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Measurement of the improved angular resolution of GRAPES-3 EAS array by the observation of the Moon shadow

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The Moon acts as a shield against the cosmic rays, preventing them from reaching the earth, which gives rise to a deficit in the flux along the direction of the Moon. The observed deficit can be used for obtaining the absolute calibration of the angular resolution and to verify the pointing accuracy of the array. GRAPES-3 is an extensive air shower experiment located at Ooty, India consisting of a dense array of scintillator detectors. It records $\sim 10^9$ showers per year with a median energy of 10 TeV. With the precise determination of the arrival time of shower particles and an accurate correction for the shower front curvature, a major improvement in the angular resolution of the array has been achieved. This was done by the array division methods including the left-right and even-odd methods. Here, we present a verification of the angular resolution estimates and the pointing accuracy by observing shadow of the Moon in the cosmic ray flux.

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1. Introduction

GRAPES-3 (Gamma Ray Astronomy at PeV Energies Phase-3) experiment, located (11.4°N, 76.7°E, 2200 m a.s.l) at Ooty, India is designed to study cosmic ray sources in TeV-PeV range by detecting the primary γ-rays propagating directly from the sources [1]. The flux of the cosmic rays dominates heavily (3-4 orders higher) over the γ-rays at these energies. To detect tiny flux of γ-rays, the angular resolution of the array needs to be very small. The closely packed array of 400 scintillator detectors (1 m^2 area each) deployed over an area of 25000 m^2 helps to achieve a good angular resolution which is further improved after proper correction of the shower front for shower size and age [3]. However, the absolute calibration of the angular resolution can be achieved by observing the shadow of the Moon as proposed by Clark in 1957 [4]. In this work, the angular resolution of the GRAPES-3 experiment has been obtained by observing the cosmic ray shadow of the Moon using three years of data.

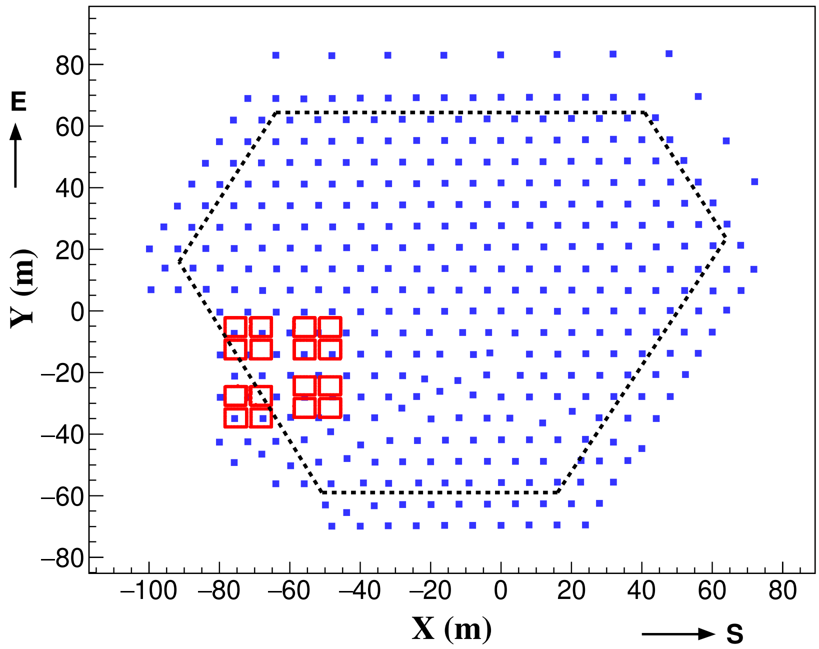


Figure 1: Schematic diagram of the GRAPES-3 array showing the Scintillator detectors (■), Muon telescope (□) and the fiducial area (**- - -**).

