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Using muon rings for the optical calibration of the ASTRI telescopes for the Cherenkov Telescope Array

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ABSTRACT

High-energy muons constitute a very useful tool to calibrate the total optical throughput of any telescope of the Cherenkov Telescope Array (CTA). Differences in precision and efficiency can however be present due to the variety of telescope types and sizes. In this contribution we present some preliminary results on simulated muon ring images collected by the ASTRI small sized dual-mirror (SST-2M) telescope in the basic configuration installed in Italy at the Serra La Nave observing station. ASTRI SST-2M is able, using 6% of the detected muon events, to calibrate with muons the optical throughput down to a degradation of the optical efficiency of 30%. Moreover, its precision in reconstructing the muon arrival direction is about one camera pixel, and its error on the reconstructed ring radius is ∼6.3%. The adopted procedures will be tested and validated with real data acquired by the prototype after the commissioning phase. The nine telescopes that will form the ASTRI mini-array, proposed to be installed at the final CTA southern site during the pre-production phase, will improve these results thanks to the higher detection efficiency and the lower optical cross-talk and after-pulse of their updated silicon photomultipliers.

Keywords: Image Atmospheric Cherenkov Telescope, CTA, muon rings, calibration, ASTRI

1. INTRODUCTION

The Cherenkov Telescope Array (CTA) consortium[1] is an international initiative to build the next generation of ground-based instruments devoted to the very high energy gamma-ray astronomy. Full sky coverage will be accomplished by two arrays, located in the northern and southern hemispheres, respectively. Three main classes of telescopes (large, medium and small) will cover, with their proper mirror size and field-of-view, the wide energy range from tens of GeV up to hundreds of TeV using cameras composed either of photomultipliers or silicon photomultipliers, and controlled by different trigger and read-out electronics.

Given such a wide diversity, it is worthwhile to use, as far as possible, unique and well-tested techniques to calibrate the optical throughput of each telescope.[2] One of such methods is the analysis of muon ring images, successfully applied to calibrate the total optical throughput of all currently operating Imaging Atmospheric Cherenkov Telescopes (IACTs). In the CTA case, the feasibility of the muon ring method is undergoing a detailed study. The first results based on Monte Carlo (MC) simulations confirm that, when using carefully selected images, the method allows the measurement of the total sensitivity to Cherenkov light with a precision of ∼5% for those telescopes that provide sufficient mirror area, such as the large and medium ones.[3] This result is valid also for the small sized telescopes envisaged for CTA, although with different efficiency, despite their reduced collecting area with respect to medium and large telescopes.

In this contribution, we describe the results obtained on simulated data for the ASTRI small sized dual-mirror (SST-2M) telescopes proposed to be installed at the CTA southern site. The ASTRI telescopes (4-meter class)

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are characterized by a wide-field dual-mirror Schwarzschild-Couder optical design[4] and by an innovative camera, composed of silicon photomultiplier (SiPM) and managed by a very fast read-out electronics.[5,6]

A prototype of such telescopes, named ASTRI SST-2M,[7] has been inaugurated in Italy at the INAF observing station located in Serra La Nave, on Mt. Etna.[8] The commissioning of the SiPM camera is foreseen in the second half of 2016. In the meantime, a collaborative and international effort, led by INAF within the CTA framework, is being carried on by Italy, Brazil and South-Africa aiming at deploying an array of at least nine ASTRI telescopes with a relative distance of the order of 300 m at the CTA southern site. The ASTRI mini-array, proposed to be part of the CTA pre-production phase, should allow early scientific investigations of prominent sources in the energy range from a few TeV up to hundreds of TeV.[9,10]

