PROCEEDINGS OF SCIENCE

Advancing the atmospheric Cherenkov-method to detect gamma-rays with one Giga electron Volt

Sebastian Achim Mueller[a,*]

[a] *Max-Planck-Institute for Nuclear Physics, Saupfercheckweg 1, 69117 Heidelberg, Germany*

E-mail: sebastian-achim.mueller@mpi-hd.mpg.de

Imaging atmospheric Cherenkov-telescopes are powerful detectors for cosmic gamma-rays. Yet the detection of gamma-rays with lower energies in the domain of Giga electron Volts (so far reserved to satellites) at the high rates provided by the large collective area of the atmospheric Cherenkov-method, can be a potential advance. This will improve our understanding of short lived transients and of distant sources which have their gamma-rays with higher energies absorbed by infrared light. With telescopes, the detection of gamma-rays with lower energies implies larger mirrors, which narrow the depth-of-field, and blur the image. Larger mirrors imply an exponential increase in costs to prevent deformations of the optics. In addition, the mirror's aberrations further blur the image and limit the field-of-view. To advance, we propose a new class of instrument (the Cherenkov-plenoscope) which senses not only the direction of Cherenkov-photons but also their point of reflection on the mirror. The Cherenkov-plenoscope turns a narrow depth-of-field into the perception of depth, compensates deformations, and compensates the mirror's aberrations. We will discuss the possibility of a Cherenkov-plenoscope dedicated to the detection of gamma-rays with energies as low as one Giga electron Volt, and our current estimate of its capabilities.

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1. Introduction

To resolve timing and variability in the sky of gamma-rays we want to detect gamma-rays with high rates. To maximize these rates we want our detectors to have large collecting areas and a good sensitivity for the abundant gamma-rays with low energies from $\approx$ 25 GeV down to $\approx$ 1 GeV. For some observations this lower range in energy is key because certain sources, such as pulsars, emit almost all their gamma-rays at energies below 10 GeV. And sources in cosmic distances have their gamma-rays with energies above $\approx$ 25 GeV significantly absorbed by the infrared light in the universe. Today we have two complementary methods to observe cosmic gamma-rays. On the one hand we have detectors on satellites which not only have a good sensitivity but also have a good specificity despite the presence of cosmic-rays. However, with collecting areas of only 1 m^2, the rates provided by satellites are rather limited. On the other hand we have the atmospheric Cherenkov-method which reconstructs the properties of cosmic particles from their atmospheric showers. Despite the need for dark nights and a limited specificity due to similar signals from cosmic-rays, the atmospheric Cherenkov-method has one big advantage when it comes to rates: Its collecting area can be as large as the pool of Cherenkov-light on ground reaching several 10^5 m^2. Today, we have arrays of Cherenkov-telescopes efficiently detecting gamma-rays with energies up to several 10 TeV. However, Cherenkov-telescopes still can not provide us with high rates because they can not be made large enough to detect gamma-rays with energies below $\approx$ 25 GeV. The square-cube-law, and the narrowing depth-of-field [1] prevent this. In this work, we investigate plenoptic perception [5] and a specific Cherenkov-plenoscope that we hope to overcome the Cherenkov-telescope's limits in order to be large enough to detect gamma-rays with energies at $\approx$ 1 GeV. Beside the Cherenkov-plenoscope's optics and mechanics we investigate its performance to detect gamma-rays in the presence of a large background from cosmic-rays. To simulate the background from low energetic cosmic-rays in the atmospheric Cherenkov-method, we address the geomagnetic cutoff and the significant deflection of showers inside the atmosphere due to earth's magnetic field. As the Cherenkov-plenoscope's design and reconstructions are still subject to change, the results are preliminary.

2. Combining atmospheric Cherenkov with plenoptics

Two physical limits prevent us from making Cherenkov-telescopes larger. First, when enlarging a telescope the structural forces scale with the size cubed while the areal cross-sections, which have to tolerate these forces, only scale with the size squared. More engineering and better materials can postpone this square-cube-law, but eventually deformations and misalignments in the optics will blur the image. Second, when enlarging a telescope, the depth-of-field of the larger mirror becomes narrower what blurs the images of showers irrecoverably. The narrowing depth-of-field can not be postponed by means of more engineering or resources and is estimated [1] to limit the useful size of a Cherenkov-telescope's mirror to $\approx$ 23 m in diameter. Interestingly, both limitations originate from the telescope's inability to better constrain the trajectory of an incoming photon, see (Fig. 1, left panel). Point is, if the telescope was able to better constrain the photons trajectories, the images could be computed from the measured trajectories using a model for ideal optics. With a bundle of measured trajectories we could compute images with the focus set to any depth of our

