Using muon rings for the optical throughput calibration of the SST-1M prototype for the Cherenkov Telescope Array

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Imaging Atmospheric Cherenkov Telescopes (IACTs) are ground-based instruments devoted to the study of very high energy gamma-rays coming from space. The detection technique consists of observing images created by the Cherenkov light emitted when gamma rays, or more generally cosmic rays, propagate through the atmosphere. While in the case of protons or gamma-rays the images present a filled and more or less elongated shape, energetic muons penetrating the atmosphere are visualised as characteristic circular rings or arcs. A relatively simple analysis of the ring images allows the reconstruction of all the relevant parameters of the detected muons, such as the energy, the impact parameter, and the incoming direction, with the final aim to use them to calibrate the total optical throughput of the given IACT telescope. We present the results of preliminary studies on the use of images created by muons as optical throughput calibrators of the single mirror small size telescope prototype SST-1M proposed for the Cherenkov Telescope Array.

The 34th International Cosmic Ray Conference,
30 July- 6 August, 2015
The Hague, The Netherlands

1. Introduction

The Cherenkov Telescope Array project (CTA) [1] will be the next generation ground based observatory in gamma-ray astronomy. It will consist of two arrays of imaging atmospheric Cherenkov telescopes (IACTs) installed in the two hemispheres to cover the full sky. In its final configuration, the Southern site of CTA will have more than a hundred telescopes of three different sizes arranged over an area of the order of few km^2. The array has been designed in such a way that it will be able to cover the wide energy range between few tens of GeV and at least 300 TeV, with an improved sensitivity by about a factor of 10 (at 1 TeV) compared to the existing experiments. The array of small-size telescopes (SSTs) will be dedicated to the observation of the most extreme gamma-ray sources emitting in energies between a few TeV and 300 TeV.

The SST-1M project is a Consortium of several Swiss and Polish institutes working on the design and construction of one of the prototypes for the SSTs of CTA [2]. The SST-1M prototype is the only SST telescope designed with one mirror. It uses the standard and well-proven Davies-Cotton design for the optics and telescope structure and an innovative camera using Silicon-Photomultipliers (SiPM), inspired by the experience of the FACT camera [3]. Thanks to their wide field-of-view (FoV) of about 9°, the SSTs are particularly well suited for spectral studies of Galactic sources and Galactic Plane Surveys. The prototype of the SST-1M mechanical structure has been installed on a test site at the Institute of Nuclear Physics PAS in Kraków in November 2013. The design of the camera has been finalized and the commissioning phase has already started [4].

The detection technique used by the IACTs consists in observing images created by the Cherenkov light emitted by electromagnetic showers induced in the atmosphere by gamma rays, or more generally cosmic rays. To analyse the observed gamma-ray characteristics, an accurate calibration of the camera [6] as well as the evaluation of the instrument optical efficiency need to be performed. Highly energetic muons penetrating the atmosphere are visualised as characteristic circular rings or arcs in the camera plane and they represent a powerful and precise method to calibrate the optical throughput of IACTs [5].

In this paper we study the possibility of using the analysis of muon ring images as a calibrator for the optical throughput of the SST-1M prototype for the Cherenkov Telescope Array.

2. Muon images in IACTs

Isolated muons produce sharply defined ring-like images in the focal plane and provide a powerful tool for monitoring the behaviour of the telescope performance characteristics like the point spread function (PSF) and the overall light collection efficiency. Muons passing through the centre of the telescope with trajectories parallel to its optical axis will produce azimuthally symmetric rings in the camera. The rings will have radii given by the Cherenkov angle of the muons and the total number of photons expected in the ring, mainly related to the muon energy, can be calculated from the measured value of this angle. The correspondence between the Cherenkov

