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# Standard Analysis for the MAGIC Telescope

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Large amounts of data are delivered every observing night by the MAGIC Telescope. New analysis methods are needed to achieve lower energy thresholds and to discover new sources. To allow for a timely implementation of these new methods or changes in the instrumentation a stable and flexible analysis is fundamental.
The event-based analysis package MARS (MAGIC Analysis and Reconstruction Software) offers a suitable framework for such a challenging analysis task. The modular concept provides the possibility to develop and implement rather easily new methods.
As a robust standard analysis MARS is applied to all MAGIC data. Results obtained with this procedure will be shown.

**Introduction** The MAGIC telescope has been designed in order to be able to detect faint air showers initiated by cosmic gamma rays with energies below 100 GeV, implying a high trigger rate (currently $\sim$ 300 Hz). The triggered events are digitized by a 300 MHz FADC system. Therefore a large data stream must be recorded and archived for the analysis. The signal charge and arrival time is calculated from the recorded samples, see [12]. Owing to the large fluctuations of low-energy showers, geomagnetic effects, as well as additional background from electrons and muons, gamma-/background-separation at low energies is the most challenging task in Cherenkov astronomy.
In order to facilitate a timely conventional analysis, while at the same time allowing for the testing and inclusion of novel analysis tools, a software project was started some time ago coined STANDARD ANALYSIS. Due to the large amounts of data obtained, stability and automation of the analysis chain were given the highest priority [3, 5]. Therefore the implemented algorithms have to be as robust as possible, e.g. the number of free parameters in cutting distributions must be kept minimal. Other design goals were simple maintainance and flexibility in order to keep pace with the ongoing development of new methods for background suppression. The event-based analysis package MARS [1] has proven to be a suitable solution for this challenging project. The package is based on a modular concept and internal coherence [1, 2, 3]. The output of the standard analysis serves as a reference for more specialized analyses on individual data sets.
Significant progress has been made implementing the complete analysis chain. Running the standard analysis delivers a set of plots characterizing data quality, image parameter distributions, signal excesses, energy spectra, etc., i.e. sufficient information to allow for a comprehensive first assessment of the scientific content of the data. In the case of tentatively interesting results from standard analysis, more advanced and specialized investigations can be launched, all attachable to the MARS framework.
In the following the main steps relevant for standard analysis are discussed and an example output is presented.

**Quality assurance** Before searching for weak signals, quality assurance is essential, because there could be fake events in the data, e.g. due to uncontrolled noises. Moreover, malfunctioning pixels could destroy much of the information contained in the shower image. Firstly, some rather simple precuts are made which remove non-gamma like events, but which do not remove any of the true gamma events. Secondly, a muon analysis [4] is run automatically for all data, providing a continuous control over the optical point-spread-function and

[1] MAGIC Analysis and Reconstruction Software

the light calibration of the photomultipliers (PMT). Furthermore, the muon rate can be measured. Due to the well-known muon flux, the actual muon rate provides a useful monitor of the quality of the observation night (e.g., the weather conditions). The muon data might also be used to correct the measured gamma ray fluxes for the effect of changing external conditions which is most important in lightcurve studies of variable sources.

**Bad pixel treatment** Bright stars in the field-of-view can alter the response of some pixels in the PMT camera. An active gain control levels down the currents of the illuminated pixels, the current fluctuations, however, will increase due to bright stars. Owing to the ALT-AZ mount of the MAGIC telescope, the images of stars move across the camera during tracking and thus the fluctuations affect different pixels. Pixels affected by fluctuations larger than five standard deviations from the mean fluctuation and other *bad* pixels (defect pixels found during calibration, missing central pixel, etc.) are treated by substituting their values with a value obtained from interpolating the surrounding pixels. Typically less than $3\%$ of all pixels are affected.

**Image cleaning** In addition to the treatment of bad pixels it is necessary to remove the noise in the camera before calculating image parameters from statistics of the intensity distribution. In order to avoid an influence of the noise level (when removing noise relative to the noise level of single pixels) on the shape of the resulting cleaned image, an absolute image cleaning is applied. This algorithm first searches for all pixels with a signal higher than $8.5\,\mathrm{phe}^-$. In addition, all pixels above $4\,\mathrm{phe}^-$neighboring a pixel with $8.5\,\mathrm{phe}^-$survive cleaning. Finally, all solitary pixels, which have survived after the first cleaning iteration, are removed.