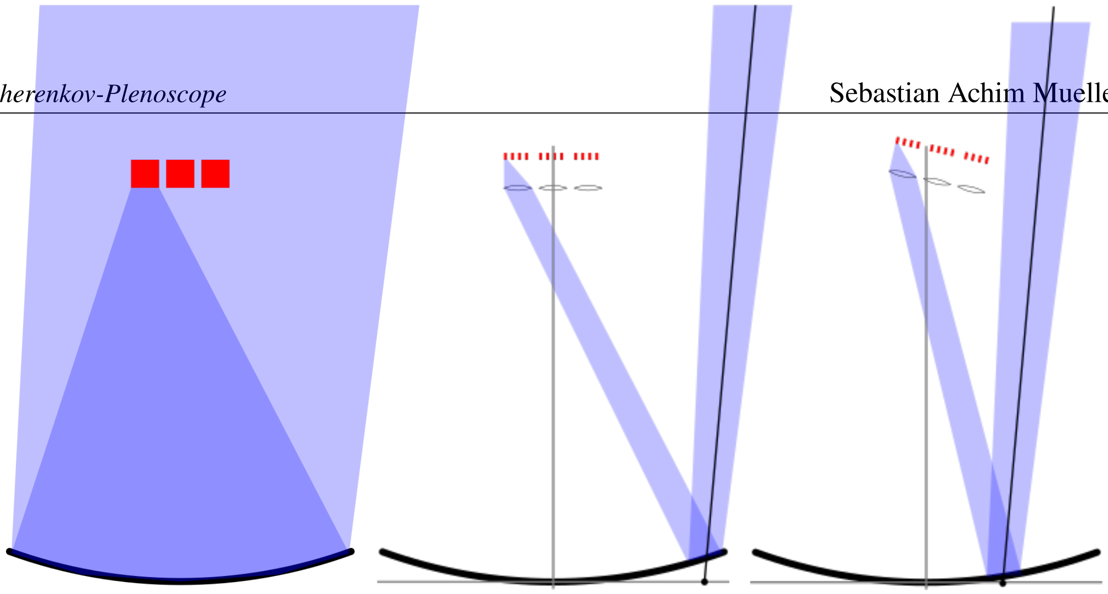

Figure 1: Photo-sensors in red. Beams constraining the photon's trajectory in blue. From left to right: Telescope with only limited constrain for trajectory. Plenoscope with good constrain for trajectory. Plenoscope with misalignment but still good constrain for trajectory.

choice [8], thereby completely resolving the physical limit of a narrow depth-of-field. With the photon's trajectory being constrained to only a part of the mirror's surface, the trajectory is also only effected by a part of the mirrors deformations and aberrations what reduces blurring in the computed images [3], [7]. Also a misalignment of the sensor relative to the mirror would no longer blur the image but only make us record other trajectories which still can be used to compute images. Based on this, the Cherenkov-plenoscope is designed to better constrain the photons trajectories, see (Fig. 1, central and right panels). In contrast to the telescope's image-sensor, which is just an array of n photo-sensors, the plensocope's light-field-sensor is actually an array of n cameras. Each camera faces the mirror and is made out of a lens and a small array of m photo-sensors behind the lens. Each photo-senor in a camera samples a beam of light which only covers m^{-1} of the mirror's surface. As a result, the plenoscope has a total of $n \times m$ photo-sensors that sample $n \times m$ beams of light, each being better constrained to only m^{-1} of the mirror's surface, compare Fig. 1, and Fig. 2. So as long as the misalignments of the sensor relative to the mirror are known and as long as the deformations of the mirror are known, the plenoscope can measure the photons trajectories to compute the images.

3. Proposing a specific Cherenkov-plenoscope named Portal

We propose a specific Cherenkov-plenoscope named Portal which we design to bring the energetic threshold down to $\approx$ 1 GeV, see Fig 2. Since Portal can compensate misalignments and deformations it mounts its mirror and its sensor on two independent cable-robots [6]. Unlike the altitude-azimuth-mount, the cable-robots kinematics have no singularity near the zenith what makes them intrinsically faster for the hunt of transients. The use of multiple small actuators with cables avoids the need for large monolithic joints and drives. The use of towers made for overhead-power-lines reduces the need for engineering. All optical surfaces in Portal are spherical to ease fabrication. All optics are composed from only two repeating primitive shapes to ease mass production: One facet for the segmented mirror, and one lens for the sensor. Portal can measure the photons trajectories in $n = 8,443$ directional bins across its field-of-view and in $m = 61$ areal bins

