Study on angular resolution of GRAPES-3 array

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***Abstract.* GRAPES-3 experiment at Ooty in India, constitutes of about 300 scintillator detectors, is a conventional air shower array which detects air showers produced by primary high energy cosmic rays. The detectors are placed in a equilateral triangle shape with distance of 8m. Good anglar resolution is required for search of gamma ray point sources that is one of the main goal of GRAPES-3. Hence, the relative arrival time of particle in an air shower plane arriving at each detectors is an important parameter which is effectively used for the reconstruction of arrival direction of primary particles. Here, we will discuss on the angular resolution of the present GRAPES-3 experiment by using the two important methods such as EvenOdd and RightLeft methods. The new results obtained from the above two methods have been compared with the outcome of the Moon and the Sun shadow observation, and will be presented elaborately.**

***Keywords*: cosmic ray, angular resolution, Moon shadow**

I. Introduction

Since the γ-ray flux from a source has to be detected, against a huge background contributed by the isotropic flux of the cosmic rays, it is necessary to achieve as good a rejection of this background as possible for the detection system. For a point source, the signal to background ratio is inversely proportional to the square of the angular resolution. Therefore, the most important requirement of an EAS detector system is its angular resolution for maximizing the signal to background ratio. The technique of relative arrival timing has been used extensively in the EAS arrays, for the determination of the arrival direction of the showers [1], [2], [3].

II. Experimental System

The experimental system of the GRAPES-3 (**G**amma **R**ay **A**stronomy at **P**eV **E**nergy**S** Phase-**3**) experiment consists of a densely packed array of scintillator detectors and a large area tracking muon detector. The EAS

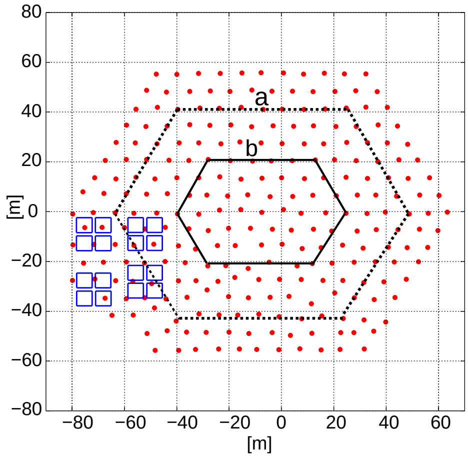

Fig. 1. The GRAPES-3 experimental system with 257 scintillator detectors and 16 muon detector modules

array consists of 257 plastic scintillator detectors, each of 1 m^2 in area. These detectors are deployed with an inter-detector separation of only 8 m. The array is being operated at Ooty in south India (11.4°N, 76.7°E, 2200 m altitude).

In order to achieve the lowest possible energy threshold, a simple 3-line coincidence of detectors has been used to generate the Level-0 trigger, which acts as the fast GATE and START for the analog to digital and time to digital converters (ADCs and TDCs), respectively. As expected, this trigger selects a large number of very small and local showers and also larger showers whose cores land very far from the physical area of the array. Therefore, it is also required that at least 10 out of the inner 127 detectors should have triggered their discriminators within 1 μs of the Level-0 trigger. This Level-1 trigger with an observed EAS rate of 13 Hz is used to record the charge (ADC) and the arrival time (TDC) of the pulses from each detector [4]. The pulse charge is later converted into the equivalent number of minimum-ionizing particles (MIPS) using the most probable charge for a single MIP measured using the trigger from a small area (20×20 cm^2) scintillation counter telescope.

III. GRAPES-3 Angular Resolution

A total of 1.4×10^9 showers have been collected over a total live-time of 9.4×10^7s, spread over a four year period, from 2000 to 2003. For each EAS, the core location, the shower age 's' representing the steepness of the Nishimura-Kamata-Greisen (NKG) lateral distribution function and the shower size N_e have been determined [5]. This was done by using the observed particle densities, following the minimization procedure discussed in detail elsewhere [6]. Also, for each shower, the zenith (θ) and the azimuthal (ϕ) angles have been calculated using the time information from the TDCs, following the minimization procedure described in [6].