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40 angle and the muon energy can be established following the Cherenkov equation:

$$\cos \theta_c = \frac{1}{n \cdot \sqrt{1 - (E_0/E_\mu)^2}} \quad , \tag{2.1}$$

41 where $E_0 \sim 0.105$ GeV is the muon rest mass, and n the refractive index of air. The typical ring
42 radius (R) is determined by the muon spectrum at the observatory altitude, e.g. $R \sim 1.2°$ at 1500 m
43 a.s.l. for $E_\mu = 20$ GeV. Muons arriving under a certain angle with respect to the telescope's axis
44 will form rings or arcs with centres that are offset from the centre of the camera, while muons
45 with non-zero impact parameters[1] will produce rings or arcs with an azimuthally dependent photon
46 density. Since the morphology and location of the muon ring allow the muon's trajectory and
47 energy to be calculated, it is possible to predict with precision the number of Cherenkov photons
48 that have been collected by the camera. Since the prediction depends only very slightly on the local
49 atmosphere, but goes linearly with mirror reflectivity, transmission of glass coating and the photon
50 detection efficiency of the camera pixels, the detector response to local muons can be calibrated in
51 absolute terms [7].

52 **2.1 Simulations**

53   The results reported in this contribution have been obtained from simulation studies using
54 standard CTA software, namely CORSIKA [8] and the `sim_telarray` package [9]. The latest
55 telescope and camera parameters (e.g. mirror reflectivity, light collectors, photon detection effi-
56 ciency of the silicon photo-multiplier sensors forming the SST-1M camera, hexagonal geometry of
57 the camera, etc.) have been included in the simulation of the instrument. The baseline trigger is a
58 digital sum trigger with sampling rate 250 MHz. Muons have been injected at a starting altitude
59 of ~ 1 km above the observation level[2], randomly distributed in a cone of $\sim 4.5°$ (corresponding
60 to half of FoV of the telescope) around the vertical axis to cover the entire FoV. The telescope
61 has been simulated pointing always to the zenith, and the impact parameter has been randomly
62 distributed from 0 m to ~ 2 m (radius of the mirror). The muon spectrum has been simulated as a
63 power law with a spectral index of -2 in an energy range between 6 GeV and 10 TeV. An example
64 of a full ring image as it would appear on the SST-1M is shown in Figure 1.

65 **2.2 Analysis of the rings**

66   The analysis of the muon images requires the calculation of the muon image parameters: the
67 ring radius, the ring width (*ArcWidth*), the opening angle of the ring fraction (*ArcPhi*) and its total
68 light content, measured in photo-electrons (*MuonSize*).

69   The analysis has been carried out using MARS, the standard software for the MAGIC tele-
70 scopes data analysis [10].

71   The search for muon rings starts after image cleaning. For this study an absolute image clean-
72 ing has been applied with 5 photo-electrons for core and 2 photo-electrons for boundary pixels [11].
73 After cleaning, every image is fitted by a circle starting at the centre of the Hillas ellipse (Hillas

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[1]The impact parameter is defined as the distance from the centre of the mirror to the impact point of the muon in the plane normal to the optical axis.

[2]The reference site for all simulations is *Aar*, the proposed site for the Southern array in Namibia, located at $h_{\text{tel}} = 1640$ m a.s.l.
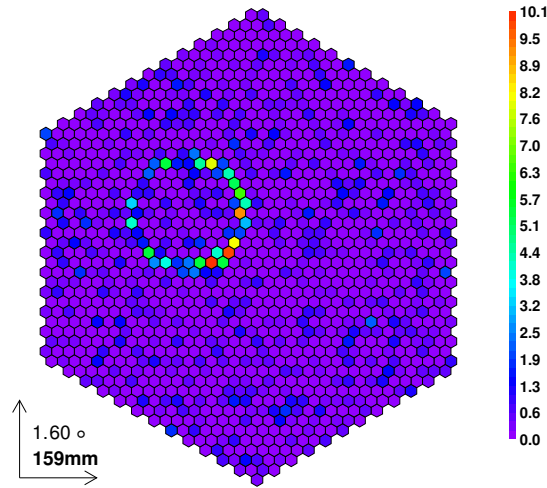
Figure 1: Example of a muon image recorded by the SST-1M telescope. The azimuthal non-uniformity is the result of a non-zero impact parameter, while the offset with respect to the centre indicates an off-axis muon direction.