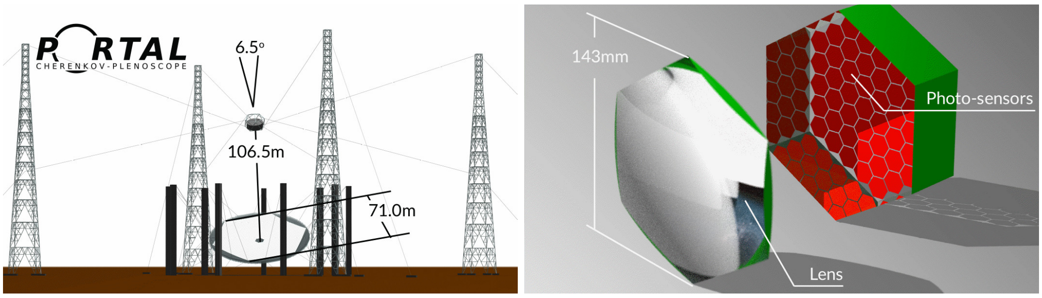

Figure 2: (right) The Portal Cherenkov-Plenoscope is a mirror and a light-field-sensor each mounted on a separate cable-robot. (left) One of $n = 8,443$ cameras in Portal's light-field-sensor. The camera's $m = 61$ photo-sensors are shown in red.

component	unit-costs / EUR	demand	total / 10^6 EUR
Photo-sensors	$5 \times 10^5\,\mathrm{m}^{-2}$	$115\,\mathrm{m}^2$	57.5
Read-out-electronics	$80\,\mathrm{channel}^{-1}$	515,023 channels	41.2
Lenses	$100\,\mathrm{lens}^{-1}$	8,443 lenses	0.9
Mirror-facets	$3 \times 10^3\,\mathrm{m}^{-2}$	$4{,}174\,\mathrm{m}^2$	12.5
Mirror-facet-actuators	$1 \times 10^3\,\mathrm{facet}^{-1}$	2,087 facets	2.1
Sum			114.2

Table 1: Costs for optics and electronics. All, except lenses, adopted from Cherenkov-telescopes.

	fraction / %	total / 10^6 EUR
Optics and electronics	51	114.2
Cable-robots	16	35.8
Central control-system	5	11.2
Project-engineering	5	11.2
Project-management	13	29.1
Site-infrastructure	10	22.4
Sum	100	223.9

Table 2: Total costs. Fractions inspired by E.S.O.-projects of similar scale.

on its mirror. A master-thesis in civil engineering [2] documents our initial design using ray-tracing, finite-element-analysis, as well as an estimate for the costs which only changed slightly since, see Tables 1, and 2.

4. Simulating Portals' response

To estimate Portal's response its simulation differs from the simulation of Cherenkov-telescopes [1] in two main aspects. First, we take into account that earth's magnetic field significantly deflects the showers of low energetic primaries. Depending on the site, this deflection between a cosmic electron and the median of its shower's Cherenkov-light can exceed 70°, and it can displace the shower's core by more than 70 km from the instrument. Because of this, we replace algorithms that scatter the position of the shower's core on ground with new algorithms that only scatter in an area where Cherenkov-light reaches the ground, while keeping track of the size of this area. Further we investigate the deflection of showers beforehand on a statistical basis to only scatter particles in a reduced, but computable space of solid angle and area. Second, we take the geomagnetic cutoff into account which effectively removes all showers induced by cosmic-rays below a certain rigidity of $\approx 10\,\mathrm{GV}$ depending on the site. However, we simulate showers below this cutoff which are induced by secondary, so to say terrestrial-rays, that originate in other showers, leaf the atmosphere and re-enter it later again [4], [9].

5. Estimating Portal's preliminary performance

This estimate has no classification yet to separate cosmic gamma-rays from cosmic-rays. Here we focus on setting up the simulation and its statistical evaluation first. Fig. 3 shows how cosmic-

