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Simulation studies of MACE gamma ray telescope : estimation of integral sensitivity, angular resolution and energy resolution

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The MACE (Major Atmospheric Cherenkov Experiment) is an Imaging Atmospheric Cherenkov Telescope (IACT) located in Hanle, India. It has highest altitude of 4270 m among all the IACTs in the world. The high altitude of MACE along with its large reflector having diameter of 21 m is expected to yield wide energy coverage of ∼ 20 GeV to ∼ 20 TeV. We have carried out detailed Monte Carlo simulations of the MACE response to gamma and cosmic ray showers in this energy range for various zenith angles between 0° to 60°. We estimated the variation of integral flux sensitivity, angular resolution and energy resolution as a function of energy, at various zenith angles. We find that the energy threshold of the MACE remains steady between ∼ 30 GeV to ∼ 50 GeV over the zenith angle range of 0° to 40° with integral flux sensitivity of ∼ 2 % Crab. The Angular resolution of the MACE improves from 0.21° near the energy threshold to 0.07° at energy of $>$ 1 TeV for zenith angle range of 0° to 40°. The expected energy resolution of the MACE in the zenith angle range of 0° to 40° varies from ∼ 40 % near energy threshold to ∼ 20 % for energies above 1 TeV. The MACE will detect Crab like point source within few minutes at all zenith angles, with best detection time of ∼ 80 seconds occurring at zenith angle of 25°.

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1. Introduction

The ground based γ ray astronomy using Imaging Atmospheric Cherenkov Telescope (IACT) has become the most powerful way of observing Very High Energy (VHE) γ rays in the energy range of 50 GeV to 50 TeV over the last 3 decades [1, 2]. The TeV catalog contains a total of 243 VHE γ ray sources, 204 of which are detected by IACTs like H.E.S.S. [3], MAGIC [4] and VERITAS [5]. To Augment the global effort towards improvement and extension of observational study of VHE γ ray sources, the Astrophysical Sciences Division of Bhabha Atomic Research Center is setting up imaging atmospheric Cherenkov technique based VHE γ ray telescope MACE (Major Atmospheric Cherenkov Experiment) at Hanle (32° 46’ 46” N, 78° 58’ 35” E), India. The MACE is located at an altitude of 4270 m, highest for any IACT in the world, giving the advantages of relatively better Cherenkov photon density, less atmospheric attenuation and consequently lower energy threshold. It has the second largest reflector area of $\sim$ 337 m^2 among the IACTs in the northern hemisphere of the globe. The primary goal of the MACE telescope is to collect high quality temporal, morphological and spectral data for the VHE γ ray sources in the wide energy range of $\sim$ 30 GeV to $\sim$ 10 TeV, while filling the observational gap that exists in the energy range of 10 GeV to 100 GeV for many of the γ ray sources.

When VHE γ rays and cosmic rays enter the earth’s atmosphere, they interact with atmospheric nuclei through electromagnetic and hadronic interactions and produce cascade of relativistic charged particles. These cascade of particles are known as Extensive Air Showers (EAS). The relativistic charged particles in EAS move through the atmosphere faster than the speed of light in the medium. This creates the Cherenkov emission from the atmosphere in the visible and UV range of electromagnetic spectrum that lasts for 5-10 ns. An IACT collects this Cherenkov emission using a simple optical reflector on the array of Photo-Multiplier Tubes (PMTs) placed at the focal plane, forming an image of the EAS. Different properties of the images of EAS collected by an IACT are then used to differentiate γ rays from cosmic rays as well as to estimate the energy and arrival direction of the γ rays. The prior knowledge of the correlations between properties of EAS images and the type, energy and arrival direction of the primary which induces the EAS is necessary condition for the detection and reconstruction of the VHE γ rays using IACT. Due to lack of any terrestrial reference VHE γ ray source, the knowledge about the correlations between EAS image properties for an IACT and VHE γ and cosmic ray showers must be obtained by performing detailed simulation of the IACT response to the simulated EAS induced by photons and hadrons.

