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Optimization of Atmospheric Cherenkov Telescopes Arrays

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Abstract: Recent discoveries in gamma-ray astronomy at a few $100\,\mathrm{GeV}$ provide many motivations for a next generation of observatories with improved sensitivity and with an energy coverage extended toward higher energies, up to several $100\,\mathrm{TeV}$. After reviewing these motivations we will present a few considerations on the design of arrays of Atmospheric Cherenkov telescopes to achieve a specified energy coverage and effective collection area.

Introduction

Ground based gamma-ray astronomy at more than $100\,\mathrm{GeV}$ has entered a phase of explosive development with, in particular, the results of the galactic plane survey by HESS in the southern sky [1]. Very High Energy gamma rays were originally considered as tracers of high energy hadron cosmic-ray interactions, especially near their acceleration sites which are still to be identified. As the high energy gamma-ray source catalog started to grow, the role played by inverse Compton interactions of high energy electrons became preponderant. As of today, we still do not have one source in which the very high energy gamma-ray emission can be unambiguously attributed to hadron interactions.

In particular, this is the case with supernova remnants (SNRs) which are still considered among the most likely cosmic-ray accelerators. The hadron picture suffers from the gamma-ray emission morphology not matching the interaction target material densities. On the other hand, the inverse Compton picture suffers from not accurately predicting the observed spectra (RXJ1713 [2]) or from implying magnetic fields of magnitude too weak to account for tight confinement of the emission region (Vela Junior[3]). The soon to come observations of the π_0 bump in SNRs with GLAST is expected to clarify whether the TeV gamma rays are of hadron origin. However, even if the gamma-ray emission from RXJ1713 for example is confirmed to result from freshly accelerated hadron cosmic rays, the $12\,\mathrm{TeV}$ cut-off in the gamma-ray spectrum [2] indicates cosmic rays there are not accelerated to much more than $\sim 100\,\mathrm{TeV}$, a factor of ~ 20 short of the knee energy.

In order to identify cosmic-ray accelerators operating up to the knee energies, the domain covered by gamma-ray astronomy has to be extended up to several hundred TeV. At such high energies, the inverse Compton contribution should be strongly suppressed as the scattering occurs in the relativistic regime making hadron processes easier to identify. At $100\,\mathrm{TeV}$ and above, absorption by the interstellar radiation field becomes a concern but was shown to remain bearable with 25% attenuation at $100\,\mathrm{TeV}$ for sources at the galactic center [4]. The fluxes also decrease very fast with the energy. The extrapolation of the energy spectra of the sources detected up to several tens of TeV by the current generation of atmospheric Cherenkov telescopes, suggests exposures of more than $100\,\mathrm{km}^2 \cdot \mathrm{h}$ are necessary [5]. Moreover, the increasing number of gamma-ray sources implies the observation time allocated to each one will decrease with future projects, further reinforcing the importance of a large effective collection area. Future telescope arrays sensitive to the highest energies should be designed with thresholds providing a good overlap with lower energy observatories. The large area required at the highest energies would then also result in a tremendous sensitivity gain at lower energies compared to the present generation of observatories.

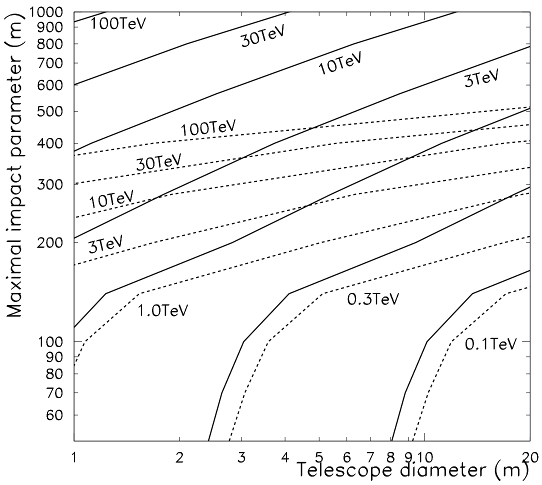

Figure 1: Iso-threshold curves for observations close to zenith in the inter-telescope distance versus telescope size plane. Solid lines are for the case in which there is no field truncation and dashed lines correspond to a $4°$ field of view.

Effective collection area, threshold and maximal energy

Imaging Air Cherenkov technique with an array of telescopes provides the highest angular resolution and instantaneous sensitivity. The technique relies on the fact that multiple views of a single shower from several positions on the ground can be used to accurately reconstruct the direction and energy of the primary photon. This requires the shower axis to be at a distance from the telescopes that is not too large compared to the inter-telescope distance. Hence the effective collection of an Imaging Air Cherenkov Telescope (IACT) array is closely related to the area covered by the array.

