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Comparison of On-Off and Wobble mode observations for MAGIC

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One of the main goals of the MAGIC telescope is to reduce the energy threshold accessible to the imaging Cherenkov technique. Due to the fact that the background suppression becomes increasingly difficult for lower energies it is important to reduce the possible systematic error of the background determination. An observation mode in which the source is not in the center of the camera allows to have a symmetrical sky position, for which the background can be determined. This ensures having similar systematics like nearly the same zenith angle and the same weather conditions. A comparison with the classical On-Off observation will be presented.

Introduction When observing a gamma ray source candidate with an IACT, standard observations are done such that the source is located in the center of the camera. To determine the background *behind* the source an independent sky region, under observation conditions as similar as possible, is observed or the background is extrapolated from an off-source region in the same measurement (eg. the region between $(\vartheta/\circ)^2 = 0.2$ and $(\vartheta/\circ)^2 = 0.4$ in 1, right). In this case having the source in the most privileged position in the camera there is the possibility of having a fake excess of events being a feature of the background rather than a gamma ray source. Instead of observing the source in the center of the camera, the telescope can be pointed to a sky position slightly off-source (for the MAGIC telescope typically $0.4°$). The background can then be extracted from a so called *anti-source* position symmetrical w.r.t the camera center. Due to the ALT-AZ mount of the telescope source and anti-source will rotate around the center of the camera which might smear out systematics due to camera defects. The distance between them is chosen such that the background measurement is not influenced too much by the source itself. This observation mode is called *Wobble Mode* because several off-axis positions around the source are observed in an alternating fashion. Typically two position symmetric w.r.t the source are convenient making source and anti-source more equivalent (eg. zenith angle). It was extensively and successfully used by the HEGRA telescopes and is currently used by the H.E.S.S. telescopes.
In this paper a comparison of observations made in wobble mode and in the on-off mode is presented.

On-Off observation mode In on-off observation mode the source is located in the camera center. For background determination a similar sky region must be observed. Because it cannot be done with the same instrument at the same time, it must be done under different conditions (weather, night-sky-background, etc.). Thus scaling of the background measurement is necessary to achieve an agreement of the background levels of the on- and off-source observations. This scaling factor can only be determined by comparing parts of the data not influenced by the signal, eg. events which have their origin not at the source position. Having good statistics this scaling factor can be determined accurately enough to get plausible results, however still introducing an additional systematic error. Having detected a source, studies on its spectrum are essential to extract the interesting physics about the source. Therefore the data sample is divided into subsamples of different energy as determined by an energy estimation algorithm [3]. To be able to calculate the gamma ray flux for each of these energy bins independently it is necessary, that the scaling of the background in all bins produces reasonable results. Having slightly different conditions for signal and background measurements, e.g. a little higher humidity or the changed star light at another sky region, the scale factor for all energy bins might not be unique anymore.
Furthermore the construction of MAGIC's camera makes the center of the camera a privileged position. Due to the gap between two outer sectors of the camera (a sketch is shown in 3) and because only the fine-pixel part of the camera triggers the readout, events are aligned towards the center.

Wobble observation mode In wobble observations a position symmetric w.r.t. the camera center for the source is available. This anti-source position is used to determine the background to be subtracted from the signal. This offers the possibility of continuous monitoring of a source without having to interrupt the observations for taking off data. For reasons of symmetry almost identical conditions for both, signal- and background-observation, are available. Consequently in the first order no scaling has to be applied to the background measurement. Due to inhomogeneities (eg. single broken PMTs) in the camera acceptance it might be necessary to apply a small correction. The rotation of the source around the camera center smears out possible inhomogeneities and further decreases a necessary small correction factor. It also improves the quality of the background measurement because it does not correspond to a unique sky position anymore. However, there

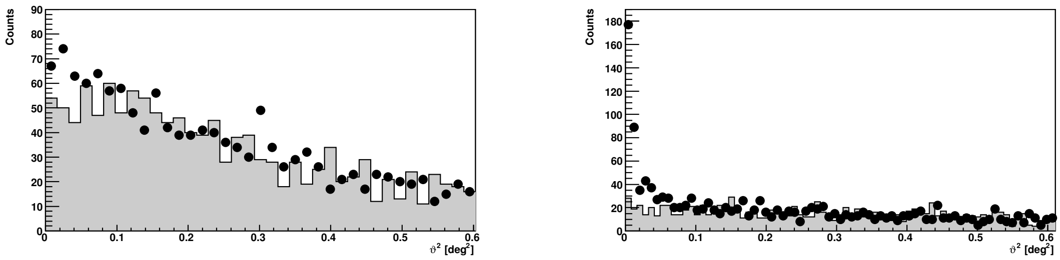

Figure 1. . Signal- (black dots) and background (gray shaded) as taken from wobble mode Crab observations (loose cuts) and without applying any scaling. Left: low size bin (around $90GeV$). Right: medium size bin (around $600GeV$).

