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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 us to study extended or off-axis sources with the appropriate analysis methods. We have developed an analysis method (called 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 achieved when applying it to 5.5 hours of Crab Nebula observed on-axis.

1. Motivation for a γ-ray arrival direction reconstruction

In the standard operation mode, an Imaging Air Cherenkov Telescope (IACT) points to the source under study. It is assumed that the source position is at the center of the camera. However, many observations involve conditions that prevent us from using this standard analysis, like observations of extended sources. This includes Galactic Supernova Remnants, Galactic plane emissions or dark matter searches. Moreover, observations of point-like sources at some offset from the telescope axis, due to important uncertainties in the a priori knowledge of the source position (as the case of unidentified EGRET sources or GRBs), due to serendipitous search for sources (when doing a sky scan [7] or in the field of view of another source), or even because on purpose off-axis observation of a well known source (called 'Wobble' observation mode), require a treatment different from the standard. 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 lies 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. Fomin et al. [2] were the first to propose 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 by the Whipple Collaboration [5] and provided a good angular resolution for single IACTs (0.12° above 500 GeV). This technique was also adopted by the HEGRA Collaboration when analyzing the data of the stand-alone HEGRA telescope CT1 [4], and by other IACTs.

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 adopted a more general parameterization. This describes better the correlation between the shower elongation and the distance shower/source and improves the angular resolution. Additionally, we have added a dependence of the parameters with the total charge (SIZE) of the shower image:

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

We have also included a correction term in LENGTH to account for images truncated at the edge of the camera, similar to the correction introduced by D.Kranich et al. [4] for the CT1 HEGRA telescope. The LEAKAGE2 parameter is defined as the ratio between the light content in the two outermost camera pixel rings and the total light content of the recorded shower image.

The optimal values of the Disp parameters can be determined from Monte Carlo (MC) simulations or real data from a well known point-like source. In this work, we have optimized these values with a MC simulated γ-ray sample (zenith angle $< 30°$) by minimizing the average angular distance (θ^2) between the real and estimated source position.

The distributions of reconstructed arrival directions are described, in a first approximation, by a bidimensional symmetric Gaussian, so that $\sim 40\%$ of the events lies within a radius of 1σ and $\sim 85\%$ within 2σ. We adopt σ as an angular resolution estimator.

2.2 'Head-Tail' information from shower images

The DISP calculation, eq. 1, provides two possible source position solutions along the shower major axis. Therefore, a method to select the correct source position is needed. Images in the telescope camera carry some information about the longitudinal development of the shower in the atmosphere. The 'asymmetry' charge distribution in the images contains the 'head-tail' information of the recorded shower, i.e, which image edge is closer to the source position in the camera plane. Cherenkov photons from the upper part of the shower create a narrower section of the image with a higher photon density ('head') than photons arriving from the shower tail. The photons from the shower tail should normally generate a much more fussy and more spread end of the image.

An image parameter, the so-called ASYMMETRY, is defined as the direction between the center of gravity of the charge distribution image and the position of the maximum signal pixel. It allows one in most cases to determine the 'head-tail' assignment to a shower, providing the selection efficiency for the photon density in the image is high. This is normally the case for high energy showers ($>$70% for SIZE$>$180 photoelectrons [phe]). In addition, we introduced new image asymmetry parameters have been defined to improve the 'head-tail' discrimination, like applying different set of weights to pixel charge contents. By combining them, through a multidimensional events classification algorithm, the achieved ratio of correct 'head-tail' assignment improves to up to 85% for SIZE$>$180 phe, but the study is not completed. Here, we have used the ASYMMETRY as discriminator, leaving the improved variable combination for further studies.

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. Also, we took 3 hours OFF data 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 is trained with MC γ-rays and a fraction of OFF data as hadron sample. Each event is then tagged with a HADRONNESS parameter which is an estimation of the probability for an event to be a background. As training parameters for the gamma/hadron separation we used those Hillas parameters which are basically 'independent' of the source position in the FOV of the camera, i.e., WIDTH, LENGTH, CONC, and SIZE. We selected the background sample such that its SIZE distribution resembled that of the MC sample in order to avoid dependences on the MC generated spectrum. With a test sample, we optimize the HADRONNESS cuts (maximizing gamma/hadron separation while retaining at least 80% of gammas and sufficient OFF events for background estimation) for the different SIZE bins. The size of the remaining OFF data sample used for the analysis (1.4h) was of about 25% compared to 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].

We approximated the distribution of the reconstructed arrival spots by a 2-dimensional bell-shaped Gaussian function leaving the sigma as a free parameter. The values of σ, obtained from fits to the MC gamma data and to the Crab Nebula data are shown in Figure 1. The global σ for SIZE>180 photo-electrons ($\sim$140 GeV) is $0.102° \pm 0.008°$. The results show a significant improvement in the angular resolution of the MAGIC telescope when compared to the results of Lessard et al [5].

