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A Probability Density Method for VHE Gamma-Ray Source Analysis

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Abstract: A probability density method for Very High Energy (VHE) γ-ray source analysis, developed using simulations and Crab Nebula data for the Whipple 10 m telescope, is presented here. Background subtraction is implemented by a modified standard approach using cuts on Hillas parameters, but the use of more complex single cut species discrimination by a kernel multivariate analysis is discussed. The probabilistic method adopted can also be extended into a log likelihood technique where data characteristics such as source strength, extension or multiple sources within the field of view can be determined.

Introduction

The work presented here is an illustrative outline of attempts to develop a complete probability density analysis method capable of detecting weak sources of VHE γ-rays with improved sensitivity. It has been developed using archival Whipple 10m telescope data [1] and Corsica simulations [2].

The method

Standard Whipple 10 m analyses [3] use moments of the elliptical shape produced by air shower images to produce Hillas parameters [4]. They also assume the true source location lies somewhere along the major axis of the image. The extent of the angular distance from the image centroid to the assumed origin point, *disp*, is dependant on the ellipticity of the image;

$$disp = \zeta \left(1 - \frac{width}{length.(1+\eta.leakage)}\right) \quad (1)$$

The additional parameter *leakage* in equation 1 was proposed by the HEGRA group [5] to correct for image truncation which adversely effects the ability to reconstruct source event origins accurately [1]. Image *leakage* is given by the total size content of pixels in the outer camera rim compared to the total image size.

Each possible source location is smoothed with a circular Gaussian or tophat error function [3]. To investigate whether further information can be obtained by using a different error function, all images taken with a point source at the center of the camera can be rotated so that their major axes lie parallel to the camera x-axis (fig.1 top). The resulting spread in reconstructed origins shows that on average the error function is more accurately described by an asymmetric Gaussian with the longitudinal error, σ_x, being larger than the transverse case, σ_y, by a typical 2:1 ratio as demonstrated by Gaussian fits (fig.1 bottom) to the cross-sections of the data (fig. 1 top), where $\sigma_x = 0.178 \pm 0.004$ and $\sigma_y = 0.076 \pm 0.003$. This approach verifies that discussed in [6]

Using a normalised asymmetric Gaussian, the probability density, *pg*, that the event originated from a particular bin in the field of view is given by

$$pg = \frac{1}{\sqrt{2\pi(\sigma_x^2+\sigma_y^2)}} e \frac{-\left[(x-x_0)^2+(y-y_0)^2\right]}{\sqrt{2(\sigma_x^2+\sigma_y^2)}} \quad (2)$$

where x_0 and y_0 are the coordinates of the reconstructed origin, and σ_x and σ_y represent the tran-

1. The *leakage* parameter and correction is not used in standard methods, but is included in this work.

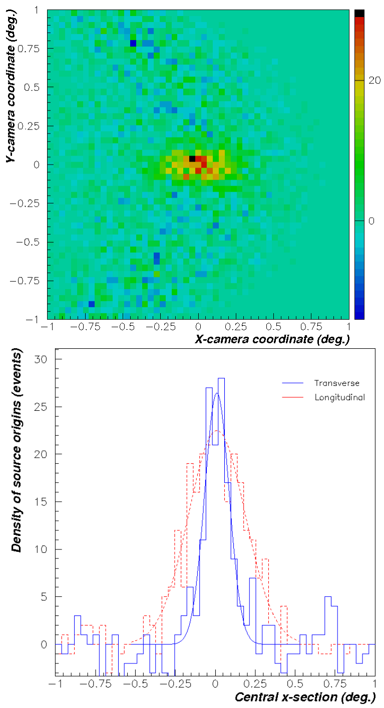

Figure 1: Top: The excess remaining from the rotated origins of ON and OFF observed fields from Crab Nebula archival data. Bottom: Gaussian fits to the transverse (solid) and longitudinal (dotted) cross-sections given above. The asymmetric distribution of the reconstructed source origins from many events is representative of the average error function in the ability to locate a source, the longitudinal direction having a greater uncertainty.

verse and longitudinal uncertainty in location respectively.