parameters are calculated in a preceding step). From that starting point, the algorithm calculates the distance of the putative image centre to every pixel, and from the distance values the mean (weighted by the pixel content) with its deviation (rms) are calculated. The algorithm minimises the deviation by changing the coordinates of the assumed centre. Figure 2 shows the resolution of the muon ring radius as a function of the energy, defined as $(R_{rec} - R_{true})/R_{true}$. The bias on the ring radius reconstruction is less than $\sim 1\%$ for the overall energy range considered and it can be easily subtracted.
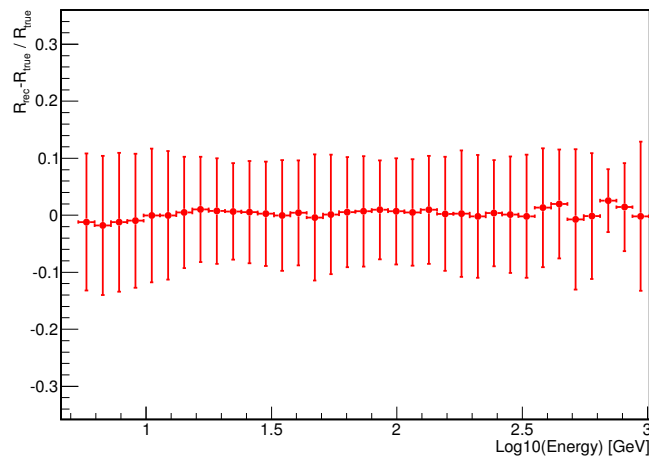
Figure 2: Resolution of the muon ring radius as a function of muon energy. The bias on the radius reconstruction is less than $\sim 1\%$.

In a second step, the image before cleaning is used to calculate the radial and the azimuthal intensity distribution of the image. For the azimuthal intensity distribution, all pixels inside a

certain margin around the radius are used. The following parameters, useful for the analysis can be defined:

- *ArcWidth* is calculated as the sigma value of a Gaussian fit to the signal region in the radial intensity distribution;

- *ArcPhi* is calculated as the sum of connected bins, which lie above a certain pixel amplitude threshold;

- *MuonSize* is calculated as the sum of the contents of all pixels along the ring.

Due to the intrinsic broadening of the ring width, the absolute value of the *ArcWidth* is not equal to the sigma value for the optical PSF, but it is related to that. Therefore, to get the size of the PSF it is necessary to compare simulated muons with different PSFs with muons extracted from observational data. Figure 3 shows an example of the radial intensity distribution of the image with a Gaussian fit to the ring region.
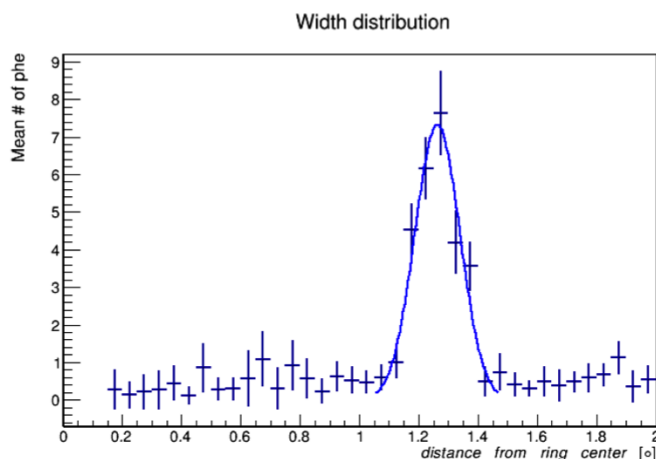
Figure 3: Radial intensity distribution with a gaussian fit for the calculation of the *ArcWidth*. The value of the *ArcWidth* is related to (but not exactly) the optical PSF.

