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Investigating Gamma/Hadron Discrimination Features to Augment Gamma-Ray Observatory Physics Capabilities

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Abstract. The C_k variable has already established as a viable gamma/hadron discriminator for showers detected in wide-field gamma-ray observatories. In this article, possible new conditions for its use are analyzed and tested, namely layout conditions being considered for the future Southern Wide-field Gamma-Ray Observatory SWGO.

KEYWORDS: Very-high-energy gamma-rays, Extensive Air Showers, Gamma/Hadron discrimination, Array layout configuration

1 Introduction

1.1 High-energy Gamma-ray Detection Techniques

Astrophysical γ-rays have a flux that rapidly decreases with the increase of the γ-ray's energy. This implies the higher the energy of a γ-ray the more area or time of observatory activity is necessary to detect it.

Gamma-rays can be detected directly before they interact with the atmosphere by satellites, but these have a very limited area of detection, meaning, with limited time, they can only detect signals with a very high flux (low energy γ-rays). To detect higher energy γ-rays there's a need to use large ground observatories, that detect the showers created when a γ-ray interacts with a particle in the atmosphere instead. These can use either arrays of telescopes, that have to be pointed towards the signal's source, or arrays of particle detectors, for instance water Cherenkov detectors.

1.2 Gamma-rays vs Cosmic-rays

When detecting gamma-rays, there's a need to pay special attention to distinguishing them from cosmic-rays. Unlike gamma-rays, which are neutral particles (photons), cosmic-rays consist of charged particles. This implies that gamma-rays travel in a straight line, revealing the exact position of their source, while cosmic-rays interact with magnetic fields and have their trajectories altered, displaying an apparent position of their sources that does not line up with their actual position in the universe and forming a background of cosmic radiation coming from apparently all sides.

The showers they create when interacting with atmospheric particles have differentiating characteristics. In the gamma initiated showers, or electromagnetic showers, the photon develops into a pair of an electron and a positron. While these travel at a high enough speed, they emit photons that subsequently turn into more pairs that may continue the shower. The shower initiated by a charged particle, or hadronic shower, on the other hand will create other charged and uncharged particles, including muons, a distinct particle that doesn't appear in γ-ray showers. These will in turn create more charged particles and will, at high energies, emit photons able to create electromagnetic sub showers. The cosmic rays create, then, more complex showers than the γ-rays, and these create a good differentiator between them.

1.3 The Southern Wide-field Gamma-ray Observatory

The Southern Wide-field Gamma-ray Observatory (SWGO) is part of the next generation of gamma-ray observatories, and is currently in research and development phase. This observatory results of a collaboration between 15 countries and will be built at a high altitude at the Atacama Astronomical Park, in Chile. It will consist of a large ground array of tanks based on water cherenkov detectors, being the first of its kind to be able to observe the galactic centre.

This observatory will still have to deal with the enormous background created by cosmic radiation, and will need excellent gamma/hadron discrimination capabilities. Commonly used techniques include muon counting, but this involves burying the tanks to shield them from electromagnetic particles, which has a very high cost and environmental impact[1]. The most likely layout at the moment relies on an array of tanks with a center area with a higher fill factor, meaning more area covered by tanks per total area, and an outer ring of tanks with a lower fill factor. To further save on costs, the possibility of grouping tanks together is also being considered. So, it would be ideal to have an alternative discrimination technique that utilizes the total signal detected by the observatory, and would be robust to these changes in the display of the detector tanks.

