Selection and 3D-reconstruction of gamma-ray-induced air showers with H.E.S.S.

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Abstract. H.E.S.S. (High Energy Stereoscopic System) is an array of four large imaging Cherenkov telescopes devoted to gamma-ray astronomy above 100 GeV. It has been fully operational since December 2003. Here, we report on a new analysis method based on a simple 3D-modeling of an electromagnetic air shower. This method allows to separate gamma-rays from background events in the field of view without any assumption on the morphology of the source or on the background distribution. This is a crucial point in the study of extended sources (e.g. Supernova Remnants) or in the search for unexpected sources in a sky survey. The performance and results of this method on galactic sources are presented.

INTRODUCTION

An important goal in the new phase of TeV gamma-astronomy opened with H.E.S.S. is the search for extended sources — e.g. supernova remnants — or for unexpected sources in a sky survey. In such a study, the hadronic background cannot be subtracted on the basis of the angular distribution (e.g. the classic $\theta^2$ or $\alpha$ plots) used for point-like objects whose celestial coordinates are known. Here, we present an analysis method based on two steps. The first step reconstructs each event, using stereoscopy and a simple model of electromagnetic shower. The second step extracts and separates gamma-ray and background distributions in a given field-of-view without any assumption on the morphology of the source or on the background distribution by using a maximum-likelihood method.

THE 3D-MODEL

The most important characteristics of electromagnetic showers considered here is that the spatial distribution of the emission points of Cherenkov photons, and the angular distribution of these photons with respect to the shower axis, are on average rotationally symmetric with respect to the shower axis. The 3D-model of $\gamma$-ray showers presented here is based on two simplifying assumptions:

1. The emission points of Cherenkov photons are distributed according to a 3-dimensional Gaussian law with rotational symmetry with respect to the shower axis; it is thus characterized by the following parameters: the direction of the
shower in the reference frame of the telescope, the position of the core on the
ground, the altitude of shower maximum, the longitudinal ($\sigma_L$) and transverse ($\sigma_T$)
standard deviations of the Gaussian distributions, referred to as “3D-length” and
“3D-width” respectively and the total number $N_c$ of emitted Cherenkov photons.
The preceding quantities, referred to as “shower parameters”, will be determined
by a maximum likelihood fit.

2. The angular distribution of Cherenkov photons with respect to the shower axis
is assumed to scale with the maximum Cherenkov angle at a given altitude and
to be independent of other variables. This average distribution is derived from
simulations.

The preceding 3D-model enables us to work out the expected number of Cherenkov
photons $q_{th}$ collected by a given pixel of a given telescope as a function of the shower
parameters listed above, by an integration along the line of sight of each pixel. The
quantities $q_{th}$ for all pixels, calculated for a set of shower parameters, are further used
to build up a likelihood function for each event including at least two images of a
given shower. The likelihood function for each event is then maximized with respect
to the 8 shower parameters defined above. Thus, for each event, we obtain a complete
description of the shower (see reference [1] for more details on the performance of the
3D-model). These informations can then be used to subtract the background with the
following “weighting method”.

**IMPLEMENTATION OF THE WEIGHTING METHOD**

The proposed method [2] assumes that the distributions of $\sigma_T$ are known both for
gamma-rays and hadronic showers. Some calibration work is thus necessary, e.g. from
data taken on point-like sources at different locations in the field-of-view, at different
zenith angles. The $\sigma_T$ distributions can of course be independently obtained from sim-
ulations. For reasons of clarity, we shall assume here that the $\sigma_T$ distributions for each
population (gamma-rays and hadrons) in a given field-of-view are independent of the
shower directions and energies. These assumptions can be easily relaxed, at the expense
of a more complex calibration procedure, the only important constraint of the method
being that the $\sigma_T$ distributions are “a priori” known as functions of the relevant parame-
ters. In the simple case considered here, we call $g(x)$ and $b(x)$ the probability distribution
functions of $x \equiv \sigma_T$ for gamma-rays and hadrons respectively.

The skymap obtained after reconstruction is divided into pixels in celestial coordinates
and the following procedure is applied separately to each pixel. Therefore, no correlation
between different parts of the field-of-view is induced by the method and no assumptions
are made on the signal or background morphology. For each event, the reconstruction
procedure described above provides the original direction (thus the relevant pixel in the
field-of-view) and the 3D-width. We now consider a given pixel containing $N$ events
with 3D-widths $x_1, x_2, ..., x_N$. We call $n_g$ and $n_b$ the expectation values of the number
of gamma-ray and background events respectively. The probability to get the observed
configuration (up to differentials $dx_1, dx_2, \ldots, dx_N$) is:

$$\frac{\exp\left(-n_g - n_b\right)}{N!} \prod_{i=1}^{N} \left[n_g g(x_i) + n_b b(x_i)\right] \, dx_1 \, dx_2 \ldots dx_N .$$  \hspace{1cm} (1)

This formula can be easily obtained, starting from Poisson distributions for the event numbers, then considering the different partitions between gamma-ray and background events leading to the values $x_1, x_2, \ldots, x_N$, while taking care of the normalization. The likelihood function is then minimized with respect to $n_g$ and $n_b$, which yields the following equations allowing an iterative calculation of $n_g$ and $n_b$, as shown below:

$$n_g = \sum_{i=1}^{N} \frac{n_g g(x_i)}{n_g g(x_i) + n_b b(x_i)}, \quad n_b = \sum_{i=1}^{N} \frac{n_b b(x_i)}{n_g g(x_i) + n_b b(x_i)} .$$

