29th International Cosmic Ray Conference Pune (2005) **6**, 21–24

# Angular Resolution of the GRAPES-3 EAS Array for UHE Gamma-Ray Astronomy

P.K. Mohanty[a], S.K. Gupta[a], Y. Aikawa[b], N.V. Gopalakrishnan[a], Y. Hayashi[b], N. Ito[b], A. Iyer[a], A. Jain[a], P. Jagadeesan[a], A.V. John[a], S. Karthikeyan[a], S. Kawakami[b], T. Matsuyama[b], D.K. Mohanty[a], S.D. Morris[a], T. Nonaka[b], A. Oshima[b], B.S. Rao[a], K.C. Ravindran[a], K. Sivaprasad[a], B.V. Sreekantan[a], H. Tanaka[b], S.C. Tonwar[a], K. Viswanathan[a] and T. Yoshikoshi[a]

*(a) Tata Institute of Fundamental Research, Homi Bhabha Road,Mumbai 400005, India*
*(b) Graduate School of Science, Osaka City University, Osaka 558-8585,Japan*
Presenter: P.K. Mohanty (pkm@tifr.res.in), ind-mohanty-PK-abs1-he11-poster

Observations on cosmic sources of ultra high energy (UHE) gamma rays provide information on the origin of cosmic rays and their acceleration mechanisms. In order to detect a UHE gamma ray source with its extremely low flux against a large isotropic cosmic ray background, an Extensive Air Shower (EAS) array with very large collection area and high angular resolution is necessary. The GRAPES-3 EAS array operating at Ooty covering an area of $\sim$ 18000 m$^2$ with $\sim$ 300 fast scintillation detectors is being used for studies on UHE gamma-ray sources. Here we have described the method of reconstruction of the arrival angle of showers and determination of the angular resolution of the GRAPES-3 array.

## 1. Introduction

GRAPES-3 is a high density air shower array designed to measure both densities and relative arrival times of shower particles to determine the energy and incident direction of primary cosmic ray particle which initiates a shower entering into the atmosphere. The array records ADCs for density and TDCs for relative arrival time measurement of shower particles. The details of the experiment with its shower detectors, shower trigger and data acquisition is described elsewhere [1]. The array has the following features required to study UHE $\gamma-ray$ souces.

1. High trigger rate $\sim$ 25 Hz with total recorded showers per day $\sim$ 2.2 million in the primary energy range 10 TeV - 10 PeV

2. Trigger efficiency for primary $\gamma - ray \sim$ 90 % for E$_\gamma \sim$ 30 TeV.

3. Arrays association with a large area ($560m^2$) muon detector which detects the muon component of the shower [2]. This helps to reject large fraction of charged cosmic rays on the basis of muon content of the shower and enhances the signal to background ratio.

In this paper, we have studied the angular resolution of the array.

The angular resolution in zenith angle $\theta$ is given by

$$\delta\theta = \frac{c\delta t}{Dcos\theta\sqrt{N/2}} \qquad (1)$$

Where $\delta t$ is the uncertainty in measuring the arrival times
D is average distance between two detectors
N is the number of detectors used to estimate the angle

