An new method to determine the arrival direction of individual air showers with a single Air Cherenkov Telescope

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Abstract

We present a new method to reconstruct the arrival direction of individual air showers. The method is based in part on the arrival direction reconstruction method of Lessard et al. [1] from the Whipple collaboration, but yields a significant 30% improvement in the obtained angular resolution. The method was successfully tested on Monte Carlo Simulations and real data of Mkn 421, Mkn 501 and 1ES1959 from the HEGRA Cherenkov Telescope CT1. Based on the same data an angular resolution of 0.1° could be derived.

1. Introduction

The determination of the arrival direction of γ-ray photons is essential for the investigation of extended sources and the search for sources with unknown or inaccurate positions. In the case of an observation with a few Cherenkov telescopes the images of at least 2 (sometimes 3) detectors are needed in order to determine the arrival direction without ambiguity. However, even for a single telescope it is possible to circumvent this problem. Since all γ-rays have a similar orientation (limited by the source's extension) one can use the images of several shower events to estimate the arrival direction of an individual γ-ray photon.

2. The Method

The method to derive 2-dimensional source maps for a single telescope is based on the procedure described in [1] and which can be summarized as follows: The arrival direction for a given shower event is estimated as the point on the major axis of the shower image located at a distance DISP to the shower centroid. The DISP parameter is a function of the elongation of the shower image and is defined as $DISP = \xi \cdot (1 - WIDTH/LENGTH)$. The scaling parameter ξ has to be determined from real observations or MC data. The final source map is build up from the arrival directions of all shower events. In the case of the CT1 data, the DISP parameter was slightly modified to include the LEAKAGE parameter:

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$$DISP = \xi \cdot \left(1 - \frac{WIDTH}{LENGTH \cdot (1 + \eta \cdot LEAKAGE)}\right) \quad (1)$$

The LEAKAGE parameter is defined as the ratio between the light content in the camera edge pixels and the total light content of the shower event. The inclusion of this parameter corrects for truncation effects of the LENGTH parameter in the small CT1 camera (3° diameter). The free variables in Equ. 1, ξ and η were determined from Monte Carlo simulations as $\xi = 1.3$ and $\eta = 6.6$.

As a modification of this method we determine a set of possible arrival directions for each shower event (in the following called arrival distribution): Taking into account the value and error of both the $DISP$ parameter and the orientation of the major axis of each shower image one can calculate the most probable intersection point for any (randomly chosen) triple of shower images by means of a χ^2 fit (see Fig. 1.). The arrival distribution for a given shower event is then defined by the subset of all those intersection points, where this event has been part of the triple*. Poorly defined intersection points with a $\chi^2/dof. > 6/3$ were rejected. Each derived arrival distribution was then normalized to unity. The final ON source map is given by the superposition of arrival distributions from all individual shower events and the final excess arrival distribution is derived by subtracting the normalized OFF from the ON source map.

The basic idea behind this approach is that all intersection points of pure γ shower triples should point towards the same sky region whereas a more or less isotropic distribution is expected whenever hadronic shower images are involved.

3. Results and Conclusions

The excess arrival distribution for the Mkn 421 CT1 data sample is shown in Fig. 2. A fit of a two dimensional Gaussian onto the data has been used to derive estimates for the angular resolution (σ_{RA} and σ_{DEC}) and the reconstructed source position ($RA_{\rm rec}$ and $DEC_{\rm rec}$). The results from this fit on several CT1 data samples are shown in Table 1. for both, the original method of Lessard et al. [1] and the modified method as presented here. As can be seen from the table, the new method yields a significant 30% improvement in the angular resolution for almost all sources. The reconstructed direction of the objects coincides with the known position within the accuracy of the shaft encoder steps (0.02°). It is also evident from Table 1., that the angular resolution strongly decreases for off-axis sources (i.e. where the telescope was pointing aside the source). This effect seems not to be related to the method itself since data which was artifi-

*Due to the large computational overhead of this method the number of intersection points per shower event have been limited to 500.

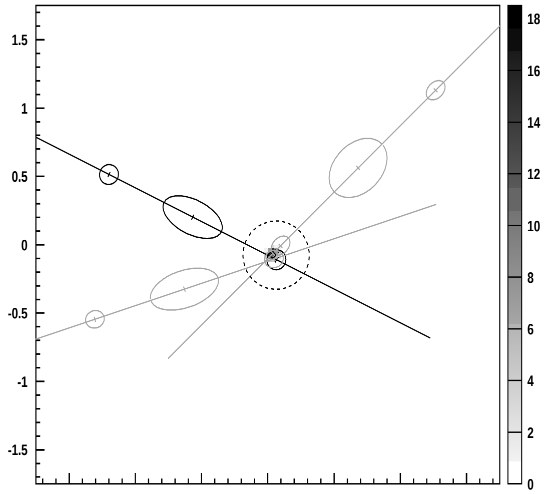

Fig. 1. Example of an event triple in the CT1 camera. The small ellipses denote the DISP based arrival direction and its uncertainty while the dashed circle gives the 1σ error of the intersection point. The 2 dimensional distribution denotes the final arrival distribution for the black shower event.

