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MUCH: an imaging Čerenkov telescope for volcano muography

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Abstract

In the last decades, several attempts have been made to investigate internal structures of large bodies, such as volcanoes, with transmission muography. High spatial resolution and reduction of the strong background noise due to protons, electrons and scattered low energy muons, are the main challenges for this technique. As a possible solution to fulfill these requirements, muography with Imaging Atmospheric Čerenkov Telescopes (IACs) has been recently proposed and the feasibility demonstrated by our team using GEANT4 simulations.

IACs are telescopes dedicated to the gamma-ray astronomy consisting of an optical system that focuses the Čerenkov light into a high-sensitive and fast read-out camera. Muons with energy above about 5 GeV induce Čerenkov radiation which is emitted in a cone with a constant opening angle around their travel direction. As IACs image in angular space, the Čerenkov light focused onto the camera forms a ring-shaped image centred at a distance from the focal plane centre proportional to the muon incidence angle. None of the previously mentioned source of background is expected to affect the IACs muon signal.

Here we present MUCH, a lightweight and compact IAC design, specifically dedicated to volcano muography. The telescope design is based on a SiPMs camera working in the 280 nm-900 nm wavelength band, equipped with a fast read-out electronics with single photon counting capability. The proposed Schmidt-like optical system is composed of a 2.5 m aspherical mirror and a 2.5 m PMMA Fresnel lens corrector. It results in a field of view of about 12°, an entrance pupil of 2.5 m diameter and an angular resolution better than 0.2° throughout the entire FoV which allows us to determine the muon direction with a reconstruction precision better than a few tenths of degree.

A Geant4 framework for the simulation of Fresnel lenses and aspherical mirrors is currently being developed for the telescope prototype achievement.

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

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1. INTRODUCTION

Particles seen by current muon telescopes are not only muons coming from the target. Indeed, muography can be affected by a huge particle background [1, 2, 3, 4] due to scattered low energy, charged particles from Extensive Air Showers (EASs), random coincidences of different particles and upward-going particles entering the back of the detector. The latter background source can be reduced by time-of-flight techniques that require a sub-ns time resolution readout system [5, 6]. The EAS particles and soft-muons components of the background can be reduced by increasing the number of detector planes and using lead walls to discriminate low-energy particles [7, 8]. This solution increases the weight and dimensions of the instrument, limiting its portability. In order to overcome this problem, muography with Imaging Atmospheric Čerenkov Telescopes (IACs) has been recently proposed [9, 10]. This technique exploits the induced Čerenkov radiation along the muon trajectory. Despite IACs can observe only at night, none of the previously mentioned source of background is expected to affect the observed muon flux. Indeed, Čerenkov radiation is induced only by muons with kinetic energy greater than about 4.5 GeV, so low-energy muons are not detected.

The feasibility of muography with IACs has been demonstrated by our team using GEANT4 simulations for muon transportation and the ASTRI-Horn telescope¹ simulator for optical ray tracing [11]. Simulation results of the muography of a volcano toy-model have shown an angular resolution better than a few tenths of degree and a muon collection area greater than the telescope aperture area.

