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Cherenkov light for gamma astronomy and not only

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1. Introduction

For energies above a few hundred GeVs, the observation of primary gamma rays from space with satellites or stratospheric balloons becomes inefficient, so that a direct measurement is impossible due to the limitation of the detection surface necessary to intercept primary gamma rays, whose flux is greatly reduced as the energy increases. We then rely on an indirect measurement, that is the detection of secondary particles produced by the interaction of gamma rays with the earth's atmosphere. Our detector is now the atmosphere, that simultaneously performs the function of absorber and converter. In the atmosphere, charged particles and gamma rays coming from the outer space, which in no case can reach the Earth's surface, interact with the atoms of the air producing a cascade of ionized particles and electromagnetic radiation, which in turn create additional secondary particles and electromagnetic radiation and so on, thus creating the so-called EAS (Extensive Air Shower). The secondary charged particles give rise to the well-known phenomenon of Cherenkov light production, that occurs when a charged particle (like an electron) crosses a dielectric medium, the air in our case, at a speed higher than the speed of light in that medium. The charged particles polarize the air molecules, which then quickly return to their fundamental state emitting photons along the direction of the charged particles, producing a weak (a few hundred photons) and very short (a few ns) light emission in the ultraviolet and visible wavelengths. The contribution in Cherenkov photons of all the charged particles of an EAS in its evolution in the atmosphere manifests itself, at an observational level, as a cone of light with its vertex at the point of first interaction of the primary particle with the air and the radius of the cone circumference of about 120m. This light can only be detected during the night by means of telescopes with large optical collecting surfaces and with fast and very sensitive multi-pixel cameras. The use of several telescopes, conveniently positioned, which operate simultaneously, improves the performance in energy resolution and the position accuracy of the gamma source observed in the sky, concurrently increasing the statistic number of the detected events (Fig.1).

The results obtained in recent years by the H.E.S.S, MAGIC and VERITAS Cherenkov telescopes demonstrate that the Universe abounds with celestial sources capable of producing very high energy gamma radiation. The CTA project (Cherenkov Telescope Array), with its two Observatories foreseen in the northern hemisphere (La Palma -

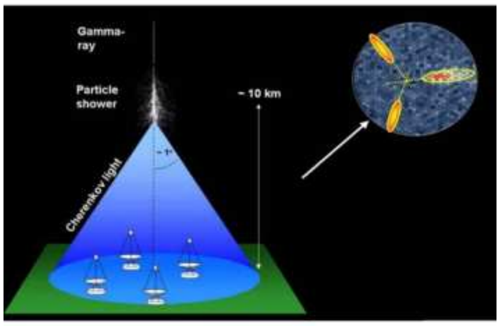

Fig. 1. Representation of a Cherenkov event. The image reconstructed on the cameras of the three telescopes allows to measure the arrival direction of the gamma photons with an accuracy of about 0.1 .

Canary Islands) and in the southern hemisphere (Chile), will contribute to an increase in sensitivity of an order of magnitude in the detection of gamma sources.

2. The ASTRI camera

With a minimum configuration of telescopes, INAF has been contributing since the beginning to the CTA initiative through the design, development and construction of a prototype telescope, ASTRI (Astrofisica con Specchi a Tecnologia Replicante Italiana) and a "pathfinder" consisting of 9 ASTRI telescopes similar to the current prototype. The ASTRI camera is designed to capture and record the fast pulses of the Cherenkov light during the night, in the wavelength range of 300-600 nm. The camera includes several components such as the detectors, the image processor, the thermal system, the calibration system, the peripheral controls and the associated circuitry, as well as the specific interface to the mechanical structure of the telescope. This also includes the lids, the input window filter and the support structure of the photon detection modules. The prototype camera consists of 21 Silicon Photo-Multiplier (SiPM) light sensor modules. Each module has 64 pixels arranged in an array of 8 x 8 pixels. Each pixel has a size of 7mm x 7mm. In total, the camera consists of 1344 pixels. The dimensions of the camera are respectively 500 mm x 490 mm x 560 mm for a total weight of 70 kg and a total consumption of 800 W (Fig.2).