The ASTRI SST-2M camera[11] is composed by a matrix of 496 Hamamatsu SiPM sensors with a total of 1984 squared pixels organized in 37 Photon Detection Modules (PDM). Each pixel has a sky-projected angular size of 0.17°, which is of the same order of the angular resolution of the optical system. This configuration allows to cover a 9.6° full field-of-view (FoV) and to obtain that the Point Spread Function (PSF), defined as the 80% of the light collected from a point like source, is contained in one pixel. The camera surface is protected by an UV transmitting plexiglas acrylic window whose transmission is negligible below 290 nm. The basic scheme of the electronics foresees two main outputs: the signal shaped with a function characterized by a shaping time of 50 ns, and the trigger, with a 15 ns shaping time. Triggers are considered valid if they occur within a single PDM module. The trigger topological configuration adopted for the prototype considers c contiguous pixels, each one with a signal above a threshold of p photo-electrons. The number of contiguous pixels and the threshold of photo-electrons can be varied depending on the level of the night sky background (NSB) and on the eventual presence of bright stars in the FoV. For a level of NSB corresponding to extra-galactic dark sky of a CTA-like site (1.9×10^{12} ph m^{-2} s^{-1} sr^{-1}) and no bright stars in the FoV, c=4 and p=5 are adequate. By making use of the same topological trigger configuration adopted for electromagnetic and hadronic shower events, ASTRI SST-2M is expected to be able to collect high-quality muon ring images produced by the light emitted along the last part of their path towards the primary mirror.

Preliminary analysis on the reconstruction of simulated muon images as detected by ASTRI SST-2M telescope has been previously published.[12] The work presented in this paper, again based on simulated data, states the feasibility of the calibration of ASTRI SST-2M telescope with muons. The procedures used for this method will be tested and validated by the prototype, when operative, taking also into account that it will run with higher level of background and lower performance with respect to the mini-array telescopes.

2. MUONS AND CHERENKOV TELESCOPES

In this section, we briefly address the formation of muon images and its use for the calibration of the optical throughput; details can be found elsewhere.[13]

Cherenkov light is emitted when charged particles travel through a medium with velocity higher than the speed of light inside that medium. Single muons, which naturally form part of hadronic air showers, emit Cherenkov light in the same way as secondary electrons in a gamma-ray shower do. Since muons in air lose energy almost exclusively through ionization, they have a large penetration depth and reach the ground with a negligible energy loss. Therefore, the Cherenkov light emitted by muons passing close to an IACT can be detected. The morphology of a (fully contained) muon images is unique: the light is imaged as an annular pattern whose radius is determined by the Cherenkov angle of light emission (about 1.3° at sea level).

The number of Cherenkov photons produced by the muons detected by the telescope depends only on the distance of the impact point with respect to the centre of the main collecting mirror, and on the camera efficiency: it can be evaluated to the same precision as these parameters are known. The size of the mirror and the camera efficiency are well known from the telescope design and the laboratory calibration. The only unknown parameter, i.e. the distance of the impact point, can be determined after the reconstruction of the ring geometrical parameters (input direction, emission Cherenkov angle) from the distribution of the light along the muon image ring.[13] To be efficient, the reconstruction is typically performed on a small number of muon events selected in order to have a sufficiently large accuracy on each reconstructed parameter. In this way, the overall efficiency computed from the ratio between the detected photo-electrons and the number of photons hitting the telescope can be computed with the required precision. Whenever the optics transmission degrades, the calibration is possible if the accuracy on the reconstruction parameters is still adequate. In practice, the optical throughput calibration of IACT telescopes with muons is feasible if it is possible to select a given number of events to be used independently on the telescope efficiency. A first step of the analysis is then the definition of this sample.

In the CTA context, large and medium telescopes will be likely able to detect muon events useful for the optical calibration even under stereo trigger configuration. This will be not the case for the ASTRI telescopes because the stereo rate for muon events will be negligible, given the ASTRI smaller mirror area and larger inter-telescope distance with respect to the large and medium sized telescopes of the CTA array. Nevertheless, each ASTRI telescope is expected to be able to detect single-muon events during regular science data taking under the nominal trigger configuration. To this end, specific algorithms, to be implemented at the level of each ASTRI telescope, are under development to flag events as candidate muon calibrators before sending them to the central array data acquisition system. Preliminary results of these pre-selection algorithms indicate the possibility to flag muons with an efficiency up to a maximum of 96% including, at the same time, about 8% of protons.[14]

In this contribution, we consider the case of the ASTRI SST-2M, operated as stand-alone telescope, and we assume that the pre-selection of muons with respect to other types of triggered events (mostly protons) is already performed through a similar procedure that allows to reject protons with a high level of efficiency; in other words, our data set includes only single muon events.

