32ND INTERNATIONAL COSMIC RAY CONFERENCE, BEIJING 2011

Monte Carlo simulation for High Altitude Gamma Ray Telescope System at Ladakh in India

L. SAHA[1], B. S. ACHARYA[2], G. C. ANUPAMA[3], R. J. BRITTO[2], P. BHATTACHARJEE[1], V. R. CHITNIS[2], S. KALE[3], T. P. PRABHU[3], A. SHUKLA[3], B. B. SINGH[2], P. R. VISHWANATH[3]
[1]*Saha Institute of Nuclear Physics,1/AF Bidhannagar,Kolkata 700064,India*
[2]*Tata Institute of Fundamental Research,Homi Bhaba Road,Mumbai 400005,India*
[3]*Indian Institute of Astrophysics,Sarjapur Road, 2nd Block,Bangalore 560034 ,India*
lab.saha@saha.ac.in
DOI: 10.7529/ICRC2011/V09/1129

Abstract: High Altitude GAmma Ray (HAGAR) experiment is an array of seven telescopes located at an altitude of 4270m in Himalayas. In order to understand performance of this experiment, large samples of extensive air showers initiated by gamma rays and various species of cosmic rays are simulated using CORSIKA package. Cherenkov photon distributions obtained from CORSIKA are later passed through the detector simulation program, which takes into account various design details of the data acquisition system of HAGAR. Performance of the experiment also depends strongly on the level of night sky background (NSB) at the observation site. Modeling of NSB is also carried out in detector simulation program. Various performance parameters like energy threshold, collection area are estimated for vertically incident showers as well for showers arriving at an angle relative to vertical. Energy threshold of HAGAR is estimated to be about 200 GeV for vertically incident gamma ray showers. Details of estimated performance parameters as well as comparison of simulations with data will be presented.

Keywords: Atmospheric Cherenkov technique, EAS simulations

1 Introduction

High Altitude GAmma Ray (HAGAR) telescope array is an experimental setup for detection of very high energy gamma rays from astronomical sources. This telescope array located at Hanle, Ladakh, in the Himalayas, at an altitude of 4270 m, is the highest altitude atmospheric Cherenkov experiment in the world. Taking advantage of the high altitude location, this experiment achieves a comparatively lower energy threshold with moderate mirror area. Installation of HAGAR began at Hanle in 2005 and was completed in 2008. Regular source observations have been going on with this complete setup of seven telescopes since September 2008. Estimation of the sensitivity of the experiment is in advanced stage, using data taken for a prolonged period from the Crab nebula which is supposed to be the standard candle source of TeV gamma rays. In this article we present details of Monte Carlo simulations for performance parameters of the HAGAR telescope system. We also compare estimates from simulations with the results obtained from experimental data.

2 HAGAR Telescope array

The HAGAR array consists of seven telescopes of which six are deployed in the form of a hexagon and the seventh one is at the center of the hexagon (see figure 1). Each telescope consists of seven parabolic mirrors. A photo multiplier tube (PMT) is mounted at the focus of each mirror. This PMT (XP2268B manufactured by Photonis) has good sensitivity to ultraviolet to blue photons, with peak quantum efficiency of about 24% at 400 nm. Signals from each PMT are brought to the control room which is situated just below the central telescope system and are recorded there using CAMAC based system. Each mirror has a diameter of 0.9 m. Mirrors are fabricated by forming 10 mm thick float glass sheets into a parabolic shape with f/d ratio fixed to unity. All the seven mirrors of each telescope are mounted para-axially on a single platform while the tele-

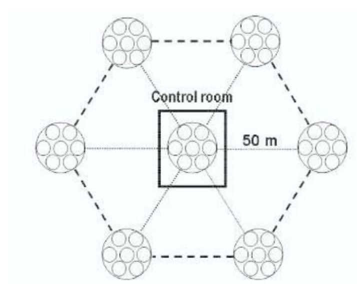

Figure 1: HAGAR telescope array setup

scopes themselves are mounted alt-azimuthally. Relative arrival time of shower front at each mirror is recorded by the TDCs accurate to 0.25ns. Cherenkov photon density at each telescope given by total charge in PMT pulses is recorded using 12 bit QDCs. For trigger formation, 7 PMT pulses of each telescope are added to form a telescope pulse called royal sum pulse. To generate a trigger, a coincidence of at least 4 royal sum pulses out of 7, above a predetermined threshold, is taken within a time window of 150 ns or 300ns depending on the zenith angle of pointing direction. Details of the array system can be found in Chitnis et al. [1].

