Background Modeling in Ground Based Cherenkov Astronomy

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Ground based Cherenkov telescope systems measure astrophysical γ-ray emission against a background of cosmic ray induced air-showers. The subtraction of this background is a major challenge for the extraction of the spectra and morphology of gamma-ray sources. The new generation of ground based very-high-energy γ-ray experiments have greatly increased the sensitivity of the technique, resulting in the detection of many unidentified and extended sources. The analysis of such sources requires a range of different background modeling techniques. Here we describe some of the techniques that have been applied to data from the H.E.S.S. instrument and compare their performance.

1 Introduction

Ground based very-high-energy γ-ray telescope systems such as H.E.S.S. [1], MAGIC [2], VERITAS [3] and CANGAROO-3 [4] have greatly increased the sensitivity of the Atmospheric Cherenkov Technique. However, these instruments can only reach their full potential if systematic effects are brought fully under control. A major systematic problem facing experiments of this type is the subtraction of the background of non-γ-ray induced air-showers. This background can be dramatically reduced using image shape selection criteria, but cannot be removed completely. The background is dominantly hadronic CR showers at energies above a few hundred GeV, with cosmic-ray electrons increasingly important at low energies and after tight image selection cuts. We note that only incorrect background subtraction (or miscounting of statistic trials) can produce an artificial source.

For single telescope instruments (for example the pioneering Whipple telescope [5]) the classical approach to background subtraction was the *on/off* observing mode. In this mode observation *runs* centred on the target source are interspersed with equal length observations of an empty field at equal zenith angle (typically a region offset in Right Ascension by half an hour). As the background is in principle equal in the two runs, the difference between them provides a measurement of the γ-ray signal. A major drawback of this approach is that only half of the available dark time can be used *On-source*. The *wobble-mode* pioneered by the HEGRA collaboration [6] avoids this problem by keeping the target in the field of view (FOV) at all times, but with an alternating offset relative to the camera centre (typical $\pm$ 0.5° in declination). A background estimate can then be derived from the opposite side of the FOV from the same run as the *On*-data.

For wide FOV instruments the probability of serendipitous detection of non-targeted sources rises dramatically (particularly for observations close to the Galactic plane). The discovery of such serendipitous sources (for example HESS J1303-631 [7]) required background models that can be applied to the whole FOV of the instrument. This is of course also true for surveys, and has proved extremely successful in the recent discovery of > 10 new γ-ray sources in a survey of the inner galaxy with H.E.S.S. [8]. Extended sources such as RX J1713.7-3946 [9] and Vela Junior [10] present additional difficulties for background subtraction.

The four main types of background model are introduced below.

2 Background Models

With cuts on image shape the cosmic-ray background can be reduced by a factor of $\sim$100. The remaining background of γ-like events must be estimated to derive the significance of any possible γ-ray signal. Given a number of counts $N_{\rm on}$ in a test region, and $N_{\rm off}$ in a background control region, the γ-ray excess is defined as $N_{\rm excess} = N_{\rm on} - \alpha\, N_{\rm off}$. The parameter α reflects the relative *acceptance* A of the test region and the control region, and can be defined as: $\alpha = \iint A_{\rm on} d\phi\, d\theta / \iint A_{\rm off} d\phi\, d\theta$. The statistical significance (S) of the excess is typically calculated following the prescription of Li & Ma [11] (equation 17). The task of a background model is to provide the quantities $N_{\rm off}$ and α. A choice of background regions such that $\alpha \ll 1$ results in general in higher statistical significance, but may also result in increased systematic errors. The principle difficulty in deriving a background estimate is to find the correct value of α. For on/off observations α is normally given as the ratio of the exposure time of the on and off runs (sometimes weighted by the overall event rate in the two runs). In general α is the ratio of the effective exposure integrated in time and angular space over the on and off regions.

In most of the models described here some knowledge of the system acceptance function A is required to generate an excess map. Although in general A is a function of both θ and ϕ it is often a good approximation to use a radially symmetric model $A(r)$. The shape of the radial acceptance is both energy and zenith angle dependent, and can be determined on a run-wise basis or extracted from a dataset of empty field observations. Figure 1 shows the zenith angle dependence of the radial system acceptance extracted from such a data set. A smooth variation with zenith angle is apparent.

