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Future imaging atmospheric telescopes: performance of possible array configurations for gamma photons in the GeV-TeV range

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Abstract: The future of ground based gamma ray astronomy lies in large arrays of Imaging Atmospheric Cherenkov Telescopes (IACT) with better capabilities: lower energy threshold, higher sensitivity, better resolution and background rejection. Currently, designs for the next generation of IACT arrays are being explored by various groups. We have studied possible configurations with a large number of telescopes of various sizes. Here, we present the precision of source, shower core and energy reconstruction for gamma rays in the GeV-TeV range for different altitudes of observation. These results were obtained through tools that we have developped in order to simulate any type of IACT configuration and evaluate its performance.

Introduction

Gamma-ray astronomy has come a long way since its inception in the middle of the last century. With the development of ground based Imaging Atmospheric Telescopes (IACT), observations were extended to the GeV - TeV domain. Currently the designs for the fourth generation of telescopes are being explored. These future systems will be expected to discover new sources, enable more precise observations of known sources as well as contribute towards answering questions in adjacent fields like cosmology and particle physics. This will require large arrays of telescopes with lower energy threshold, higher sensitivity, better resolution and background rejection.

Simulation tools for the study of telescope designs

IACT systems have a large number of parameters such as the number of telescopes, their position, size and field of view and the altitude of observation that can be optimised to improve detection capabilites. In order to study IACT systems, we have developed a tool capable of simulating any type of telescope configuration and evaluating its performance. We use atmospheric showers simulated through the CORSIKA package [1]. The reflection of the Cherenkov photons from the shower by a parabolic mirror and their impact on the telescope camera are then carried out by our IACT simulation tool. The program allows complete freedom in the choice of telescope diameter, focal length, camera size, photomultiplicator size, telescope position and orientation and altitude of observation. Up to 100 telescopes of variable individual characteristics can be simulated at the same time so as to enable the study of very large arrays.

Shower parameter reconstruction methods

Once shower images are obtained through the tools described above, they can be used to reconstruct the source position, the shower's core position on the ground (herafter simply called shower core or core) and its energy.

Source reconstruction

Both the source and core reconstruction methods make use of the simultaneous information availbale from several telescopes in IACT array observations of the same shower. Each telescope gives a shower image whose elongation and orientation depend mainly on the position of the telescope with respect to the shower core. The main axis of symetry corresponds to the image of the shower axis. When this axis is extended beyond the image in the camera frame of reference, it contains the position of the source. In multi-telescope observations, if the images from all telescopes are superposed in the camera frame of reference (see figure 1), then this source position corresponds to the intersection of the axes of all images.

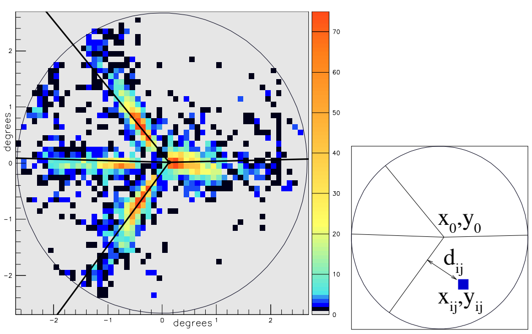

Figure 1: The superposed images of a 500 GeV shower obtained by four telescopes. The reconstructed axis of each image is shown in black.

The soure position is then reconstructed by maximising the likelihood function:

$$\ln(L_{all}) = -\sum_{j=1}^{N_{tel}} \sum_{i=1}^{N_{pix}} \frac{N_{ij} t_{ij}^2}{2\sigma_t^2}, \qquad (1)$$

with $d_{ij} = \frac{|(y_{cj}-y_o)(x_{ij}-x_o)-(y_{ij}-y_o)(x_{cj}-x_o)|}{\sqrt{(x_c-x_o)^2+(y_c-y_o)^2}}$. Here N_{tot} is the sum of all photo-electrons in all images, N_{ij} is the content of i^{th} pixel from the j^{th} telescope and d_{ij} is its distance from the image axis. $(x_{ij}$ and $y_{ij})$ and (x_{cj}, y_{cj}) are the coordinates of the pixel and the centroid of the image, respectively. The following assumptions are used. (1) Each image axis is a straight line passing through a point (x_o, y_o) common to all axes which gives the position of the source image in the camera frame of reference and whose coordinates are free parameters. (2) The distance of the pixels in an image from the corresponding axis (in other words the transvere image profile) is assumed