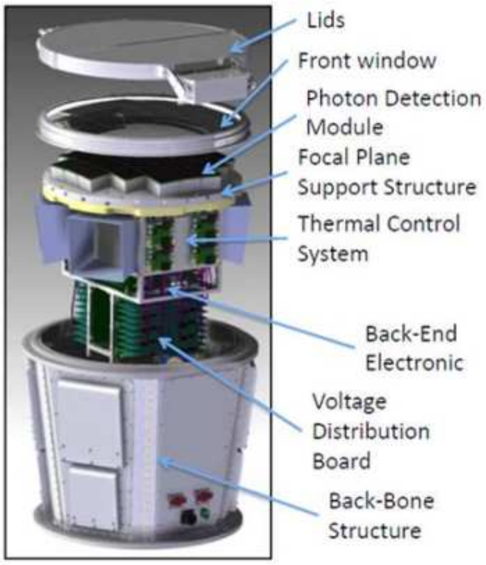

Fig. 2. Exploded view of the ASTRI camera.

The prototype opto-mechanical structure of the telescope was installed on September 24, 2014 in the INAF astronomical site of Serra La Nave (CATANIA), on the slopes of Mount Etna. Subsequently, ASTRI saw the first optical light in May 2015, and the first Cherenkov light was also obtained in May 2017 (Fig.3).

3. Relevant scientific aspects of ASTRI

ASTRI was conceived as one of the three types of telescopes selected for CTA. As such it is part of a project in which each telescope helps to cover a significant part of the gamma energy spectrum. ASTRI is dedicated to the detection of the most energetic gamma photons, from some TeV to a few hundred TeV. The wide field of view makes it possible to detect Cherenkov events even 400 m away from telescopes, effectively increasing the geometric sampling area and, in concert, the statistics of (very rare) high-energy events. The energy region above a few tens of TeV is still unexplored

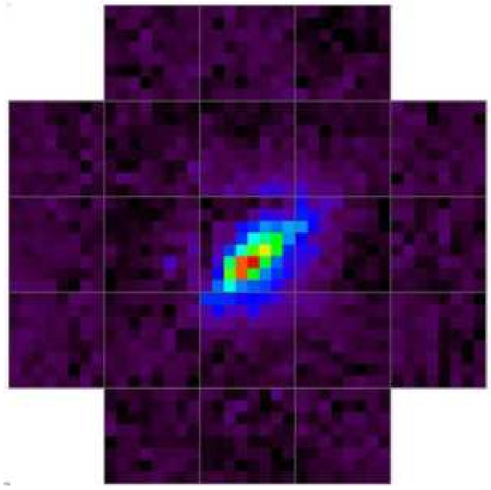

Fig. 3. Image of the first Cherenkov light detected in the ASTRI camera.

and could lead to important scientific discoveries. In particular, in addition to the classic gamma astronomy range, thanks to its large field of view, ASTRI, in multi-telescope configuration, will allow the detection of the most energetic photons ever observed before and the sampling of the highest energy particles coming from the Galaxy in search of their acceleration mechanisms, of particular importance for the identification of the cosmic ray sources, being foreseen their production, at a certain level, during their acceleration. Also, the detection of SNRs (Super Nova Remnants) with extended energy spectrum up to 100 TeV energies would be of fundamental importance to establish whether the emission of gamma rays is of leptonic or hadronic origin, which is still debated.

The large field of view of the ASTRI telescopes also has a dual application function in CTA. In fact, ASTRI telescopes are designed to detect any signal excess from sky areas outside the limited region of the source pointed by the telescope and to indicate to the larger and more sensitive telescopes their position for a more accurate study of the morphology and energy spectrum of the source, and at the same time, and to extend the observations towards the higher energies, precluded to the other types of telescopes. It is therefore of fundamental importance to identify sources of gamma rays whose spectra extend themselves, without any appreciable suppression, well over 10 TeV.

4. Relevant technological aspects of ASTRI

ASTRI certainly adopts many important and innovative technological solutions. INAF, proposing itself as a leader in the construction of small telescopes for CTA, has developed several innovative concepts that make the ASTRI telescope unique in its kind.

The double-mirror Schwarzschild-Couder configuration, which provides a double reflection on two mirrors, allows good angular resolutions over the entire field of view reducing the focal length, the physical pixel size and the overall size of the camera, while maintaining a field of view of about 10 degrees, extremely large compared to that of the current Cherenkov telescopes.

The entrance window, consisting of an optical filter, is another important technological innovation. The filter formed by three thin glass sheets, covered with dielectric through the multi-layer deposit technique, allows to block photons with a wavelength greater than 600 nm, maintaining unaffected those photons with a wavelength of less than 600 nm .

