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ANN based energy estimation procedure and energy spectrum of the Crab Nebula as measured by the TACTIC gamma-ray telescope

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A novel energy reconstruction procedure based on the utilization of Artificial Neural Network has been developed for the TACTIC atmospheric Cerenkov imaging telescope to estimate the energy of the primary gamma-rays in the TeV energy range. The procedure uses a 3:20:1 configuration of the ANN with resilient back-propagation training algorithm to estimate the energy of a γ-ray like event on the basis of its image SIZE, DISTANCE and zenith angle. The results obtained by using the CORSIKA code simulated data suggest the energy resolution of the telescope is $\sim$40% for retaining $\sim$ 90% of the γ-ray events in a particular energy bin which is comparable to the energy resolution of other single element imaging telescopes. Details of the energy estimation procedure along with results obtained by determining the Crab Nebula energy spectrum in the energy range 1-16 TeV as measured by the TACTIC telescope are presented in the paper.

1. Introduction

Estimating the energy of primary γ-rays on the basis of their Cerenkov light content on the ground is an important advantage which endows the atmospheric Cerenkov technique with calorimetric capability. Although the light intensity in an image (also known as image SIZE), recorded by a single atmospheric Cerenkov imaging telescope represents a key parameter for determining the energy of the primary γ-ray, one has to also consider its dependence on the core-position and zenith angle for attaining an energy resolution in the range of $\sim$30-40%. Since, the core distance can not be measured directly with single telescopes, an approximate measure of this can be found by using the 'DISTANCE' parameter of the Cerenkov image. The γ-ray energy estimation thus becomes a function of three variables (viz., SIZE, DISTANCE and zenith angle), whose analytical form is not known. Given the inherent power of ANN (Artificial Neural Network) to effectively handle the multivariate data fitting we have, in this paper, developed an ANN-based energy estimation procedure so that after detecting a candidate γ-ray source, one can also determine its energy spectrum.

2. Salient features of the TACTIC telescope

The TACTIC (TeV Atmospheric Cerenkov Telescope with Imaging Camera) gamma-ray telescope has been set up at Mt. Abu (24.6° N, 72.7° E, 1300m asl), a hill resort in Western India, for studying emission of TeV γ-rays from celestial sources. The telescope deploys a F/1 type tracking light collector of $\sim$9.5 m^2 area made up of 34 x 0.6 m diameter, front coated spherical glass facets which have been prealigned to produce an on-axis spot of $\sim$ 0.3° diameter at the focal plane. The telescope uses a 349-pixel, photomultiplier tube (ETL 9083UVB) based imaging camera with a uniform pixel resolution $\sim$0.3° and a field of view $\sim$6°x6° to take a fast snapshot of the atmospheric Cerenkov events produced by an incoming cosmic ray particle or a gamma ray photon with an energy above 1 TeV. The back end signal processing hardware of the telescope is based on inhouse developed medium channel density NIM and CAMAC modules. The data acquisition and control system of the telescope has been designed around a network of PCs running the QNX (version 4.25) real-time operating system. The innermost 121 pixels ($11\times$ 11 matrix) are used for generating the event-trigger based on the 3NCT (Nearest Neighbor Non-Collinear Triplets) topological logic by demanding a signal ≥ 7 pe for the 3 pixels which participate in the trigger-generation. The telescope has a pointing and tracking accuracy of better than ±3 arc-minutes. The details about of the various subsystems of the telescope are discussed in [1-3]

3. Simulated data base generation and ANN-based energy estimation procedure

The simulation studies presented here are based on the CORSIKA air-shower simulation code [4] and are valid for Mt. Abu observatory altitude of 1300m. The simulated data has about 33000 γ-ray showers in the energy range 0.2-20TeV with an impact parameter of 0-250m. These showers have been generated at 5 different zenith angles (5°,15°,25°,35° and 45°) so that zenith angle dependence of various image parameters (especially image SIZE) can be properly accounted for while estimating the energy of γ-ray events. Furthermore, a data-base of about 39000 proton initiated showers in the energy range 0.4-40 TeV and distributed isotropically within a field of view of 6°x6°, have also been generated so that the quality factor and the sensitivity of the TACTIC imaging telescope can be determined. A supplementary code has been developed for the ray tracing of the Cerenkov photons and to take into account wavelength dependent atmospheric absorption, the spectral response of the PMTS, reflection coefficient of mirror facets and light cones. The data-base, consisting of the number of photoelectrons registered by each pixel was then subjected to the following analysis: (a) noise injection, (b) image cleaning and (c) 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)). The details of the energy estimation procedure employed for determining the energy of a γ-ray event on the basis on S, zenith angle (z) and D are discussed below.