2. Details of simulation

The large database consisting of a total of $\sim$ 1.2 billion EAS was simulated using widely used EAS simulation software CORSIKA [6]. The CORSIKA along with IACT/ATMO extention [7] provides the wavelength, position, direction and time of arrival at the observation level for all the Cherenkov photons generated by an EAS. The air showers induced by γ rays, protons, electrons and alpha particles having energy in the range of 10 GeV to 20 TeV were simulated.

We have developed C++/ROOT based program for the simulation of an IACT response to EAS. The program processes the output data of the CORSIKA. The IACT simulation software simulates the response of different components of an IACT to Cherenkov photons. These include

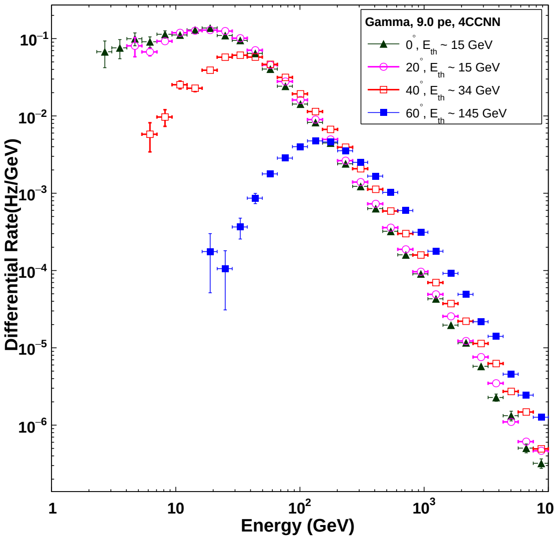

Figure 1: Differential trigger rates for the MACE telescope at zenith angles of 0°,20°,40° and 60°

reflector, PMT camera, trigger, Light Of Night Sky (LONS) and data analysis procedures for triggered images like image cleaning and image parameterization.

3. Results

3.1 Trigger energy threshold

The MACE can be operated in different trigger configurations with trigger multiplicity ranging from 3 to 6 along with programmable single channel discrimination threshold. The optimum trigger configuration for the MACE operations was found to be 4 CCNN trigger along with the single channel discrimination threshold of 9.0 photo-electrons (pe) [8]. The data for the variation of the single channel rates against the discrimination thresholds for the 3 gain calibrated PMTs were used to estimate the Chance Coincidence Rates (CCR) for all possible trigger configurations at different single channel discrimination threshold ranging from 5 pe to 20 pe. The trigger configuration that keeps the CCR below 50 Hz while yielding trigger energy threshold of $\sim$ 20 GeV was chosen as the optimum trigger configuration. All the estimates throughout this work have been made for the trigger configuration of 4 CCNN with single channel discrimination threshold of 9.0 pe.

The effective collection area was estimated by calculating the trigger probability of the MACE as a function of energy, impact parameter and offset of the arrival direction of the primary with respect to telescope pointing direction. The effective collection area of the MACE as a function of energy of the primary for the γ rays, protons, electrons and alpha particles was estimated at zenith angles of 0°, 20°, 40° and 60°. 10^6 EAS were simulated at each of the above zenith angles for each primary for the estimation of trigger performance. The differential and integral trigger rates for each of the above primaries at zenith angles of 0°, 20°, 40°o and 60° were found out by multiplying the estimated effective area of the primary with differential particle flux of the primary. For the γ rays, Crab nebula spectrum following power law with spectral index of -2.59 was used to estimate differential trigger rate. The power law spectra with spectral indices of 2.73, 2.64 and 3.07 were

