MUCH: a compact imaging Čerenkov telescope for volcano muography

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Abstract

Significant progress has been made in the last years in the field of volcanic muography. This technique takes advantage of the large penetrating power of atmospheric muons and allows us to infer information about the internal structure of volcanoes observing the differential absorption of muons passing through the target. This, in conjunction with other monitoring techniques, can help to determine the state of activity of a volcano and to reduce the risk related to paroxysmal events. The main challenge in the application of this technique is given by the background noise, that affects detectors. To improve the signal-to-noise ratio it is necessary to use several detection layers and shielding plates that make the detector expensive and difficult to transport. In order to overcome these issues, the use of Imaging Atmospheric Čerenkov Telescopes (IACTs) devoted to muography has been recently proposed.

Here we present the MUography CHerenkov (MUCH) telescope, a compact IACT specifically designed for volcano muography. The telescope design is characterized by a Schmidt-like optical system and a Silicon Photo-Multipliers (SiPMs) camera working at wavelengths between 280 nm and 900 nm, equipped with a fast read-out electronics capable to operate SiPMs contemporarily in charge integration and photon counting mode.

Keywords:
Muography, Geant4, Ray Tracing, Imaging Atmospheric Čerenkov Telescope, RADIOROC

1. Introduction

Muography with IACTs is a recently proposed technique [1, 2] that exploits the muon-induced Čerenkov radiation in atmosphere in order to perform radiography/tomography of massive targets. When a muon with energy above about 5 GeV passes near the telescope aperture, Čerenkov photons induced along the trajectory form on the telescope camera an easily recognizable arc-shaped signal [3] from which it is possible to determine the muon arrival direction with a resolution on the target of a few meters. Although IACTs are not able to operate in the daytime, a large muon collection area and a high angular reconstruction precision are expected, thanks to IACTs imaging capability. Furthermore, the primary sources of background noise, scattered low-energy muons and high-energy charged particles from extensive air showers [4, 5, 6], that affect muography detectors are not expected to affect IACTs observation. Owing to the high energy threshold of the Čerenkov process, the former are not detectable. The latter are easily rejected from images analysis.

The feasibility of muography with IACTs has been demonstrated by our team using Geant4 simulations for muon transportation and Čerenkov photons emission and the ASTRI-Horn telescope[1] simulator for optical ray-tracing [7]. Simulation results of the muography of a volcano toy-model have shown a muons collection area greater than the telescope aperture area and a mean angular resolution better than a few tenths of degree (smaller than the muon angular deviation inside the target).

The MUCH telescope is an ASTRI evolution concept. Unlike the ASTRI-Horn telescope, it is lighter, transportable and equipped with a higher performance camera for what concern time and charge resolution. The core of the camera is the novel ASIC (Application-Specific Integrated Circuit) named RADIOROC (RADIOgraphy Read Out Chip) allowing measurements in faint light conditions, using single photon counting, and the detection of bright events, using charge integration.

2. MUCH telescope design

2.1. Optical design

The MUCH optical system is derived from the Schmidt camera design. It has an entrance pupil of 2.5 m diameter and is composed of a PMMA Fresnel lens corrector, an aspherical mirror and a flat focal plane.

The 5 mm thick Fresnel corrector is placed at the focal point of the mirror, yielding to a highly compact configuration. The optical system scheme is shown in figure 1. The telescope lens and mirror design has been optimized with Zemax OpticStudio[2]. Optical aspherical surfaces profile are described by the