3 Monte Carlo Simulations

3.1 Atmospheric air shower simulations

CORSIKA [2, 3] is a Monte Carlo program to study the evolution of extensive air showers (EAS) in the atmosphere initiated by photons and various species of charged particles including protons, alpha particles i.e. helium nuclei as well as other nuclei. CORSIKA version 6.720 is used for atmospheric air shower simulations. VENUS code is used for high energy hadronic interactions and GHEISHA program is used for the low energy hadronic interactions. For electromagnetic interactions EGS4 program is used. We used HAGAR detector geometry in input data card choosing IACT option in CORSIKA. Geomagnetic field appropriate for Hanle location and altitude of Hanle (4270 m) is used in simulations. We have used US standard atmospheric profile for generation of Cherenkov photons. Wavelength dependent absorptions of Cherenkov photons caused by atmosphere, reflectivity of mirrors (average value of 80%) and quantum efficiency of PMT are introduced in CORSIKA. Information about Cherenkov photons with wavelength in the range of 200nm- 650nm is stored. Impact factor is varied over the range of 0-200 m and viewcone is kept 0° around the pointing direction for gamma ray initiated showers and varied over $0^\circ - 3^\circ$ for cosmic ray generated showers. Showers from gamma rays, protons, alpha particles and electrons are simulated using following spectral shapes :

$$\frac{dN_\gamma}{dE} = 3.27 \times 10^{-7} E^{-2.49} \mathrm{TeV}^{-1}\mathrm{m}^{-2}\mathrm{s}^{-1}$$

$$\frac{dN_{pr}}{dE} = 0.0867 E^{-2.7} \mathrm{TeV}^{-1}\mathrm{m}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$

$$\frac{dN_\alpha}{dE} = 0.0595 E^{-2.7} \mathrm{TeV}^{-1}\mathrm{m}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$

$$\frac{dN_e}{dE} = 636.97 E^{-3.3} \mathrm{TeV}^{-1}\mathrm{m}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$

respectively. No. of showers generated and energy ranges used in simulations are given in Table 1 for vertically incident showers. We have also simulated showers for inclination angles of 15°, 30° and 45°.

From CORSIKA simulations we get the information about the number of Cherenkov photons falling on the mirrors, their arrival angle and arrival time information i.e. the time when these photons hit the telescope since first interaction.

Type	Energy range GeV	# of showers generated
Gamma rays	20-5000	1×10^6
Protons	50-5000	3×10^6
Alpha particles	100-10000	6×10^6
Electrons	20-5000	3×10^5

Table 1: Samples generated for vertical showers

3.2 Detector simulation

CORSIKA simulation gives information about arrival time of Cherenkov photons at each PMT. This information is passed through detector simulation program. This mrogram takes into account details of entire HAGAR system including PMTs, coaxial cables, trigger formation etc. In addition to Cherenkov photons, night sky background photons are also incident in actual experiment. These NSB photons are simulated assuming the flux of 2×10^8 ph cm^{-2} s^{-1} sr^{-1} in the wavelength range of 200-650 nm, measured at Hanle using single photo-electron counting technique. (NSB flux measured at Hanle varied between 0.8×10^8 - 2×10^8 ph cm^{-2} s^{-1} sr^{-1} depending on the region of the sky as well as on the season.) NSB photons are simulated in 0.2 ns bins using Poissonian distribution around this measured value and following typical wavelength dependence of NSB. These NSB photons are added to Cherenkov photons from CORSIKA simulations. PMT response function is approximated with a Gaussian with rise time of 2 ns and width of 3.3 ns. Convolving time profile and the no. of photons in each bin with PMT response function, the PMT pulses are generated using average PMT gain of 1.5×10^6. Attenuation of these pulses in coaxial cables (30 m of LMR-Ultraflex-400 and 55 m of RG213) is taken into consideration. Pulses from individual PMTs of a telescope are added together to get telescope pulse or royal sum pulse. Trigger is generated when at least 4 royal sum pulses out of 7 cross the discriminator threshold of 220 mV. Once trigger is generated, TDC and QDC values are calculated using various calibrations carried out with HAGAR setup. These values are written to output file.