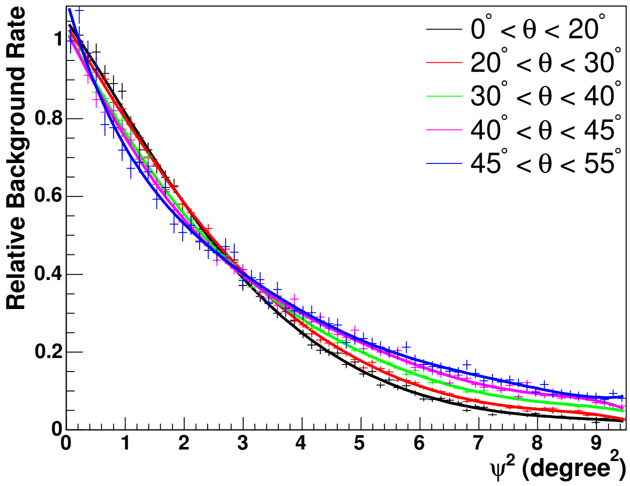

Figure 1: The variation of radial system acceptance with zenith angle. The data are selected from a large (> 100 hour) sample of empty field observations.

The variation of radial acceptance in different FOVs at the same zenith angle is rather small for H.E.S.S., $< 3\%$ within $1°$ of the observation position and $< 10\%$ out to $3°$. The energy dependance of the acceptance is much stronger, greatly complicating the use of models that require an acceptance correction for spectral analysis. Deviations from radial symmetry occur most commonly in the form of linear gradients across the field. Such gradients are expected at large zenith angles due to the significant (zenith angle induced) change in event rate across the field. However, for moderate zenith angles ($< 45°$) such effects are generally small ($< 5\%$).

A method that is robust in the face of linear gradients in arbitrary directions is the *Ring*-background model. In this model a ring around the trial source position (in celestial coordinates) is used to provide a background estimate for any point in the field of view. For this method the parameter α is approximately the ratio of the solid angle of the ring (of typical radius $0.5°$) to the trial source region $\Omega_{\rm on}/\Omega_{\rm off}$, and is typically $\sim$1/7. This method is illustrated schematically in figure 2 (left).

The *Reflected-Region*-background was originally developed for *wobble* observations, but can be applied to any part of the field of view displaced from the observation position. For each trial source position a ring of $n_{\rm off}$ off-regions is used (see figure 2 right). Each off-region is the same size and shape as the on-region and has equal offset to the observation position. In the general case as many off-regions as possible are fit

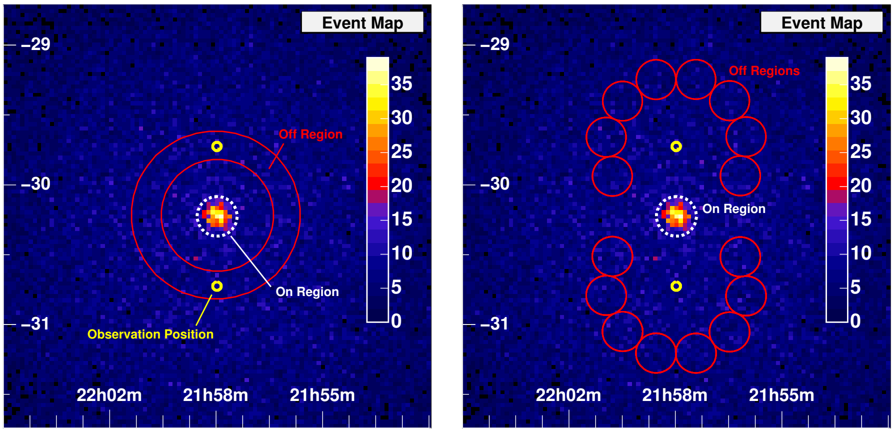

Figure 2: Count map of γ-like events from 5 hours of H.E.S.S. observations of the active galaxy PKS 2155 [12]. The ring- (left) and reflected-region- (right) background models are illustrated schematically.

in to the ring whilst avoiding the area close to the test position to prevent contamination of the background estimate by mis-reconstructed γ-rays. Due to the equal offset of on- and off- regions from the pointing direction of the system, no radial acceptance correction is required with this method and α is just $1/n_{\rm off}$. This is particularly helpful for spectral analysis where an energy-dependent radial acceptance function would otherwise be required.