The density pattern of the Cherenkov light projected on the ground consists of a relatively uniform plateau extending to a radius of $\sim 130\,\mathrm{m}$ from the shower axis and beyond which the Cherenkov light density decreases rapidly with the distance to the shower axis. This tail in the Cherenkov light density distribution can however in principle still be used to detect showers with large impact parameters. The threshold of the array is closely related to the light collecting area of each telescope and inter-telescope distance. The threshold decreases with increasing telescope diameter d and with decreasing inter-telescope distances D . This is illustrated by the solid lines on Figure 1 in the case of a simplified telescope model in which the triggering condition is based on the total quantity of light received. For inter-telescope distances $D > 130\,\mathrm{m}$, iso-threshold lines are such that D/d^α is constant with $\alpha \approx 0.5$ (straight lines on Figure 1). A more realistic telescope model, taking into account pixilation, increasing image length and time spread with increasing impact parameter would result in similar curves but with $\alpha < 0.5$.

As the impact parameter increases, the angular distance between the source and the shower image increases almost linearly. For a given inter-telescope distance, the field of view of each camera must be chosen in such a way that a large enough fraction of the images remains within the field of view so it can effectively be used for the reconstruction, and this even at the largest energies considered. The dashed lines on Figure 1 are iso-threshold curves in the case of a $4°$ field of view, comparable to the present generation of telescope arrays. This threshold increase can be avoided by choosing the field of view ψ proportional to the inter-telescope distance D. The proportionality constant is then set by the maximal energy to be covered by the experiment. At this point we do not include necessary provisions for sources that are extended or of poorly known position.

Array design

The primary capabilities of a telescope array are the energy range it covers and the effective collection area A which sets the sensitivity. Another important parameter is the effective gamma-ray field of view which we will consider later. The primary parameters defining a telescope array are the diameter of each unit, the distance between the units and the camera's field of view. Here, we restrict ourselves to arrays made of a single type of telescopes. There is not a one to one relation between the capabilities and the physical parameters of the array. An external constraint must be used for a choice to be made and that constraint is unfortunately almost always of financial nature. The price of a large telescope array is dominated by the cost of the telescopes. The cost of the infrastructure can be considered to be relatively independent from the design of the array. The number of units scales as $\frac{A}{D^2}$. The price of individual telescopes is usually subdivided in two parts: the telescope itself and the focal plane instrumentation. The telescope price typically scales like the third power of its diameter. For a given electronics design, the price of the camera scales like the solid angle it covers or ψ^2. Hence, the array price P scales as $P \propto \frac{A}{D^2}(c_1 \cdot d^3 + c_2 \cdot \psi^2)$. Using the scalings identified in the previous section ($\psi \propto D$ for a given maximal energy and $d \propto D^{1/\alpha}$ for a given threshold and inter-telescope distances greater than $\sim 130\,\mathrm{m}$) we can also write the price $P \propto A(c'_1 \cdot D^{3/\alpha-2} + c'_2)$. Each unit is generally designed so the price of the telescope and of the focal plane instrumentation are comparable. So it appears the inter-telescope distance should be chosen possibly greater than, but close to, the $130\,\mathrm{m}$ radius of the Cherenkov light pool central plateau for zenith observations. The radius of the Cherenkov light pool plateau increases with the angular distance from zenith. Taking into account observation are made most frequently around $30°$ from zenith suggests $150\,\mathrm{m}$ must be close to ideal for the inter-telescope distance. Choosing a larger inter-telescope distance would result in an increased threshold which could have been achieved over the same area with a greater number of smaller telescopes for a lesser cost.

Field of view

In what precedes we have assumed a point source at the center of the field of view. Increasing the field of view has two benefits. First, a large effective gamma-ray field of view allows for extended and poorly localized objects to be studied and provides better background estimates. Really large field of views also imply less time is necessary to survey a large portion of the sky. Even at the threshold energy, a larger field of view improves the sensitivity by increasing the time spent on each source. This requires the all telescopes to be equipped with larger field of view cameras.

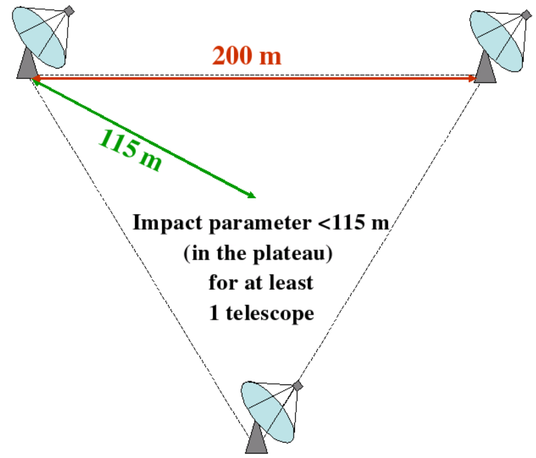

Figure 2: We have simulated the details of an array of $200\,\mathrm{m}$ spaced $5.4\,\mathrm{m}$ telescopes with $4°$ field of views.

