

CORSIKA-based simulation studies of the TACTIC Array

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Abstract

The TACTIC is a compact array of 4 synchronously-tracking Cerenkov telescopes, placed at the centre and the 3 corners of a triangle of side 20 m. The central telescope, referred to as the Imaging Element (IE), will eventually carry a photomultiplier-tube based, 349-pixel imaging camera (at present, 225 pixels), covering a FoV of $\sim 6^\circ \times 6^\circ$ with a pixel resolution of $\sim 0.31^\circ$. In this paper, we use the CORSIKA air-shower simulation code to estimate the quality factor of the IE based on image-supercuts background rejection procedure and examine the possibility of exploiting the relatively large FoV of the TACTIC imaging camera for concurrent on-source/off-source monitoring.

1 Introduction:

In the TeV γ -ray domain, the dominant background for a narrow-beam Cerenkov system comprises cosmic-ray events which outnumber signal (γ -ray) events from a typical point-source by at least a factor of ~ 100 . The Cerenkov image processing and classification schemes, so far used, are based on calculation of mainly second moments of the image, like the Hillas parameters or its improved versions, viz., supercuts and dynamic cuts. In the supercuts methodology, the parameter space used consists of image angular Length (L), Width (W), Distance (D) and Alpha (α) and by exploiting the differences found in the respective values of these parameters for signal events (γ -rays from a compact source) and the isotropic cosmic-ray background events, both Monte Carlo simulations and experimental data have shown that it is possible for a typical Cerenkov imaging telescope (single element) to reject cosmic-ray background at 99% level while retaining $\sim 50 - 60$ % of the signal events. This leads to a quality factor, $Q \sim 8 - 10$ in the TeV γ -ray energy range, the exact value depending upon the actual experimental details. In the paper, we estimate Q for the IE of the TACTIC instrument. Furthermore, as the TACTIC is the first imaging system which uses a large FoV camera ($\sim 6^\circ \times 6^\circ$) with a uniform pixel granulation, it is important to establish that it can be used efficiently for concurrent on-source/off-source observations, an observation mode so far neglected, but potentially of great practical relevance, since it can on one hand, help to cut down effective observation time by a factor of ~ 2 in case of steady γ -ray emitters and, on the other, provide a more efficient monitoring mechanism for episodic γ -ray emissions.

2 TACTIC Imaging Element:

Experimental key-features of the 4-element TACTIC array, being set-up at Mt. Abu (24.65° N, 72.7° W, 1300 m asl), have been discussed elsewhere (Bhat et al. 1997). We confine ourselves here to a discussion of the front-end optics and focal-plane instrumentation (imaging camera) of the IE. The light-reflector (effective light collection area $\sim 9.5m^2$) has a tessellated structure comprising 32×0.6 m diameter, glass mirrors with spherical surfaces of ~ 8 m radius of curvature. The individual mirror facets are suitably mounted on the telescope mechanical basket and so aligned that the overall light collector surface approximates to a Davis-Cotton optical configuration with an effective focal length of ~ 4 m. The experimentally-measured spot-size for on-axis light incidence is consistent with the corresponding simulation results and yields a value of $\sim 0.20^\circ$ for the diameter of circle within which 95% photons are collected. For the simulation studies presented here, we have used a uniform – pixel-granulation ($\sim 0.31^\circ$) imaging camera consisting of 349 fast photomultiplier tubes (PMT), placed in a closely-packed 19×19 square matrix geometrical configuration (with truncated corners) to cover a FoV of $\sim 6^\circ \times 6^\circ$. The PMT are provided with metallic light-guides on the front side to ensure more or less uniform light collection efficiency by the PMT pixel over a large range of

angles of incidence, ($< 20^\circ$) from the light collector. The PMT voltage gains are closely monitored on-line and appropriate corrections made for inter-and intra-pixel gain variations in an off-line manner. The event triggers are generated from within the central 225 pixels of the imaging camera, leading to a trigger FoV $\sim 4^\circ$ as against an overall image FoV $\sim 6^\circ$. These triggers are topological proximity triggers of Nearest Neighbour Non-Collinear Triplet (3NCT) type (Bhat et al 1994).