¹<http://www.ifc.inaf.it/index.php/projects/the-astri-telescopes/>

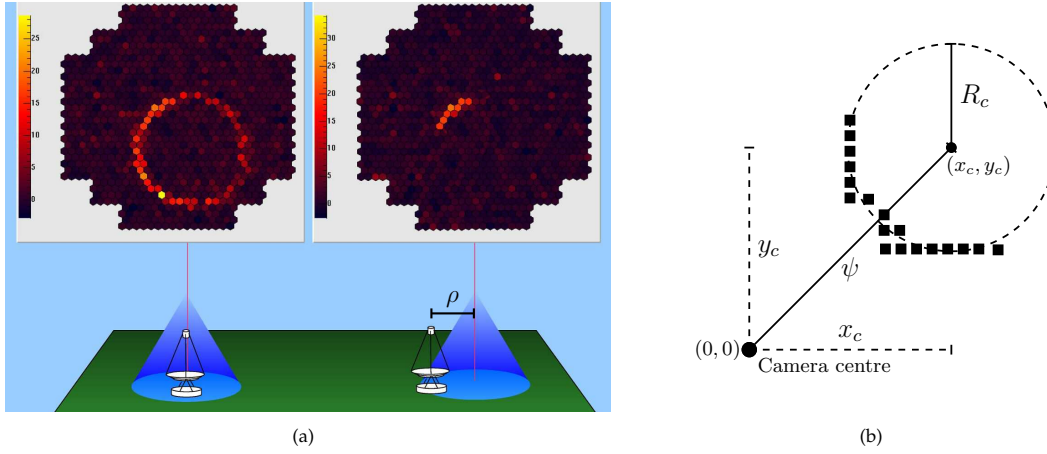


FIGURE 1: **(a)** Muons hitting an IACT aperture plane in the center and at a distance ρ (credit:[13]). When the muon passes through the aperture plane the ring appears complete, otherwise its angular extent decreases with increasing ρ . **(b)** Reconstruction of muon direction and Čerenkov angle from radius and center of an IACT muon image.

2. MUON DETECTION WITH IACTS

A charged particle induces Čerenkov radiation when it passes through a refractive medium at a speed greater than the speed of light in that medium. Photons of energy ϵ are emitted with an angle θ_c , relative to the particle direction, which depends on the particle speed βc_0 , where c_0 is the speed of light in vacuum, and on the medium refractive index $n(\epsilon)$

$$\theta_c = \arccos \frac{1}{\beta n(\epsilon)} \quad (1)$$

For muons in atmosphere at sea level, this implies a process energy threshold of about 4.5 GeV and a limit on Čerenkov angle of about 1.4° . The energy spectrum of the emitted photons per unit path length is given by the Frank-Tamm formula

$$\frac{dN}{dz} = \frac{\alpha}{\hbar c_0} \left(1 - \frac{1}{\beta^2 n^2(\epsilon)} \right) \quad (2)$$

where α is the fine-structure constant and \hbar is the reduced Planck constant.

Consider a muon passing near an IACT with a track, nearly parallel to the optical axis, that intersects the telescope aperture plane at a distance ρ (the *impact parameter*) from the aperture center (see figure 1a). The induced Čerenkov photons do not cover the telescope aperture plane uniformly. Indeed, the radial distribution of photons has inverse-distance dependence from the impact point

$$\sigma_{\text{ph}}(r) \propto \frac{1}{r} \quad (3)$$

As a consequence, at fixed ρ/R_a , the number of Čerenkov photons reaching the telescope aperture is not proportional to the telescope aperture area but to its aperture radius R_a . With a 2.5 m telescope aperture only the photons emitted in about the last 100 m can be seen, resulting in a signal of few ns. The number of photons on the aperture decreases with the impact parameter; a minimum of about 1000 photons and a maximum of about 3000 photons are expected for $\rho < 2$ m.

As IACTs image in angular space, the Čerenkov light focused onto the camera forms a ring-shaped image centred at a distance from the focal plane centre corresponding to the angle of incidence of the muon and with an angular extent ϕ_{ext} that decreases as the impact parameter increases [12]

$$\phi_{\text{ext}} = \begin{cases} 2\pi & \text{if } \rho < R_a \\ 2 \arcsin \left(\frac{R_a}{\rho} \right) & \text{if } \rho \geq R_a \end{cases} \quad (4)$$

After a cleaning procedure on the image, the muon arrival direction (the ring center) with respect to the telescope axis can be measured with a mere geometrical analysis (see figure 1b). In addition, from the ring radius one can infer the muon energy up to about 20 GeV; above this energy the Čerenkov angle saturates at about 1.4° at sea level.