is some danger that the background measurement is not statistically independent from the signal of a strong source. Therefore a special anti-source cut has to be applied, i.e. any event analyses can not be assigned to both positions. Already simple technique (classical α method) suppress this bias well. More advanced analysis', assigning a single source position to each shower image like Whipple's Disp-method [5], suppress this bias almost completely. This is done by applying source-position dependent cuts, also as a veto to the anti-source position and vice versa. Figure 1 shows a ϑ^2 signal- and background-plot [2] taken from wobble mode Crab observations without applying any scaling. Figure 2 shows the size distribution (solid line) of Monte Carlo gamma events assigned to the source position by surviving such cuts (plus gamma-/background-separation cuts) and the distribution (dashed line) of the same events which were wrongly assigned to the anti-source position only. It can be seen that the there are less than 1% wrongly assigned events in the lowest size bins which is negligible compared to statistical errors. For lower sizes this effect increases further, but it can be suppressed by more sophisticated cuts or using the Monte Carlo distribution for correction.

Discussion An example for a measurement can be seen in 1. For simplicity the binning was not chosen in estimated energy but in size, the total measured intensity of the shower image (which has an almost linear correlation to the energy of the primary particle). The plots show the ϑ^2-signal (black dots) of a wobble mode measurement of Crab and the measured background (signal of the anti-source). It can be seen that both measurements fit quite well and only small scaling corrections might be necessary, introducing only a small additional systematic error. Furthermore the scaling factor also depends on the way of its determination (eg. unifying the integral between $(\vartheta/\circ)^2 = 0.3$ and $(\vartheta/\circ)^2 = 0.5$), introducing another small systematic error. Extrapolating an accurate background from the large ϑ-region into the low ϑ-region, in the low-energy case as shown in the plot, seems problematic. Different functions may fit the background well at large ϑ or α, while giving quite different predictions for the background in the signal region. well. Having identical conditions for signal and background measurement in wobble mode means also an important reduction in the work necessary to ensure the compatibility of both measurements, eg. making sure that the image parameter distributions fit well which is influenced by environmental conditions like weather, zenith angle, etc. Because the compatibility of signal and background measurement is given by construction the results are more robust.

Comparison To avoid systematic errors in on-off observation mode due to wrong scaling, as explained earlier, a background measurement must be done under conditions as similar as possible to the ones taking on-data. Therefore any on-measurement must be followed by a prompt off-measurement. To get enough statistics it is essential to take roughly the same amount of off- and on-data. On the other hand wobble mode observations with the MAGIC telescope result in a loss of sensitivity of less than 20% . This is due to more showers not contained in the trigger area (mainly the inner part of the camera) anymore or leaking out of the camera due their size. Figure 3 shows a comparison of the distribution of the center-of-gravity of Monte Carlo gammas in the camera after cuts f or on-off and wobble observation mode. For this study the position information of the shower in the camera has not been used, it might further improve the sensitivity in wobble mode. To compare both observation modes, data of the Crab Nebula has been taken at similar zenith angles in both

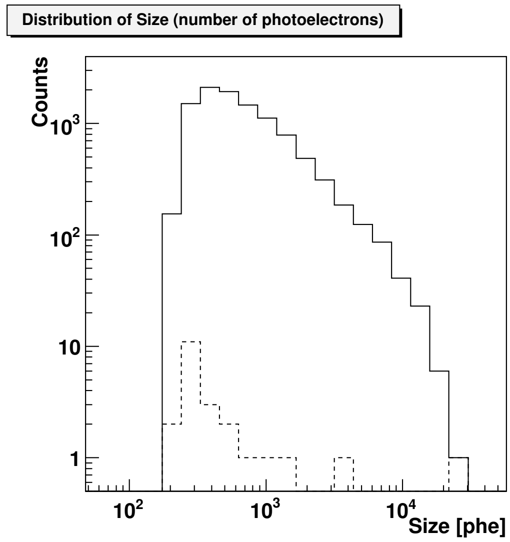

Figure 2. Size distribution obtained from Monte Carlo [4] gamma ray events surviving the cuts assigned to the source position (solid) and the anti-source position (dashed).