As mentioned in the §I, one of the most critical parameter in the search for the point sources of cosmic γ-rays, using a particle detector array, is its angular resolution. An improvement in the angular resolution allows the rejection of a larger fraction of the background EAS, initiated by the charged cosmic rays. This in turn would increase the signal to background ratio and may enable the discovery of the new cosmic γ-ray sources. This requires an accurate determination of the relative arrival time of the shower front at various detectors and an accurate determination of the shape of the shower front. Since the detectors in the EAS array are distributed over a large area and exposed to the outside weather, the timing accuracy is affected by the temperature dependence of the response of various components of the scintillation detector system. Observations have shown that the temperature coefficient for the scintillator, the photomultiplier, the signal cables, and the electronic modules (amplifiers, discriminators and the TDCs) are significantly different from each other and undergo measurable variations.

IV. The even-odd method

The EAS detectors in the GRAPES-3 array are sequentially numbered from the centre outwards, with the detector number increasing clockwise over each successive hexagonal ring. Therefore, it was decided to divide the array in two sub-arrays, namely, the first with the even-numbered and the second with the odd-numbered detectors. Next, a comparison of the arrival directions determined independently with the two sub-arrays, labeled 'even' and 'odd', respectively, is carried out. Since these two sub-arrays have a very substantial spatial overlap, they provide similar estimate of the EAS direction and also an important insight into the angular determination capability of the experiment [7]. An important limitation of this approach arises from the systematic errors that are common to both of the sub-arrays and therefore can not be measured. But, due to the spatial overlap of the 'even' and 'odd' sub-arrays, the direction determined by them would contain the same systematic error. In this method, event cut was imposed on the core location of the shower to lie within the hexagon labeled 'a', as shown in Fig. 1. Since the data from these two sub-arrays are independent of each other, the actual error in the determination of the angle is smaller by a factor of $\frac{1}{\sqrt{2}}$, than the value quoted above. Since, only half of the total number of hit detectors, are used in each of the two sub-arrays, the angular resolution for the full array would be smaller by a further factor of $\frac{1}{\sqrt{2}}$.

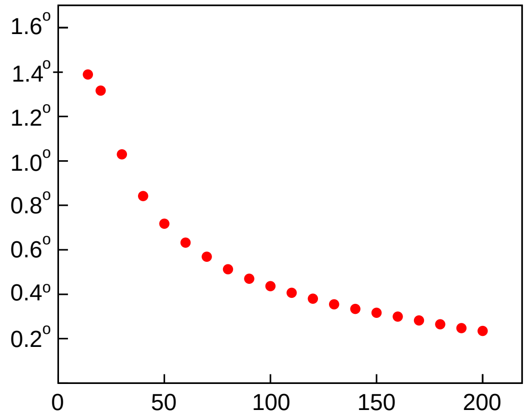

Fig. 2. Variation of the median angle as a function of the number of hit detectors.

In Fig. 2, the median angle, which is an alternative measure of the angular resolution of our array, is shown as a function of the number of hit detectors. The magnitude of the median angle initially decreases rapidly with increasing number of hit detectors up to $\sim$50 detectors, indicating rapid improvement in the angular resolution. However, thereafter the improvement is relatively slower.

V. The left-right method

Here, we present the results of a study that demonstrates the existence of the curvature in the shower front. A considerable improvement is seen in the angular resolution when a cone-shape is used to describe the curvature in the shower front. The curvature of the shower front is easily studied by dividing the array into two independent halves, namely, the left and the right half-arrays. For this purpose the following procedure is adopted. First, the location of the shower core is determined and then the line joining the shower core with the centre of the array is used to divide the array into the left- and the right-half arrays. Although this array division is implemented on an event-to-event basis, yet this procedure ensures that the number of detectors hit in each of the two half-arrays are approximately equal.