Once the convergence is achieved, for each event, the following quantities:

$$w_{gi} = \frac{n_g g(x_i)}{n_g g(x_i) + n_b b(x_i)} \quad \text{and} \quad w_{bi} = \frac{n_b b(x_i)}{n_g g(x_i) + n_b b(x_i)}$$

can be interpreted as the weights of event $i$ in the gamma-ray and hadron hypotheses respectively since $n_g = \sum_{i=1}^{N} w_{gi}$ and $n_b = \sum_{i=1}^{N} w_{bi}$; furthermore $n_b + n_g = N$. By repeating the preceding procedure for each pixel of the field-of-view independently, one gets two maps, one for gamma-rays and the other for the hadronic background. The method also provides a consistency check, since the histograms of the 3D-width of all events weighted according to $w_{gi}$ and $w_{bi}$ respectively should be compatible with the original distributions $g(x)$ and $b(x)$.

**FIGURE 1.** Distribution of the direction of the primary particles (gamma-rays and hadrons) in the field-of-view. The map is centered on the position of the Crab nebula. The pixel size is $0.05^\circ \times 0.05^\circ$.

**CALIBRATING AND TESTING THE METHOD ON THE CRAB NEBULA**

The Crab nebula is a point-like source which has been well studied by H.E.S.S. The 3D-reconstruction procedure described above has been applied to a data set representing 2.7
First of all, the data have been used to determine the functions $g(x)$ and $b(x)$. Figure 2 shows the 3D-width distributions obtained from the data in two different regions of the field of view. The solid-line histogram corresponds to a region close to the source ($\theta^2 < 0.05 \text{ deg}^2$), $\theta$ being the angle between the reconstructed direction of the shower and that of the source, whereas the dotted histogram, referring to a region with no significant gamma-ray contribution ($\theta^2 > 0.2 \text{ deg}^2$) yields the 3D-width distribution of the background. Since gamma-rays are not expected to contribute to large widths, the two histograms have been normalized to the same number of events with 3D-widths greater than 40 m, which allows a straightforward subtraction of the background, yielding the 3D-width distribution for gamma-rays, shown by the solid-line histogram in figure 3. Gamma-ray events with a Crab-like spectrum were also simulated in the same conditions of observation and submitted to the same reconstruction procedure; the corresponding 3D-width distribution, shown by the dotted histogram in figure 3, is very similar to the experimental one.

In order to determine the functions $g(x)$ and $b(x)$, the solid-line histogram of figure 3 and the dotted histogram of figure 2 were fitted.

The method was then applied to the Crab nebula 2003 data set, yielding the two sky maps shown in figure 4, one for gamma-rays and the other for background events. On the first map, the signal is actually distributed according to the point-spread function expected from simulations. Figure 5 shows the 3D-width distributions in which each event contributes according to its weight $w_{gi}$ (as a gamma-ray) and $w_{bi}$ (as a hadron) respectively (“a posteriori” distributions). As a consistency check of the method, the

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**FIGURE 2.** 3D-width distributions from Crab data. (a) Solid-line histogram: events for a region close to the source ($\theta < 0.05 \text{ deg}^2$). (b) Dotted-line histogram: events in a region that excludes the source ($\theta^2 > 0.2 \text{ deg}^2$). Both histograms are normalized to the same number of events with widths greater than 40 m.

**FIGURE 3.** 3D-width distribution of gamma-rays. (a) Solid-line histogram: experimental distribution obtained from figure 2 after background subtraction (see text). (b) Dotted-line histogram: distribution obtained from simulated gamma-rays.
FIGURE 4. Separated distributions of events in the field-of-view of the Crab nebula. (a) Gamma-rays. (b) Background events.

FIGURE 5. “A posteriori” 3D-width distributions for gamma-rays (left) and hadrons (right), compared to functions $g(x)$ and $b(x)$ used in the method.

histograms in figure 5 are superimposed to the functions $g(x)$ and $b(x)$ conveniently renormalized. A perfect agreement is obtained for gamma-rays, whereas a slight difference is detected for hadrons, due to the simplifying assumption that $b(x)$ should be independent of the position in the field of view.

THE METHOD AS APPLIED TO THE SUPERNOVA REMNANT RXJ 1713-3946

The satisfactory results obtained on the Crab nebula allow us to consider them as a measurement of the functions $g(x)$ and $b(x)$ which can be applied to other fields of view and in particular to RXJ 1713-3946. The present sample corresponds to 17.8 hours of observation at different zenith angles (from $16^\circ$ to $46^\circ$). The distribution of $\sigma_T \cos \zeta$ was assumed to be independent of the zenith angle $\zeta$ [1]. Figure 6 shows the distributions of the origins of gamma-rays. We can clearly see the shell morphology of the supernova
remnant with a significance of nearly 38 sigmas and a threshold of about 200 GeV.

CONCLUSION

By parametrizing the 3D-width distributions for gamma-rays and for hadrons, it is thus possible to avoid using cuts. This contrasts with the classic analysis based on cuts on several Hillas parameters. On the other hand, the present method is as sensitive as the standard one on a point-like source like the Crab and it has the advantage to be directly applicable to extended sources. Even with a rather crude calibration, the method explained above gives satisfactory results on the H.E.S.S. data taken on RXJ 1713-3946 with two telescopes. The weighting method explained above has been applied to H.E.S.S. data taken on RXJ 1713-3946. No restriction to high energy events has been used in the present analysis and the background subtraction is nevertheless satisfactory.

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REFERENCES