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Design philosophy of TACTIC—a high sensitivity VHE gamma-ray telescope

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Abstract. TACTIC is a high-sensitivity ground-based telescope designed for undertaking comprehensive temporal and spectral studies of galactic and extragalactic gamma-ray sources. Its main design specifications, leading to a projected figure of merit of Q ~ 26, are discussed.

Key words : high-sensitivity—figure of merit—imaging technique

1. Introduction

The overall scope of investigations in observational astronomy at TeV energies has been quite restricted so far (Bhat 1993) due to the grossly inadequate detection sensitivity of the conventional VHE gamma-ray telescopes. The excessive flux of cosmic-ray generated atmospheric Cerenkov events (p-ACE) provide the background against which the much weaker flux of signal photons (γ-ACE) has to be retrieved in a time period which is limited to, at best, ~ 300 hours per source per year.

2. Sensitivity improvement schemes

In principal, the way out of this impasse lies in appealing to a data-filtering procedure which removes a substantial fraction of p-ACE from the recorded data-base, while ensuring simultaneously that there is only a marginal loss of γ-ACE. The resulting improvement in detection sensitivity, symbolised by the figure of merit Q, is given by : $Q = f\gamma / \sqrt{fp}$, where $f\gamma$ and fp are respectively the fractions of the γ- and p-ACE left behind in the 'filtered' sample. The practical significance of the quality factor Q is that it is related to the signal recovery time T by : $T \sim 1/Q^2$, so that, for decreasing T from hundreds of hours (generation-I system limit) to a few hours (generation-II system specification), $Q \sim 10$ will be required, implying a p-ACE rejection factor $(1 - fp)$ of 99.75% for a typical $f\gamma \sim 0.5$.

Though the underlying basic ideas have been afloat for a long time, it is only recently that the above-mentioned value of Q has been realized (and bettered) in practice, by using the Cerenkov Imaging Technique (CIT) (Hillas 1985). Following this approach, the Whipple group (Weekes 1992) have detected weak d.c. signals from the classic plerion Crab Nebula and the active galaxy MK 421 at convincing statistical significance levels. Besides, the differential photon spectrum of a TeV γ-ray source (Crab) has been measured for the first time and the intrinsic angular resolution of the technique has been shown to be as high as ~ 6 arcmin. Recently, it has been shown, using simulated and real (Crab) data, that, by using more sophisticated image-pattern recognition and analysis procedures like SUPER CUTS, CLUSTER MASK and NEURAL-NETS, it is feasible to realise at this stage a $Q \sim 20\text{-}26$ and hence a further reduction in the signal retrieval time by a factor of ~ 4-7 (Punch *et al.* 1991; Hillas & West 1991).

Having said this, it is important to note that the image orientation parameters like AZWIDTH, MISS and ALPHA are not sensitive to γ-ray emissions from non-compact sources, resulting in a relatively poorer sensitivity for these potentially important searches through CIT. Furthermore, this technique has apparently 'failed' in retrieving signals expected from several well-known point candidate-sources, including Crab pulsar, Cyg X-3 and Her X-1 (Akerlof *et al.* 1991 and Reynolds *et al.* 1991). In view of these reasons, it is advisable to look for other effective p-ACE (Vladimirsky *et al.* 1989; Konopelko *et al.* 1991) discriminants which can supplement (or replace) CIT in further boosting Q for various types of γ-ray emissions. Two such fairly well proven discriminants, exploit the differences in the spectral and temporal features of the γ-p-ACE and when used individually, are expected to yield $Q \sim 2.5$ and 3-4 respectively.

3. TACTIC γ-ray telescope

This instrument, being developed presently against the foregoing backdrop, seeks rejection of p-ACE, at the hardware level, by working at the lowest possible threshold energy and using an optimum FoV for the telescope. Further augmentation of sensitivity is sought at the software level, by employing imaging, spectral and temporal data of the recorded events along the lines outlined in section 2. Furthermore, concurrent on- and off-source observations are planned, thereby cutting down the effective observation time at least by a factor of 2 for dc signals and ensuring a more reliable detection of periodic and episodic events. TACTIC comprises $4 \times 10\ m^2$ spherical light reflector units, one of which is provided with a 400-pixel Cerenkov light camera (CLIC) to generate medium resolution ($0.36° \times 36°$) images of the detected ACE, while the other three are appropriately instrumented to generate on- and off-source ACE triggers and record their time profiles as well as U/V spectral content. Additional details about TACTIC electronics and instrumentation are given by Bhat *et al.* (1993) and Koul *et al.* (1993). The minimum detectable Cerenkov light density is estimated to be ~ 5 photons m^{-2} in λ = 300-600 nm, corresponding to a γ-ray threshold energy of ~ 0.2 TeV. The average event rate for each detector channel, mostly due to p-ACE, is estimated to be 3 s^{-1}, corresponding to a total trigger rate of 27 s^{-1} for the entire telescope. Good quality images are expected for γ-rays of energy > 0.5 TeV.

