Monte Carlo Study on the Large Imaging Air Cherenkov Telescopes for > 10 GeV gamma ray astronomy

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Abstract. The Imaging Air Cherenkov Telescopes (IACTs), like, HESS, MAGIC and VERITAS well demonstrated their performances by showing many exciting results at very high energy gamma ray domain, mainly between 100 GeV and 10 TeV. It is important to investigate how much we can improve the sensitivity in this energy range, but it is also important to expand the energy coverage and sensitivity towards new domains, the lower and higher energies, by extending this IACT techniques. For this purpose, we have carried out the optimization of the array of large IACTs assuming with new technologies, advanced photodetectors, and Ultra Fast readout system by Monte Carlo simulation, especially to obtain the best sensitivity in the energy range between 10 GeV and 100 GeV. We will report the performance of the array of Large IACTs with advanced technologies and its limitation.

Keywords: VHE γ− ray, Cerenkov telescope, simulations

I. INTRODUCTION

Recently, ground-based very high-energy (VHE) γ-ray astronomy achieved a remarkable advancement in the development of the observational technique for the registration and study of γ-ray emission above 100 GeV. The southern hemisphere HESS array of four 12 m IACTs, located in Namibia, and the northern hemisphere VERITAS array of four similary designed telescopes, located in Arizona, have proven many outstanding advantages of stereoscopic observations of VHE γ rays with the ground-based detectors. The MAGIC telescope, consisting of a single 17 m telescope, equipped with a fast response, high-resolution imaging camera, and located at La Palma in the Canary Islands, has demonstrated its performance, comparable to that of HESS and VERITAS, in observations of γ rays with energies above 100 GeV in addition to the unique capability of detecting γ-ray showers ranging in energy well below 100 GeV, though at a limited sensitivity level. Currently, the MAGIC collaboration is commissioning a second 17 m telescope on the same site in order to enable stereoscopic observations, which will drastically boost the sensitivity of future detections of γ-ray fluxes in the sub-100 GeV energy domain. Based on Monte Carlo simulations, we have studied the response of an array of few large telescopes of larger aperture, e.g., 20-25 m class in conjunction with an array of modest medium sized telescopes of 12 m class. We investigate the key parameters, i.e. sensitivity, angular resolution, energy resolution of such a system, primarily in the sub-100 GeV range and also try to improve the sensitivity at energies above 100 GeV.

II. SIMULATIONS

The Monte Carlo simulation of the array is divided into three stages. The CORSIKA [1] program simulates the air showers initiated by either high energy gammas or hadrons. We have used the CORSIKA version 6.500 for our simulations, the EGS4 code for electromagnetic shower generation and QISJET-II and FLUKA for high and low energy hadronic interactions respectively. We have also used new atmospheric models for MAGIC on the basis of studies of total mass density as a function of the height. The second stage of the simulation, Reflector program, accounts for the Cherenkov light absorption and scattering in the atmosphere and then performs the reflection of the surviving photons on the mirror dish to obtain their location and arrival time on the camera plane. Finally, the Camera program simulates the behaviour of the MAGIC photomultipliers, trigger system and data acquisition electronics. Realistic pulse shapes, noise level and gain fluctuations obtained from the MAGIC real data have been implemented in the simulation software.

For the present study a total of $2.1 \times 10^9$ gammas between 20 GeV and 50 TeV have been produced, as well as $4.5 \times 10^7$ protons between 10 GeV and 50 TeV. The energy distribution of both primary gamma rays and protons is a pure power law with a spectral index of -2.0. The telescope pointing direction is uniform between 0 and 30° in zenith, with the directions of protons scattered isotropically within a 6° semi-aperture cone around the telescope axis. Maximum impact parameters of 1 km and 1.5 km have been simulated for gammas and hadrons respectively. Each shower was reused 10 and 20 times for gammas and protons respectively using the shower reuse option in CORSIKA. The contribution of electrons was neglected. To this has been added the contribution of Helium and heavier nuclei which is estimated to be ~ 50% of the proton rate.

The array configuration studied here is shown in Figure 1. In addition to the two 17 m MAGIC telescopes (from now on MAGIC-2) which are separated by a distance of 85 m, we have considered different cases by placing a 23 m telescope at a distance of 85 m from the
MAGIC telescopes by making a triangle configuration. In addition we have two 23 m telescopes Large Size Telescopes (from now on LST) separated by a distance of 100 m which makes a trapezoidal configuration with the MAGIC telescope system. We have also placed 6 telescopes of medium size structure (∼12 m class) in a circular pattern at a distance of 200 m from the centre of the array. The performance of the large telescope array system along with these small telescopes have been studied for 2 more distance configurations, viz., by placing the small telescopes at a distance of 250 m and 300 m respectively (from now on MSTRing1, MSTRing2 and MSTRing3 for distances 200, 250 and 300 m respectively). One telescope in the first ring had to be removed because of a problem in the assignment of the coordinate system for that particular telescope. The f/D of the MAGIC-2, LST and 12 m class telescopes are 3.5, 5 and 5 degrees respectively and the camera is equipped with 1039, 2245 and 859 pixels with super bialkali high quantum efficiency photomultipliers which has a peak quantum efficiency of ∼32%. The pixel sizes for the large telescopes are 0.1 deg. and that for the 12 m class are 0.2 deg.