The optical calibration system of the light sensors of the camera, together with its low cost (the cost of a LED and an optical fiber meter), greatly simplifies the relative calibration measures of the light sensors gain. The system is based on the property of light which is scattered and diffused in a transparent material. By illuminating an optical fiber with a LED, both with continuous and pulsed light, placed in contact with the outer edge of the last filter glass, a part of the photons of the light pulse is dispersed in the glass and reaches the photosensors, keeping unaltered the timing characteristics of the original luminous pulse. The intensity of the light signal and its almost uniform distribution on the camera focal plane allow to simultaneously calibrate the gain of all light sensors.

Fig. 4. The CITIROC1 ASIC.

The SiPM reading electronics are quite different from those used in all other Cherenkov telescopes. As previously mentioned, the Cherenkov light signal is of very low intensity with a duration of only a few ns. The camera, therefore, must have a high sensitivity and a very high speed in acquiring the Cherenkov flashes of light. In order to achieve the required performance in terms of sensitivity and speed of acquisition, upon our suggestion and request, changes were made to an ASIC marketed by the French company Weeroc, which recognizes intellectual property rights to INAF (Fig.4).

The thermoregulation system allowing SiPMs to be kept at a constant fixed temperature employs a technique that makes use of a simple and reliable passive heat transfer system **(heat pipes)**, and a high thermal conductivity. Compared to traditional thermoregulation systems based on chillers with continuous liquid recirculation, the passive heat transfer has no moving parts, has the ability to transport heat over long distances, and is quiet and vibration-free.

5. An innovative application of the "Made in Italy" modern astronomy technologies: the muography

With a recent patent, the National Institute for Astrophysics has shown that the technologies developed in Italy in the framework of one of the most prestigious infrastructures of modern astronomy recommended by ESFRI, the Cherenkov Telescope Array, lend themselves to the realization of particular cameras capable of performing real radiographs and/or tomographies of complex geological and tectonic structures of large dimensions. For example, in the case of volcanoes, information can be obtained with an unprecedented detail related to the geometric characteristics of the conducts and the surface accumulation zones, improving the predictions on the volcano's activity status and consequently mitigating the risk linked to the occurrence of paroxysmal events. The muography is a technique similar in principle to radiography, which we all know. The substantial difference between radiography and muography lies in the completely different property of the penetrating radiation. Medical diagnostics use X-rays, photons of energies of about 100 eV, to obtain radiographs, i.e. "photographs" of internal organs. Biological tissues are opaque in different ways to X-rays, that is, they absorb them more or less intensely depending on their composition. When crossing the material, X-rays undergo an attenuation that depends on the thickness and the specific weight of the crossed material. The greater the thickness and specific weight of the irradiated material, the larger the attenuation. However, X-rays have a limited path and are able to pass only through a few tens of centimetres of concrete without being absorbed. Very different is the muography. The muons, from which the term muography, are generated by energetic particles (cosmic rays) that come from deep space and continuously bombard the earth. These particles, interacting with the atoms of the atmosphere, produce a rain of other particles, among which the pions, which decay very quickly in muons. The muons reach the earth's surface through a flux of penetrating charge radiation which, at sea level, is equal to about 1 muon/cm^2/min with an average energy of 2 GeV.

Even if about 207 times the mass of the electron and therefore more penetrating, also muons lose energy when they cross the material, with a flux reduction that depends on the thickness and density of the crossed material. The muons can however be used to obtain information on the distribution of densities within massive structures with densities that do not exceed that of 1 km of equivalent rock. Therefore, by measuring the absorption of muons in the massive structure of the volcano we can trace the inner density distribution (density structure), recognizing voids and/or zones with anomalous characteristics. The term muography is often accompanied by the term muon tomography. It is easy to realize that if several instruments are observing the same object from different angles, a 3D image will be obtained by combining the observations of each instrument. Obviously, the tomography would be able to solve with greater detail the geometric characteristics of the voids/areas of the internal massive structure.