3. SIMULATION DATA SET

To study the features and performance of muon events as calibrators for the optical throughput of any single ASTRI telescope, a set of specific simulations has been produced for a telescope observing at 2150 m asl and adopting a quasi-tropical atmosphere. Two million μ^+ and μ^- events have been simulated with CORSIKA[15] (version 6.99). Muon spectra are simulated with a power-law of spectral index -2 in the energy range 6 GeV – 1 TeV. In order to have complete ring images, the muon impact parameter lies within the radius of the primary mirror (2.153 m) and the incoming direction is uniformly randomized in a view-cone of 4° around the zenith. The injection height, i.e. the muon starting altitude, has been fixed to about 500 m above the primary mirror.

The simulation of the telescope structure, mirrors, and camera has been performed using a code developed at INAF/IASF-Palermo.[16] It is a stand-alone ray-tracing code that models the interactions of the input Cherenkov photons with all the telescope components and follows them up to the eventual detection in the camera at the focal plane. In the current set of simulated data we used the camera configuration of the ASTRI SST-2M prototype with FoV of 9.6° and angular pixel size of 0.17°. The adopted level of night sky background has been set to one photo-electron per pixel in the 50 ns integration time of the signal, which corresponds to the dark sky conditions. Figure 1 shows an example of simulated ring muon event as seen by the ASTRI SST-2M camera.

For each simulated event we produced a set of images with degraded optical efficiency, randomly cutting the fraction of photo electrons produced by the muons corresponding to the assumed degradation level. The NSB level has been reduced coherently, while the electronic noise has been kept constant despite of the reduced telescope efficiency. We investigated the effect of the degradation down to 10% of the nominal efficiency.

4. ANALYSIS

For each event, a first strong cut on the signal of individual pixels is applied to the image in order to keep the pixels which likely contain the muon ring light content over the NSB. The level of the cut is fixed to 5 times the *rms* of the background: all pixels with a lower number of photoelectrons are zero-suppressed. The background *rms* is evaluated in a region where no signal is detected. The best way to identify this region are under studies, a possible method is to use the level of the PDM with the lowest number of pe. Only events which have a number of pixels left after cuts greater than 4 are analysed.

The geometrical parameters of all events are reconstructed through a fitting procedure that evaluates the coordinate of the center (x_c, y_c) and the radius (R) of the ring with the Taubin method[17] using the following function:

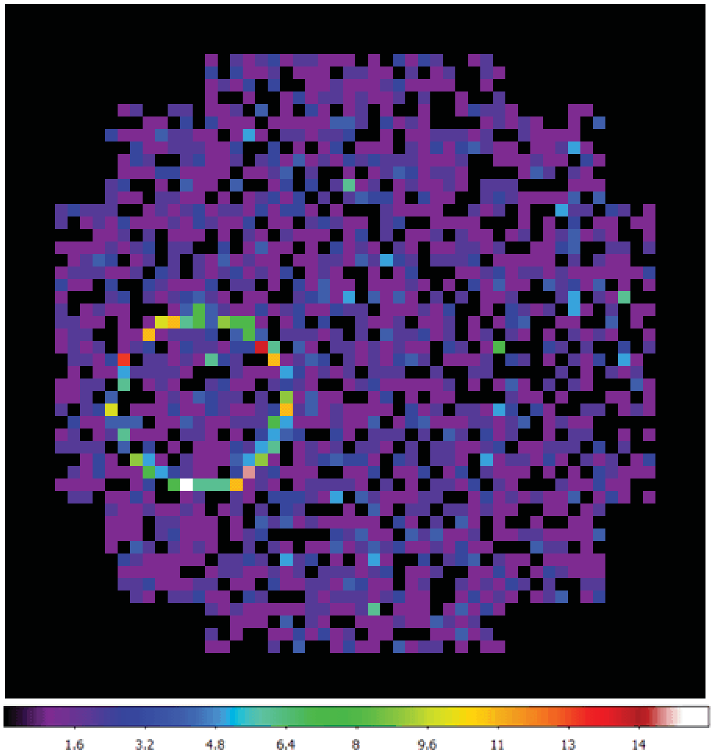

Figure 1. Example of a simulated muon ring image triggered by the ASTRI SST-2M telescope. The ring is produced by a positive muon with energy 9 GeV superimposed to the NSB signal.

$$\xi = \frac{\sum_{i=1}^{N_{pix}} [(x_i - x_c)^2 + (y_i - y_c)^2 - R^2]^2}{\sum_{i=1}^{N_{pix}} [(x_i - x_c)^2 + (y_i - y_c)^2]} \tag{1}$$

where x_i,y_i are the coordinates of the N_{pix} pixels that have been not rejected in the image cleaning procedure.