Fig. 1. Simulated Array Configuration

III. Analysis of Stereo Events

The stereoscopic observation mode allows a precise reconstruction of the shower parameters as well as a stronger suppression of the hadronic showers and other background events. The analysis of stereoscopic events is performed by individually analyzing the images from each telescope. A set of parameters (Hillas parameters [2]) is obtained from each image and they are combined to obtain the shower parameters. Only showers triggering the large telescopes are considered under the stereo analysis. The trigger threshold is estimated to be ∼25 GeV when 2 LSTs participate in the trigger. The images from each telescope are combined following the algorithm in [3]. The intersection point of the major axes of the ellipses recorded in the telescope cameras, provides the location of the source of a particular shower. The location of the shower core on ground is obtained by intersecting the image axes from the telescope positions on the ground. In addition, the height of the shower maximum \( (H_{\text{max}}) \) can also be obtained.

The data analysis was carried out using the standard MAGIC analysis and reconstruction software MARS [4]. Before image parametrization, a tail-cut cleaning of the image was performed, requiring signals higher than a pre-defined absolute amplitude level and time coincidences with neighbouring channels. The time coincidence effectively suppresses pixels containing only noise from the night sky. The procedure used in this work can be summarized as:

- After selecting the core pixels, we reject those whose arrival time is not within a time \( \Delta t_1 \) of the mean arrival time of all core pixels.
- In the selection of the boundary pixels we add the constraint that the time difference between the boundary pixel candidate and its neighbor core pixels is smaller than a second fixed time constraint \( \Delta t_2 \).

For most of the analysis the minimum required pixel content is 6 phe for so-called core pixels and 3 phe for boundary pixels for the MAGIC type telescopes and 12 m class telescopes. For the 23 m telescopes, the pixel content was raised to 9 phe and 5 phe for core and boundary pixels respectively. The choice of these values is supported by a study based on Monte Carlo data for the single dish MAGIC telescope (see [5] and [6] for more details). Width and Length, the most important parameters for gamma/hadron separation, depend on the distance from the shower core to the telescope. Hence a correct estimation of the impact parameter is required to properly evaluate these parameters. With a single telescope, the observer cannot easily resolve the ambiguity between a close by, low energy shower and a distant, high energy one. With two or more telescopes, in most cases the ambiguity disappears because of the stereoscopic vision of the showers.

In order to combine the parameters from both images, we compute the Mean Scaled Width (MSW) and Length (MSL) parameters. These new parameters are obtained by subtracting the mean and dividing by the RMS of the parameter distribution for Monte Carlo gammas. While combining the images from different telescopes, a cut of 40 phe was applied to the images to throw away the very small images which may be contaminated by a lot of noise and hence are very difficult to reconstruct.

To reject the hadronic background a multi-tree classifier algorithm based on the "Random Forest (RF)" method [7], [8], [9] was used for the γ/hadron separation. The selection conditions were trained with Monte Carlo simulated γ-ray samples [10] and a sample of experimental background events. In the RF method for each event the so-called HADRONNESS parameter \( (H) \) was calculated from a combination of all the image parameters. \( H \) assigns to each event a number between 0 and 1 of being more hadron-like (high \( H \)) or γ-ray like (low \( H \) values). The selection of events with low \( H \) value enriches γ-ray events in the surviving
data sample. For this study, the parameters that have been used in Random Forest are: average amplitude (Size), core distance, $H_{\text{max}}$, MSW and MSL. These set of parameters, however, should not be considered as optimal and some improvement could be expected with an optimized parameter selection. In the final analysis, gamma/hadron separation is based on the Hadronness and $\theta^2$ parameter $^1$ is used to extract the signal events.

