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The DISP analysis method for point-like or extended γ source searches/studies with the MAGIC Telescope

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Many of the Galactic sources of interest for the MAGIC Telescope are expected to be extended. The good telescope angular resolution of about 0.1° allows to study extended or off-axis sources with the appropriate analysis methods. We have developed an analysis method (Disp) that uses the information of the shower image shape to reconstruct the position of the source for each detected shower. Starting from the previously successful application by the Whipple Collaboration, the Disp method has been improved and adapted to MAGIC. We report on the performance and present the results obtained on 5.5 hours of Crab Nebula data observed on-axis.

1. Motivation for reconstructing the arrival direction of γ-rays

In the standard operation mode, an Imaging Air Cherenkov Telescope (IACT) points to the source under study, implying the source direction to coincide with the camera center. However, analysis methods which assume that the position of the source in the camera is known can not be used for many observations: extended sources, as Galactic Supernova Remnants or dark matter searches; sources whose position is a priori badly known, as is the case of unidentified EGRET sources or GRBs; or new sources in the camera field of view (FOV), for example when doing a sky scan [7] or serendipitously found in the FOV of another source. An analysis method (Disp) which reconstructs the individual γ-ray arrival direction has been developed to treat all these cases. This contribution reviews the implementation of the method and its performance for the analysis of data recorded with the MAGIC Telescope [6].

2. The concept of the Disp method

The Disp method uses the information of the shower image shape to reconstruct the position of the source on an event-by-event basis. The source position is assumed to lie on the major axis of the Hillas ellipse that fits the shower image in the camera, at a certain distance (DISP) from the image center of gravity (COG). Fomin et al. [2] proposed the use of the 'ellipticity' of the shower images (defined as WIDTH/LENGTH) to infer the position of the source of individual showers using a single IACT. The method was applied, among other IACTs, by the Whipple Collaboration [5] and the HEGRA Collaboration for the stand-alone CT1 telescope [4]. It provided a good angular resolution for single IACTs (0.12° above 500 GeV).

2.1 The DISP parameterization

Lessard et al. [5] proposed a parameterization of DISP using the minor (WIDTH) and major (LENGTH) axes of the Hillas ellipse that characterizes the shower image. Because of the different features of the MAGIC

Telescope, such as its parabolic reflecting surface and low energy threshold, we adopt a more general parameterization. It describes better the correlation between the shower elongation and the distance shower-COG/source-position, providing an improvement of the angular resolution:

$$DISP = A(SIZE) + B(SIZE) \cdot \frac{WIDTH}{LENGTH + \eta(SIZE) \cdot LEAKAGE2} \quad (1)$$

The new parameterization includes a second order polynomial dependence of the parameters on the logarithm of the total image charge (SIZE). We have also included a correction term in LENGTH to account for images truncated at the edge of the camera, similarly to the correction introduced by D.Kranich et al. [4] for the CT1 HEGRA telescope. The LEAKAGE2 parameter is the ratio between the charge content in the two outermost camera pixel rings and the total charge content of the recorded image.

Optimal values for the Disp parameter functions (A, B and η) can be determined from Monte Carlo (MC) simulations or real data from a well known point-like source. In this work, a sample of MC simulated γ-rays (zenith angle $< 30°$) has been used. The average angular distance (θ^2) between the real and estimated source position is the parameter required to be minimized.

The distributions of reconstructed arrival directions are described, in a first approximation, by a bidimensional symmetric Gaussian, so that 39.3 % of the events lies within a radius of 1σ and 86.5 % within 2σ. We adopt σ as the angular resolution estimator.

2.2 'Head-Tail' information from shower images

The DISP calculation, Eq. 1, provides two possible source positions along the shower major axis. Therefore, a method to select the correct one is needed. Images in the telescope camera contain information about the longitudinal development of the shower in the atmosphere. Cherenkov photons from the upper part of the shower create a narrower section of the image with a higher photon density ('head'), photons from the shower tail normally generate a much more fussy and spread image end ('tail'). Therefore, asymmetries in the charge distribution of the images can indicate to which image edge the source position is closer.