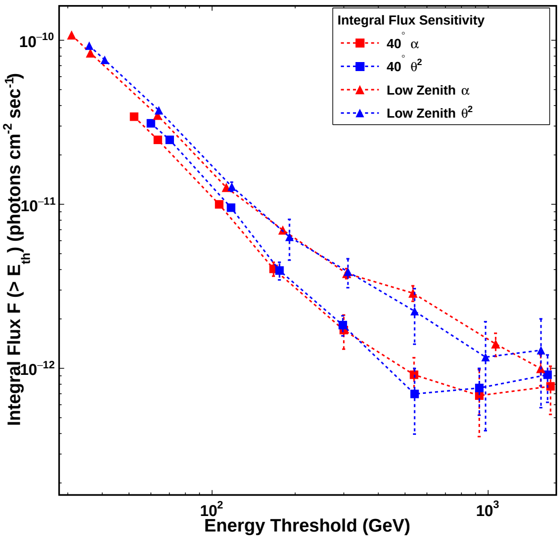

Figure 2: Integral flux sensitivity of the MACE telescope using α and θ^2 analysis

used as differential flux for protons, alpha and electrons respectively. The energy corresponding to the peak of the differential trigger rate curve at given zenith angle for given primary particle is used as the estimate for the trigger energy threshold of the MACE telescope for the primary. The trigger energy threshold of the MACE for the γ rays is found to be $\sim$ 15 GeV at the zenith angle of 0°. The trigger energy threshold marginally deteriorates to $\sim$ 34 GeV at zenith angle of 40°. At 60° zenith angle the trigger energy threshold of the MACE is estimated to be $\sim$ 145 GeV.

3.2 Integral flux sensitivity

The integral flux sensitivity of an IACT is defined as the minimum integral flux of VHE γ rays from a Crab like point source which can be detected by an IACT in the 50 hours of observation with following 2 conditions ; 1) at least 10 γ like events are detected and 2) γ like events detected are more than 5% of the background events. The integral flux sensitivity of the MACE telescope using two analysis methods namely, Alpha analysis and θ^2 analysis were estimated. The contribution of protons, alpha particles and electrons to the background were taken into account while estimating sensitivity. The power law spectra with spectral indices of 2.73, 2.64 and 3.07 over the enrgy range of 20 GeV to 20 TeV, were used for the proton, alpha and electron respectively. The Crab like power law spectrum with index of 2.6 was used to simulate γ ray showers in the energy range of 10 GeV to 20 TeV. The complete telescope response was simulated for all the simulated EAS, the images of the EAS which met trigger criterion were stored and all the data analysis procedures like image cleaning and parameterization were applied on the stored images. The random forest classification algorithm was used for γ/hadron segregation. The Size, Distance, Length, Width, Frac2, Asymmetry and Alpha parameters were used to train the random forest classifier in Alpha analysis. The θ^2 analysis was performed by using θ^2 parameter instead of Alpha parameter during the random forest training. One random forest classifier was trained for each zenith angle. The integral flux sensitivity of the MACE in the low zenith angle range was found to be 24 mCrab units at the analysis energy threshold of $\sim$ 31 GeV using alpha analysis. The same was found to be 17

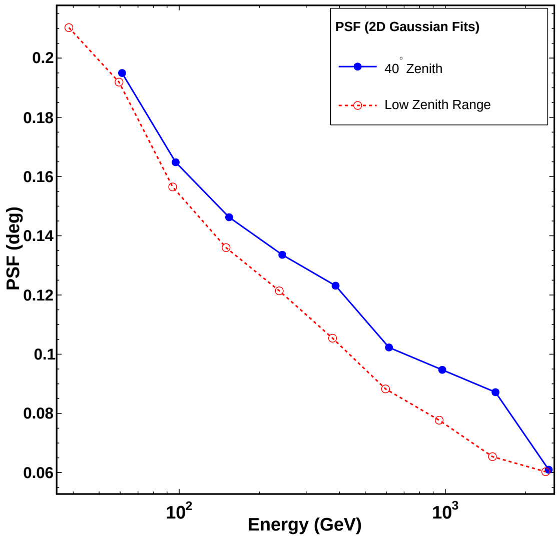

Figure 3: Angular resolution of the MACE telescope as function of energy

mCrab units at the analysis energy threshold of ∼ 52 GeV at the zenith angle of 40°. The integral flux sensitivity using the θ^2 analysis for the zenith angle range of 0° to 30° was estimated to be 26 mCrab units above energy of 35 GeV. For the zenith angle of 40° the integral flux sensitivity using θ^2 analysis was found to be 20 mCrab units above energy threshold of 60 GeV. The study indicates better performance of alpha analysis as compared to θ^2 analysis. It should be noted here that the energy threshold is defined as the energy at the peak of after analysis differential rate curve of the γ rays. MACE will detect γ like events having energy below the quoted threshold as well.