3. OPTICAL AND DETECTION SYSTEM OF THE MUCH TELESCOPE

3.1. Telescope design

The MUCH optical system is derived from the Schmidt telescope configuration. It utilizes a Schmidt corrector plate and a primary mirror as in the conventional Schmidt configuration, but:

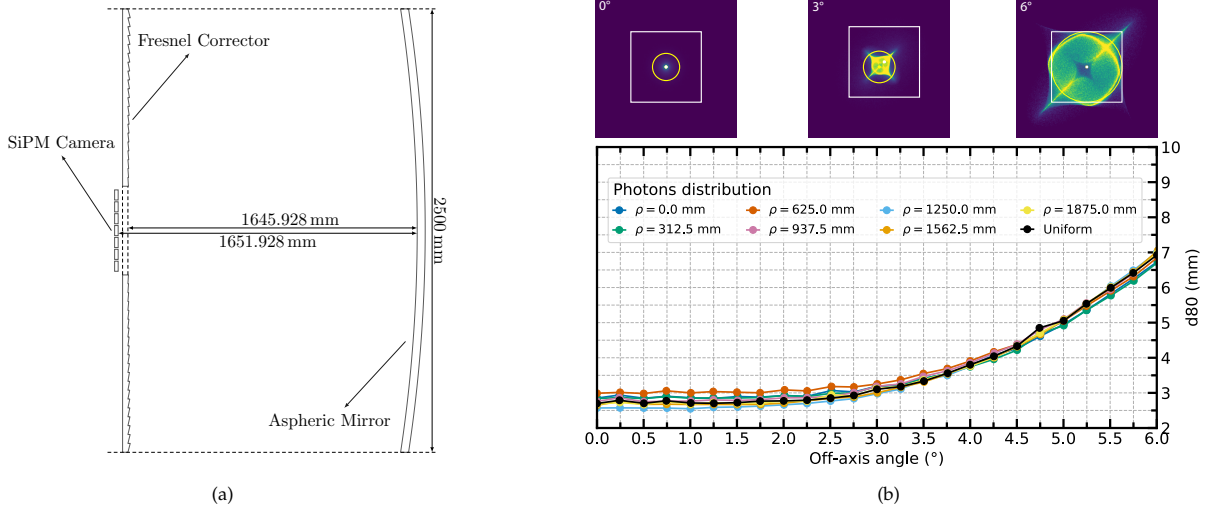


FIGURE 2: **(a)** Sketch of the optical system of MUCH. **(b) Above)** Optical system spot diagram at 0° , 3° and 6° off-axis angle. The white box is $7\text{ mm} \times 7\text{ mm}$. **Below)** 80 % encircled photons diameter (d_{80}) as a function of off-axis angle and with different photons distributions on the aperture: uniform and induced by muons with different ρ . Simulations have been performed with a dedicated GEANT4 simulator.

- 41 • the corrector is implemented as a 5 mm thin Fresnel lens;
- 42 • the corrector is placed at the focal point of the mirror instead of at its center of curvature;
- 43 • the mirror profile is aspherical instead of spherical.

44 Furthermore, the optical system focal surface results flattened. The position of the corrector yields to a very compact configuration
 45 and to an easy-to-manufacture flat focal surface, but at the expense of the simplicity of the mirror optical surface. In order to reduce
 46 the optical aberration across the field of view, the telescope lens and mirror design has been optimized with Zemax OpticStudio².
 47 The optical surfaces sagitta of the system is described by the equation

$$s(r) = \frac{cr^2}{1 + \sqrt{1 - c^2r^2(1+k)}} + \sum_{i=1} \alpha_i r^{2i} \quad (5)$$

48 where c is the lens curvature, k is the conic constant, and α_i are the aspheric constants. The optimized profiles parameters are listed
 49 in table 1. The diameter of both corrector and mirror is 2500 mm and the axial distance between them is 1645.93 mm. The effective
 50 focal length of the system is 1854.66 mm and the telescope plate-scale is $32.37\text{ mm}/^\circ$. These and others parameters of the optical
 51 design are summarized in table 2. The distance between the mirror and the focal plane is 1651.93 mm. The focal plane is covered
 52 by a matrix of 7×7 PDMs, each one composed of a matrix of 8×8 SiPMs sensor with a $6.95\text{ mm} \times 6.95\text{ mm}$ active area working in the
 53 $280\text{ nm} - 900\text{ nm}$ wavelength band, so the pixel angular size is $0.22^\circ \times 0.22^\circ$.

TABLE 1: MUCH lenses profile parameters.