In the even-odd case, the density of the detectors is reduced by a factor of 2, while the area of the each sub-array remains nearly the same as the area 'A' of the full array. However, in the left-right case the density of the detectors remains unchanged, but the area of each half-array gets reduced by a factor of 2 to $\frac{A}{2}$. Therefore, we expect the ratio of the areas in the two cases to be 2. Since the angular resolution is inversely proportional to the linear extent of the array, we expect the angular

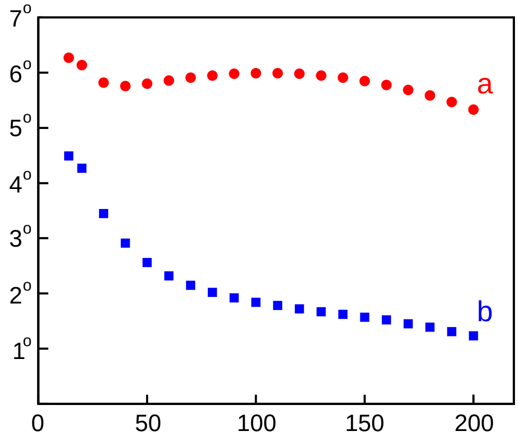

Fig. 3. Variation of the median angle, (a) α_{mp} for plane fit shown by filled circles , (b) α_{mc} for cone fit shown by filled squares, as a function of number of hit detectors .

resolution to worsen by a factor of $\frac{1}{\sqrt{2}}$ in the left-right case, as compared to the even-odd case. Thus a correction by a factor of $\frac{1}{\sqrt{2}}$ is required when comparing the results from the above methods.

In Fig. 3, the median angle α_{mp} is shown as filled circles, as a function of the number of hit detectors. The magnitude of α_{mp} shows a very small change with increasing number of hit detectors, right up to 200 detectors.

VI. Shadows of Moon and Sun

It is well-known that the observations of the shadow of the Moon or the Sun cast on the flux of cosmic rays observed at the Earth provides an ideal method to determine the angular resolution of an EAS array. It allows both, the statistical error in the angle determination as well as the systematic error in pointing towards a given direction to be measured.

The following procedure has been adopted for the analysis of the GRAPES-3 data. (a) Divide the field of view around the centre of the Moon or the Sun, in concentric circles of equal solid angle area Next, the number of showers incident along directions lying in each concentric bin are counted. The inner most bin (disk) has a diameter of 0.5°, which equals the angular diameter of the Moon. The solid angle of each bin is $6{\times}10^{-5}$sr, which therefore equals the solid angle projected by the Moon or the Sun. (b) For determining the background, similar concentric circles are drawn centred at two different directions, on either side of the Moon (or the Sun) that are offset by 8° in the azimuthal angle, but at the same zenith angle. This selection of the background region ensures that the shower attenuation in both the Moon/Sun and background regions is identical, allowing a direct comparison of the shower rates in the two regions to be made.

Fig. 4, the 2-dimensional map of the number of showers arriving from the directions around the Moon are shown. The map is centred on the Moon and covers ±5° both in the right ascension and the declination. The shadow of the Moon on the primary cosmic ray flux is clearly visible in Fig. 4. We had employed a 2-D Gaussian

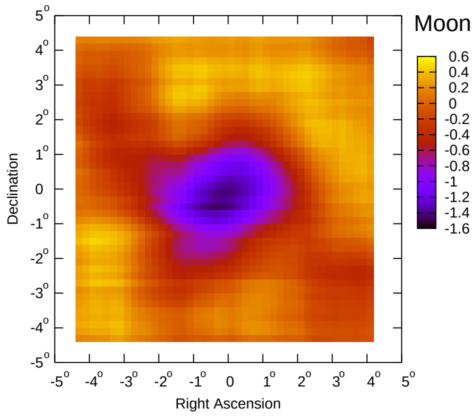

Fig. 4. (a) A 2-D map of % variation in number of showers from the directions around the Moon. The map is centred on the Moon and covers ±5° in R.A. and declination. A significant decrease is seen in a region of ∼1.5° around the Moon.