3 CORSIKA-generated data-bases:

The CORSIKA air-shower simulation code with Cerenkov option (version 5.61; Heck et al., 1998) has been used for generating γ -ray (cosmic-ray proton) data-bases in the energy bracket $\sim 0.5 - 5$ TeV ($\sim 1 - 10$ TeV) for γ -rays (protons). A total of 4000 events of either progenitor type have been considered, following the representative integral spectral form $\sim E_p^{-1}$, where E_p is the primary energy. In accord with the actual situation likely to be encountered in case of a compact source, all the γ -rays are assumed to be incident along the IE axis, while the background cosmic-ray events are assumed to be randomly oriented around this axis within a circle of $\sim 4^\circ$ diameter (\sim trigger FoV of the IE). For convenience, the telescope axis has been held fixed at the typical zenith angle $\theta \sim 20^\circ$ for the purpose of the present simulations and, in conformity with the geometry of the 4-elements TACTIC array, a rectangular matrix of IE-like light collectors has been considered with inter-element spacing of 10 m and 6 m along the 2 Cartesian axes. The shower axis has been fixed at the centre of the matrix, permitting Cerenkov light to be sampled at core distances of upto 205 m along one Cartesian axis. The altitude (~ 1300 m) and magnetic field values (~ 35.86 and 26.6μ Tesla horizontal and vertical component respectively), used in the CORSIKA input card, correspond to the permanent location of the TACTIC array at Mt. Abu. The Cerenkov photon wavelength band chosen for generating the basic data-base is $\lambda \sim 300-450$ nm; a photon bunch-size of 1-5 has been used to keep the data-base size within manageable limits. Cerenkov photons likely to be received in other λ regions, consistent with the spectral responses of the IE mirror and the PMT in the imaging camera are duly accounted for in an off-line manner. λ -dependent atmospheric extinction is considered for all the Cerenkov photons, using the standard atmospheric model. The photons reflected from a given light collector are ray-traced into the imaging camera pixels and the data-bases of resulting photoelectron (pe) distributions are subjected to the Cerenkov image analysis. In close agreement with the situation encountered in practice (after image cleaning), no significant sky-noise is assumed to be present and the Cerenkov image parameters for the IE, at a given distance from the shower core, are derived from the corresponding pe distribution pattern, present in the above-referred data-base. The parameters calculated are the image size (S), Length (L), Width (W), Distance (D) and Alpha (α), etc., as per the super-cuts prescription given by Fegan (1996). For each E_p value, the total number of images considered for the analysis work is sampled as per $\sim R$ scaling, where R is the distance of the IE from the centre of the array. This gives basic data-base comprising 90305 events of either type.

4 Results and conclusions:

Without introducing the size (S) cuts in the beginning, the distribution of the image parameters, L,W, and D for γ -ray and proton events are compared and the optimum ranges are found for these three parameters to secure maximum acceptance of γ -ray and maximum rejection of proton events. These windows in the present case (no S cut) turns out to be $0.18^\circ \leq L \leq 0.58^\circ$, $0.06^\circ \leq W \leq 0.26^\circ$ and $0.35^\circ \leq D \leq 1.55^\circ$, containing 56475 and 8981 γ -ray and proton events respectively out of the above-referred total of 90305 events. When projected on the α -plane, as expected, the proton events distribute themselves more or less uniformly over $0 \leq \alpha \leq 90^\circ$ with 100 events per degree as against 39400 γ -ray events clustering between $0 \leq \alpha \leq 12^\circ$ (γ domain) . The fraction of proton and γ -ray events which thus constitute the γ -ray domain are 1200 and 39400 respectively, leading to a Quality factor of $Q \sim 3.8$ with no size cut. Using the above-referred image parameter domains, Q is found to change with S as shown in the Figure 1, first increasing fast and then flattening with $Q \sim 8$ for $S \geq 80pe$.

Taking $Q \sim 7.5$ as a reasonable minimum value to be specified for the figure of merit for the extraction

of a γ -ray signal (the signal recovery time required would be ~ 3 hours at 5σ confidence level from the standard candle Crab Nebula). We can use Fig. 1 to yield the effective image threshold level for the IE; it turns out to be 80 pe, corresponding to a median γ -ray energy of ~ 0.9 TeV. The maximum value of Q, suggested by the present simulation studies (Fig.1), is compatible with the value experimentally derived for the IE when it detected a strong γ -ray signal from the Mkn 501 during an observation campaign carried out in April - May, 1997 with a 81-pixel prototype camera (Bhat et al.1997).