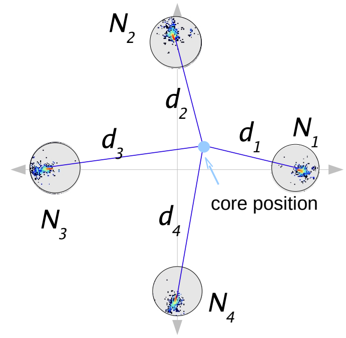

Figure 2: The reconstruction of the core position from the images of a 500 GeV shower observed by four telescopes. The image is not to scale so as to emphasize the configuration of the system.

to follow a Gaussian probability density function[1]. σ_t is the average standard deviation obtained from the Gaussian fit of transverse image profiles [2]. (3) Each axis is made to pass through the centroid of the corresponding image. The likelihood function is then maximised for x_o, y_o through and yields the position of the source and reconstructed image axes as shown in figure 1.

Shower core reconstruction

In the frame of reference of the ground the axis of the individual images points towards the shower core position. The point of intersection of the axes from all shower images corresponds to the core position[3] as is presented in figure 2. The core po-

1. It can be shown through simulations that although the transverse profile is best represented through the sum of three Gaussian functions, the single Gaussian probability density function accounts for about 88% of the total signal contained in the transverse profile

2. We carried out an extensive study of the Gaussian fits of the transverse profiles. It showed that the value of σ_t is nearly independent of the shower energy for for fixed distances within the Cherenkov pool. Moreover, the use of a different value of σ_t only changes the normalisation of equation 1 and does not affect the reconstruction of the source.

3. This is true when the source position is at the zenith, for other source positions, the point of intersection of the shower images needs to translated by an amount equivalent to the offset of the source image position on the camera.

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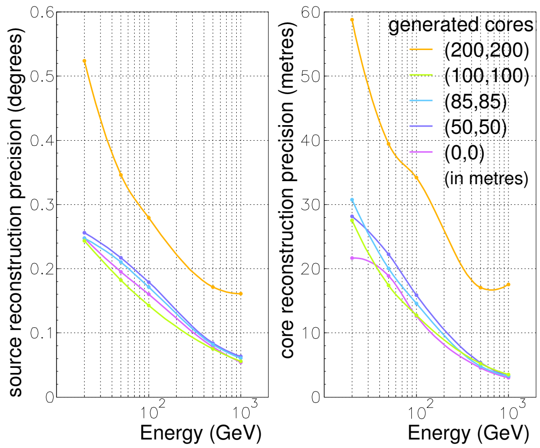

Figure 3: The precision on the source (left) and core reconstruction (right) for showers with different core positions along the diagonal of the telescope system whose center is at (0,0).

sition can then be reconstructed through a likelihood minimisation similar to the one performed for source reconstruction. Equation 1 is rewritten with the position of each pixel expressed and σ_t expressed in the ground frame of reference. It is required that each axis passes through the reconstructed source image on the corresponding camera (In this case x_{cj}, y_{cj}, represent the coordinates of the source image position on each telescope camera, expressed in the ground frame of reference coordinates.). The minimisation of this likelihood function yields the shower's core position on the ground as shown in figure 2.

Energy reconstruction

The energy reconstruction makes use of the linear relationship between the average number of photoelectrons obtained on a given telescope at a given distance from the shower core. We have made tables of values with the average number of photoelectrons in images at a wide range of fixed distances and shower energies. When a shower is observed, the number of photo-electrons N_i in the image from the i^{th} telescope is known. After core reconstruction, one also knows the distance d_i between that telescope and the core position. These values can be used to reconstruct the energy E_i by interpolating the values in the number of photoelectrons table. The final energy of the shower is calculated by averaging the reconstructed E_i from all telescopes.

Results with a four telescope system In figure 3, we present the precision of source (left) and core position (right) reconstruction for a four telescope system [4]. At higher energies, the shower images are better defined as they have more photoelectrons allowing better reconstruction of the shower parameters. The precision deteriorates when telescopes are well outside the Cherenov light pool (see orange curve for shower cores at (200, 200) metres from the centre of the telescope system.). When telescopes are close to or within the Cherenkov pool, the level of precision has very little dependence on the position of the cores.