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2 Exploring the shower footprint

2.1 The C_k variable

One of the characteristics that distinguishes the showers developed is their footprint. These footprints will contain azimuthal asymmetries than can be quantified by defining a ring k of n_k tanks at a set distance r_k from the core of the shower and comparing the difference in signal detected in each tank with the mean signal in this ring of tanks $\langle S_k \rangle$, being the signal for a specific tank identified with S_{ik} [2]. Using these structure variables the C_k variable comes as follows:

$$C_k = \frac{2}{n_k(n_k-1)} \frac{1}{\langle S_k \rangle} \sum_{i=1}^{n_k-1} \sum_{j=1+1}^{n_k} (S_{ik} - S_{jk})^2 \tag{1}$$

where n_k is the

This variable has been established as a valid discriminator for cosmic and γ-rays [2], since it will behave in a similar way in both a gamma initiated shower and a proton initiated one, but at different values. Having a more complex shower structure, the hadronic shower will have a higher value C_k [2], as can be seen in Fig. 1

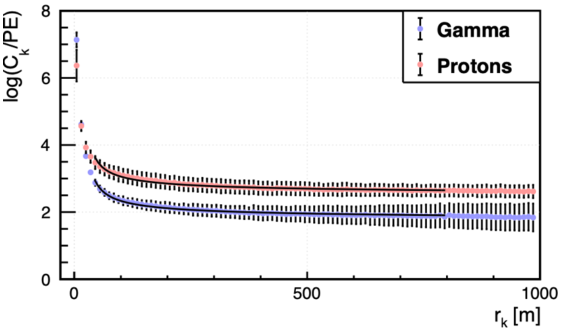

Figure 1. C_k variable for gamma and proton showers

2.2 Array Layout Configuration

In previous studies regarding the C_k variable and its applications, there has been analysis done on the impact the layout of detector tanks would have. Namely, it's been confirmed that an array layout with a denser core area of tanks and a more disperse outer ring (as has been previously discussed as an option for the SWGO), would not negatively impact the validity of this discriminator [3]. However, there's a gap of research surrounding the impact of clustering the tanks together, and since this variable is dependent on the geometry of the obtained signal, there's a need to confirm its reliability.

3 Simulations

3.1 To.M.M.A.S.O.

To further analyze the behavior of the C_k in the context of previous research, the Toy Montecarlo Model of an Air Shower Observatory, To.M.M.A.S.O., was developed. This consists of a Python framework that has the capacity to simulate the detection of gamma-ray showers in a highly controlled environment. It uses both array layouts designed by the SWGO collaboration and custom layouts, and can inject both known signals (specific tanks, shown in Fig. 2, or signal distributions, such as the NKG distribution that simulates the average signal of a γ-ray shower) and CORSIKA simulation (Fig. 3) showers into its tanks.

3.2 Clusterization

To test the reliability of the C_k variable in environments with clustered tanks, a model was made to create arrays representing clustered tanks, fixing the total fill factor, meaning the amount of array area covered by tanks, and the array radius. These layouts were then used to compare the results of simulations run in arrays with the same conditions, but no clusterization, clusters of three tanks or clusters of seven tanks (see Fig. 4).

3.3 Main Simulation

Many layouts were developed and simulations were ran while testing this variable, but this article will focus on the results of applying an approximation of the previously mentioned NKG signal to a layout that's known to be a possibility for the SWGO [4]. In this sense, a signal of:

$$S_{tank} = C \left(\frac{d_{tank} + 0.01}{r_M} \right)^{s-2} \left(\frac{d_{tank} + 0.01}{r_M} + 1 \right)^{s-4.5} \tag{2}$$

where $C = 1000$, $r_M = 1000$, $S = 1$, that simulates the distribution of a real signal being injected, is applied to an array of detector tanks with a radius of 1 km and a fill factor of 12.5%. When these conditions were applied on an array with no clustering, the results were as shown in Fig. 5, where the first figure shows the footprint of the shower, the second shows the lateral distribution of the signal and the third shows the value of the C_k. Applying the same signal to layouts with the same radius and fill factor, but with clusters of three and seven tanks, the results were as shown in Fig. 6 and 7, respectively.

4 Results and Conclusions

Superimposing the results of these simulations, it is possible to observe that the clustering of tanks has a negligible impact on the lateral distribution recorded. On the C_k variable the impact is more apparent before the 100 *m* radius mark, but also becomes insignificant after that (see Fig. 8).