We now turn to investigate whether the large FoV ($\sim 6^\circ$ with uniform pixel granulation of 0.31°) can be utilised to carry out concurrent on-source/off-source observations through a simple tracking sequence of the IE where the point-source is throughout kept on-axis. In Figure 2, we have plotted distributions of distance D parameter for both, γ and proton events. It is clear from this figure that only 3% of γ -ray events contributing to $D > 1.7^\circ$ and a substantial 32% of proton-events lie in the corresponding distance range. This allows us to demarcate $D \leq 1.7^\circ$ as the on-source region (where essentially all γ -rays from an on-axis point source should be expected, in addition 68% randomly distributed proton events), and $D \geq 1.7^\circ$ as the reference off-source region, where a statistically significant fraction(32%) background cosmic-ray events should

lie. Figures 3 and 4 compare the α -plots for the two event species in the redefined on-source and off-source domains. The more noteworthy thing in context of the present investigation is the α -distribution for the proton events for $D \leq 1.7^\circ$ (on-source) and $D > 1.7^\circ$ (off-source). They are compared in Fig. 5 after proper normalization, to account for different total number of proton events present in the two D-ranges (normalization factor =2.6). With respect to the normalized average level of 7 events per bin, the bin-to-bin fluctuations in the two distributions are found to lie well within 2σ . This should therefore allow the off-source proton α -distribution ($D > 1.7^\circ$) to be used reliably, after normalization, for estimating the cosmic-ray background level with respect to which one can determine the possible γ -ray excess for $\alpha < 12^\circ$ from the on-source region data. It may be noted that a similar picture about the on-source/off-source demarcation is obtained for other S values.

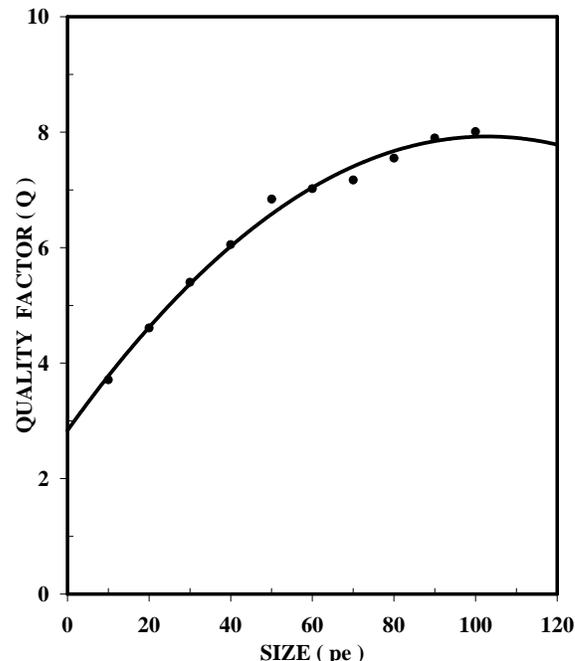


Figure 1: Estimate of quality factor for TAC-TIC Imaging Element as a function of the image size(S).

References

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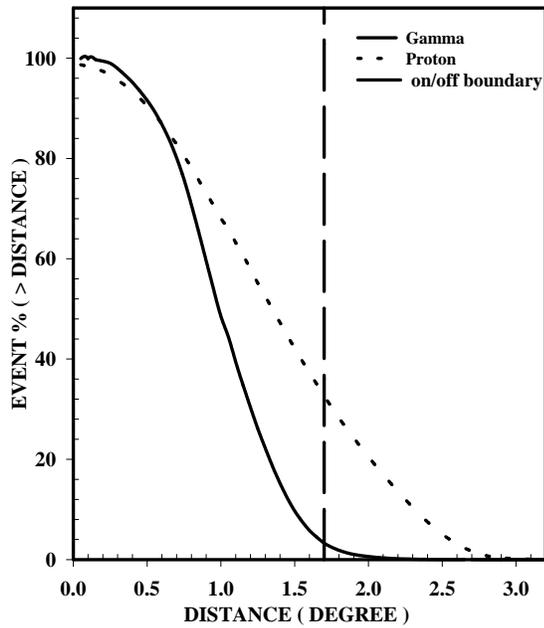


Figure 2: Integral distribution of gamma- and proton events as a function of image distance (D). Vertical dashed line at $D = 1.7$ degree demarcates on-source and off-source regions for TACTIC Imaging Element.