Parameter	Fresnel lens	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	$1.103\,78 \times 10^{-24}$	$-1.295\,832\,8 \times 10^{-25}$

TABLE 2: MUCH optical system main parameters.

Parameter	Value
Effective focal length	1854.66 mm
Entrance pupil diameter	2500 mm
$f/\#$	0.74
Plate scale	$32.37\text{ mm}/^\circ$
Mirror diameter	2500 mm
Corrector diameter	2500 mm
Corrector central window side	420 mm
Focal plane side	420 mm
Corrector-mirror distance	1645.93 mm
Back focal length	1651.93 mm

²<https://www.zemax.com/products/opticstudio>

54 *Electronics*. An innovative fast front-end electronics will be used for the SiPMs readout. The Application-Specific Integrated Circuit
 55 (ASIC) designed, the RADIOROC (RADIOgraphy Read Out Chip) [14], is an improvement of an existing ASIC, used in the ASTRI-
 56 Horn project. RADIOROC is capable to operate SiPMs both in charge integration and in single photon counting (150 MHz). The
 57 latter is essential for acquire the very brief in time (few ns) muon signal minimizing the night sky background.

58 3.2. GEANT4 simulation results

59 *MUCH simulator*

60 In order to simulate a telescope that combines Fresnel lenses and aspherical mirrors, a dedicated GEANT4 simulation framework is
 61 currently being developed. The purpose is to provide a flexible module for the creation of Fresnel lenses, mirrors and SiPM cameras
 62 reducing the complexity of GEANT4 geometry description and simplifying the implementation of materials optical properties. The
 63 framework main classes are:

- 64 • MuchFresnelLens class, that allows for creation of customizable Fresnel lenses;
- 65 • MuchStandardLens class, that allows for creation of customizable “aspherical shell” solids;
- 66 • MuchCamera class, that allows for creation of customizable SiPM cameras.

67 *Optical performance simulations*

68 As already mentioned in section 2, Čerenkov photons induced by muons are not uniformly distributed on the telescope aperture
 69 plane. Since the optical performance depends on both photon incidence angle and incidence position on the corrector, simulation
 70 with muon-induced photon distribution have been performed. To simplify the characterization of the telescope optical performance
 71 as a function of the sole impact parameter ρ , we derived, using equation 3, a photon distribution induced by muons uniformly
 72 distributed over a thin ring of radius ρ

$$\sigma_{\text{ph}}(r, \rho) \propto \frac{1}{|r - \rho|} K \left(-\frac{4r\rho}{(r - \rho)^2} \right) \quad (6)$$

73 where r is the distance from impact point and K is the complete elliptic integral of the first kind. Using such photon distribution,
 74 the derived optical performance descriptors are averaged over muon impact azimuth angle and depend only on ρ . Moreover, the
 75 photon spectrum used in the simulations is the convolution of the Čerenkov spectrum (2) with the SiPM photon detection efficiency.

76 Simulation results are shown in figure 2b. The diameter, d_{80} , of the smallest circle that encircles the 80 % of photons focused
 77 on the focal plane has been used to characterize the system performance. The polychromatic d_{80} is below the dimension of a SiPM
 78 pixel up to 6° off-axis. It is worth noting that the d_{80} depends only slightly on the muon impact parameter, which means that the
 79 system response is uniform over the whole aperture.

80 4. CONCLUSION

81 Muography with IACTs is a novel promising technique that exploits the muon-induced Čerenkov radiation in the atmosphere in
 82 order to perform muon detection. Due to IACTs image capability and high Čerenkov energy threshold, negligible background,
 83 muon collection area greater than the telescope aperture and an angular resolution better than a few tenths of degree are expected.

84 MUCH, a compact Schmidt-like IACT designed for muography, has been presented. The design provides an angular resolution
 85 better than 0.22° (pixel angular size) over the entire FoV of 12° . The SiPM camera will be equipped with a new fast front-end
 86 electronics capable to acquire the muon Čerenkov flash minimizing optical background signals. An international patent has been
 87 registered (PCT/IB2016/056937).

88 *Conflicts of interest*

89 The authors have no conflicts of interest to declare that are relevant to the content of this article.

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