The *template*-background model was first developed for the HEGRA instrument and is described in [13]. This method uses background events displaced in image shape parameter space rather than in angular space. A subset of events failing γ-ray selection cuts are taken as indicative of the local background level. One issue concerning this model is that the system responds differently to the hadron-like events, resulting in a different radial acceptance function. The ratio of the gamma-ray and hadron acceptances is thus required to determine α. This method has the advantage that the background is determined in the same region as the signal and hence any localised problem, for example due to a bright star, will affect both.

The final method considered here is the *field-of-view*-model. The entire field (excluding regions of known γ-ray emission) is used for the normalisation of an acceptance model to the data and the acceptance ratio α approaches zero. The acceptance model is derived from empty field observations. The advantage of this model is that can be readily applied to extended sources and results in the highest possible statistical significance. However, the method is very sensitive to any deviations of the true system acceptance from the model applied.

Another method that has been applied to H.E.S.S. data is the *weighting* method. Related to the template background, this approach is described in detail elsewhere in these proceedings [14].

3 Model Comparison

A satisfactory background model must meet two main criteria: that it produces a normal distribution of significance for an empty field; and that it produces an excess compatible with other model estimates when a significant signal exists. To test the first of these criteria, the four main background models described here have been applied to the FOV around the supernova remnant SN 1006, a source for which no evidence of γ-ray emission has been found by H.E.S.S. [15]. Figure 3 shows significance maps of the field derived using the four models. The maps show statisfactory agreement with the exception of the region close to a bright ($m_B = 2.5$) star in the lower right of the FOV. Bright stars cause a reduction in the local rate of background events, producing a dip in all maps except that derived using a template-background. For the particular choice of hadron-like events employed here, the template model over-corrects for the dip in the γ-ray acceptance.

Figure 4 shows the distribution of significance for independent bins the field of view of SN 1006 for the ring and reflected-region models. Despite the influence of the bright star the distributions show statisfactory agreement with the expected normal Gaussian.

A systematic comparison of the γ-ray excess estimated by different background models has been performed for the whole H.E.S.S. 2004 Galactic plane survey. Figure 5 shows the correlation between the excesses derived using ring- and template background models. The correlation is close to linear over a large dynamic range. The spread is consistent with statistical fluctuations in N_{off}.

4 Conclusions

Several different background models are available for ground based Cherenkov astronomy. Different models are appropriate for different purposes. Searches for weak sources are best performed with the robust ring-background model and/or template-background. For spectral analysis the reflected-region-background is favoured. Ex-

