comparisons to outline the particular values of resolution that better fit experimental data. The results for the $\sigma_{\Delta\phi} = 4^o$ are shown in Fig. 6. As one can see the best agreement ($\chi^2 = 0.96$) was reached to $\sigma_{\Delta\theta} = 1.4^o$. This value remained practically unchanged in the interval

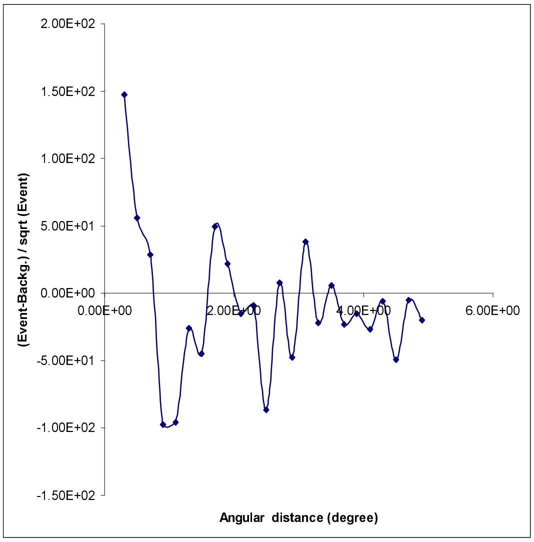

Fig. 5. *The weights distributions vs angular distance from the Sun (Moon).*

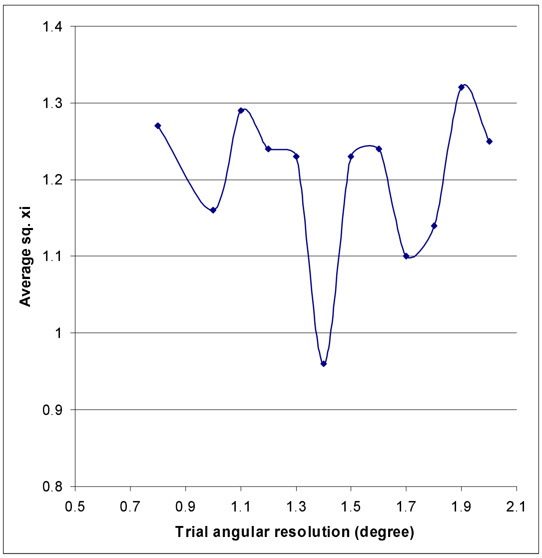

Fig. 6. *Average χ^2 vs trial angular resolution for the $\sigma_{\Delta\phi} = 4^o$.*

$3^o \leq \sigma_{\Delta\phi} \leq 5^o$.
Results on Sun (Moon) shadowing prove that MAKET-ANI array angular resolutions are not worse than $\sigma_{\Delta\theta} \simeq 1.4^o$ and $\sigma_{\Delta\phi} \simeq 5^o$. These resolutions are in good agreement with results from section 2, taking into account that the shadowing statistics correspond to angular range of $20^o < \theta < 45^o$.

4 Concluding Remarks

• The MAKET-ANI installation timing system provide angular accuracy of EAS incidence approximately 1.5^o for zenith angle and 5^o for azimuthal one, for zenith angles $\theta < 45^o$.
• Approximation functions for the accuracies are the following:

$$\sigma_{\Delta\theta} = 1.13 + 2.4 * 10^{-4} * \theta^2. \tag{3}$$

$$\sigma_{\Delta\varphi} = 64.4/(\theta - 3.16). \tag{4}$$

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