[1]`http://www.ifc.inaf.it/index.php/projects/the-astri-telescopes/`

[2]`https://www.zemax.com/products/opticstudio`

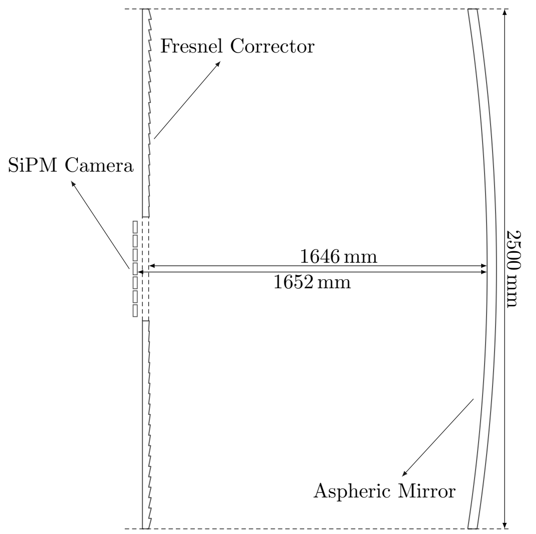

Figure 1: Sketch of the MUCH telescope optical system.

even aspheric equation

$$s(r) = \frac{cr^2}{1 + \sqrt{1 - c^2 r^2 (1+k)}} + \sum_{i=1} \alpha_i r^{2i} \quad (1)$$

where c is the lens curvature, k is the conic constant, and α_i are the aspheric coefficients. Parameters of optimized surfaces are listed in table 1. These result in a nominal field of view (FoV) of about 12° and an angular resolution better than 0.2° throughout the entire FoV.

The focal plane is covered by a matrix of 7×7 Photo-Detection Modules (PDMs), each composed of a matrix of 8×8 SiPM sensors (Hamamatsu S14521) with a 6.95 mm×6.95 mm active area (0.21°×0.21° angular size) working in the 280 nm-900 nm wavelength band.

2.2. Electronics

The camera is equipped with an innovative fast electronics based on the new RADIOROC front-end [8] [9], which is an improvement of the ASIC used in the ASTRI-Horn telescope. It is a 64-channel chip capable of measuring the amount of light revealed by SiPM detectors both in Single Photon Counting (SPC) mode and in charge integration mode with a very large dynamic range. In SPC the ASIC is able to distinguish two photons arriving onto the SiPM with a time difference of 7.5 ns, corresponding to a maximum counting rate capability of 150 MHz, thanks to a programmable pole zero cancellation circuit. This characteristic is essential for acquire the very brief muon signal, minimizing the night sky background.

Table 1: MUCH optical surfaces parameters.

Parameter	Fresnel lens corrector	Aspherical mirror
R	1250 mm	1250 mm
$1/c$	−7332.285 mm	−3784.375 mm
k	0.0	0.0
α_1	0.0	0.0
α_2	$2.176\,931\,7 \times 10^{-11}$	$-4.396\,288\,9 \times 10^{-12}$
α_3	$5.141\,933\,8 \times 10^{-19}$	$1.769\,375\,7 \times 10^{-19}$
α_4	$1.103\,78 \times 10^{-24}$	$-1.295\,832\,8 \times 10^{-25}$

3. Geant4 simulator

In order to simulate a telescope that combines Fresnel lenses and aspherical mirrors, a dedicated Geant4 [10][11][12] simulation framework is currently being developed. Providing objects for the creation of Fresnel lenses, aspheric mirrors and SiPM cameras, this framework allows for easy geometrical construction of the optical telescope components and simplifies the implementation of materials optical properties. The framework main classes are:

- `MuchFresnelLens` class, that allows for creation of customizable Fresnel lenses. Lens grooves are concentric hollow conical frustums with same width and linear cross section, computed from the lens profile. Major manufacturing errors (draft angle and error on slope angle) are taken into account;
- `MuchCamera` class, that allows for creation of customizable SiPM cameras. Two focal surfaces have been implemented: spherical and flat. PDMs are positioned and rotated in order to shape the telescope focal surface.
- `MuchStandardLens` class, that allows for creation of customizable “aspherical shell” solids. To this purpose, a new Geant4 CSG solid for aspherical lens simulations has been implemented. The sagittal profile is the same for both front and back solid surfaces and must not have inflection points. Intersections with the solid are computed with the Newton-Raphson method using some reference surfaces (see figure 2) to analytically find intervals with a unique solution.