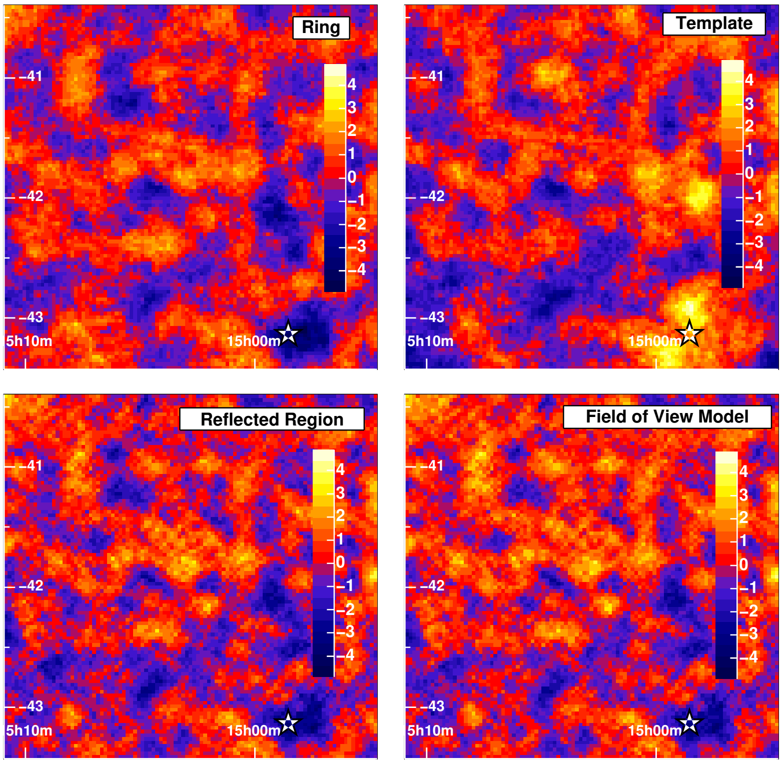

Figure 3: Statistical Significance maps for the field around the supernova remnant SN 1006 derived using four different background models. 6 hours of 4-telescope H.E.S.S. data are used. The white star in each field marks the position of a bright $m_B = 2.5$ star.

tracting the morphology of extended sources is often most reliable with the on/off, field-of-view or template models. In general, a comparison of several models (with different systematics) is necessary to establish the existence of a new source. It is important to remember that the estimated statistical significance of a source is largely irrelevant if background systematics are not under control.

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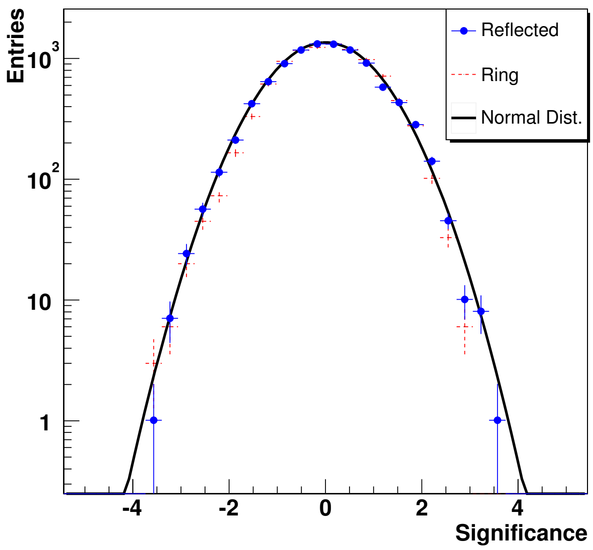

Figure 4: Distribution of significance in the FOV around SN 1006 for the ring and reflected-region background models. The solid black curve illustrates the expected normal Gaussian distribution. Deviations from the expected behaviour are at the less than 1% level.

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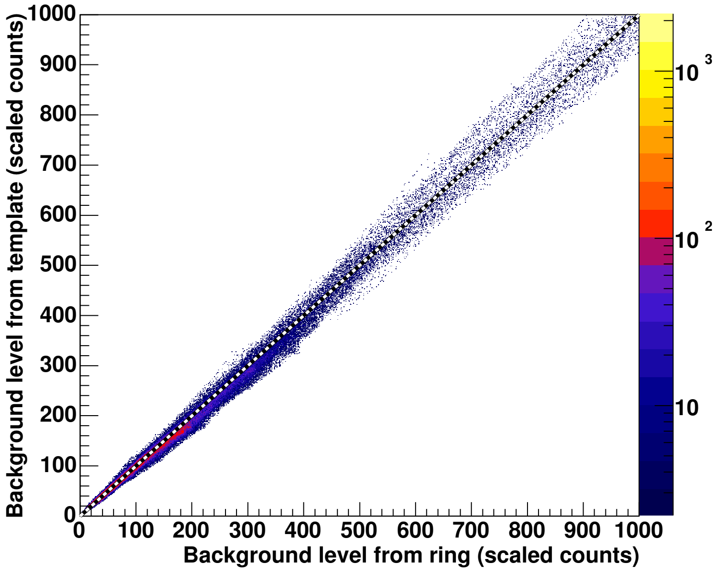

Figure 5: Correlation of excess counts derived from the template and ring background models for the full region of the H.E.S.S. 2004 Galactic plane survey. The gradient of the correlation is 1.007. See [16] for more details.

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