6. Types of existing "muographies"

Up to now, most of the muon radiographies of active volcanoes have been obtained using detectors with scintillating bars read by traditional or silicon photomultipliers. Usually, the instrument consists of 3 or more parallel detection planes with a distance between one plane and another which is calculated according to the desired field of view. The signal produced by these instruments is affected by the influence of fortuitous coincidences (low energy particles that simultaneously strike the different planes of the detector, simulating an event) and back-flux (flux of particles that comes from the opposite direction with respect to the flux crossing the target). Furthermore, these tools do not provide information on the energy spectrum of the incident muons that must be known to calculate the integrated flux model that crosses the volcano, to be compared with the observed data. The noise due to multiple coincidences can be reduced to acceptable levels by increasing the number of scintillator planes and inserting lead and steel absorbers between planes. This solution allows to reduce the non-coherent muon background, but also has the effect of increasing the weight and dimensions of the instrument, reducing its compactness and limiting its portability and, as such, the possibility of use in inaccessible areas (e.g., the summit area of an active volcano). The recognition of the back-flux with respect to the useful flux (which crosses the target) requires the use of systems that allow the measurement of the flight time of the muons with a temporal resolution better than 1 ns. Such systems are not always easy to implement and manage in the context of installations on sites with poor logistics condition.

Another technique used for muon radiography consists in nuclear emulsions. The physical principles of nuclear emulsions are similar to those of photographic emulsions. While the photons forming an image are detected in the photographic emulsions, the ionizing particles, and therefore the muons, which pass through the emulsion are detected in the nuclear emulsions. Nuclear emulsions are usually composed of silver bromide crystals (AgBr) suspended in a gel (often from organic origin). A muon, like other ionizing particles, sensitizes the crossed crystals by ionization, leaving a latent image, which in the development process (similar to that of photographic emulsions) is subsequently fixed by means of appropriate chemical treatments. The ionization of the silver bromide gives rise to the formation of blackened grains, with a typical diameter of about 0.5 mm along the trajectory of the particle, with the grains aligned along the path of the particle in the emulsion layer. A very thin layer of emulsion (30~40 μm) can give 3D traces with angular precision of the order of 0.5 degrees. It must be said, however, that the nuclear emulsions are sensitive from their production until the moment they are developed. Nuclear emulsions are cheap (some /film) and passive, without requiring any associated electronics. Therefore, they are ideal for long-term measurement campaigns in places where electricity is not available. However, it must be kept in mind that thermal effects and humidity may cause the deletion of the latent image. Furthermore, a developed emulsion shows the traces of all the ionizing particles passing through it, including those due to natural and environmental radioactivity and cosmic radiation during transport to the exposure site. A careful treatment of the background is therefore generally required when the muographic exposures have to probe large objects

(>500 m of rock). Instrumental effects and background noise (ionizing particles) add false counts (even in the order of 10 tracks/cm^2), making it difficult to detect the very few muons crossing the object, influencing the statistics with an excess of muons, which leads to an underestimation of the average density of the target.

The newly developed "ASTRI" technique is based on the detection and spatial location of muons in the target through the Cherenkov light emitted by muons along their path. The detection of muons with this technique is limited to nights but with practically no background noise. The Cherenkov effect is a threshold effect that implies that a muon in the atmosphere can produce Cherenkov light if its kinetic energy is greater than 4.5 GeV. This is of particular importance for the "ASTRI" muography. In fact the sensitivity of ASTRI for muons and charged particles is around 10 GeV, implying that all particles under this energy threshold are not detected and therefore it cannot exist any contamination of the detected flux of muons by other charged particles or muons of lower energy. For those muons incident on the telescope a first selection is obtained by the threshold level of the Cherenkov effect itself, while for the other charged particles the selection is given by the sensitivity of the telescope. This important difference with other techniques is illustrated in the graphs produced with detailed GEANT (GEometry ANd Tracking) and Monte Carlo simulations (Fig.5).

GEANT is a complex software tool for simulating the passage of particles through matter with the aid of computational methods based on random Monte Carlo sampling.

7. What does the "muon-imaging" of volcanoes consist of?

In the volcanological field, muon imaging is of great interest. In fact, the models used to simulate the dynamics of magma and gas in the superficial part of the active system require information on the geometrical characteristics of the conducts and the low-depth accumulation zones. The detailed knowledge of the surface structure of a volcano is therefore a key element for making predictions about its state of activity and for mitigating the risk linked to the occurrence of paroxysmal events. Another aspect concerns the stability of the volcanic cones. The accumulation of pyroclastic material emitted during eruptive events implies the rapid growth of craters whose flanks can be characterized by a marked instability. It is therefore important to obtain information on the internal structure of the pyroclastic cones that could be affected by collapse phenomena (possible presence and distribution within them of voids, fractures, high porosity areas, etc.) and on the conditions that can trigger or aggravate the conditions of instability. The most commonly used geophysical imaging techniques (based on seismic, gravimetric and geoelectric data) are affected by intrinsic ambiguities, may require the execution of many risky measures in active areas and, in most cases, do not allow to obtain an adequate spatial resolution. On the other side, ASTRI-like muon imaging provides information on the internal structure of the volcano with adequate spatial resolution (from one to a few tens of meters) and without implying a serious risk for the personnel involved in on-field operations, as it is only necessary to install the detection system (telescope) in the active zone, while the data are subsequently acquired independently.