In view of the fact that the backpropagation network takes a long time to converge and global minimum is not always assured, we have used a resilient backpropagation model [5] for estimating the energy of a γ-ray initiated Cerenkov event. The configuration of the network chosen is 3:20:1 (i.e 3 input nodes, 20 nodes in one hidden layer and 1 output node). While 3 inputs correspond to cos(z), S and D, the output represents the expected energy (in TeV) of the event. In order to make training easier for the ANN, we first calculate $< S >$ and $< D >$ by clubbing together showers of a particular energy in various core distance bins with each bin having a size of 40m. The purpose of training the ANN in this manner by presenting it with average behaviour of showers (instead of using individual events as such) is to smoothen event to event fluctuations so that a desired convergence level of the network can be achieved much faster. Furthermore, in order to restrict the dynamic range of the ANN, we have also divided the simulated data into two groups, i.e, 0°-25 ° and 25°-45° zenith angle ranges, so that two separate neural nets can be employed for predicting the energy of the γ-ray depending on the zenith angle of the actual event. Once satisfactory training is achieved, the corresponding ANN generated weight-files are then used as a part of the main data analysis program so that the energy of a Cerenkov event can be predicted without using the ANN software package.

A plot of error in the energy resolution function obtained by testing the ANN with individual showers in the two zenith angle ranges is shown in Fig.1. With regard to finding an appropriate choice for the energy bin size, it is evident from Fig.1 that for having about 6 energy bins per energy decade, we require a bin size of about 1.6σ (where σ is the standard deviation of the Gaussian fit to the histograms shown in Fig.1b and Fig.1d). Since the σ values of both these distributions are nearly equal, we can safely say that the energy resolution is $\sim$40% for retaining $\sim 90\%$ of the γ-ray events in a particular energy bin. The results thus obtained suggest the energy resolution of the proposed method is comparable with the energy resolution of other single element imaging telescopes.

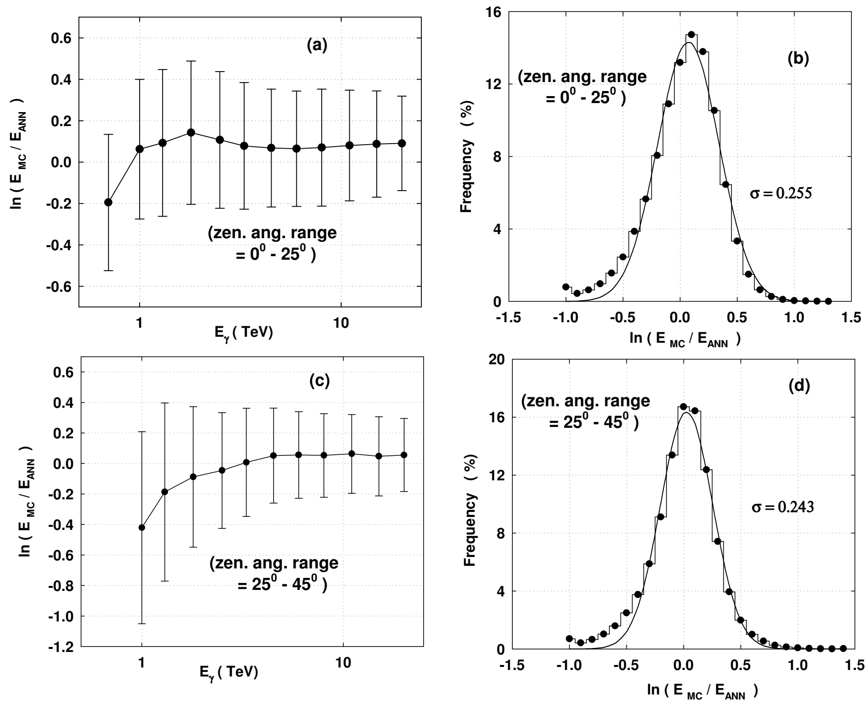

Figure 1. (a) Error in the energy resolution function (ln (E $_{ANN}$/ E$_{MC}$)) as a function of the energy of the γ- rays for the simulated showers generated within 0°-25° zenith angle range. (b) Frequency distribution of (ln (E $_{ANN}$/ E$_{MC}$) for all events shown in Fig.1a along with a Gaussian fit. Figs. (c) and (d) are same as (a) and (b), except that the zenith angle range covered here is 25° -45°.