It is possible then to conclude that the C_k variable is still a reliable differentiator between cosmic and γ-rays in these conditions, and that the clusterization of detectors is compatible with its use.

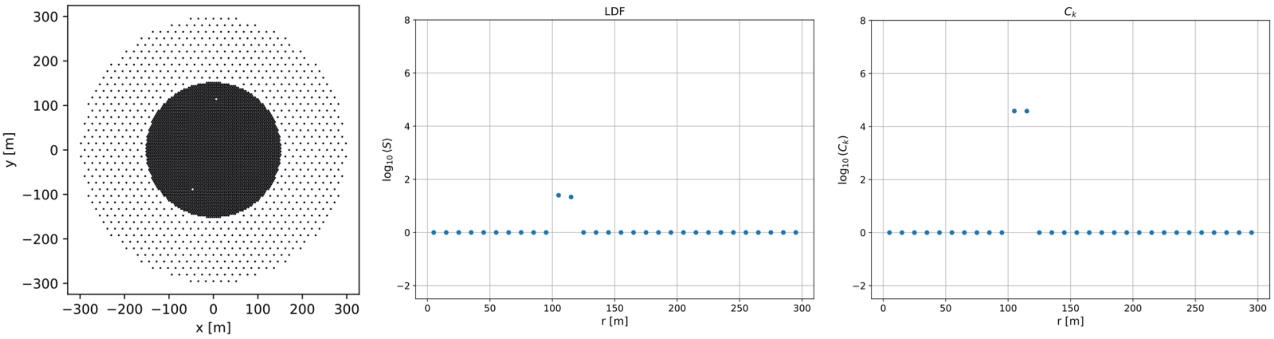

Figure 2. Simulation with signal injected into 2 tanks.

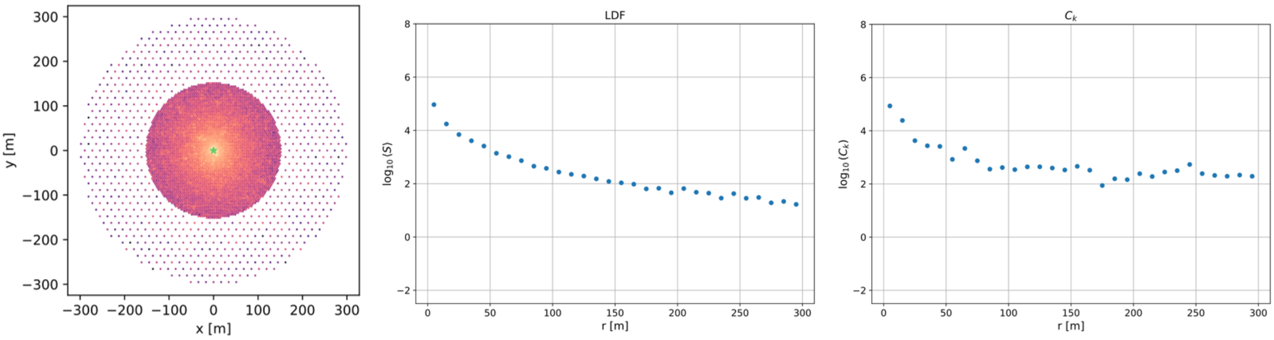

Figure 3. Simulation using a CORSIKA shower.

