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Monte Carlo studies for improving the sensitivity of the TACTIC telescope by using zenith angle dependent Dynamic Supercuts

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The sensitivity of atmospheric Cerenkov imaging telescopes is strongly dependent on the rejection of the cosmic ray background events. While the efficiency of using Hillas parameters for performing this segregation has been confirmed by the detection of several γ-ray sources by various independent groups, one has to also consider energy and zenith angle dependence of these parameters so that the energy spectrum of the γ-ray source can be reliably determined. The main aim of the present simulation work is to study the comparative performance of various γ-ray selection methodologies at different zenith angles so that zenith angle dependent Dynamic Supercuts procedure can be used for the TACTIC telescope for determining the energy spectrum of a source. The results of the Monte Carlo simulations, carried out at four different zenith angle values of 15°, 25°, 35° and 45°, indicate that the zenith angle dependent Dynamic Supercuts provide the best combination of sensitivity and γ-ray acceptance as compared to the Supercuts and the Dynamic Supercuts methodologies.

1. Introduction

Ground-based γ-ray astronomy in the energy range above 100 GeV has made dramatic progress in the last decade with the rapid development of the atmospheric Cerenkov imaging technique at a number of observatories. Since the sensitivity of a Cerenkov imaging telescope is strongly dependent on the rejection of the cosmic-ray background events, it is important to assess the potential of various γ-ray selection methodologies so that the weak γ-ray signal can be isolated from the dominant hadron background with a high signal-to-noise ratio. Simulation work pioneered by Hillas [1] to quantitatively predict image features, has led to the development and successful usage of several γ-ray selection methodologies like Supercuts [2] and Dynamic Supercuts [3]. While energy dependence of the imaging parameters has been duly considered in the Dynamic Supercuts procedure, it has been argued that the zenith angle dependence of these parameters can be ignored if a candidate γ-ray source is observed only upto a zenith angle of $\sim$30°. Since in the zenith angle range 30°-45°, the shower development takes place at a higher effective altitude, it is obvious that some of the image parameters (e.g DISTANCE, LENGTH and WIDTH) will also have a zenith angle dependence [4]. The main aim of this paper is thus to study this behaviour by performing detailed Monte Carlo simulation studies for the TACTIC telescope at 4 different zenith angles between 15° - 45° so that zenith angle dependent Dynamic Supercuts can be used for extracting the weak γ-ray signal from the dominant hadron background with an adequate signal-to-noise ratio.

2. TACTIC telescope and generation of simulated data-base

The TACTIC (TeV Atmospheric Cerenkov Telescope with Imaging Camera) γ-ray telescope has been set up at Mt.Abu, India (24.6° N, 72.7° E, 1300m asl), for studying emission of TeV γ-rays from celestial sources. The telescope uses a F/1 type steerable tessellated light collector of $\sim$9.5 m^2 area made up of 34 x 0.6 m diameter, front aluminised spherical glass facets. The telescope uses a 349-pixel imaging camera with a uniform pixel resolution $\sim$0.3° and a field of view $\sim$6°x6° for recording the images of atmospheric Cerenkov events produced by an incoming cosmic ray particle or a γ-ray photon. The innermost 121 pixels (11×11

matrix, FOV∼3.4°x3.4°) are used for generating the event-trigger based on the 3NCT (Nearest Neighbour Non-Collinear Triplets) topological logic by demanding a signal $\geq$ 7 pe for the 3 pixels which participate in the trigger-generation. The simulation studies presented here are based on the CORSIKA air-shower simulation code [5] and are valid for Mt.Abu observatory altitude of 1300m. The simulated data base for γ-ray showers uses about 25000 showers in the energy range 0.2-20TeV with an impact parameter of 5-250m and a differential spectral index of ∼-2.6. These showers have been generated at 4 different zenith angles (θ= 15°, 25°, 35° and 45°). Furthermore, a data-base of about 30000 proton initiated showers in the energy range 0.4-40 TeV and distributed isotropically within a field of view 6°x6°, have also been generated. Wavelength dependence of atmospheric absorption, spectral response of the PMTs, reflection coefficient of mirror facets and light cones has also been taken into account in the present simulation studies. The data-base, consisting of number of photoelectrons registered by each pixel has been then subjected to noise injection, image cleaning and trigger condition check. The resulting two dimensional 'clean' Cerenkov image of each triggered event is then used to determine various image parameters (viz., SIZE (S), LENGTH(L), WIDTH (W), DISTANCE (D), APLHA (α) and FRAC2 (F2)).

3. Comparative performance of various γ-ray selection methodologies

The optimized image parameter domains for the TACTIC telescope using three different γ-ray selection methodologies (viz., Supercuts (SC), Dymanic Supercuts (DSC) and zenith angle dependent Dynamic Supercuts (ZDSC)) are given in Table 1. The optimized image parameter domains of the three γ-ray selection

Table 1. Optimised image parameter domains for the three γ-ray selection methodologies.