4 Performance parameters

Sample generated for vertically incident showers from gamma rays and cosmic rays using CORSIKA is shown in Table 1. We have estimated performance parameters for this sample. HAGAR trigger is generated when at least 4 telescope pulses out of 7 cross discriminator threshold in narrow coincidence window. Performance parameters are estimated for this condition ($\geq$4) as well for other trigger conditions involving at least 5 telescopes ($\geq$5), at least 6 telescopes ($\geq$6) and all 7 telescopes (=7) triggering. Performance parameters for various trigger conditions for vertically incident showers are given in Table 2. Performance parameters for trigger condition of $\geq$4 for various incidence angles are given in Table 3.

Cosmic ray trigger rate estimated from simulations, assuming bulk of the triggers to come from protons, alpha particles and electrons, is 13.2 Hz for $\geq$4 trigger condition. This matches very well with the observed trigger rate from HAGAR near vertical. Expected gamma ray rate for Crab like source near vertical is 6.6 counts/minute. Trigger rate decreases for higher fold trigger conditions as seen from Table 2. It also decreases for higher zenith angles as seen from Table 3.

Energy threshold of HAGAR is obtained from the differential rate plot. Peak of the differential rate curve is conventionally quoted as energy threshold. Values of this parameter for various conditions are listed in Tables 2 and 3. In case of vertically incident gamma rays, energy threshold is about 204 GeV and increases at higher folds. Differential rate curves for various trigger conditions are shown in Fig. 2. Energy threshold also increases with inclination angle. Threshold for $\geq$4 trigger condition increases from 204 GeV near vertical to 513 GeV for zenith angle of 45°.

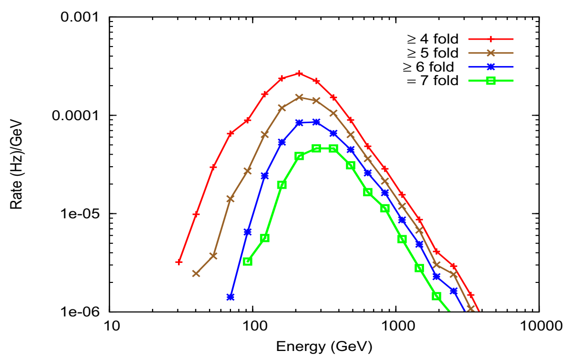

Figure 2: Differential rate plot for different trigger conditions

Effective collection area is estimated for various trigger conditions. Fig. 3 shows variation of effective area with energy for vertically incident gamma ray showers, protons and alpha particles for trigger condition of $\geq$4. Average value of effective area is 3.2×10^4 m^2 and decreases at higher folds as seen from Table 2. In the case of inclined showers, effective collection area increases with zenith angle as seen from Table 3.

Based on the cosmic ray and gamma ray trigger rates obtained from simulations, sensitivity of HAGAR is estimated. Fig. 4 shows observation duration needed to detect source at 5σ significance level as a function of source flux in Crab units. So HAGAR will be able to detect Crab nebula like source at a significance level of 5σ in 15 hours of observation duration. This corresponds to the sensitivity of $1.3\sigma/\sqrt{hour}$.

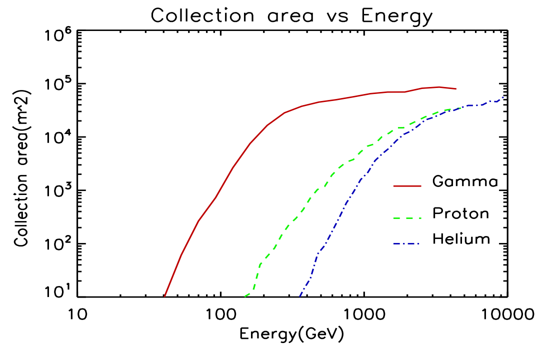

Figure 3: Effective area vs energy of primary from MC for vertical incidence

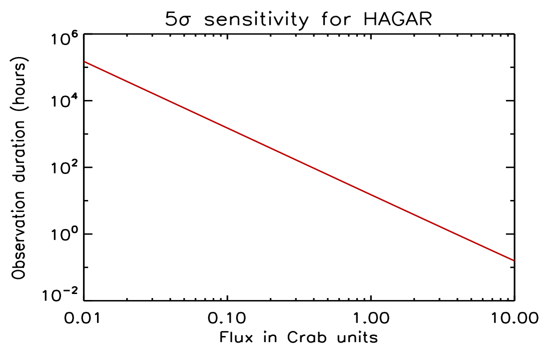

Figure 4: Observation duration vs source flux for detection of source at 5σ significance level with HAGAR

5 Comparison of data with Monte Carlo simulations

As mentioned earlier, estimate of cosmic ray trigger rate from simulations matches well with the observed rate near vertical. We have also compared variation of trigger rate with zenith angle as obtained from simulations with the data. For this purpose, data obtained by tracking dark region of the sky passing through zenith was used. Fig. 5 shows the comparison of observed trigger rate (shown by plus sign) as a function of zenith angle with simulated rates (shown by diamonds with error bars) at various angles between 0°-50°. There is a good agreement between the two.

