Altitude Effect in Čerenkov Light Flashes of Low Energy Gamma-ray-induced Atmospheric Showers

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Summary. At present the ground-based Very High Energy (VHE) gamma-ray astronomy is racing to complete construction of a number of modern gamma-ray detectors, i.e. CANGAROO III, MAGIC, H.E.S.S., and VERITAS. They should be fully operational in a year’s time. After much debate, the further development of this gamma-ray astronomy in the foreseeable future must be widely anticipated to proceed with the designing and building of a new instrumentation, which is primarily intended for the further drastic reduction of the energy threshold in gamma-ray observations down to about 10 GeV. On the ground one can hardly reach such low energy thresholds without considerably larger, up to 30 m diameter, optical telescopes, which might be able to collect sufficient amount of Čerenkov light from the atmospheric gamma-ray showers of that low energy. If not taken off the ground entirely (like GLAST), then it seems to be profitable to mount future low energy Čerenkov telescopes at higher altitudes in the atmosphere in order that they will be able to detect substantially more unabsorbed Čerenkov light from a shower. There are a few sites up on the high mountains of roughly 5 km height worldwide, which can be used for such a venture. However, one has to remember that actual time profile, and in particular a two-dimensional distribution (image) of Čerenkov light flash from atmospheric gamma-ray showers, undergo a rapid change after an increase in the observational level. This paper briefly describes the results of a topological analysis of Čerenkov light images calculated at both conventional and desirable altitudes of 2.2 and 5 km above the sea, respectively. A discussion on major upgrades of image topology at high altitude is also given.

1 Introduction

The usual way to proceed with design studies for a future project, at least in a field of VHE gamma-ray astronomy, is to perform full scale simulations of detector response for various anticipated event types. Apparently, gamma-ray-induced atmospheric showers represent a sample of signal events, whereas cosmic-ray showers form a dominating background (for review of Čerenkov imaging technique see [1]). For a future low-threshold instrument a correct tuning of detector design to optimize its response to gamma-ray events becomes a most important issue, due to the fact that the sensitivity of such
a detector will be given by \textit{angular and energy resolution for signal events}. Both of these will finally determine an efficiency of background rejection. Here we have studied how a single parameter of detector design, particularly the height of the observational site, may affect a topology of signal events. Therefore, we have calculated the response of a ground-based Čerenkov light telescope of 30 m diameter, assuming an ideal focal-plane detector. Comparative analysis of simulated events helped us to understand what are the major differences in parametrization of the Čerenkov light flashes from gamma-ray induced air showers, registered at two observational levels, i.e. 2 and 5 km above sea level. Considering the analysis results, there is a discussion at the end of this paper as to which observational level might be considered as more favorable for effective shower imaging.

2 Simulations

Numerous comparisons of a few shower simulation codes have been recently performed by different groups. They have revealed a rather good level of agreement in basic parameters of Čerenkov light emission in gamma-ray-induced air showers over broad energy range, starting from 100 GeV and expanding up to 20 TeV. Calculations presented here have been carried out using one of those simulation codes, namely ALTAI code \cite{2}. This numerical code was extensively used for production of the simulated data for the HEGRA system of five imaging atmospheric Čerenkov telescopes at La Palma \cite{3}.

Shower simulations have been done for the standard continental atmosphere (US standard atmosphere) \cite{4} for the wavelength range of Čerenkov light photons from 300 to 600 nm. Absorption of Čerenkov light photon in the atmosphere due to Rayleigh and Mie scattering was modelled according to the data given in \cite{4, 5}. The detector simulation procedure used here accounted for all efficiencies involved in the process of the Čerenkov light propagation and registration \cite{3}. It includes (i) mirror reflectivity; (ii) the acceptance of the funnels placed in front of the photomultipliers (PMTs) (iii) the photon-to-photoelectron conversion inside the PMTs (bi-alkali photocathode).