The ASYMMETRY parameter, defined as the signed distance between the charge distribution COG and the pixel with the maximum signal, allows in most cases to determine the 'head-tail' of a shower image, providing the selection efficiency for the photon density in the image is high. This is normally the case for high energy showers (>70% correct 'head-tail' reconstruction for SIZE>180 photoelectrons [phe]). New image asymmetry parameters have been defined to improve the 'head-tail' discrimination, like applying different weights to the pixel positions when calculating moments of the photon distribution in the camera. By combining them, through a multidimensional events classification algorithm, the correct 'head-tail' assignment improves up to 85% for SIZE>180 phe. However, studies on these new parameters are still ongoing and here we use ASYMMETRY as 'head-tail' discriminator.

3. Application to real data: Crab Nebula

In order to assess the angular resolution provided by the Disp method, we have analyzed 5.5 hours of Crab Nebula taken on September and October 2004, at zenith angle below 30°. The source was observed on-axis. 3 hours of OFF data have also been analyzed for background estimation. After data calibration and image cleaning, we have used the Random Forest method [1] to discriminate γ-ray from hadron events. The Random Forest has been trained with MC γ-rays and a fraction of the OFF data as hadron sample. Each event is then tagged with a HADRONNESS parameter which is a probability for an event to be background. As training parameters for the gamma/hadron separation only Hillas parameters independent on the source position in the camera has been used, i.e., WIDTH, LENGTH, CONC, and SIZE. The background sample has been selected such that its SIZE distribution resembled that of the MC sample, in order to avoid dependencies on the MC generated spectrum. With a test sample, the HADRONNESS cut is optimized (maximizing the gamma/hadron separation while retaining at least 80% of gammas and sufficient OFF events for background estimation) for different SIZE bins. The remaining OFF data sample used for the analysis (1.4h) was just about 25% of the ON sample. Therefore, in order not to be dominated by the OFF fluctuations, we have adopted models to fit the background in the excess region [3].

To estimate the angular resolution provided by the Disp method, the distribution of reconstructed arrival directions was fitted by a 2-dimensional bell-shaped Gaussian function, leaving σ as a free parameter. Results for MC gammas and for the Crab Nebula data are shown in Figure 1. The global σ for SIZE>180 phe ($\sim$140 GeV) is $0.102° \pm 0.008°$. The improvement in the angular resolution is significant when compared to previous single IACT results.

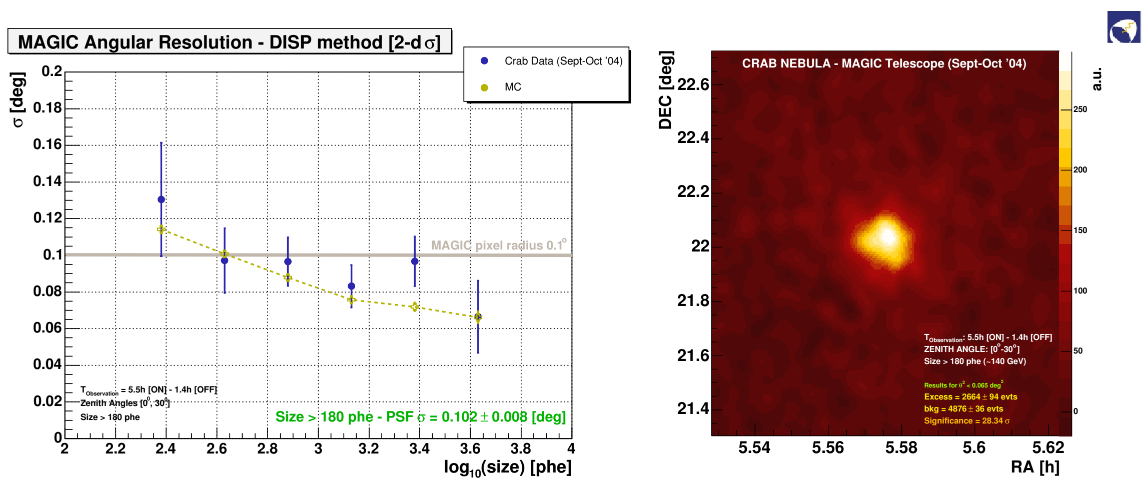

Figure 1. Left: σ of the 2-dimensional Gaussian fit to the distribution of reconstructed arrival directions, both for MC and Crab Nebula data, for the SIZE bins in Table 1. Right: Smoothed skymap for Crab using the Disp analysis method.

