Acceptance of the GRAPES-3 experiment towards gamma-ray showers


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Compared to satellites and balloon-borne experiments, ground based air shower detectors enjoy larger fields-of-view and higher effective areas, making them ideal for studies of gamma rays above TeV energies. The Gamma Ray Astronomy at PeV EnergieS Phase-3 (GRAPES-3) experiment is an extensive air shower (EAS) array located in Ooty, India, with ~400 densely packed scintillator detectors accompanied by a 560 m² muon telescope. With the recent improvement in the angular resolution and an effective background rejection efficiency, the GRAPES-3 experiment has an excellent ability to study gamma-ray sources in the ultra-high energy (UHE) regime. In this work, we will present the acceptance of the GRAPES-3 towards gamma-ray-initiated showers, studied using CORSIKA simulated data.
1. The GRAPES-3 experiment

The GRAPES-3 (Gamma Ray Astronomy at PeV EnergieS – phase 3) is an extensive air shower (EAS) array located at Ooty (11.4° N, 76.7° E, 2200 m a.s.l.), Tamil Nadu, India. It consists of 400 plastic scintillators, each 1 m² in area, and arranged in a hexagonal configuration. The scintillators are spread over a physical area of 25,000 m² with 8 m of inter-detector separation [1, 2]. The EAS array records about $3 \times 10^6$ events per day in the energy range $10^{12}$–$10^{16}$ eV.

The other major component is a large area tracking muon telescope (560 m²) which comprises 3712 proportional counters (PRCs) housed in 4 stations [3]. Each station consists of 4 modules where in each module, the PRCs are arranged in 4 layers. Each layer consists of 58 PRCs of length 6 m having a square cross-sectional area of 0.1 m × 0.1 m. The alternating PRCs layers are orthogonally placed each separated by 15 cm thick concrete layer. The orthogonal configuration permits a two-dimensional reconstruction of muon tracks in two vertically orthogonal planes. Above each module, there is a mass overburden of 550 g.cm⁻² in the form of concrete blocks stacked in an inverted pyramidal shape. The concrete absorber provides an energy threshold of $\sec \theta$ GeV for muons incident at zenith angle $\theta$.

GRAPES-3 uses two-level trigger, namely, level-0 and level-1. The level-0 trigger is a simple 3-line coincidence with 100 ns time window and the level-1 trigger requires hit in atleast 10 detectors in 1 μs time window. A schematic view of the GRAPES-3 array is shown in Fig. 1.

![Figure 1: Schematic of the GRAPES-3 EAS array. The blue filled squares represent scintillator detectors and the red squares represent muon telescope modules. The dotted line represents the fiducial area.](image)

2. Gamma-ray simulation & shower reconstruction

We performed a detailed Monte-Carlo simulation of an EAS development using CORSIKA (v7.6900)[4] for primary gamma-rays. The hadronic interaction models used are QGSJET-II [5, 6] and FLUKA-CERN [7, 8], for high and low energies, respectively. The showers are generated in
The energy range 1 TeV to 1 PeV for zenith angle less than 60° with a differential energy spectrum of $E^{-2.0}$. Table 1 summarizes the values of some CORSIKA parameters used in the simulation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Particle (Id)</td>
<td>Gamma (1)</td>
</tr>
<tr>
<td>Primary Energy</td>
<td>$10^3 - 10^6$ GeV</td>
</tr>
<tr>
<td>Energy Slope</td>
<td>-2.0</td>
</tr>
<tr>
<td>Zenith Angle</td>
<td>$0^\circ - 60^\circ$</td>
</tr>
<tr>
<td>Observation Level</td>
<td>2200 m</td>
</tr>
</tbody>
</table>

Table 1: Summary of CORSIKA parameters used for the simulation

3. Efficiency and Acceptance

3.1 Trigger and reconstruction efficiency

The reconstructed showers are divided into eight angular (sec$\theta$) bins ranging from 1.00 to 1.40 with a bin-width of 0.05, and 15 logarithmic energy bins ranging from 1 TeV to 1 PeV. For each energy and sec$\theta$ bin, we calculate the trigger efficiency ($\epsilon_{tr}$) by the fraction of EAS having the shower core within the fiducial area that passes the level-0 and level-1 trigger conditions. In a similar fashion, we calculate the reconstruction efficiency ($\epsilon_{rec}$) by the fraction of triggered EAS that passes the below reconstruction quality cuts:

- Successful reconstruction of shower parameters.
- Shower age (s) lies between 0.12 to 1.8.
Figure 2: Trigger efficiency (top) and reconstruction efficiency (bottom) of GRAPES-3 for gamma-ray initiated showers.