Each of the scintillator detectors is instrumented to record the particle density as well as the arrival time for every air shower triggered within the GRAPES-3 array. The lateral densities of each air shower are then fitted with the well-known Nishimura-Kamata-Greisen (NKG) function to obtain the various shower parameters such as shower core, shower size and shower age [5, 6]. Simultaneously, the arrival time in each detector is measured precisely with a 32 channel high performance time-to-digital converter (HPTDC). The arrival time is then used for reconstructing the arrival direction of the air shower. The dependence of the shower front curvature on the shower age and size gets corrected appropriately which improves the angular resolution of the GRAPES-3 array .

2. Data selection

Three years of air shower data (January 01, 2014 to December 31, 2016) were analyzed to observe the shadow of the Moon.

Following quality cuts are applied on the events for this analysis.

1. Successful NKG fit.
2. The reconstructed shower cores to be inside fiducial area (area within the dashed line in Figure 1).
3. Shower age was restricted between 0.2 and 1.8.
4. Zenith angle below $45°$.

3. Analysis methods

The Moon (angular radius $\sim$$0.26°$) is a massive object in the sky and acts as a sink for the cosmic rays passing through it. Hence, a deficit in the cosmic ray flux is expected along the direction of the Moon while an isotropic background is expected from the off-source regions. To observe the deficit along the direction of the Moon, the background needs to be studied properly. For this analysis, one on-source (Moon) region and a total of six off-source (fake Moon) regions were defined, each with $10°$ shifts in azimuthal angle successively from the Moon keeping the zenith angle the same as the Moon. The observed events are binned in equal incident angle (ψ) bins measured from the center of the Moon. In each bin, the relative deficit in the cosmic ray events is computed by,

$$\frac{\Delta N_i}{\langle N \rangle} = \frac{N_i^{on} - \langle N_i^{off} \rangle}{\langle N_i^{off} \rangle} \tag{1}$$

while the uncertainty in the deficit is given by,

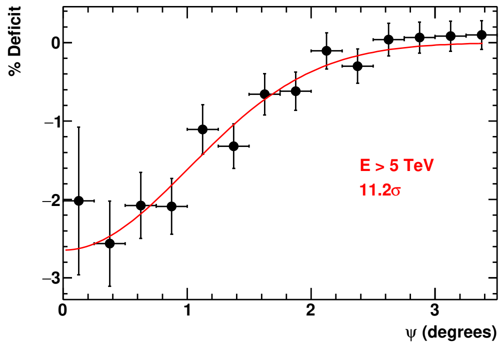
$$\sigma_{\Delta N/\langle N \rangle} = \frac{N_i^{on}}{\langle N_i^{off} \rangle} \sqrt{\frac{1}{N_i^{on}} + \frac{1}{6 \langle N_i^{off} \rangle}} \tag{2}$$

where, N_i^{on} is the number of events in the i^{th} bin when pointing towards the Moon and $\langle N_i^{off} \rangle$ is the average number of events in the i^{th} bin for the off-source regions.

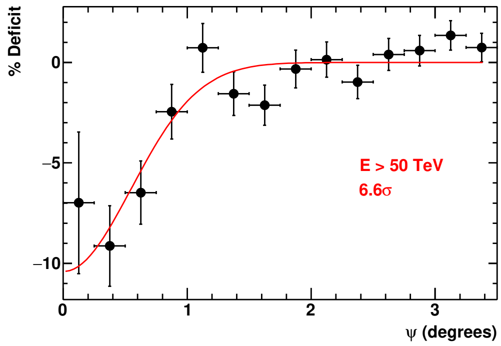
Observations have been made at several energies (E) to estimate the angular resolution (σ_ψ) at corresponding energies. A clear deficit in the events around the center of the Moon can be seen in Figure 2. The deficit in the events can be described by a two-dimensional Gaussian function given by,

$$N(\psi) = N_0 \frac{\psi_M^2}{2\sigma_\psi}\, e^{-\frac{\psi^2}{2\sigma_\psi^2}} \tag{3}$$