Parameter	Supercuts (SC)	Dynamic Supercuts (DSC)	Zenith angle dependent Supercuts (ZDSC)
SIZE (S)	> 50 pe	> 50 pe	> 50 pe
LENGTH (L)	$0.10^o \leq L \leq 0.37^o$	$0.10^o \leq L \leq L1$ $L1 = (0.24 + 0.055 \ln(S))^o$	$0.10^o \leq L \leq L2 \cos^{0.6}\theta$ $L2 = (0.24 + 0.045 \ln(S))^o$
WIDTH (W)	$0.07^o \leq W \leq 0.17^o$	$0.07^o \leq W \leq W1$ $W1 = (0.08 + 0.035 \ln(S))^o$	$0.07^o \leq W \leq W2 \cos^{0.4}\theta$ $W2 = (0.08 + 0.027 \ln(S))^o$
DISTANCE (D)	$0.5^o \leq D \leq 1.2^o$	$0.4^o \leq D \leq 1.3^o$	$0.4^o \cos^{0.7}\theta \leq D \leq 1.6^o \cos^{0.7}\theta$
FRAC2 (F2)	> 0.53	not used	not used
ALPHA (α)	$\leq 18^o$	$\leq 18^o$	$\leq 18^o$

methodologies, valid in the zenith angle range 15°-45°, have been obtained by demanding that SC, DSC and ZDSC methods should yield the best possible sensitivity, 50-60% γ-ray acceptance and the best combination of both of these, respectively. The variation of effective collection area as a function of primary energy, for the three γ-ray selection methodologies is shown in Fig.1.

The results shown in this figure suggest that the SC method is biased towards lower energies (particularly at lower zenith angles), as might be expected since this method was optimized to give the maximum significance. In order to evaluate the efficiency of a discrimination technique, while it is a common practice to calculate the Quality Factor(Q) (where Q= $\eta_\gamma/\sqrt{\eta_p}$, with η_γ and η_p being the γ-ray and protons acceptance factors, respectively after the application of selection cuts), we have instead used a more rigorous approach by calculating T_{min} (defined as the minimum observation time required for detecting Crab Nebula at a statistical significance of N_σ). Assuming that the detection sensitivity is limited by statistical fluctuations of the ON-source

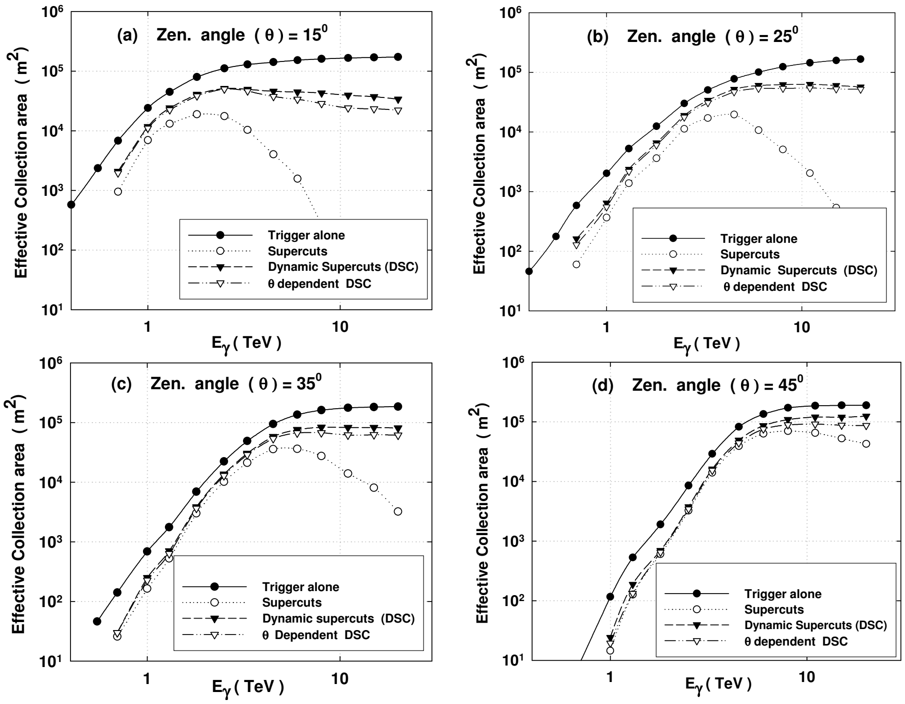

Figure 1. Effective collection area as a function of the primary γ-ray energy for the three γ-ray selection methodologies at different zenith angles : (a) θ=15° (b) θ=25° (c) θ=35° and (d)θ=45°. The corresponding effective area when no cuts are applied to the data is also shown here for comparison.