Second, a large camera field of view allows showers falling further away outside the array to be detected. The difference between the solid and dashed lines in Figure 1 illustrate this clearly. The effective area then increases with the energy, from the array geometrical area at the energy threshold up to a maximal area at the energy for which field truncation effects become too important. It is therefore possible to obtain a larger collection area at the largest energies by placing a few larger field of view telescopes on the outer edge of the array. The field of views of all the telescopes could be chosen so large that the cost of the focal plane instrumentation dominates the telescope price. In this case, the logic that led us to identify $150\,\mathrm{m}$ as an optimal inter-telescope distance breaks down. It might then be interesting to place the telescopes further apart.

Design example

As an example, we have simulated one triangular cell of an array of $5.4\,\mathrm{m}$ telescopes. Slightly departing from the conclusion reached in the previous sections, we have chosen a $200\,\mathrm{m}$ inter-telescope distance. We motivated this choice by considering the fact that during zenith observation, a shower will always have at least one telescope within the Cherenkov light pool plateau (see Figure 2). The

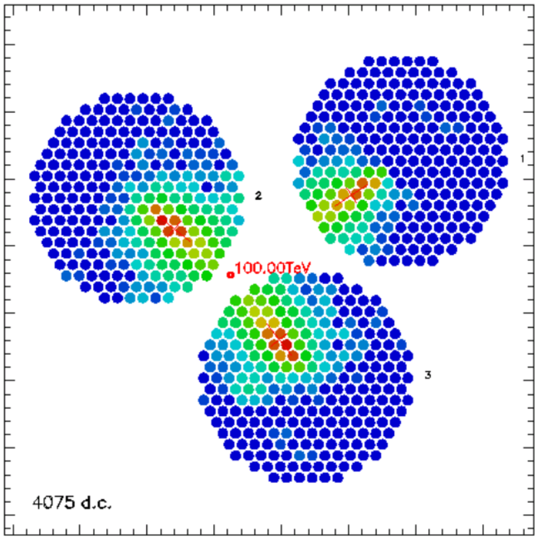

Figure 3: A $100\,\mathrm{TeV}$ event inside the array produces images that are well contained within the 4° field of views in the telescopes of the cell the shower axis goes through.

field of view was chosen to be 4° and we verified that showers initiated from sources at the center of the field of view produce images that are well contained even for energies of $100\,\mathrm{TeV}$ provided the shower axis passes through the triangular cell (see Figure 3). The electronics and photodetectors were modeled in the same way as for our Whipple $10\,\mathrm{m}$ telescope simulations. With 0.25° spaced pixels we observed the triangular cell trigger threshold to be $330\,\mathrm{GeV}$ ($240\,\mathrm{GeV}$) for a 3/3 (2/3) telescope cell trigger condition at 60° elevation. Here we define the threshold as the energy above which the trigger probability is larger than 50% for a shower axis passing through the triangular cell. We compared the angular resolution obtained from standard reconstruction techniques with different pixel sizes. We observed that degrading the pixel size from 0.25° to 0.5° dramatically degrades the angular resolution while, choosing a pixel size of 0.125° does not significantly improve the angular resolution. The angular resolution at the threshold energy is of the order of 0.1° comparable to what is achieved with current telescope arrays. The angular resolution from a single triangular cell is close to 1 arc-minute at $100\,\mathrm{TeV}$.

An array of 37 such telescopes (54 cells) would result in an effective collection area $> 1\,\mathrm{km}^2$ at $330\,\mathrm{GeV}$ and $\sim 2\,\mathrm{km}^2$ at $100\,\mathrm{TeV}$. Because of the relatively small size of the telescopes and low pixilation, it could be constructed for less than $\$20\mathrm{M}$[6].

Conclusion

We have found that once an area and an energy range is chosen, the most economical approach for designing the array consists in choosing a $\sim 150\,\mathrm{m}$ inter-telescope distance. The curves in figure 1 are inaccurate as an imaging telescope would generally not have a threshold based on the total quantity of light. More detailed simulations are needed but these curves can serve as guidelines and the conclusion remains unchanged: a greater number of smaller telescopes is more economical to achieve a given collection area and energy threshold. Increasing the number of units increase the importance of the low failure rate of the telescopes. Taking advantage of this, it appears that if the requirement for a $100\,\mathrm{GeV}$ threshold were relaxed to a few hundred GeV, arrays with appropriate sensitivity up to a few $100\,\mathrm{TeV}$ could be constructed on budgets comparable to the gamma-ray observatories in operation.

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