The sample of events suitable for the calibration of the optical throughput was identified determining in several trials the reconstructed parameter ranges that keep constant the number of selected events independently on the telescope efficiency.

For each selected event, we then computed the precision on the reconstructed input direction (which gives us an estimation on the uncertainties and bias of the reconstruction). In particular, the error on the angle between the muon direction and the telescope axis (zenith angle) is defined as the difference between the simulated value (ϑ_{sim}) and the distance of the ring centre from the focal plane centre:

$$\Delta\vartheta = \quad \vartheta_{sim} - \sqrt{x_c^2 + y_c^2} \tag{2}$$

where $\Delta\vartheta$ is the error in the zenith angle.

A similar definition is used for the angle respect to the telescope x axis (azimuthal angle). However in this case we evaluated the relative error defined as:

$$\Delta\varphi = \quad \frac{\varphi_{sim} - \mathrm{atan}(\frac{y_c}{x_c})}{\varphi_{sim}} \tag{3}$$

where $\Delta\varphi$ is the relative error on the azimuthal angle and φ_{sim} the simulated value.

Considering that to reconstruct the number of input photon the Cherenkov angle is required, we investigated the reconstruction precision on this parameter. Errors are evaluated as the difference between the reconstructed Cherenkov angle, that is the radius of the ring R, and the value obtained from theoretical relation according to the following equation:

$$\cos(\theta_{sim}) = \frac{1}{n\sqrt{1-(E_o/E_\mu)^2}} \tag{4}$$

where, θ_{sim} is the angle corresponding to the simulated muon energy E_μ, E_o= 0.105 GeV the muon rest mass, and n the refractive index of the air.
Also for this parameter we preferred to evaluate the relative error defined as:

$$\Delta\theta = \frac{\theta_{sim} - R}{\theta_{sim}} \tag{5}$$

5. RESULTS

We found that events with ξ <0.05, and $0.9^\circ < R < 1.5^\circ$ have a reconstruction precision suitable for the optical throughput calibration down to a degradation of the telescope efficiency of 30%. The requirement on the precision (5%) limits to this level the application of this calibration method. This result is clearly shown in Fig. 2 where the number of selected events normalised to the number corresponding to the nominal efficiency (no degradation) as a function of the optical efficiency in unit of the nominal one is shown. However, this selection leaves only 6% of the detected muons. The distribution of the energies of the selected muons is shown in Fig. 3: we note that events with energies lower than ∼20 GeV are too scarce for calibration.

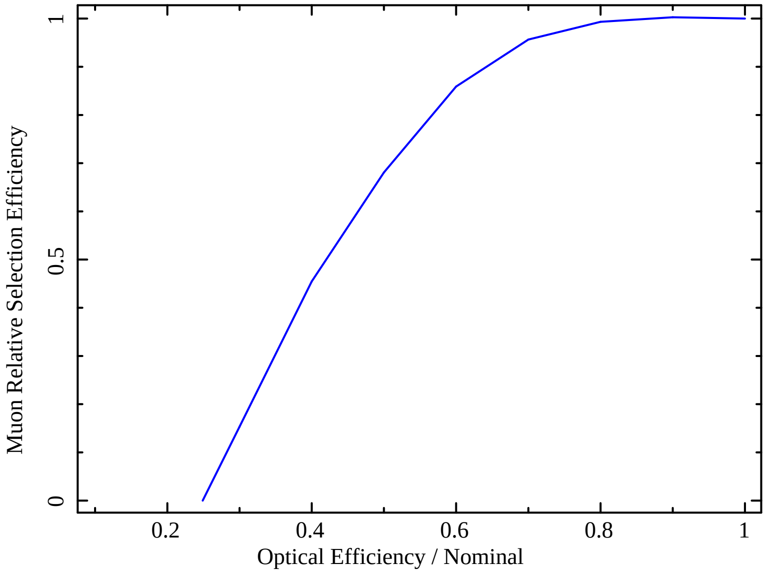

Figure 2. ASTRI SST-2M telescope selection efficiency relative to the nominal value (no degradation) as a function of the optical efficiency in unit of the nominal one for muons within the selection criteria ξ <0.05, and $0.9^\circ < R < 1.5^\circ$.