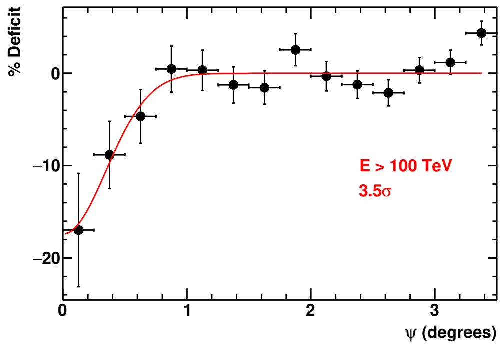
where ψ is the incident angle measured from the direction of the Moon, ψ_M is the radius of the Moon ($0.26°$), N_0 is a constant and σ_ψ is the angular resolution. The plots were fitted using Equation 3 to get the angular resolution at different energies.



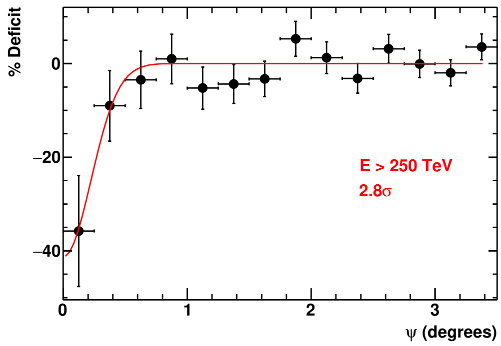
(a) E > 5 TeV



(b) E > 50 TeV



(c) E > 100 TeV



(d) E > 250 TeV

Figure 2: The angular resolutions obtained from the Moon shadow are, (2a) $1.01° \pm 0.08°$ for E > 5 TeV, (2b) $0.54° \pm 0.09°$ for E > 50 TeV, (2c) $0.35° \pm 0.08°$ for 100 TeV and (2d) $0.23° \pm 0.08°$ for E > 250 TeV with a significance of 11.2σ, 6.6σ, 3.5σ and 2.8σ respectively.

The optimum angular radius for a Gaussian distribution is given by $1.58\times$ angular resolution (σ_ψ). The statistical significance is calculated by,

$$S = \frac{\sum (N_i^{on} - \langle N_i^{off} \rangle)_{\psi_i \leq 1.58 \times \sigma_\psi}}{\sqrt{(\sum \langle N_i^{off} \rangle)_{\psi_i \leq 1.58 \times \sigma_\psi}}} \tag{4}$$

Table 1: Results obtained from the fit using equation 3

Energy (TeV)	Angular resolution (°)	Maximum deficit (%)	Significance
> 5	1.01 ± 0.08	2.5 ± 0.5	11.2σ
> 50	0.54 ± 0.09	10 ± 2.0	6.6σ
> 100	0.35 ± 0.08	19 ± 6.1	3.5σ
> 250	0.23 ± 0.08	40 ± 12	2.8σ

Table 2: Number of events observed from the direction of Moon (N^{on}) and fake-Moon (N^{off}) positions in each angular bins

S.No	Angular bin	Energy > 5 TeV		Energy > 50 TeV		Energy > 100 TeV		Energy > 250 TeV	
		N^{on}	N^{off}	N^{on}	N^{off}	N^{on}	N^{off}	N^{on}	N^{off}
1	0.00°- 0.25°	12684	12945	821	883	221	266	38	59
2	0.25°- 0.50°	12581	12912	812	894	247	271	58	63
3	0.50°- 0.75°	12681	12950	834	892	254	266	58	60
4	0.75°- 1.00°	12652	12921	867	889	272	271	60	60
5	1.00°- 1.25°	12764	12907	894	888	274	273	58	61
6	1.25°- 1.50°	12765	12936	874	887	268	271	57	60
7	1.50°- 1.75°	12799	12884	865	883	267	271	59	61
8	1.75°- 2.00°	12817	12897	881	884	274	267	62	59
9	2.00°- 2.25°	12882	12896	884	883	269	269	61	60
10	2.25°- 2.50°	12862	12901	875	883	267	271	57	59
11	2.50°- 2.75°	12881	12876	888	884	267	273	61	60
12	2.75°- 3.00°	12889	12881	885	880	269	268	60	60
13	3.00°- 3.25°	12875	12865	894	882	272	269	58	59
14	3.25°- 3.50°	12885	12873	886	880	279	267	60	58