**Image Parameters** From the intensity distribution of the cleaned image, several image parameters are computed as described in [11]:

- center of gravity (COG $< \vec{p} >$)
- standard deviation along the major axis (Length $l$)
- standard deviation along the minor axis (Width $w$)
- distance of COG from the position of the target source in the camera (Dist $d$)
- angle between the major axis of the shower image and the line between COG and the target source position (Alpha, $\alpha$)
- total number of measured photo electrons in the image (Size $S$)
- third moment of the distribution along the major axis ($m_l$)

In addition to these *standard* parameters a lot of quality parameters are computed, too, like for example the number of islands[2] surviving image cleaning.

The parameters mentioned above are calculated as follows: Be $p_i$ the positions of pixels with signal $s_i$. $n$ is the number of pixels which have survived image cleaning. $\vec{S_0}$ position of source on camera (events with $n < 3$ are skipped).

$$\text{Size:} \quad S = \textstyle\sum_{i<n} s_i \tag{1}$$

$$\hat{M} := \sum_{i<n} s_i \cdot \vec{u_i}^T \cdot \vec{u_i} \qquad \text{with} \qquad \vec{u_i} := \vec{p_i} - <\vec{p}> \quad \text{and} \quad <\vec{p}> := \frac{\sum_{i<n} s_i \vec{p_i}}{S}$$

$$\vec{r} := \hat{R} \cdot \vec{v} \qquad \text{with} \qquad \hat{R} = \begin{pmatrix} \cos\delta & \sin\delta \\ -\sin\delta & \cos\delta \end{pmatrix} \quad \text{and} \quad \vec{v} := <\vec{p}> - \vec{S_0}$$

[2]Islands are isolated clusters of pixels connected together

$$\vec{m}_i := (z_{i,x}^3, z_{i,y}^3) \qquad \text{with} \qquad z_i := \hat{R} \cdot \vec{u}_i$$

Width and Length: $$w = \sqrt{\frac{M_{xx} \cdot \tan^2 \delta - k + M_{yy}}{(\tan^2 \delta + 1) \cdot S}} \qquad l = \sqrt{\frac{M_{yy} \cdot \tan^2 \delta + k + M_{xx}}{(\tan^2 \delta + 1) \cdot S}} \quad (2)$$

Dist and Alpha: $$d = |\vec{v}| \qquad \alpha = \arcsin{(r_y/d)} \quad (3)$$

Third moment : $$m_l := \sqrt[3]{|<\vec{m}>_x|} \cdot \text{sgn}(<\vec{m}>_x) \cdot \text{sgn}(r_x/d) \quad \text{with} \quad <\vec{m}> := \frac{\sum_{i<n} \sum_i \cdot \vec{m}_i}{S} \quad (4)$$

**Gamma-/Hadron-Separation** For the standard analysis of MAGIC data cuts in the distributions of image parameters were searched, which are most robust w.r.t. possible variation of the external environment (weather conditions, night-sky-background, etc.) and which can be universally used for comparative analyses and quick-look analysis. A wide range of possible cuts optimized for these purposes were investigated systematically [9].

**Energy estimation** The energy of the primary gamma rays can be estimated from the correlation between the image parameters and Size. A detailed study has been done in [8]

**Effective observation time** The effective observation time $T_{eff}$ is defined as the time range, within which the recorded number of cosmics events $N$ would be obtained under ideal conditions (without dead-time).
$T_{eff}$ can be determined from the distribution of time differences $\Delta t$ between successive cosmics events. The exponential slope $\lambda$ of this distribution is the event rate for cosmics in the ideal case. If $N$ is the total number of recorded cosmics events, $T_{eff}$ is obtained by

$$T_{eff} = N/\lambda$$

In the case of a finite dead time $T_d$ the distribution (for $dt > T_d$) is exponential with the same slope $\lambda$, fitted in a region of $\Delta t$, which is not affected by the dead time.