IV. SIMULATION RESULTS

The sensitivity is defined as “integral flux resulting in gamma excess events, in 50 hours of observation, equals to 5 times the standard deviation of the background”. While estimating the sensitivity, a conservative number up to 2% systematic error has been taken into account for each flux point. All the sensitivity numbers are quoted in terms of percentages of Crab (standard candle in Very High Energy $\gamma$-ray astronomy). While computing the sensitivities, we have restricted our analysis up to 500 GeV as beyond that it is difficult to compute a meaningful sensitivity due to lack of background events after application of cuts. The stereoscopic technique allows for a better sensitivity below 100 GeV and also a reduction of the analysis threshold is achieved over a single telescope [12]. One of the biggest advantages of stereoscopy is that the direction of gamma rays is better reconstructed. For a single telescope, the angular resolution is estimated using a modified parametrisation of the so called DISP method [11]. However, this method suffers from a drawback as a result of which a certain fraction of gamma events are misreconstructed. With two or more telescopes, this drawback is easily overcome since the source direction is obtained as the intersection of major axes of the images in the camera. The distribution of arrival directions for simulated $\gamma$-ray showers can be fitted to a two-dimension Gaussian function. The $\sigma$-parameter of the Gaussian fit stands for the angular resolution of the directional reconstruction. The angular resolution as a function of gamma ray energy is shown in Figure 2. While estimating the angular resolution a minimum of 2 telescopes is required, the angular resolution improving substantially when the minimum number of required telescopes is increased. From the Figure 2 it is seen that the angular resolution at and below 100 GeV improves significantly if the configuration MAGIC-2+LST+MSTRing1 over the other configurations and also for MAGIC-2 system alone [12].

The stereoscopic analysis also results in a better energy reconstruction over a single telescope due to better estimate of the shower axis and also a multiple sampling of the light pool. The energy is reconstructed for each telescope with lookup tables based on image size (i.e., number of photoelectrons in the image $^1$), impact parameter, height of the shower maximum and zenith angle. These lookup tables are built from Monte Carlo simulations of $\gamma$-ray showers. The energy resolution for gammas as a function of primary energy is shown in Figure 3 for two different cases:

- $2 \times 23\text{ m LST}$
- $2 \times 23\text{ m LST} + \text{MAGIC-2}$

An energy resolution of $\sim 15\%$ is achieved above 500 GeV. It must be noted that both the angular resolution and the energy resolution improves significantly if the minimum number of telescopes in the analysis is raised, however, in such a case, the energy threshold of the primary also increases depending on the number of telescopes used.

Figure 4 shows the sensitivity of the array for the following configurations:

- $2 \times 23\text{ m LST}$
- $2 \times 23\text{ m LST} + \text{MAGIC-2}$
- $2 \times 23\text{ m LST} + \text{MAGIC-2} + \text{Ring1}$

It must be noted that a very standard analysis of stereoscopic data has been performed here and a better optimisation of the analysis over different energy ranges is expected to improve the sensitivity of different configurations. It is seen that the sensitivity for all three configurations improve over a system of 2 MAGIC telescopes [12] at 100 GeV and above. Specially

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$^1$ $\theta^2$ is defined as the square of the angular distance from the real source image in the camera and the reconstructed one for each event.
above 100 GeV, the LST+MAGIC-2+Ring1 configuration achieves the best sensitivity (~a few milliCrab) for the cases studied here. Below 100 GeV, the improvement in sensitivity over a system of two MAGIC telescopes is very modest as compared to a system of MAGIC-2 telescopes only [12] reaching to about 3-4% of Crab at around 80 GeV. We have also investigated the effect of the rings, however both the telescope configurations with MSTRing1 and MSTRing3 yielded comparable sensitivities (see Figure 5).

Figure 6 compares the sensitivities of the configuration of MAGIC-2 + 1 × 23 m LST telescopes with 2 different rings added to the 3 telescope configuration. It is seen that at higher energies (> 100 GeV), the sensitivity improves with the addition of the ring, whereas there is marginal or no improvement at energies below 100 GeV. In addition, comparing the sensitivity curves for Figure 4 and Figure 6, one can see that the curves follow a very similar pattern apart from the fact that one is able to reach a lower threshold in the first case by the addition of a large 23 m telescope. Thus, more the number of bigger telescopes, lower the energy threshold one can reach. We have also studied the sensitivities for the array configuration of 3 × 23 mt LST with and without outer rings added to it. However, this configuration does not yield good sensitivity due to the very nature of the configuration where the third telescope is placed very close to the other two 23 mt LST. (see Figure refarray)

V. CONCLUSIONS

We have performed extensive Monte Carlo simulations to study the response and performance of an array of Large Imaging Air Cerenkov Telescopes. This IACT can serve as a prototype for future low energy ground based γ-ray experiment at > 10 GeV. The angular resolution of such a system has been shown to be significantly better than MAGIC-2 system of telescopes at around 100 GeV. The sensitivity of the system has been shown to be better than MAGIC-2 reaching below 1% of Crab around 100 GeV and improves significantly at moderately high energies (~ few milliCrab below 800 GeV). So, future arrays of large telescopes along with few medium sized ones can be efficient enough for effective detection of γ-rays of a few tens of GeV and can be very competitive instruments. However, below 100 GeV, the improvement in sensitivity is found to be modest. A sophisticated analysis to improve the sensitivity below 100 GeV is required and is currently under investigation.

REFERENCES

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