In order to compare our bidimensional analysis to the standard ALPHA-based analysis we have computed the number of excess events and significance for different SIZE obtained using both analysis. To make them comparable, we use for the α-analysis those images that points to the center (based on the ASYMMETRY parameter). This adds an additional cut, like the one introduced in the Disp-analysis with the 'head-tail' discrimination, which reduces the background in the excess region by 50% as well as 20% of the excess events. The results are shown in table 1. The α-plot and θ^2-plot above 180 phe are shown in figure 2. The used bidimensional analysis gives a better sensitivity compared to the standard α-analysis.

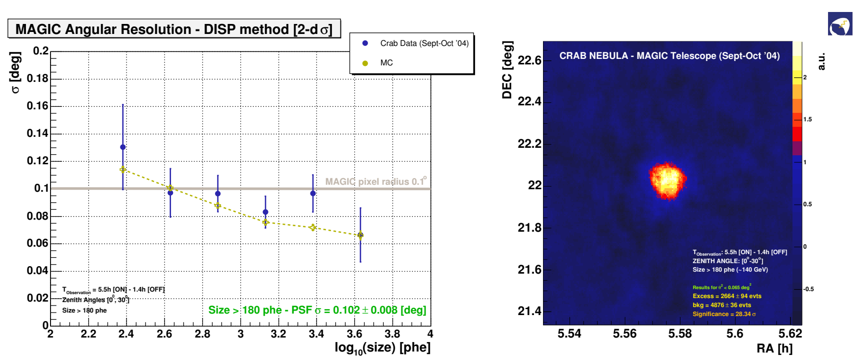

Figure 1. (*left*) Results of 2-dimensional Gaussian fits to the distribution of reconstructed arrival directions, both for MC and Crab Nebula, for the different SIZE bins considered. The PSF obtained for SIZE > 180 phe is displayed in lower-right text. (*right*) Smoothed skymap for Crab Observations using the DISP analysis method.

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 measurements yield angular resolutions better than $0.1°$. The studies show that the performance does not dramatically degrade for lower

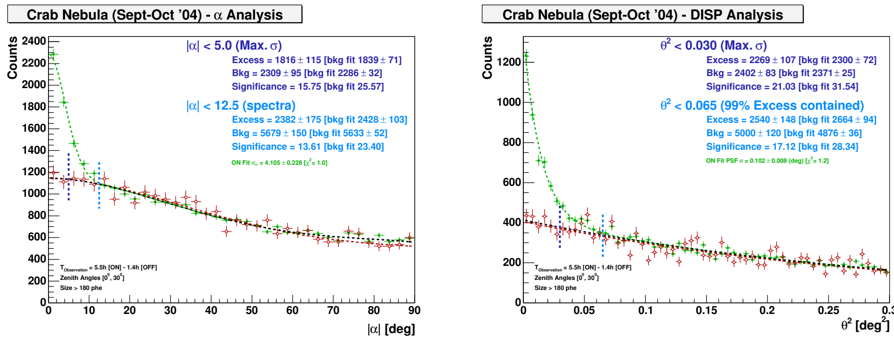

Figure 2. Crab Nebula α-plot and θ^2-plot for SIZE>180 phe. Two cuts applied: the one which maximize significance and the one which retain 99% of the excess signal. Results for ON-OFF$_{fit}$ are displayed in brackets.

Table 1. Results for the Disp analysis to Crab Nebula compared to 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)	.113 ± .030	<.115 (<17.5)
320 < SIZE < 570	738 ± 48 (794 ± 71)	1219 ± 19 (2062 ± 46)	15.31σ (11.17σ)	.086 ± .007	<.070 (<20.0)
570 < SIZE < 1010	801 ± 42 (676 ± 45)	737 ± 17 (861 ± 22)	18.72σ (14.94σ)	.101 ± .006	<.095 (<15.0)
1010 < SIZE < 1800	511 ± 27 (432 ± 29)	198 ± 7 (331 ± 10)	18.41σ (14.62σ)	.069 ± .005	<.045 (<10.0)
1800 < SIZE < 3200	312 ± 23 (275 ± 23)	205 ± 6 (218 ± 8)	13.14σ (11.60σ)	.082 ± .006	<.065 (<10.0)
3200 < SIZE < 5690	72 ± 10 (128 ± 14)	30 ± 3 (67 ± 4)	6.79σ (8.81σ)	.035 ± .017	<.015 (<7.5)

energies, 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 analysis is competitive, respectively slightly superior compared to the standard ALPHA-based analysis for point-like on-axis sources.

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