## 2. Time Resolution of the GRAPES-3 Showers Detectors

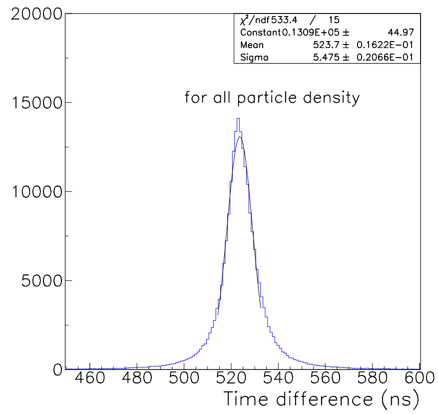


**Figure 1.** Distribution of arrival time difference of showers between two closely placed shower detectors

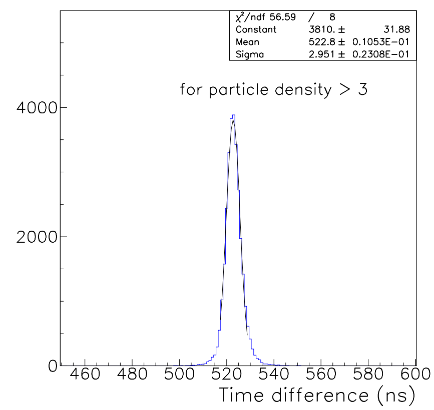


**Figure 2.** Arrival time difference when each detector has more than 3 particles

The time resolution $\delta t$ which is contributed by finite thickness of shower disk and instrumental timing error has been measured placing two shower detectors side by side. The width of the time difference distribution for all particle density shown in figure 1 is 5.5ns and for particle density $> 3$ shown in figure 2 is 2.9 ns. The time resolution of individual detector for all particle density is 5.5ns/$\sqrt{2}$ = 3.9 ns and for particle $> 3$ is 2.9/$\sqrt{2}$ = 2 ns. At higher particle density both the detectors sample the showers mainly near the core where shower thickness is small. The main contribution to $\delta t$ comes from instrumental time resolution.

Using $\delta t$ measured by above method, a simple Monte-Carlo simulation has been performed to get a rough idea about the angular resolution which can be achieved by GRAPES-3 array. Taking $\theta = 25\ ^o$, D = 8 meter ( separation between two GRAPES-3 detectors, N=20 and $\delta t$ = 3.9 ns, the computed angular resolution is $1.8^o$.

## 3. Reconstruction of Arrival Direction of Shower

The arrival direction of shower characterized by zenith angle $\theta$ and azimuth angle $\phi$ has been reconstructed by fitting a plane to the observed relative arrival times of shower particles at individual detectors using least square method. Before doing the fit, these arrival times have been corrected for the time offsets for the individual detectors which arise due to difference in photomultiplier transit time, electronic propagation delay etc. These time offsets have been determined from the shower data itself by a method developed and used by KGF group [3].

The angle is reconstructed for those showers, for which highest recorded density detector is on and within the second last ring of the array. This condition is imposed because the shower which gives highest density in the last ring, its core might be landed out side the array boundary and with partial information available, the angle determination can be highly inaccurate. This selection rejects 21% of showers from angle reconstruction.

The $\theta$ and $\phi$ distributions are shown in figure 3 and 4 with the analysis of data from 1-10th April 2005. $\phi$ is measured with reference to north direction and clockwise. Figure 4a - 4d show $\phi$ distribution for different zenith angle ranges. The $\phi$ distribution is flat in figure 4a which is expected due to the isotropic arrival of cosmic rays, whereas deviations seen in figure 4b - 4d from flat distribution. The deviation is quite large in

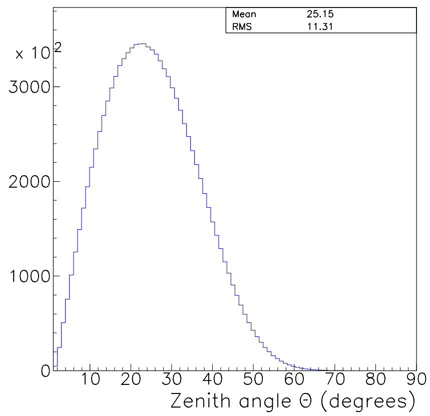


**Figure 3.** Zenith angle distribution of showers

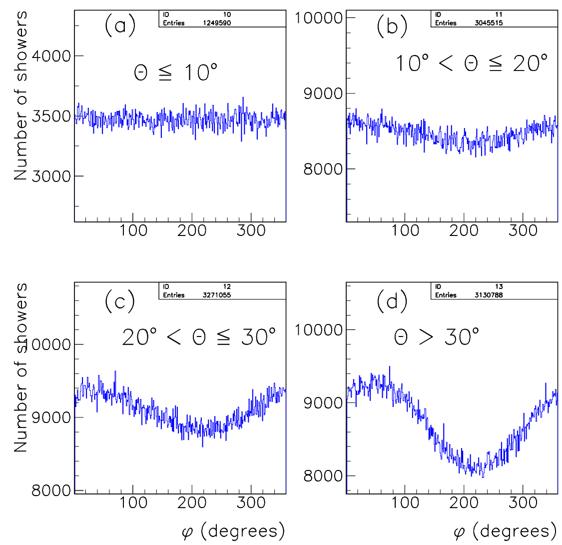


**Figure 4.** Azimuth angle $\phi$ distribution for different zenith angle ranges. A large decrease is seen at higher zenith angle from expected flat distribution

figure 4d for $\theta > 30^o$. The increase in the deviation for higher zenith angle shows the effect of ground slope on the shower trigger. The array has slope mainly in the east-west direction. A more detail analysis is in progress to understand this $\phi$ asymmetry quantitatively though Monte-Carlo simulation.