Fig. 6 shows comparison of the space angle distributions from simulations and observations. For each triggering event, direction of shower axis is reconstructed approximating TDC data with plane front. Space angle is defined as an angle between pointing direction of telescope (position of source in the sky) and reconstructed shower direction (see britto et al. [4] for details). Space angle distribution obtained from data taken pointing all the telescopes in vertical direction is shown in Fig. 6 by histogram with red colour and dashed line. Distribution obtained from simulations, using proton and alpha particle initiated events, is shown by histogram with blue colour and solid line. There

Trigger condition	Proton trigger rate (Hz)	Alpha trigger rate (Hz)	Electron trigger rate (Hz)	Gamma Ray rate (/min)	Energy Threshold (GeV)	Collection Area (m^2)
≥ 4	9.8	3.3	0.11	6.6	204.2	3.2×10^4
≥ 5	5.4	2.3	0.05	4.2	229.1	2.5×10^4
≥ 6	2.9	1.3	0.03	2.6	257.0	1.8×10^4
$= 7$	1.5	0.78	0.01	1.6	309.0	1.3×10^4

Table 2: Performance parameters for HAGAR telescope array for vertical Shower

Zenith angle (°)	Proton trigger rate (Hz)	Alpha trigger rate (Hz)	Gamma Ray rate (/min)	Energy Threshold (GeV)	Collection Area (m^2)
0	9.8	3.3	6.6	204.2	3.2×10^4
15	11.6	3.58	7.1	204.2	3.4×10^4
30	9.8	3.93	5.5	316.2	4.9×10^4
45	8.3	2.50	4.3	512.9	10×10^4

Table 3: Performance parameters for various zenith angles

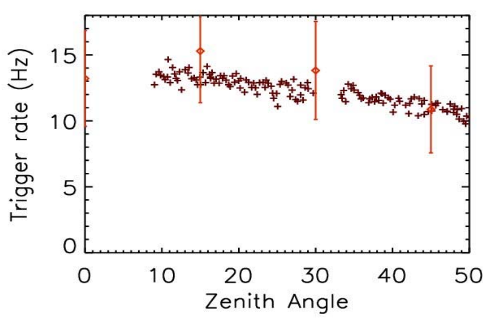

Figure 5: Trigger rate vs zenith angles from MC for different elevation angles.

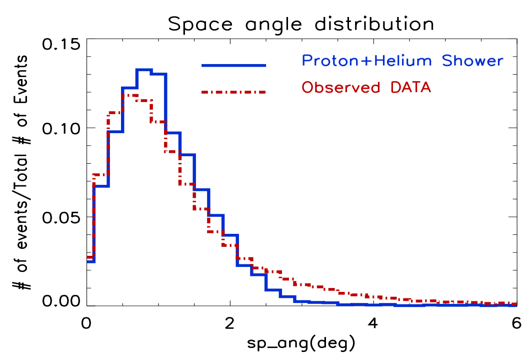

Figure 6: Comparison of space angle distribution from MC for vertical shower with data

is a fair agreement between the two distributions except for the tail region with larger space angles.

6 Conclusions

Monte carlo studies show that energy threshold of HAGAR is about 200 GeV. This telescope system will be able to detect Crab like sources in 15 hours of observations with the significance of 5σ. Comparison between space angle distributions and variation of trigger rate with zenith angle obtained from simulations are in good agreement with the observed data indicating that HAGAR telescope system is well understood and accurately modeled. Parameter estimates given here depend on value of NSB flux and average PMT gain used. At present, work is underway to simulate PMT/telescope rate vs discriminator threshold curve as well as the shape of the pulse height spectrum due to pure NSB. This work is expected to lead to robust estimates of the parameters.

References

[1] V. R. Chitnis et al., Proceedings of 31st ICRC, Łódź, Poland, 2009

[2] J. Knapp and D. Heck, Extensive Air Shower Simulation with CORSIKA: A User's Guide, Version 6.7, 2007

[3] D. Heck et al., Forschungszentrum Karlsruhe Report FZKA 6019, 1998

[4] R. J. Britto et al., These proceedings, 2011, OG 2.5, abstract ID 943