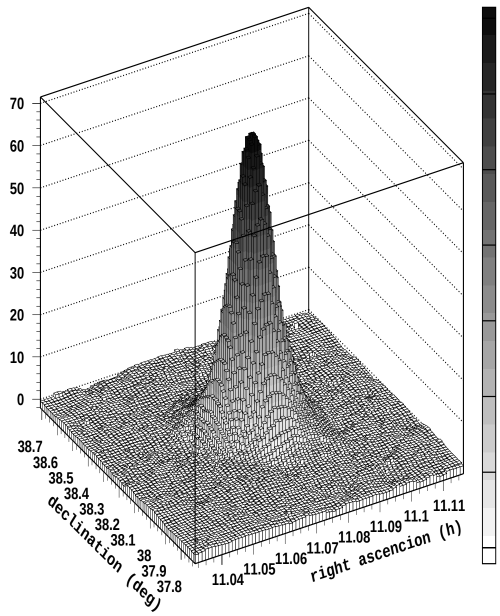

Fig. 2. The excess arrival distribution for the Mkn 421 CT1 data sample.

cially shifted towards an off-axis position† didn't result in a decreased angular resolution. One possible reason could be that for off-axis observations the small CT1 camera (about 3° diameter) leads to a larger number of truncated images, which then lower the effectiveness of both arrival direction estimation methods. This is currently under investigation.
The decrease in angular resolution between the 1997 (Mkn 501) and the 2001/2002 (Mkn 421, 1ES1959) data is addressed to the CT1 mirror upgrade at the end of 1997. The new CT1 mirror was increased from 5 m^2 to 10 m^2 and shows some increased aberration effects due to the larger mirror diameter.
Even though the derived angular resolution for 1ES1959 is similar for both methods, the distribution of the excess arrival direction as obtained with the new method is superior (see Fig. 3.) and yields a much clearer excess peak.

In summary the presented method to determine the arrival direction of individual photons for a single Cherenkov telescope gives a 30% improvement compared to the original method. The derived angular resolution of $\sim 0.1°$ is similar to the result one would obtain from a system of Cherenkov telescopes

†Here the image parameters ALPHA and DIST were recalculated relative to a shifted camera center while the WIDTH and LENGTH parameters were kept.

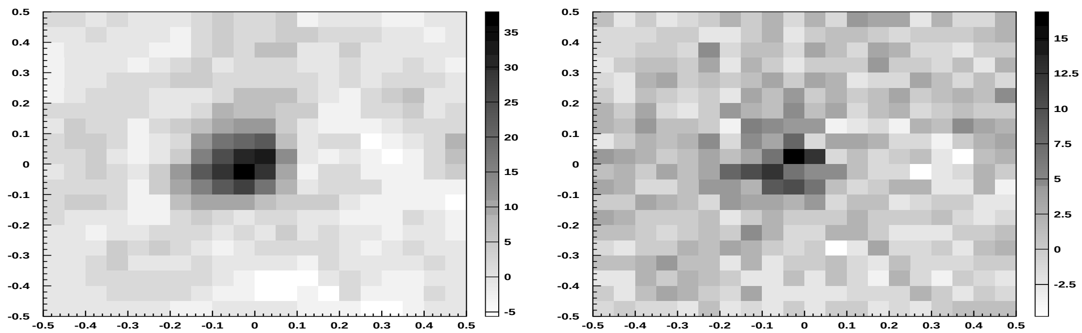

Fig. 3. The excess arrival distribution for the 1ES1959 data sample of 2002 as determined with the new (left) and original (right) method.

Table 1. Results of the new (this paper) and original [1] arrival direction reconstruction method as derived from different CT1 data samples. σ_{RA} and σ_{DEC} denotes the angular resolution in RA and DEC direction, RA_{rec} and DEC_{rec} the corresponding reconstructed source position. Δ_{RA} and Δ_{DEC} denote the difference between the real and the reconstructed source position ($\Delta_{RA} := RA_{\text{source}} - RA_{\text{rec}}$ and $\Delta_{DEC} := DEC_{\text{source}} - DEC_{\text{rec}}$). The term 'oa' denotes data where the telescope was not directed towards the source but at an angular distance of 0.3°.

data sample	**new method**				**original method**			
	σ_{RA}	σ_{DEC}	Δ_{RA}	Δ_{DEC}	σ_{RA}	σ_{DEC}	Δ_{RA}	Δ_{DEC}
Mkn 421, 2001	0.075	0.073	0.005	0.014	0.100	0.099	0.004	0.015
Mkn 501, 1997	0.058	0.056	-0.023	-0.035	0.078	0.077	-0.023	-0.035
Mkn 501, oa, 1997	0.082	0.068	0.017	-0.010	0.109	0.101	0.008	-0.030
1ES1959, 2002	0.077	0.085	0.035	-0.001	0.082	0.088	0.052	0.003
MC	0.052	0.052	-0.010	0.022	0.073	0.072	-0.010	0.023
MC oa	0.081	0.081	-0.040	0.019	0.119	0.123	-0.039	0.022

[2]. This improvement should also allow for an increased cut sensitivity, which, however, has not been investigated yet.

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4. References

1. Lessard R. W. et al. 2001, APh 15, 1
2. Daum A. et al. 1997, APh 8, 1