A total 2d probability density map is then built by the superposition of all candidate events remaining from a dataset after selection. This sum is called *PON* for the ON (source present in field of view during observations) and *POFF* for the OFF fields respectively, and the significance in this work is given by

$$\sigma = \frac{PON - POFF}{\sqrt{Var(PON) + Var(POFF)}} \quad (3)$$

The validity of this approach has been tested and confirmed by an independant toy model described in [7].

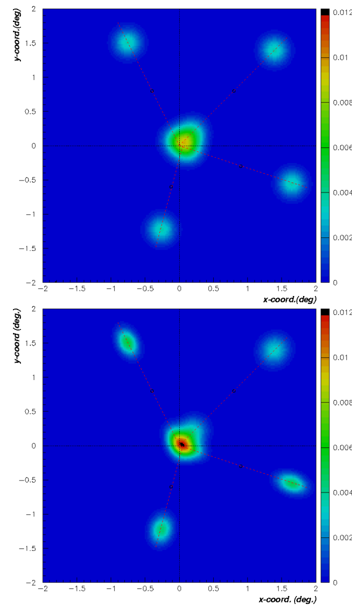

Figure 2: Example of how the probability contours from two events are implemented to built up a 2d probility density (*PON*) map. The top plot uses the circular Gaussian function typical of the standard approach, whereas the lower case shows the use of an appropriate asymmetry in σ_x and σ_y applied to each event. The event centroids and major axes are indicated.

Ideally, in the weak source case, the significance would be expected to scale with *signal*/$\sqrt{background}$, leading to an upper limit improvement of $\sqrt{2}$. The toy model has also been used to demonstrate how a probabilty, *pgamma*, that the candidate event is of γ-ray origin might be superior to the box selection cuts on Hillas parameters which previously have been shown to be very robust over a wide range of observing conditions (fig. 3 right).

Whipple 10 m image cleaning algorithms are dependant on candidate pixels having a signal to noise ratio equal to or above a given threshold. By the introduction of a total island threshold for each patch of signal in the field of view, Bond et al [8] showed using simulations that many pixels containing only background could be excluded and individual pixel S/N thresholds reduced. This work applies Island cleaning to real data and has been shown to be particularly effective for low energy

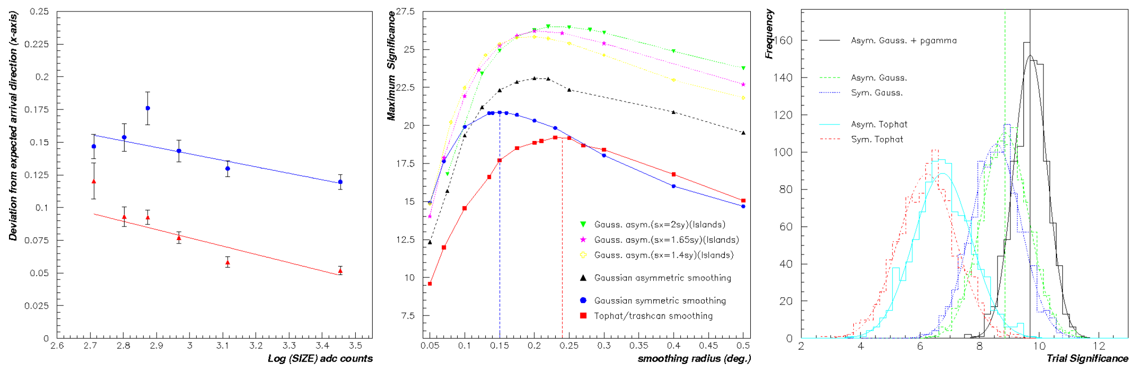

Figure 3: Left: dependence of σ_x (circles) and σ_y (triangles) on log *size*, illustrating the changes to both the extent and asymmetry of the error function for γ-ray simulations. Center: significance achieved for different analysis approaches and smoothing radii used. Right: distribution of significances for 1000 trials from a toy model [7] for different approaches, indicating example benefit of $\sim 10\%$ (black solid line cf. dashed line) for the use of gamma probablity, *pgamma*, above box selection methods for background suppression.

events or the smaller events produced by very large zenith angle observations.