Shower simulations were made here in the so-called ”batch” mode. A shower propagating time, corresponding atmospheric depth, and a number of emitted Čerenkov photons were saved for each multiple-scattering segment of all electron trajectories in a shower. The actual segment size was chosen as small as 0.1 [gr/cm$^2$]. CPU time needed for simulation of such low energy gamma-ray shower ($E_o=10$ GeV), using customary computers, is short, and it is not an issue for any scheme’s optimization. One record for a single multiple-scattering segment was treated as an individual ”batch” of emitted Čerenkov photons. At the second step of this simulation procedure all recorded batches were restored and finally used in the calculation of the response of a number of Čerenkov telescopes, situated at different atmospheric
altitudes. Such an approach provides an opportunity to use exactly the same simulated showers for various telescope arrangements at different observational levels. It should be noted that the estimated statistical error for the parameters of the Čerenkov light emission given below is $\leq 10\%$.

For the next generation of ground based Čerenkov telescopes a dish of roughly 30 m diameter is foreseen. Issues around the design of such a big reflector are addressed in [6]. The simulation setup here consisted of 12 such telescopes, which were arranged along one line at distances from 0 to 300 m from the shower axis. Note that the same showers were used in calculations for each of these telescopes. It allows for a direct comparison of the telescope’s responses at different distances from the shower axis, and the accurate study of fluctuations in Čerenkov light flashes at different shower impacts.

3 Results

Distribution of Čerenkov light emission from atmospheric showers can be characterized using a smooth function

\[ \eta = \eta(t, r, \theta), \quad (1) \]

which gives a mean number of photons per unit area arriving at the observational level at time $t$, with space, $r = \{x, y\}$, and angular, $\theta = \{\theta_x, \theta_y\}$, coordinates, calculated with respect to the shower axis. The presentation (1) presumes averaging over a number of photons at any local spot, because Monte Carlo simulations have provided the list of individual photons with their coordinates. In the ideal case a space-angular distribution of Čerenkov photons in the observational plane is simply a sum of $\delta$-functions constructed for each individual photon.

The lateral distribution of Čerenkov photons at the observational level, which is supposed to be perpendicular to the shower axis, is given by

\[ \rho(r) = \rho(|r|) = \int_0^\infty \int_0^{2\pi} \eta(t, r, \theta) dt \, d\Omega. \quad (2) \]

The function $\rho(r)$ is the density of Čerenkov light (the number photons hitting the unit square at $r$).

In a similar way one can derive a temporal distribution of a Čerenkov light pulse, and a two-dimensional angular distribution (image) of a Čerenkov light flash

\[ p(t) = \int_{A(r_o)} \int_{\Omega_o} \eta(t, r, \theta) r dr \, d\Omega_o, \quad (3) \]

\[ q(\theta) = \int_{A(r_o)} \int_0^\infty \eta(t, r, \theta) r dr \, dt, \quad (4) \]
where $A(r_o)$ and $\Omega_o$ are the area of the reflector and the angular camera size, respectively, of the telescope placed at $r = r_o$.

The function $\eta(t, r, \theta)$ can be well described by a set of functions $\rho(r)$, $p(t)$, and $q(\theta)$, given for a number of telescope locations, $r_o^{(i)}$, $i = 1, n$.

3.1 Čerenkov light density

It was emphasized in [7], that a substantial increase in Čerenkov light density at high altitudes in the atmosphere might be very promising for a further reduction of the effective energy threshold of a telescope array, which can be erected at a height of about 5 km above the sea. One can see in Figure 1 that for a 10 GeV gamma-ray-induced atmospheric shower the density of Čerenkov light at 5 km above sea level, in a range of distances of the telescope to the shower core limited by $r \leq 100$ m, is about a factor of 2.5 higher than the corresponding density at 2 km altitude. At the same time in a range of relatively large impact distances, $r \geq 125$ m, the Čerenkov light density remains the same at both observational heights. (see Figure 1).