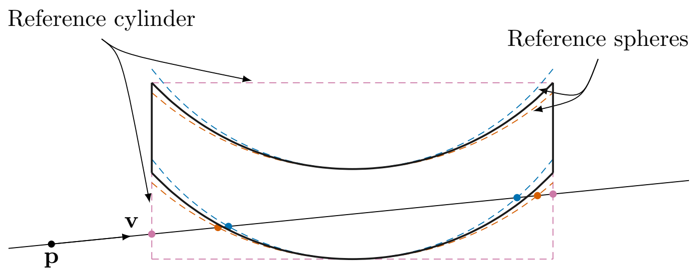

Figure 2: Example of the ray tracing through an aspherical shell. Intersection points of a ray moving in the direction **v** from point **p** are numerically computed using reference surfaces to constrain the root-finding interval.

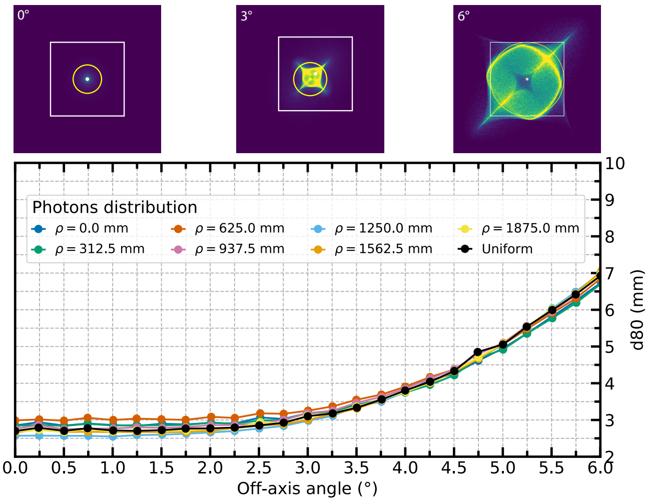

Figure 3: Geant4 ray-tracing results. (Above) Optical system spot diagram at 0°, 3° and 6° off-axis angle. The white box has the size of a pixel, the yellow circle encircles the 80 % of photons. (Below) d80 as a function of off-axis angle for different impact parameters.

3.1. Optical performance simulations

As already described in [13], we use the diameter (d80) of the smallest circle that encircles the 80 % of photons focused on the focal plane. Moreover, since the system response depends on the spatial distribution of incident photons, we use a photon distribution induced by muons uniformly distributed over a thin ring of radius ρ centered at the center of the telescope aperture:

$$\sigma_{\mathrm{ph}}(r,\rho) \propto \frac{1}{|r-\rho|} K\left(-\frac{4r\rho}{(r-\rho)^2}\right) \quad (2)$$

where r is the distance from the aperture center and K is the complete elliptic integral of the first kind. In this way, the d80 is averaged over all muon impact azimuth angles.

Simulation results are shown in figure 3. The photon spectrum used in the simulations is the convolution of the Čerenkov spectrum with the SiPM nominal photon detection efficiency. The resulting nominal d80 is below the dimension of a SiPM pixel up to 6° off-axis. The d80 has been tested for different impact parameters and shows a slight dependence on the muon impact parameter, which means that the system response is the same regardless of the muons impact point.

4. Conclusion

The MUography CHerenkov telescope, a compact Schmidt--like IACT, has been presented. The design provides an angular resolution better than 0.21° (pixel angular size) over the entire FoV of 12°. The SiPM camera will be equipped with a new fast front-end electronics capable to acquire the brief muon Čerenkov flash, reducing optical background signals. The first step to obtain real data as soon as possible will be the installation of the MUCH camera on board the ASTRI-Horn telescope; the big distance of the telescope from the craters will limit the spatial resolution but will allow to evaluate the new technique and let us improve the software and the hardware of the camera. An international patent has been registered (PCT/IB2016/056937).

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