In order to compare our bidimensional analysis to the standard α-based analysis we have computed the number of excess events and significance of the signal with both methods for different SIZE bins. To make them comparable, an additional cut in ASYMMETRY has been used in the α-analysis, like the one introduced in Disp for the 'head-tail' discrimination, which reduces the background by 50% and the number of excess events by 20% in the signal region. Results are shown in Table 1. The α-plot and θ^2-plot above 180 phe are shown in Figure 2. The bidimensional Disp analysis gives better sensitivity compared to the standard α-analysis.

4. Conclusions

The Disp method for the reconstruction of the γ-ray arrival directions has been successfully used to analyze the MAGIC Telescope data. For energies above 140 GeV both MC and real data computations yield angular

Table 1. Results for the Disp analysis applied to Crab Nebula compared to the α-analysis (numbers in brackets)

Size Bin [phe]	Excess Counts	Background Counts	Significance	2-d σ [deg]	$\theta^2(\alpha)$ [deg^2]([deg])
180<SIZE<320	316±73(248±78)	4158±29 (3688±47)	4.33σ(3.16σ)	.130±.031	<.115(<17.5)
320<SIZE<570	738±48(794±71)	1219±19 (2062±46)	15.31σ(11.17σ)	.097±.018	<.070 (<20.0)
570<SIZE<1010	801±42(676±45)	737±17(861± 22)	18.72σ(14.94σ)	.096±.013	<.095(<15.0)
1010<SIZE<1800	511±27(432±29)	198±7(331±10)	18.41σ (14.62σ)	.083±.012	<.045(<10.0)
1800<SIZE<3200	312±23(275±23)	205±6(218±8)	13.14σ (11.60σ)	.097±.014	<.065(<10.0)
3200<SIZE<5690	72±10(128±14)	30±3(67±4)	6.79σ (8.81σ)	.066±.020	<.015(<7.5)

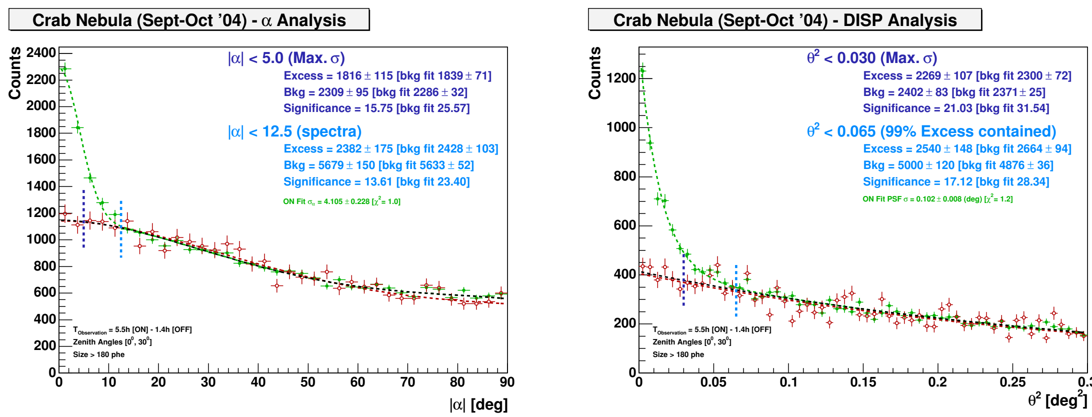

Figure 2. Crab Nebula α-plot and θ^2-plot for SIZE>180 phe. Two cuts applied: one maximizing the significance and one retaining 99% of the excess events. Results for background fitting are displayed in brackets.

resolutions better than 0.1°. For lower energies the performance does not dramatically degrade, but the lack of statistics excluded a possible MC/data comparison. The application of the method to Crab Nebula on-axis data shows that this bidimensional Disp analysis is competitive with the standard α-based analysis.

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