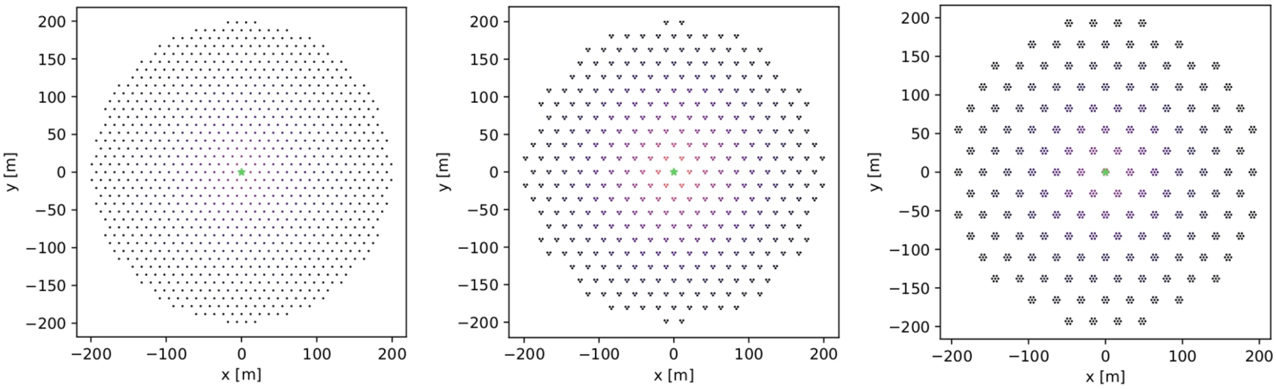

Figure 4. Layout with no clusterizarion, cluster of 3 and clusters of 7 tanks.

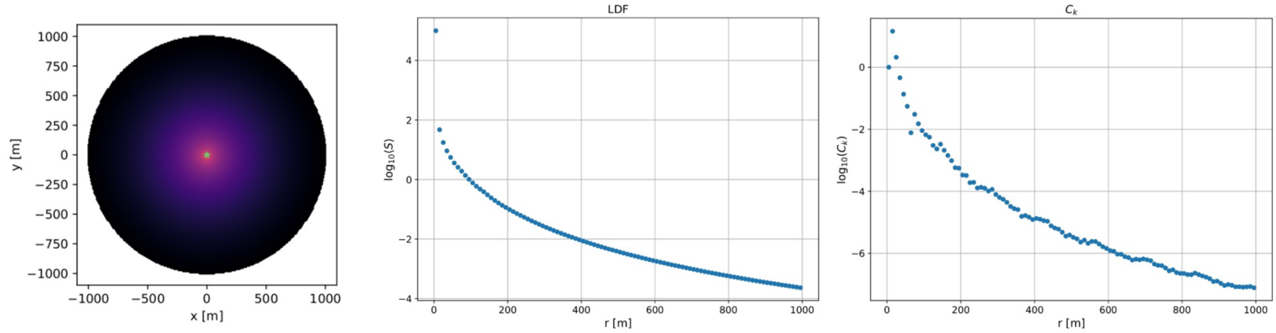

Figure 5. Footprint, LDF and C_k for an array with no clusterization.

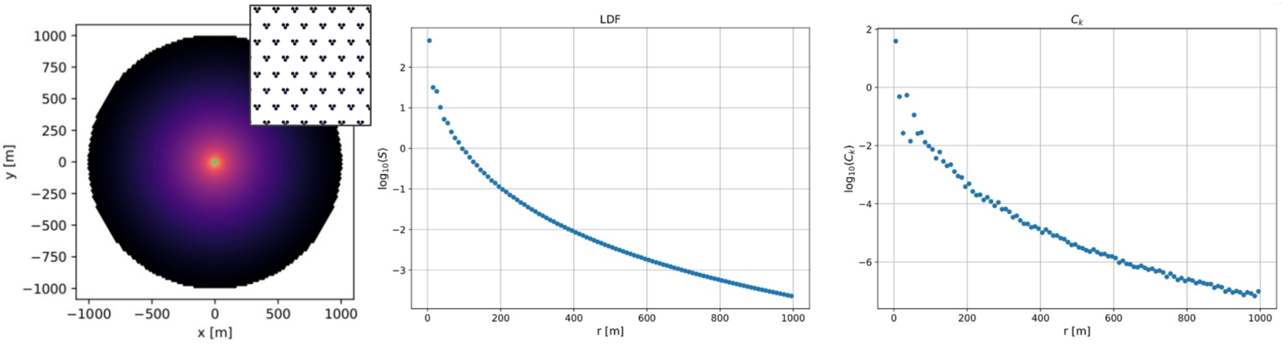

Figure 6. Footprint, LDF and C_k for an array with clusters of 3 tanks.