Background subtraction has been implemented in the following by applying a set of Hillas image parameter cuts evaluated for Island cleaned images by maximising for significance on the Crab Nebula. Using the above 2-dimensional probability density (2DPD) techniques, the ability to map γ-ray sources has been shown, for significance achieved, to be superior to previous methods by up to 20%.

As figure 3 left shows, the ability to locate a source origin is highly energy (*size*) dependant, with greater accuracy for higher *size* events. This corresponds to a change in σ_x (circles) and σ_y (triangles) with log *size* as illustrated by fig. 3 right, which can be dynamically applied to each event. Fig. 3 center and table 1 gives the resulting significances and γ-ray rates for the different smoothing and image cleaning approaches to analysis adopted, showing that 2DPD method introduces no bias in the basic symmetric case. Fig. 4 compares the standard and 2DPD methods for 11.7 hours of Crab Nebula data taken during 2003. This work is discussed in detail in [9].

Analysis	Significance	Rate (γmin^{-1})
Stan ($\sigma_{x/y}$ = 0.135)	21.06	2.13
2dpd ($\sigma_{x/y}$ = 0.135)	21.07	2.13
2dpd+asym	22.37	2.13
2dpd+isl	24.54	1.97
2dpd+isl+asym	25.06	1.97
2dpd+isl+asym+s	25.69	1.97

Table 1: Changes to significance and γ-ray rate with different choice of analyses, where stan = standard anaysis, isl = islands cleaning, asym. (σ_x = 0.15 and σ_y = 0.08) the use of asymmetric as opposed to circular smoothing and s size dependance

Further development

The single cut approach to background selection can be implemented in various forms. Those already tested include the kernel multivariate analysis [10], the semi-analytical and 3d modeling methods used by HESS [11], and random forest techniques [12]. This work has developed a new, independant kernel analysis which, in addition to the background rejection and spectral analysis abilities demonstrated by [10], can use the resulting γ-ray probablity as a weight of each event. Furthermore, since the kernel background subtraction technique allows estimation to be made of various event characteristics, the most notable being evaluation of the primary energy, then similar estimation of additional event characteristics, such as the uncertainty in the event origin and the appropriate value of σ_x and σ_y, can also be applied when mapping individual events for improved 2d reconstruction.

Calculation of the value of *pg* at a given location allows a more complex analysis of the dataset by a log likelihood approach, so that for example the

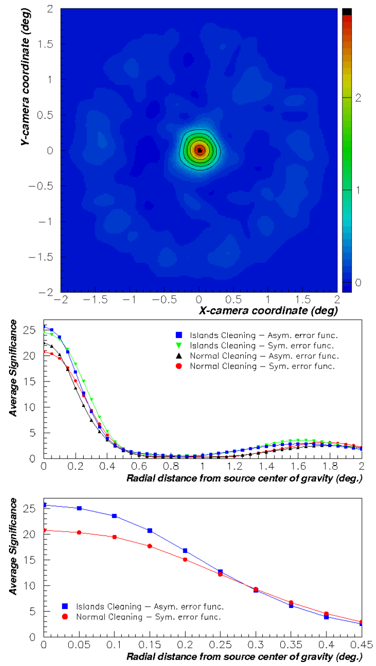

Figure 4: Top: excess map of the Crab Nebula field using the 2DPD and asymmetric smoothing approach. Significance contours are superimposed in 4σ intervals from 8σ. Center: comparitive radial profiles of 2DPD probability density maps for different cleaning and smoothing methods over entire field. Bottom: improvement achieved over source region.

relative likelihood of a dataset of source photons originating from a point source as opposed to an extended or diffuse emitting region can be evaluated.

Work with the kernel multivariate analysis, the log likelihood technique, and the application of the 2DPD method to stereoscopic scenarios are ongoing and will be discussed in [7].

Conclusions

The 2d probability density method has been introduced and compared to standard Whipple telescope analysis and shown to be superior by up to 20% when applied to archival Crab Nebula data. The approach and application has been independantly verified with a toy model. Work continues to apply the technique to candidate weak sources in the Whipple archival data, and to extend the probility density method to stereoscopic observations and survey analysis.

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