Telescopes based on the Cherenkov light detection technique produced by muons have never been used for radiographs of geological structures. The detection technique through the light emitted by muons is, however, well known in the experiments of gamma astronomy at the TeV, where the muons are used for the calibration of the cameras.

A Cherenkov telescope detects the brief flash of light (some ns) created by charged particles. Only when a muon arrives on the reflecting part of the mirror or in its immediate proximity, the Cherenkov light emitted along the final part of its path (from 100 to 300 meters) is conveyed by the optic on the focal plane of the instrument, forming a circular ring of easily distinguishable light (Fig.6).

A relatively simple geometric analysis of the ring allows to reconstruct the physical pa-

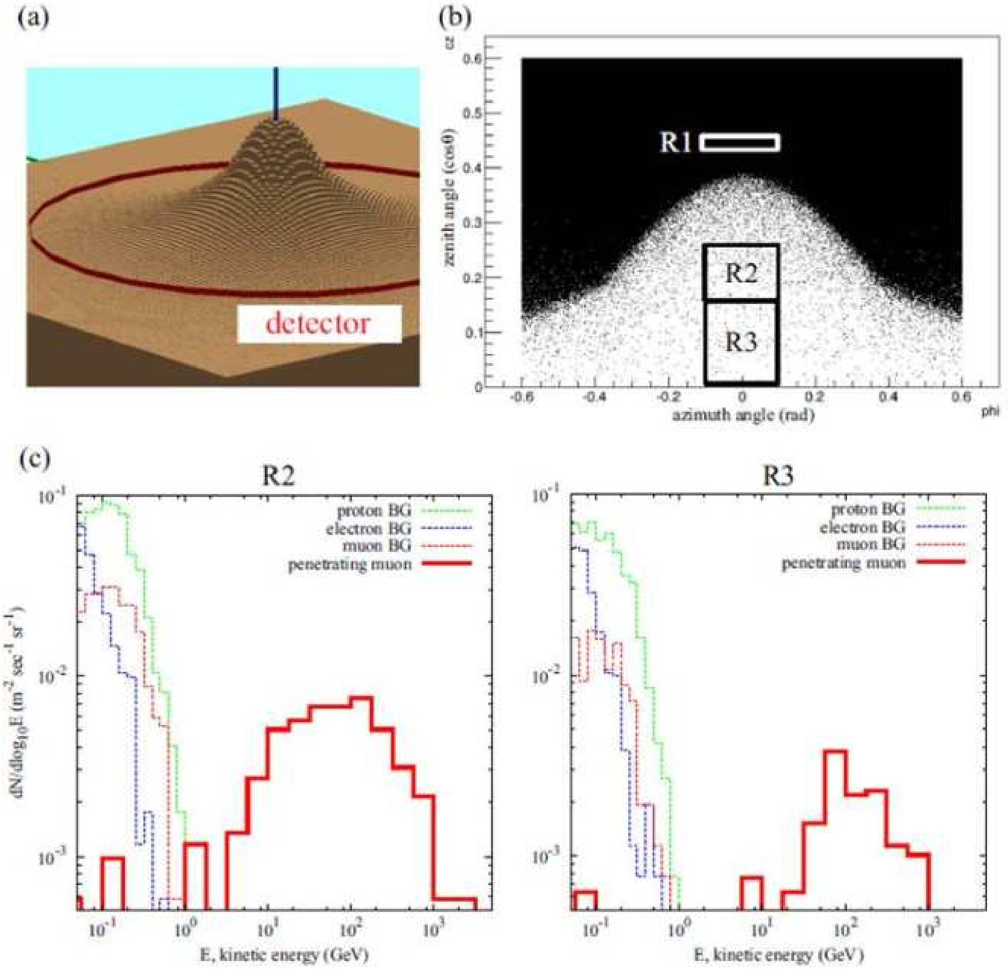

Fig. 5. (a) Virtual mountain and detector built in the computational space with GEANT4. (b) Angular distribution of particles arriving at the virtual detector, which shows three angular regions R1, R2 and R3 defined for a quantitative analysis. (c) Number of histograms of particles arriving at the virtual detector. The energy of the distributions of the penetrating muons and the background particles (BG) are drawn with solid lines and dotted lines, respectively.

rameters of the muon, i.e. its energy and the direction of arrival.