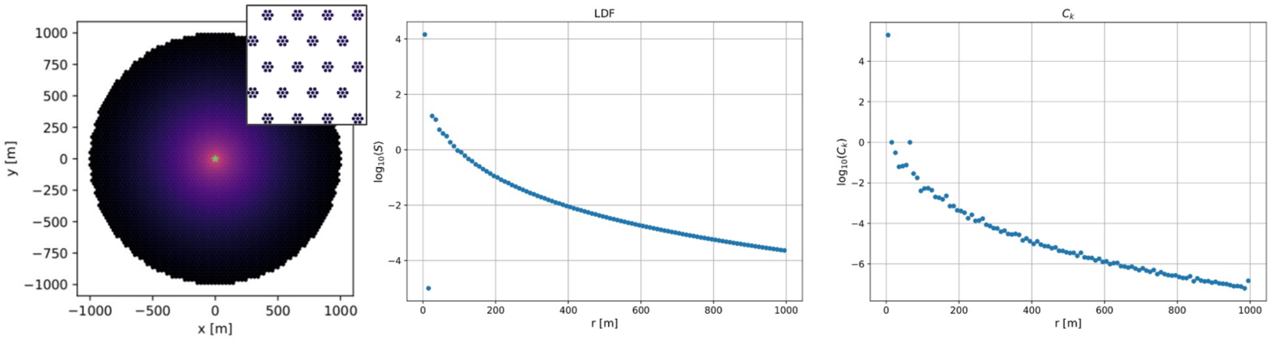

Figure 7. Footprint, LDF and C_k for an array with clusters of 7 tanks.

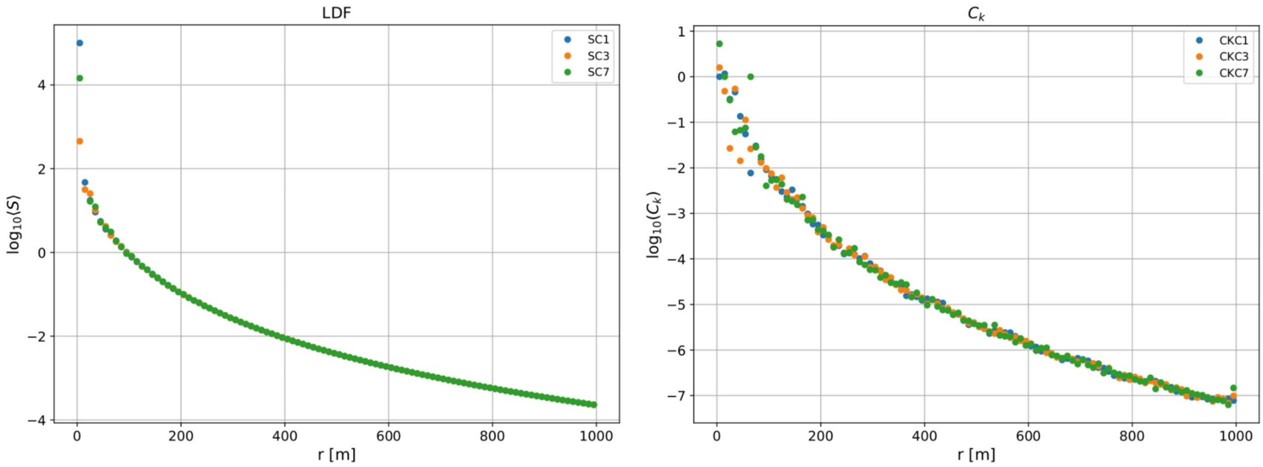

Figure 8. LDF and C_k for an array with no clusterization and clusters of 3 and 7.

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