4. TACTIC flux sensitivity

We present here estimates of the TACTIC flux sensitivity for the less tractable case where a d.c. signal (as against a periodic signal) from a point source is to be recovered from the cosmic-ray-generated p-ACE. (For details, see Bhat *et al.* 1993). Figure 1 shows how the recovery time for a 5σ - significance signal, $T_{5\sigma}$, varies with f_p for several representative flux levels given in CRABS (1 CRAB = 4.5×10^{-7} photons $m^{-2}\ s^{-1}$ at $E_\gamma > 0.5$ TeV). Also shown

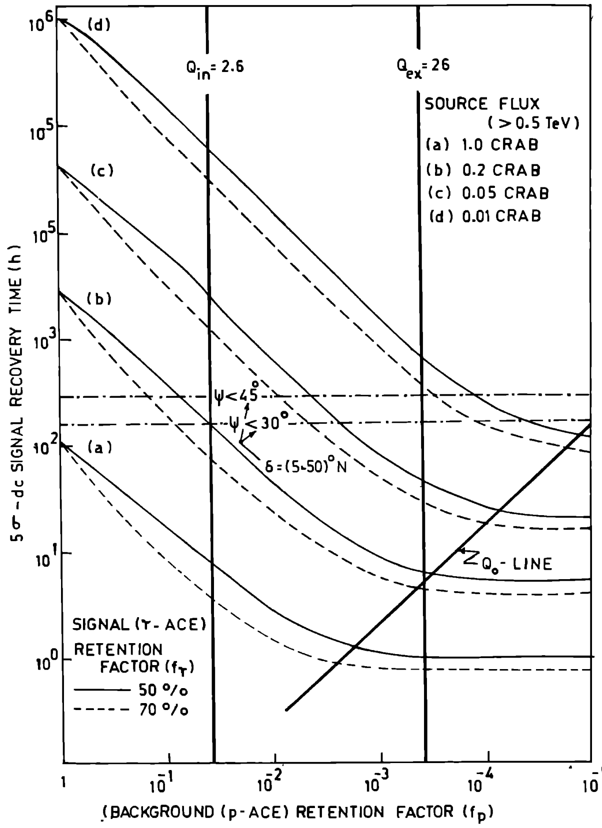

Figure 1. Sensitivity estimate of TACTIC plotted in terms of the signal recovery time for a 5σ d.c. signal as a function of p-ACE background retention factor, *fp*. Q_{in} = 2.6 and Q_{ex} = 26 give the two expected sensitivity limits of TACTIC (see text for details).

in the figure is the average observation time expected at Gurushikar per calender year for source lying in the declination band δ = 5°-50°N. Two practically useful values of the source zenith distance ψ, < 30° and < 45° are considered, yielding a maximum observation time of ~ 160 h and ~ 270 h per source per 'observation season' for the two cases respectively.

$f\gamma$ = 0.5 and 0.7 are adopted as two bounds in these calculations, except for fp =1, where $f\gamma$ is taken as 1, as would apply in case no p-ACE background events were rejected (Q = 1 system). In actual practice, however, there is an automatic rejection of some background events in a TACTIC-like Cerenkov system, for the detection range and hence effective collection area is more for a γ-primary of a given energy compared with that for a proton with the same total energy. For the threshold energy $E\gamma$ = 0.5 TeV, adopted here, this leads to an intrinsic quality factor, Q_{in} = 2.6 for the TACTIC. Thus, as shown in figure 1a, this factor alone would reduce $T_{5\sigma}$ for the Crab Nebula signal from ~ 100 h (Q = 1) to ~ 10 h, thereby clearly bringing out the advantage of working at a lower $E\gamma$. Extrinsic background rejection, involving use of image parameters as well as spectral and time-profile discriminants, are expected to further improve the sensitivity of TACTIC by at least a factor of 10, corresponding to an extrinsic quality factor, $Q_{ex} \geq 26$. As is evident from the figure, this will reduce $T_{5\sigma}$ for the Crab Nebula signal to < 1 h (total on + off time), while a source with a flux of 0.2 CRAB can be detected in just about the corresponding optimal signal recovery time, T_0 < 10 h, as is indicated by the Q_0-line in the figure (This line gives the optimum Q required to retrieve a signal of a given strength in the least possible time T_0—increasing Q further leads to only a marginal reduction of $T_{5\sigma}$). For $Q_{ex} = 26$, the expected sensitivity of TACTIC in its present form, the system will need $T_{5\sigma} > T_0$ to retrieve a signal flux < 0.2 CRAB. Thus, for a d.c. flux of 0.01 CRAB, $T_{5\sigma} \leq 195$ h, and up to one observing season would be required to detect this extremely weak signal. Periodic signals with a comparable strength can be detected even faster, depending upon the duty-cycle. TACTIC sensitivity estimates compare favourably with the generation-II, High Resolution Imaging system of the Whipple Observatory.

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