The total efficiency ($\varepsilon_{tot}$) is determined by the product of trigger and reconstruction efficiency. Due to limitations of the poissonian and binomial error calculation, we calculate the error in total efficiency as [13]:

$$\sigma_i = \sqrt{\frac{(k_i + 1)(k_i + 2)}{(n_i + 2)(n_i + 3)} - \frac{(k_i + 1)^2}{(n_i + 2)^2}}$$  \hspace{1cm} (2)

where, for a given angular bin, $n_i$ and $k_i$ are the number of EAS having the shower core within the fiducial area, and the number of EAS that pass both the trigger conditions and reconstruction quality cut, respectively, in the $i^{th}$ energy bin.
The trigger efficiency and the reconstruction efficiency for all angular bins are shown in Fig. 2. The total efficiency is shown in Fig. 3. The trigger efficiency increases with energy of the primary gamma-rays because at higher energies large number of secondary particles will be produced with relatively higher energy. Hence, the probability of triggering the EAS array will increase as can be seen for the first angular bin \((1.0 \leq \sec \theta < 1.05)\), where the trigger efficiency increases from 14.0% at 8.0 TeV to 99.9% at 80.0 TeV. Also, it is to be noted that the trigger efficiency at a given energy decreases with increase in the zenith angle since the effective length travelled by the EAS increases and causes more attenuation of the EAS. Hence, the probability of the trigger decreases.

### 3.2 Gamma-ray Acceptance

The acceptance is defined as the product of effective area of the detector and the effective viewing angle with the inclusion of total efficiency. It is also a function of zenith angle and energy.

\[
\delta_{tot}(E_t) = \frac{\pi A}{2} \sum_{k=1}^{n} \epsilon_{tot}(E_t, \theta_k)(\cos^2 \theta_k - \cos^2 \theta_{k+1}),
\]

where \(A\) is the fiducial area, \(n\) is the total number of angular intervals, \(\theta_k\) and \(\theta_{k+1}\) is the lower and upper edge of each angular bin, and \(E_t\) is the energy of the primary gamma rays.

In Table 2, we tabulate the total acceptance of GRAPES-3 for gamma-ray initiated showers and are also plotted in Fig. 4.

### 4. Summary

In this work, we perform a detailed MC simulation for primary gamma-rays to estimate various efficiencies in the energy range 1 TeV – 1 PeV. We find the total efficiency for near vertical showers to be < 0.1% for 1 TeV increasing to > 99% above 50 TeV.

Similarly, we estimate the total acceptance of the EAS array to be \(~3.32\) m\(^2\) sr at 1.58 TeV reaching a maximum of \(~22226.6\) at 794 TeV.
Table 2: Summary of total acceptance of GRAPES-3 for gamma-ray showers.

<table>
<thead>
<tr>
<th>Bin</th>
<th>Mean Energy (TeV)</th>
<th>$\delta_{tot}$ ($m^2$ sr)</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>1.58</td>
<td>3.32</td>
</tr>
<tr>
<td>2</td>
<td>1.99</td>
<td>17.27</td>
</tr>
<tr>
<td>3</td>
<td>3.16</td>
<td>79.37</td>
</tr>
<tr>
<td>4</td>
<td>5.01</td>
<td>306.54</td>
</tr>
<tr>
<td>5</td>
<td>7.94</td>
<td>1021.69</td>
</tr>
<tr>
<td>6</td>
<td>12.59</td>
<td>2835.67</td>
</tr>
<tr>
<td>7</td>
<td>19.95</td>
<td>6226.81</td>
</tr>
<tr>
<td>8</td>
<td>31.62</td>
<td>10556.1</td>
</tr>
<tr>
<td>9</td>
<td>50.12</td>
<td>14708.3</td>
</tr>
<tr>
<td>10</td>
<td>79.43</td>
<td>18070.5</td>
</tr>
<tr>
<td>11</td>
<td>125.89</td>
<td>20449.8</td>
</tr>
<tr>
<td>12</td>
<td>199.53</td>
<td>21765.1</td>
</tr>
<tr>
<td>13</td>
<td>316.23</td>
<td>22246.0</td>
</tr>
<tr>
<td>14</td>
<td>501.19</td>
<td>22303.7</td>
</tr>
<tr>
<td>15</td>
<td>794.33</td>
<td>22226.6</td>
</tr>
</tbody>
</table>

Figure 4: Total acceptance of GRAPES-3 array.

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References