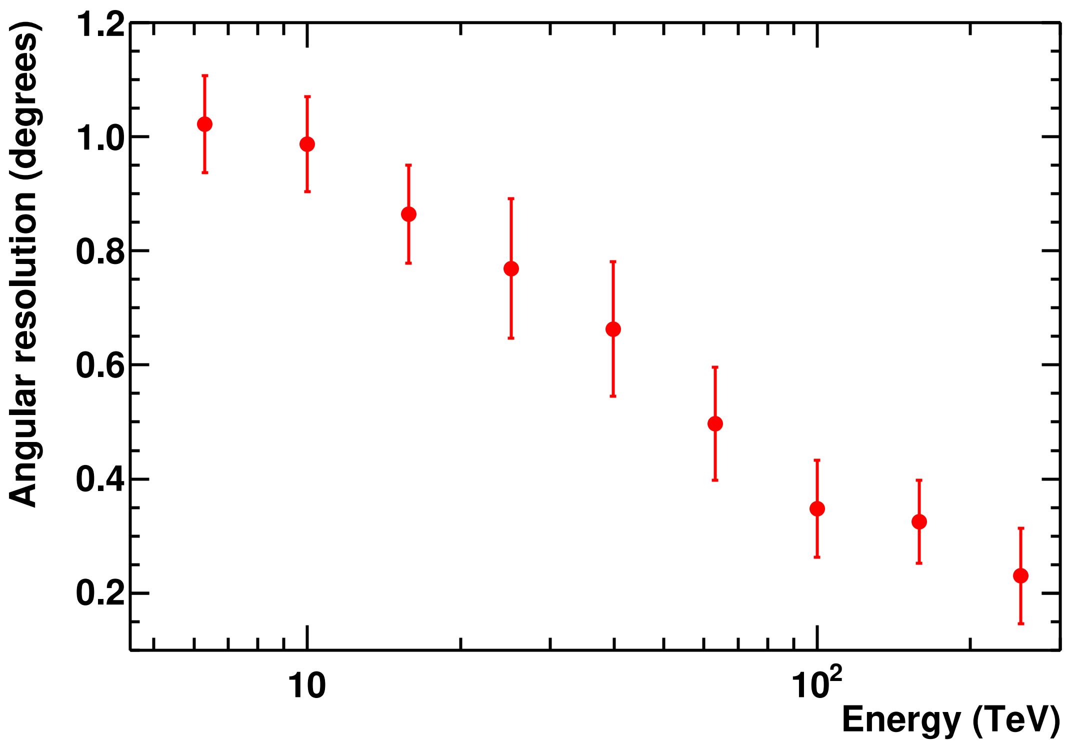


Figure 3: GRAPES-3 angular resolution obtained from the Moon shadow as a function of energy.

4. Discussion and Summary

With 3 years of air shower data, we have observed the cosmic rays shadow of the Moon from which, the angular resolution has been obtained to be $\sim 1.0°$ above 5 TeV energies with a 11.2σ significance of deficit. At energies above 50 TeV, a deficit of 10% has been observed with 6.6σ significance which gives an angular resolution of $\sim 0.54°$. The angular resolution further improves at higher energies as shown in Figure 3. The better angular resolution at higher energy can help to detect the point sources of cosmic rays by opening a narrow solid angle around the source region. Using the angular resolution obtained from the Moon shadow observation, we are trying to detect the γ-rays from the Crab Nebula which is considered to be the standard candle in high-energy astrophysics.

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