**Effective collection area and correction coefficients** The effective collection area $A_{eff}(E)$ has been calculated from the number of events $N_0$ produced in a well defined area $A_0$ around the telescope and the number of events surviving the cuts $N$. The correction coefficients $f(E_{est})$ accounting for the asymmetric spill-over due to a steep source spectrum are calculated from the number of events $N(E_{mc})$ before energy estimation and after $N(E_{est})$ energy estimation.

$$A_{eff}(E) = A_0 \cdot \frac{N(E)}{N_0(E)} \qquad f(E_{est}) = \frac{N(E_{mc})}{N(E_{est})}$$

**Spectrum calculation** The energy spectrum can now be calculated as:

$$N(E_{mc}) = \frac{N_{exc}(E_{est}) \cdot f(E_{est})}{A_{eff} \cdot T_{eff}}$$

To make sure that the resulting spectrum is consistent with the originally produced Monte Carlo [10] spectrum, the result is fed into the algorithm and the Monte Carlo events are weighted (assuming that the Monte Carlo production and integration range is from $E_{min}$ to $E_{max}$, the spectral index 2.6 and the new spectral index $\alpha$) by weights $w$. This procedure is followed iteratively until the weighted spectrum and the resulting one agree. In this case also a good agreement between the size distribution of Monte Carlo gammas and Excess events is expected and can be checked. Therefor the distribution of Monte Carlo gammas is scaled by a factor $f$:

$$w = \frac{\int E^{-2.6} dE}{\int E^{-\alpha} dE} \cdot \frac{E^{-\alpha}}{E^{-2.6}} \qquad f = \int_{E_{min}}^{E_{max}} E^{-\alpha} dE \frac{A_0 \cdot T_{eff}}{N_0}$$

The resulting distribution is equivalent to a Monte Carlo distribution measured in the observation time $T_{eff}$ from a source spectrum with spectral index $-\alpha$.

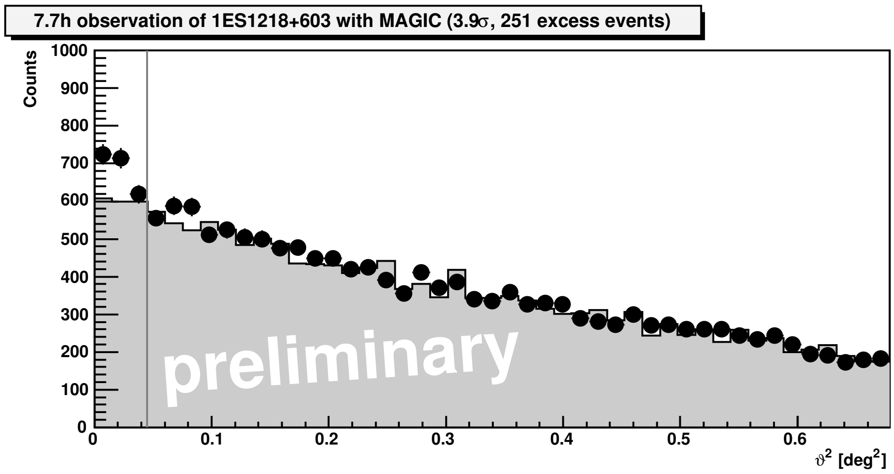


**Figure 1.** $\vartheta^2$ plot for 7.7 h of 1ES1218+603 data at zenith angles $< 12^\circ$ after cuts as described in [9]. The off-data used is shown gray shaded, it was scaled by the integral between $0.2deg^2$ and $0.5deg^2$ with a factor 1.13. The Li/Ma-significance and the number of excess events was calculated from the data below $0.045deg^2$ (marked by a gray vertical line). The on-data is shown with full dots.

**An exemplary results** The procedure above is run automatically on all MAGIC data taken as described in [5]. One promising result delivered by this procedure is a marginal detection of 1ES1218+304 [6] as shown in figure 1. Further investigations on the data quality have to be done manually now to ensure that the signal seen is not due to systematic errors or the external environment.

**Conclusion** The concept of the event-based framework MARS featuring the discussed robust *Standard Analysis* has been shown to fulfill the experimental requirements. Applied to more than 12 TB corresponding to 600 h of data it has proven to be stable and effective discovering new sources from the data.

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