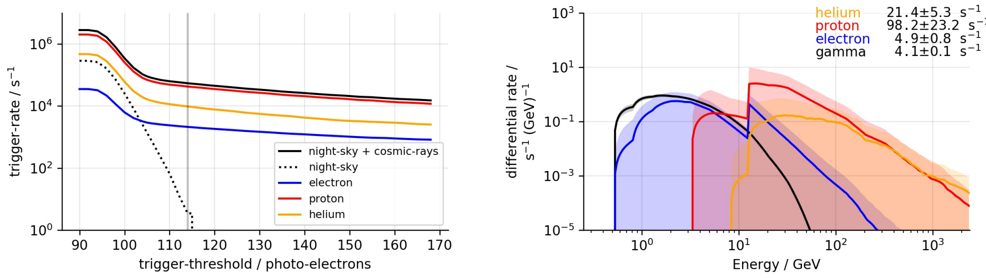

Figure 3: (left) The trigger's rate vs. it's threshold, vertical line marks the threshold, saturation at low thresholds is due to limited statistics. (right) Expected rates in the on-region after all cuts. See the cutoff in cosmic-rays at a rigidity of 12 GV. Energetic threshold, is about 1.5 GeV.

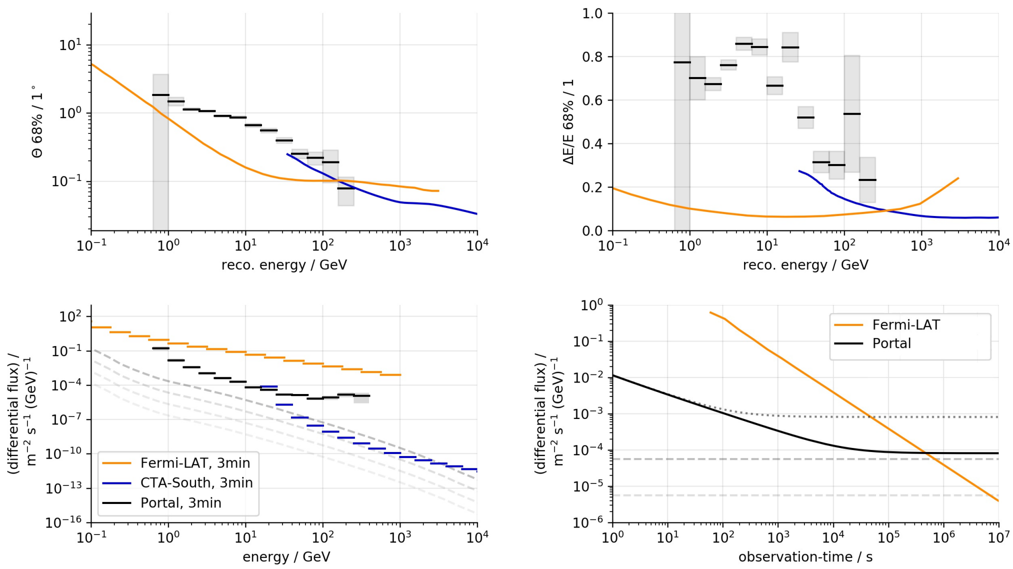

Figure 4: Black: Portal, Blue: CTA-South, Orange: Fermi-LAT. Dashed lines: Crab-nebula's flux 100%, 10%, 1%, 0.1%. (top left) Direction. (top right) Energy. (bottom left) Differential sensitivity after 3 minutes. (bottom right) Sensitivity vs. time at 2.5 GeV, systematic uncertainty: Dotted is 1%, solid is 0.1%.

rays and the brightness of the night-sky effect Portal's trigger and the rates in its on-region ('on' as in on-off-measurement). We investigate several sites, but here we only show Gamsberg Namibia. While our directional resolution seems to be a decent start, (Fig. 4, top left) our energetic resolution leaves room for improvement (Fig. 4, top right). Our estimate for Portal's differential flux-sensitivity shows true energy and respects the poor resolution in energy by enlarging the energetic window for the background as far as necessary to detect 68% of the signal (Fig. 4, bottom left). Portal's sensitivity at 2.5 GeV first improves as the statistical uncertainties shrink with time, and is finally held back by systematic uncertainties (Fig. 4, bottom right).

6. Conclusion

Observing gamma-rays with energies down to ≈ 1 GeV at high rates due to the large collecting area of the atmospheric Cherenkov-method might become a reality with the Cherenkov-plenoscope for a cost that is only the fraction of a satellite-mission. This might be an opportunity to push the astronomy with gamma-rays into a complementary direction where the timing of not only near but also the most distant bursts, mergers, and flares is key to gain insights into cosmic events. To evaluate the Cherenkov-plenoscope's full potential for astronomy we investigate its limitations, especially a background coming from showers induced by cosmic-, and secondary-rays with energies down to below ≈ 1 GeV. In our current estimate this background limits the detection of faint sources, but it is promising to see that already now flares or bursts could be resolved in more detail than before.

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