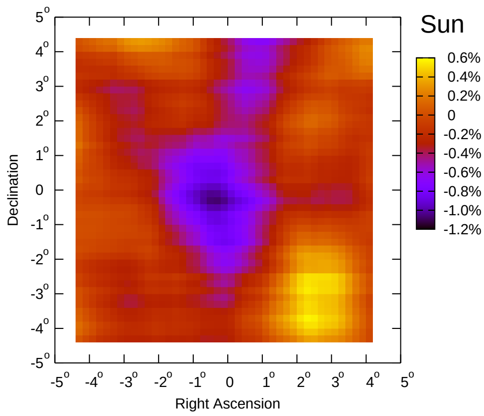

Fig. 5. (a) A 2-D map of % variation in number of showers around the Sun. The map is centred on Sun and covers ±5° in R.A. and declination. A significant decrease seen in a region of ∼2°×2° around the Sun.

Now, we display the shadow of the Sun in a 2-dimensional map of the number of showers arriving from the directions around the Sun in Fig. 5. This map is centred on the Sun and covers ±5° both in the right ascension and declination. Once again the effect of the shadow of the Sun is visible in Fig. 5, although it appears to be much more fuzzy than the shadow of the Moon as shown in Fig. 4. We observed the shadowing effects from the direction of the Sun, although with significantly larger fluctuations. This is not unexpected, since our observations during 2000-2003 coincided with the period of maximum solar activity.

VII. Discussion

For a direct comparison of the angular resolution of the GRAPES-3 array by the use of three different methods, we have converted the shower size N_e into the energy of the primary protons, using the CORSIKA Monte Carlo simulation program, version 6.500 with

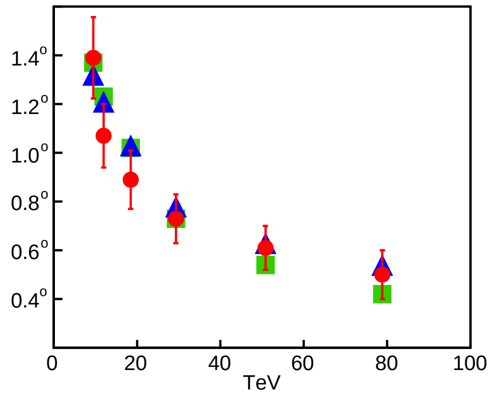

Fig. 6. Variation of angular resolution with primary energy (TeV) by methods, (a) left-right, filled triangles , (b) even-odd, filled squares , (c) Moon shadow, filled circles

the QGSJet generator [8]. A comparison of the angular resolution of the GRAPES-3 array, as determined by the three completely different methods namely; the even-odd, the left-right and the Moon shadow, as outlined in §IV, §V, §VI respectively, are shown in Fig. 6. For the even-odd case the angular resolution is extracted from the 2-D Gaussian fit to the angular distribution of events for a given number of detectors hit. This value is divided by 2 as explained in §IV to obtain the true value of the angular resolution.

VIII. Summary

We have analyzed the EAS data collected by the GRAPES-3 experiment over the four year period from 2000 to 2003. The division of the array into even and odd sub-arrays is used to estimate the shower energy dependent angular resolution of the GRAPES-3 array. An alternative method of estimating the angular resolution by using the concept of left and right half-arrays with cone-shaped shower front has yielded a value of 0.5°, which is slightly larger than the value of 0.4° obtained by the even-odd method for showers of energy ≥80 TeV. The even-odd method provides the best estimate of the angular resolution attainable in an array free from systematic errors. The agreement between the angular resolution obtained from the even-odd and the left-right methods provides the evidence, that the cone-shaped shower front used in determining the shower direction is an adequate representation of the shower disk. Finally, the reduction in the isotropic flux of the cosmic rays due to the shadow of the Moon yields an angular resolution of 0.5° for showers of energy ≥80 TeV. The absolute pointing accuracy of the GRAPES-3 arrays is ∼0.2° and the small offset observed, based on the present data set, is consistent with a null value. The Sun data also yields a similar value of the angular resolution, although with significantly larger uncertainty for the reasons mentioned in §VI. We conclude that the high density of the detectors in the GRAPES-3 experiment has been instrumental in obtaining the observed angular resolution.

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