4. Energy spectrum of the Crab Nebula as measured by the TACTIC telescope

In order to test the validity of the energy estimation procedure, we have used the data collected by the TACTIC imaging telescope on the Crab Nebula for ∼103.6h during Dec 17, 2003 - Feb 23, 2004. The 3-fold prompt coincidence rate of the telescope varied between 2 - 3 Hz during these observations. Various image parameters were calculated for all the events after subjecting each raw Cerenkov image to cleaning and flat fielding. Based on simulation studies carried out for the TACTIC telescope, γ-ray-like events were then selected from the overall data-base by using the Dynamic Supercuts procedure [6]. The events selected after using this selection procedure yield an α-distribution as shown in Fig.2a, where a statistically significant excess of ∼960±87 γ-ray events with a significance of $\sim 11.1\sigma$ is seen. The corresponding residual background level has been estimated on the basis of $18° \leq \alpha \leq 90°$ events . The γ-ray differential spectrum obtained after using appropriate values of effective collection area and γ-ray retention efficiency (along with their energy and zenith angle dependence) is shown in Fig.2b. Since energy spectrum determination also requires an 'instrument calibration' factor for converting image size in CDC counts to number of photoelectrons, this was determined by using the 'excess noise factor method' which yielded a value of ∼10.1±1.5 CDC counts /pe. The best fit differential energy spectrum shown in Fig.2b has a reduced χ^2=0.4 and is given by : (3.18±0.41) (E/1TeV)$^{-2.65\pm0.11}10^{-11}cm^{-2}$ s^{-1} TeV^{-1}. Matching of this spectrum with that obtained by the Whipple and HEGRA groups validates the energy estimation procedure.

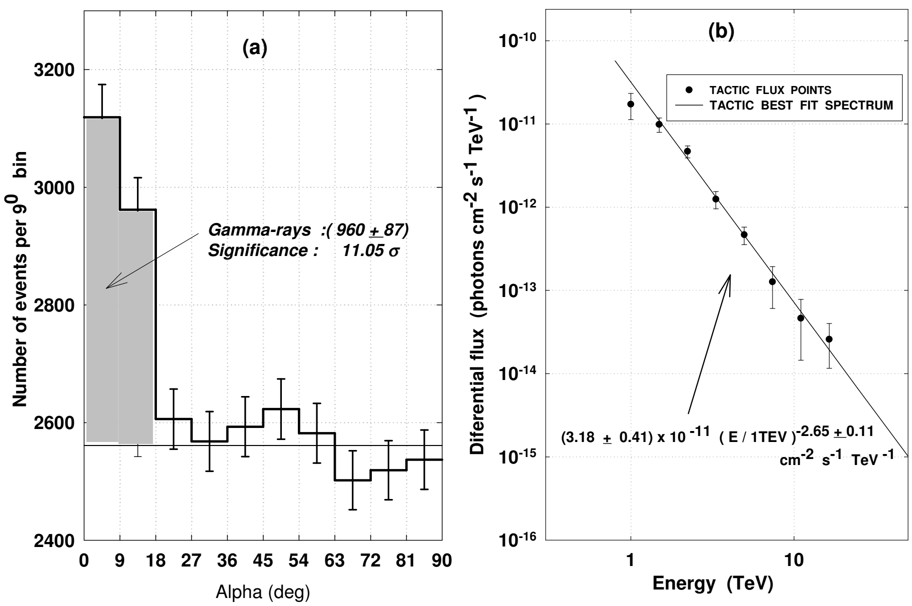

Figure 2. (a) Distribution of the α-parameter for events selected by the Dynamic Supercuts procedure. The source and the background regions used in the analysis are α=0° − 18° and α=18° − 90° respectively. (b) The differential energy spectrum of the Crab Nebula as measured by the TACTIC telescope.

5. Conclusions

A novel ANN-based energy estimation procedure is proposed for finding the energy of γ-rays. The results obtained by applying this procedure to determine the energy spectrum of the Crab Nebula indicate that the spectrum can be determined quite reliably. The sensitivity of the TACTIC telescope, however, needs to be further improved so that relatively weaker sources can also be detected by the telescope.

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