3. Study of the optical degradation

The analysis presented in the previous section has been developed to study the capability of the SST-1M telescope to trigger on muon events and its ability to calibrate the optical throughput, possibly without trigger bias. The effect of the summed pixel amplitude threshold and selection cuts have been investigated with the purpose of obtaining a muon efficiency curve independent from the optical degradation of the telescope. Simulations have been carried out using different scales of mirror reflectivity degradation. In order to select good muon events[3] the following quality cuts have been applied based on the previously described analysis:

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[3]Cuts are based on muon simulations only. No study about the cosmic ray rejection has been performed at this stage.

- 103 • the ring fitting the muon image is fully contained in the camera;

- 104 • the reconstructed radius is between 0.5° and 1.5°;

- 105 • the projected ring width along the ring radius has a gaussian shape (reduced chi square of the
- 106   *ArcWidth* fit < 2);

107 Figure 4 (left) shows the muon efficiency (calculated as the ratio between the observed and simu-
108 lated muons) curves obtained with a trigger threshold of 100 ADC counts as a function of the muon
109 energy above 10 GeV. The effect of the muon energy on the muon efficiency is rather negligible
110 for all the considered optical efficiencies. The right side of Figure 4 shows the muon efficiency
111 for energies above 10 GeV as a function of the optical efficiency. The muon efficiency has a con-
112 stant value of around 60% in the region of interest (between 60% to 100% of optical efficiency).
113 The trigger rate seems to be rather insensitive to the optical efficiency of the system when a lower
114 trigger threshold of 100 ADC counts is adopted[4].
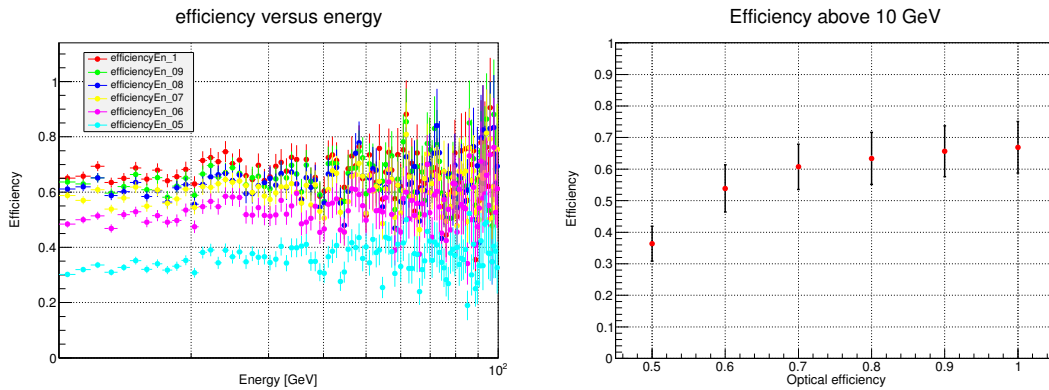
Figure 4: Left plot: Muon efficiency for SST-1M obtained with a trigger threshold of 100 ADC counts as a function of energy for different optical efficiencies (100% in red, 90% in green, 80% in blue, 70% in yellow, 60% in magenta, and 50% in cyan). Right plot: Muon efficiency for SST-1M obtained with a trigger threshold of 100 ADC counts and as a function of the optical efficiency for muons with an energy above 10 GeV.

115 4. Conclusions

116   Muon rings have been used as a method to calibrate the total optical throughput of practically
117 all previous Imaging Atmospheric Cherenkov Telescopes [12, 13, 14]. In this contribution we
118 have presented simulations and analysis of the ring images carried out in the framework of the
119 SST-1M project. This work is done in close collaboration with the other SST teams of the CTA
120 Consortium [15, 16]. Preliminary results show that muon images are adequately selected despite
121 a degradation of the optical efficiency of the instrument. Building on this encouraging result the
122 SST-1M collaboration continues to work towards further improving the trigger efficiency for muon
123 rings. In this direction, additional dedicated muon triggers are currently under study.

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[4]the general *Prod2* simulation for CTA has been done using a trigger threshold of 127 ADC counts.

Acknowledgements

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