## 4. Angular Resolution by Even-Odd Array Method

Here two independent estimate of the angle of the shower has been compared to find the angular resolution, one calculated using even numbered detectors of the array and the other using the odd numbered detectors. The angular resolution is calculated dividing by $\sqrt{2}$ . $\sqrt{2}$ with the space angle distribution between the two estimates. one $\sqrt{2}$ comes because we are comparing two distribution where the error adds quadratically and the other $\sqrt{2}$ comes because we are using nearly half of the detectors to calculate the angle.

From figure 5 it can been seen than the angular resolution is better with more number detectors used in angle fit. The median value of angular resolution is $2^o$ for NFIT $> 10$ and it improves to $1^o$ for NFIT $> 40$.

## 5. Discussion and Conclusions

The above analysis gives a rough estimate of angular resolution determined by plane fit. The angular resolution improves with NFIT. A More detail analysis is in progress which may help to improve further the angular resolution taking into account the shower curvature correction and electronic slewing effect. We are trying to see the Moon shadow which will verify our calculation of angular resolution.

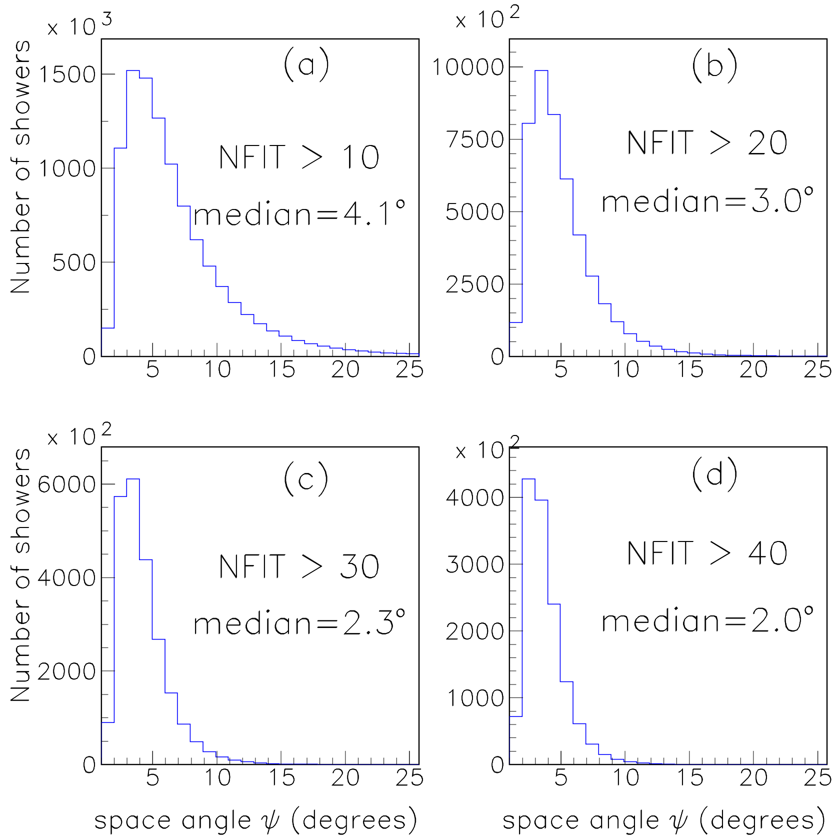


**Figure 5.** space angle distribution between Even and Odd array as a function of number detectors participated in the angle fit (NFIT). The width of the distributions become narrower from (a) to (d) which tells that the angular resolution is better with more number of detectors.

## 6. Acknowledgments

We thank D.B. Arjunan, A.A. Basha, G.P. Francis,I.M. Haroon, V. Jeyakumar,K. Manjunath, B. Rajesh, K. Ramadass, C. Ravindran, and V. Viswanathan for help in construction and operation of GRAPES-3 experiment. We acknowledge partial financial support from Ministry of Education, Government of Japan.

## References

[1] S.K. Gupta et al., Nucl. Instr. & Meth. A 540, 311 (2005).
[2] Y. Hayashi et al., Nucl. Instr. & Meth. A 545, 643 (2005).
[3] B.S. Acharya et al., J.Phys. G: Nucl. Part. Phys. 19(1993) 1053-1068