3.3 Angular resolution

γ ray induced EAS in the energy range of 10 GeV to 20 TeV, following power law spectrum with index -1, were simulated at each of the zenith angles 5°, 25° and 40° for the estimation of angular as well as energy resolution. The Disp procedure of reconstructing the arrival direction [9] of the γ rays was used to find the source positions in the camera for individual γ ray events. The random forest regression algorithm was used to estimate the Disp parameter from the parameters Size, Length, Width and Leakage. The energy range of 30 GeV to 3 TeV was divided into 5 energy bins per decade. The angular and energy resolutions of the MACE for each of the energy bins were estimated at low zenith angle range as well as zenith angle of 40°. The angular resolution of the MACE was found to improve from 0.21° in the energy range of 30 GeV to 47 GeV to 0.07° in the energy range of 1.8 TeV to 3.0 TeV at the low zenith angle range. At the zenith angle of 40° the angular resolution of the MACE varies between 0.19° in the energy range of 47 GeV to 75 GeV to 0.06° in the energy range of 1.8 TeV to 3.0 TeV.

3.4 Energy resolution

The energy of each γ ray event was reconstructed using the random forest regression algorithm [10] where image parameters Size, Distance, Length and Width were used as the inputs. The variation of the energy resolution against the γ ray energy was estimated for the low zenith angle

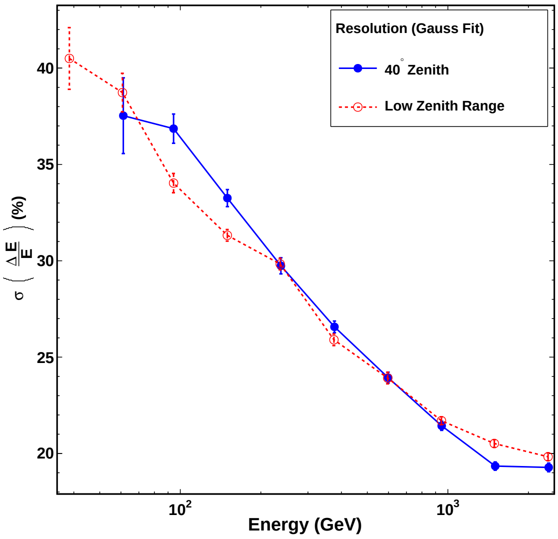

Figure 4: Energy resolution of the MACE telescope as function of energy

range and zenith angle of 40°. The energy resolution of the MACE at the low zenith angle range was found to be 40% in the energy range of 30 GeV to 47 GeV. It improved to the value of 19% at higher energy range of 1.8 TeV to 3.0 TeV. At the zenith angle of 40° the energy resolution of the MACE improved from 38% in the energy range of 47 GeV to 75 GeV to 20% in the higher energy bin of 1.8 TeV to 3.0 TeV. Estimation procedures of the MACE integral flux sensitivity, angular resolution and energy resolution is reported in [11].

It is clear that over the wide zenith angle range of 0° to 40°, the energy threshold of the MACE will vary between the narrow energy range of 30 to 50 GeV. This will possibly allow spectral measurements for variety of VHE γ ray sources up to low energy of 30 GeV for the first time. The space based Fermi/LAT observes the γ ray sky in the energy range of $\sim$ 20 MeV to 300 GeV. However it has very weak sensitivity at γ ray energies of more than 10 GeV [12] due to the small detection area of $\sim 1\ m^2$. With the integral flux sensitivity of 1.5 to 2.5% of Crab over the wide zenith angle range of 0° to 40°, the MACE will be able to collect good quality temporal data for many VHE γ ray sources in the energy range of 10 GeV to 100 GeV. It will thus offer unique insights into the high energy astrophysical phenomena.

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