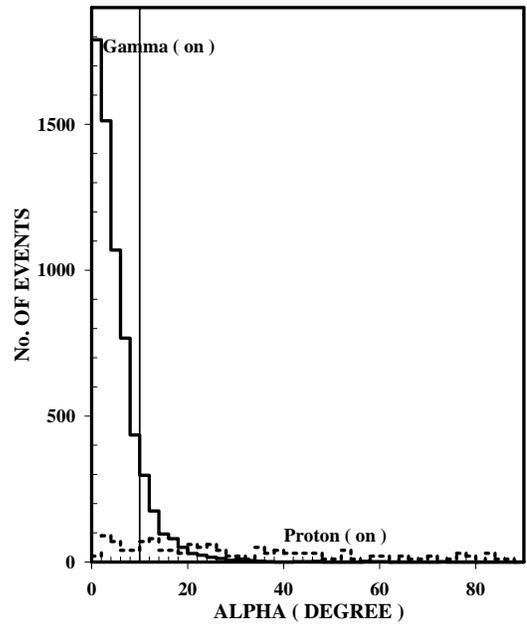


Figure 3: Alpha distribution for gamma- and proton Cerenkov images belonging to on-source ($D \leq 1.7$ degree) region.

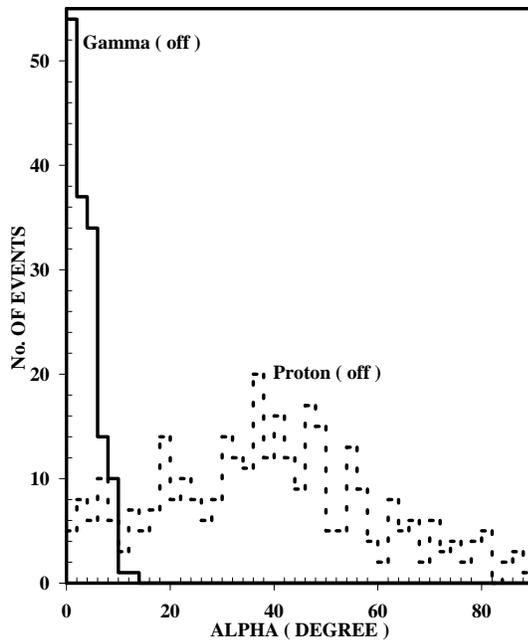


Figure 4: Same as Fig.3 but for off-source region ($D \geq 1.7$ degree).

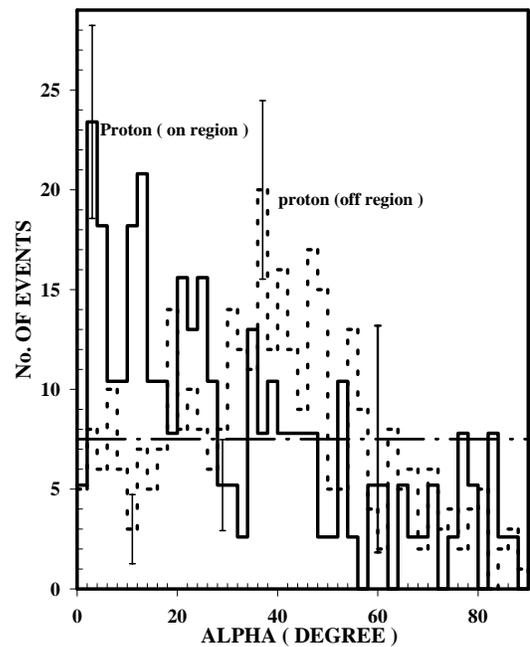


Figure 5: Normalised alpha distribution for proton images in the on-source and off-source regions. All bin-to-bin fluctuations are ≤ 2 sigma w.r.t. the mean level at 7 events per bin.