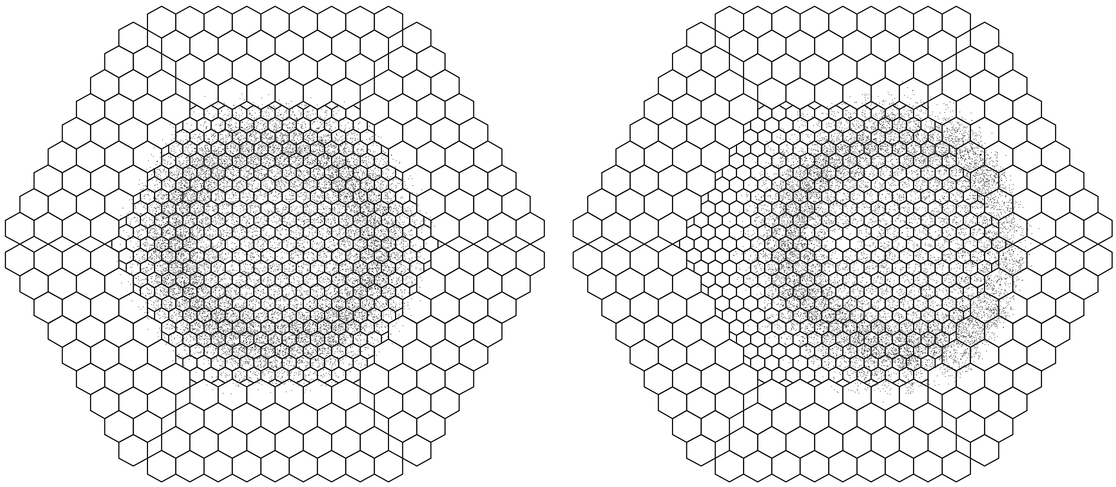

Figure 3. Distribution of center-of-gravity of the intensity distribution of Monte Carlo [4] gamma showers. Left: The source centered in the camera. Right: The source 0.4○ off center. The loss into the coarse pixel region of the camera in wobble-mode is small, while there are also showers on the left side which now are fully contained in the camera or the fine pixel region.

Observation Mode	Data Period	Zd range	Observation Time		Significance (Li/Ma)	Background Scale Factor
On/Off	Sep'04 - Jan'05	5.6°-23.7°	(On) 14837s	4.12h	30.5	0.94
Wobble	Sep'04 - Jan'05	5.6°-17.2°	13642s	3.79h	22.3	1.00

Observation Mode	Threshold	Excess Events	Background Events	Excess Rate	Background Rate	Significance per On-Time
On/Off	205-236GeV	2233	1727	9.0evt/min	7.0evt/min	$15.2\sigma/\sqrt{h}$
Wobble	205-236GeV	1621	1864	7.1evt/min	8.2evt/min	$11.5\sigma/\sqrt{h}$

Table 1. Top: Information about the observations and results. The off-data duration only differs from on-data in the order of seconds. Bottom: Information derived from the measurement shown.

modes. The analysis is explained in more details in [2] and [1]. The data analyzed has gone though a strict selection (w.r.t. weather conditions and apparatus performance). Robust and conservative cuts as [2] have been used for both datasets. They were trained dividing the samples each in two subsamples. Gamma-/background-separation has been optimized for maximum significance for both subsamples independently. This, however, raises the analysis threshold, but gives the most reliable output for the a study like this. After being convinced that both subsamples gave similar cut coefficients the full sample was analyzed with an artifical compromise between the two sets of cut coefficients. The energy threshold has been determined as the maximum bin in a dN/dE distribution after cuts of MC gammas produced with a spectral index of -2.6. Table 1 (top) contains the information about the data analyzed for this study and the results. Table 1 (bottom) contains derived values which are more useful for a comparison of both modes.

Conclusions When comparing the on-off and wobble observation modes in the framework of the MAGIC telescope, three aspects deserve particular attention: 1) loss of sensitivity for off-axis observations in the small camera, 2) efficiency of gamma-/background-separation at low energies and 3) the possibility of continuous monitoring of the source on wobble mode. It has been shown that the decrease in sensitivity for wobble observations employing a 0.4° offset from the camera center is compensated by the possibility of observing the source continuously, assuming that in on-off mode half of the time is devoted to the off observations. This can be compensated by defining more than one statistical independent off-region in the same distance to the camera center. The necessity of having non-overlapping on and off regions on the camera makes it difficult to use the wobble mode described here for extended sources ($> 0.1°$). The analysis, specially at low energies, benefits from the precision gained in the background determination in wobble observations. If the background is determined from off observations, scaling and uncontrollable statistical and systematic effects (e.g. due to varying night sky conditions) render the reproducibility of the measurements more difficult, implying generally larger errors of the background estimate in the signal region.

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