An advantage offered by the use of Cherenkov systems for muon imaging consists in the almost total absence of fortuitous coincidences, or noise, since the muons are detected through the photons that point towards the telescope optics (directional and highly collimated signal), a condition that also eliminates the back-flux problem. Furthermore, the telescope based on the Cherenkov light detection technique allows to estimate, directly at the installation site, the energy spectrum of the incident muons, necessary to derive the absorption within the target. It is therefore not necessary to use theoretical models, based on analytical calculations or numerical simulations, which, if they are not accurate enough, can increase the level of uncertainty on the estimation of the density distribution within the volcano itself.

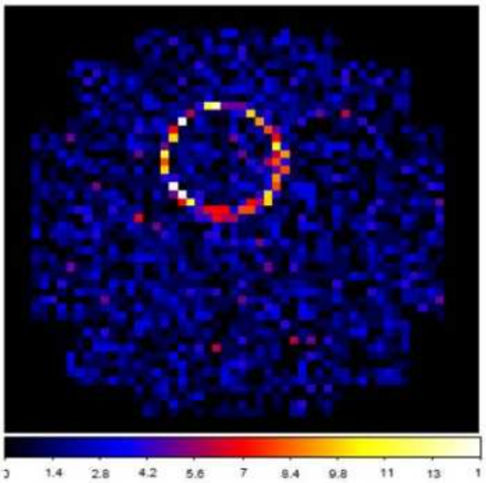

Fig. 6. Simulated ring Cherenkov image.

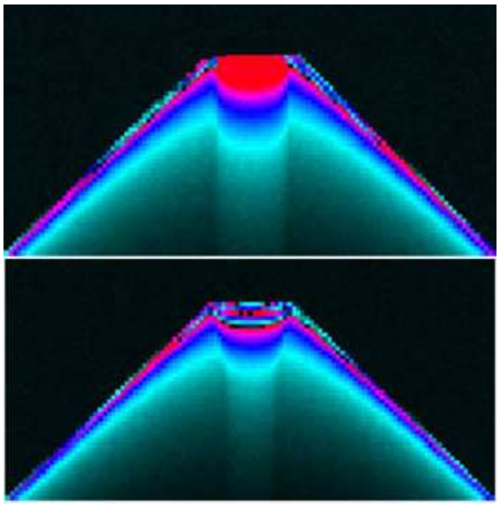

Fig. 7. Simulated images of the interior of a volcanic structure in which the profiles of the conduit respectively of 100 and 50 meters radius are visible.

Preliminary Monte Carlo simulations, performed on a model of volcano-like structure, confirm the potentiality of the proposed method that guarantees high efficiency and accuracy in the measurement of the muon flux (Fig.7).

8. Possible future developments of this type of research

The use of Cherenkov detectors to perform muon radiography in the volcanological field is completely unprecedented and will allow an important advancement of this methodology, given that, compared to common scintillation systems, it will be possible to drastically improve the relationship between signal and noise. The know-how that will be developed will allow the integration of the solutions adopted to allow the use of Cherenkov systems in the volcanological field to obtain high spatial resolution radiography of active volcanic structures. The fields of applicability of the detection system and of the method are numerous. In the Cherenkov telescope, if a stronger angular resolution is required, the camera can be modified by increasing the number of focal plane pixels. The modularity of the electronics makes it possible to operate in this sense, without degrading performance. A future development to make the Cherenkov detector even lighter may consist in the use of plastic Fresnel lenses. Depending on the applications, different mechanical structure configurations can be thought of and adapted to the logistic-observational needs to perform prospecting in the field of civil engineering, archaeology, volcanology and tectonics and wherever a non-invasive radiographic and/or tomographic inspection of structures, even if of considerable size, is necessary. The proposed method, with the necessary optimization and engineering, is potentially suitable for the creation of start-ups and of strong interest for the industries operating in the fields of application. There are therefore the prerequisites for the development of an innovative technique for muon radiography applied to volcanoes by exploiting the technological know-how and scientific experience of the INAF personnel involved in the construction of the ASTRI telescope.