(signal+background) and OFF-source (background) events, the expression for T_{min} is given by

$$T_{min} = N_\sigma^2 \left(\frac{1}{\int_{E_{min}}^{E_{max}} \frac{dN_\gamma}{dE} A_\gamma(E)\eta_\gamma(E)dE} + \left(\frac{\beta+1}{\beta}\right) \frac{\int_{E_{min}}^{E_{max}} \frac{dJ_p}{dE} A_{p,\Omega}(E)\eta_p(E)dE}{(\int_{E_{min}}^{E_{max}} \frac{dN_\gamma}{dE} A_\gamma(E)\eta_\gamma(E)dE)^2} \right) \quad (1)$$

where $dN_\gamma/dE = 2.83\times10^{-11}(E/1TeV)^{-2.62}$ cm^{-2} s^{-1} TeV^{-1} is the differential energy spectrum of the Crab Nebula, $A_\gamma(E)$ is the effective collection area for γ-rays in m^2, β(=4) is the ratio of OFF-region (α=18°-90°) to ON-region (α=0°-18°), $dJ_p/dE=1.10\times10^{-5}(E/1TeV)^{-2.75}$ cm^{-2} s^{-1} sr^{-1} TeV^{-1} is the differential energy spectrum of the protons, $A_{p,\Omega}(E)$ is the product of effective collection area and the solid angle for protons in m^{2}sr. The calculations presented in this paper have been done by using the following values: N_σ=5, E_{max}=20TeV and varying E_{min} (i.e. $E_{min}\sim E_{threshold}(\theta)$ so that possible inaccuracies resulting from the sharp dependence of the effective collection areas for E< $E_{threshold}(\theta)$) can be avoided. Variation of η_γ and T_{min} as a function of zenith angle for the three γ-ray selection methodologies is shown in Fig.2.

The reason for having a relatively low η_γ (e.g. $\sim$0.27 for SC and $\sim$ 0.60 for DSC at θ=25° as against the mostly quoted values of $\sim$0.40 and > 0.80 for the two cases, respectively) is that apart from being zenith angle dependent, this factor also depends on the pre-filtering procedure (e.g., like removal of small SIZE events or events with too large or too small DISTANCE parameter etc.,). Since no such pre-filtering conditions have been imposed here, computing η_γ directly on the basis of number of triggered events will naturally make this parameter relatively small. Referring back to Fig.2b, it is obvious that once a γ-ray source has been detected

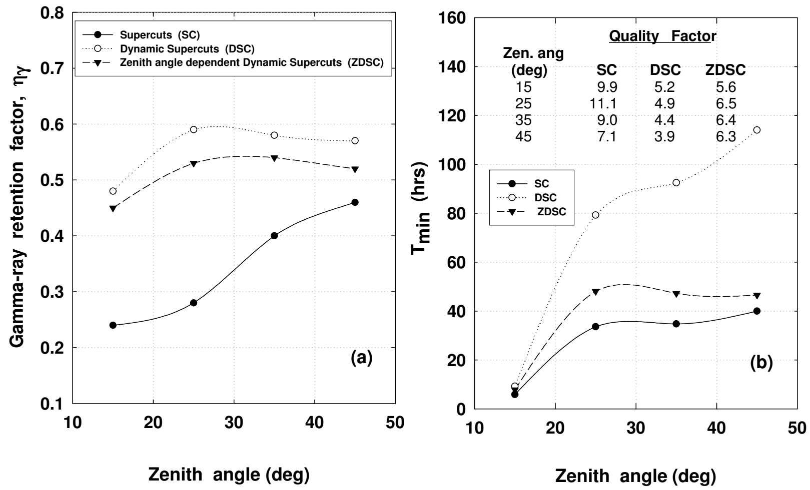

Figure 2. (a) Variation of γ-ray acceptance (η_γ) as a function of the zenith angle. (b) Variation of T$_{min}$ (defined as the minimum observation time required to detect a 5σ γ-ray signal from the Crab Nubula) as a function of the zenith angle. The corresponding Quality Factor values are also tabulated in the figure for comparison.

by using the SC methodology, using the ZDSC methodology as against the DSC method for determining the energy spectrum saves significantly on the observation time at a marginal additional loss of about 5% γ-ray events.

4. Conclusions

The results of the simulation studies indicate that the zenith angle dependent Dynamic Supercuts (ZDSC) method provides the best combination of η_γ and T$_{min}$ as compared to that of the Supercuts (SC) and Dynamic Supercuts (DSC) methods. The effectiveness of this method is however being evaluated by applying it to the actual data collected by the TACTIC telescope.

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