Discussion on various parameters of telescope systems

Energy range of observation We will restrict our studies to the 50 GeV-10 TeV domain, where large IACT arrays are expected to perform well. Above this range, the fluxes of gamma-rays from sources diminish significantly so that the main requirement of telescope systems is to have very large effective areas. Below this range, the intrinsic fluctuations in the showers become important and the shower images often don't have enough photo-electrons to allow the accurate reconstruction of the shower parameters. For a detailed discussion on various energy regimes in gamma-ray astronomy see [2].

Telescope size and number Among other factors, the mirror size determines the amount of light contributing to a shower image. The 50 GeV-10 TeV energy range can be divided into two subranges i.e. 50-300 GeV and 300 GeV-10 TeV. IACT systems have already shown that they perform well in the latter range, where a good precision on shower parameter reconstruction is ob-

4. The system is situated at an altitude of 1800 m and consists of 4 telescopes of 12.5 metres diameter each and a field of view of about 4.5° situated at the corners of a 120 m square.

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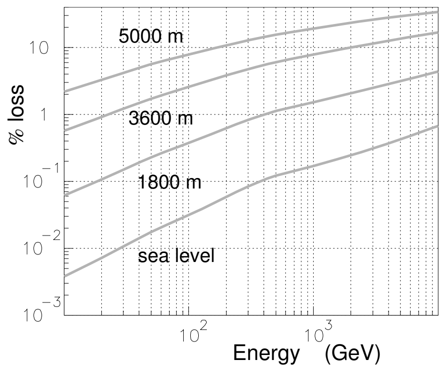

Figure 4: The average percentage of electromagnetic showers cut off at various altitudes as a function of the energy.

tained, even with smaller telescope sizes. In order to improve the observations in this range, the effective surface of the arrays needs to be increased so as to achieve greater sensitivity. For lower energies, larger mirror sizes are required in order to get images that can be exploited for parameter reconstruction. We will therefore consider two different telescope sizes : 30 m and 12.5 m for the two different energy regimes.

Altitude of observation At high altitudes the Cherenkov pool is smaller and denser, allowing shower images with larger number of photoelectrons for fixed telescope size. At the same time, the high energy showers have not completed their development at these altitudes leading to a potential loss of information. In figure 4, we show the percentage of showers cut-off by different ground levels as a function of energy. While most showers in the energy range develop fully above the sea level and show the loss of a few percent at the most at 1800 metres, the losses are greater at 5000 metres. For 10 TeV showers around 40% of the shower is cut off at the ground level. Due to this factor and cost considerations we have restricted our study to 1800 metres and 3600 metres.

Work on optimum telescope separation and array configuration As a first step we present the effective area obtained for a four telescope system as a function of telescope seperation for two energies in each energy sub-range in figure 5. The simple trigger used requires that at least two telescopes, have images with a minimum of 50 photoelectrons. The use of different telescope size for each energy range allows results in similar effective areas for a given seperation. The smaller size of the Cherenkov pool at 3600 m gives smaller effective area as compared to 1800 m. While the effective area remains emains important even for very large seperations such as 400 m, this information needs to be complemented with the evolution of the precision on reconstructed parameters which tends to fall beyond a couple of hundred meters (as we saw in the example in figure 3). We will show results on the dependence of precision obtained from simulations. We will also use the optimised telescope seperation in possible array configurations with a large number of telescopes and present the precision on reconstructed shower parameters for them.

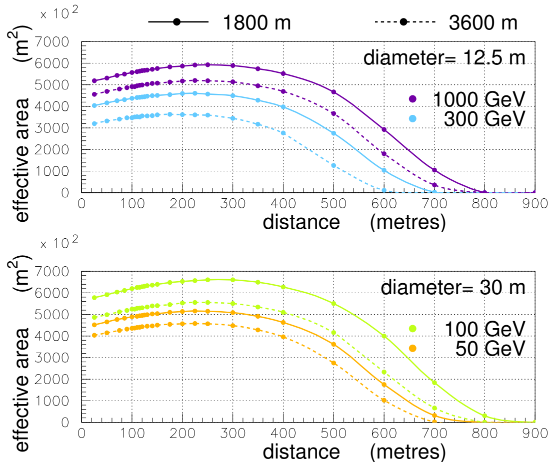

Figure 5: The effective surface of a four telescope system at 1800 m altitude (solid line) and 3600 m (dashed line) as a function of telescope seperation for 12.5 m diameter telescopes (top) and 30 m diameter telescopes (bottom).

References

[1] D. Heck et al., Report FZKA 6019, 1998; available from `http://www-ik.fzk.de/`

[2] F. Aharonian, astro-ph/0511139v1, 2005

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