To evaluate the reconstruction precision on the analysed parameters, their relative distributions (assuming the nominal optical efficiency) are accumulated and fitted with Lorentian functions. We assumed as reconstruction error the average value of the distributions and as uncertainty the width of the functions. Results are shown in Table 1. No systematic in the reconstructed parameters is observed for the azimuth and Cherenkov angles that are reconstructed with an error of 1.3% and 6.3%, respectively. The zenith angle is determined with a systematic

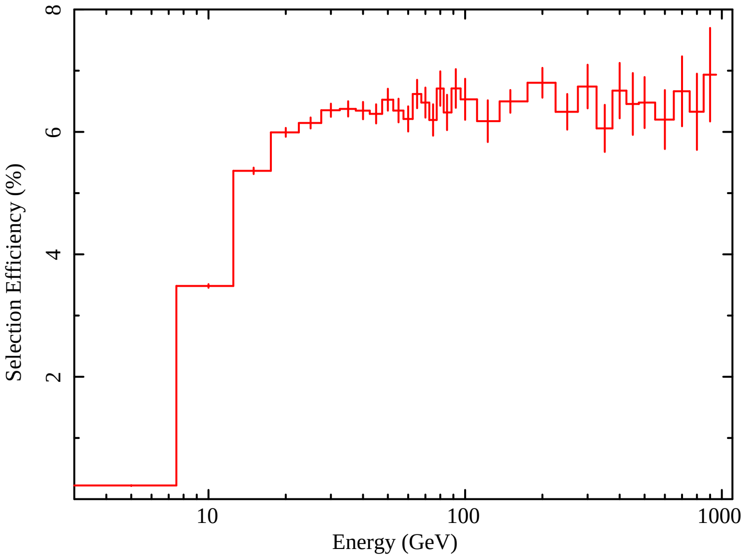

Figure 3. Muon selection efficiency as function of energy for muons within the selection criteria $\xi < 0.05$, and $0.9^\circ < R < 1.5^\circ$.

shift of about 1 pixel (whose reasons are under investigation) and with an uncertainty slightly larger that one pixel.

Table 1. Error on reconstructed geometrical parameters

Zenith angle ($\Delta\vartheta$)	0.16°±0.23°
Azimuth angle ($\Delta\varphi$)	0.0±1.3%
Cherenkov angle ($\Delta\theta$)	0.0±6.3%

6. CONCLUSION

The preliminary results obtained for the simulated data set described in this contribution show that, using 6% of the detected muon events, it should be possible to select a sample of events that allow us to calibrate the ASTRI SST-2M optical throughput with muons down to a degradation of the optical efficiency of 30%, with the same precision achieved at the nominal optical efficiency. In these conditions, the precision in reconstructing the muon arrival direction is about 0.23° (slightly larger than the ASTRI SST-2M camera pixel size) for muon energy higher than 20 GeV and impact parameter within the primary mirror up to an off-axis angle of 4°. The reconstruction of the muon ring radius seems to be possible with an error of ∼6.3%.

The results are promising and the muon analysis described here will be tested with real data foreseen in fall 2016, when the muons will be acquired from the regular science data taking during the science verification phase of the ASTRI SST-2M prototype. The work on simulations and analysis are in progress in order to complete the muon rings reconstruction algorithms (e.g. for the impact parameter) necessary to evaluate the precision on the telescope efficiency. New simulation data sets will also be produced to investigate the effects in case of not-vertical zenith angles and higher level of background considering that the conditions in which the prototype will operate are different from those assumed in this analysis. To complete the analysis, the capability in monitoring the PSF of the telescope from the geometrical parameter of the muons must also be investigated.

In parallel, new silicon photomultipliers, characterized by an higher detection efficiency as well as by a strong reduction of the cross-talk and after-pulse, are now being set up to be used for the ASTRI mini-array proposed to be installed at the final CTA southern site.[18] Such sensors will provide better quality images, increase the number of good muon rings, and furtherly reduce possible trigger biases due to the improved efficiency of the overall system.

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