The atmospheric depth of the shower maximum can be estimated as $X_{max} = t_o \ln(E_o/E_c)$, where $t_o$ is the radiation length in air ($t_o \simeq 37$ g/cm$^2$), $E_o$ is the primary energy of air-shower, and $E_c$ is the so-called critical energy ($E_c \simeq 80$ MeV). Thus for a 10 GeV $\gamma$-ray-induced air-shower the atmospheric depth of its shower maximum is about $180$ g/cm$^2$. A substantial fraction of Čerenkov light photons emitted from the shower maximum will be absorbed while traveling down to the observational level. Between 30% and 16% (in the wavelength range of 300-600 nm) for the heights of 2.2 and 5 km above sea level, respectively. At the same time the Čerenkov light pool shrinks significantly at higher altitudes. The approximate radial size of the light pool at 2.2 km is about 130 m (see Figure 1), whereas at 5 km it might be roughly limited by $\simeq 90$ m. It results in a corresponding increase of Čerenkov light density by approximately a factor of 2. This geometrical effect has a major contribution on the increase of Čerenkov light density at high altitude as shown in Figure 1.

For a large telescope of a 30 m diameter, a requirement of a minimum number of 15 ph.-e.$^1$ in the Čerenkov light flash, which is sufficient to trigger the telescope, will limit the allowed range of impact distances for 10 GeV gamma-ray showers to roughly $r \leq 300$ m (see Figure 1). It corresponds to the same effective detection area of $S = 3 \times 10^5$ m$^2$ at both observational heights. On the other side, assuming that the Čerenkov light density scales with primary shower energy as $\rho \propto E^{1.1}$, one can roughly estimate the minimal primary energy of the gamma-ray shower, which has still sufficient

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$^1$This requirement of a minimum number of ph.-e. for the telescope trigger is in fact not a generic value, and it might be slightly different in certain circumstances, but it does not affect the general discussion given here.
amount of light at the density profile plateau (r<125 m) and can still trigger the telescope. Simple calculations yield, accordingly, a factor of 4 and 10 for 2 and 5 km altitudes, respectively. It means that one can catch gamma-ray events of energy \( \geq 2.5 \, \text{GeV} \) and \( \geq 1 \, \text{GeV} \) at 2 and 5 km observational height, respectively, using the same telescope. It is important to mention that all these extremely low-energy events will be concentrated within a radius of roughly 100 m, which is determined by the actual shape profile of a lateral distribution function of Čerenkov light. The drastic drop in photon density beyond 120 m will prevent the detection of such gamma-ray showers at larger distances to the shower axis. As a result the detection area for these events will be a weak function of primary shower energy. Furthermore, the detection area of high energy gamma-ray showers will be of the same size at both observational heights.

### 3.2 Time profile of Čerenkov light flash

The longitudinal extension of an atmospheric shower, and its location in space with respect to the telescope, finally determine a time profile of the Čerenkov light flash. For a gamma-ray shower of a certain primary energy, e.g. of 10 GeV, recorded at fixed observational level (e.g. 2 or 5 km above sea level), the shape of the Čerenkov light flash basically depends only on
Table 1. Parameters of the fit in Eq. 5. \(D\) [gr/cm\(^2\)] denotes an atmospheric depth at a given observational level. \(R\) is the impact distance of the telescope to the shower axis.

| \(H\) [km] | \(D\) [gr/cm\(^2\)] | \(R\) [m] | \(C\)   | \(\alpha\) | \(t_o\) | \(\beta\) |
|-----------|---------------------|---------|------|---------|------|------|
| 5         | 500                 | 50      | 2.595\(\times\)10\(^{-5}\) | 8.533 | 3.463 | 13.778|
|           | 100                 | 2.650\(\times\)10\(^{-10}\) | 14.149 | 4.670 | 19.076|
|           | 150                 | 2.424\(\times\)10\(^{-11}\) | 12.495 | 6.500 | 15.827|
|           | 200                 | 4.824\(\times\)10\(^{-13}\) | 12.154 | 9.085 | 15.081|
|           | 250                 | 7.352\(\times\)10\(^{-14}\) | 11.277 | 12.240 | 13.770|
| 2.2       | 843                 | 50      | 1.360\(\times\)10\(^{-6}\) | 7.689 | 5.824 | 19.295|
|           | 100                 | 2.871\(\times\)10\(^{-15}\) | 17.936 | 6.620 | 32.634|
|           | 150                 | 4.031\(\times\)10\(^{-17}\) | 17.907 | 8.157 | 26.966|
|           | 200                 | 1.225\(\times\)10\(^{-18}\) | 17.551 | 9.988 | 23.094|
|           | 250                 | 3.512\(\times\)10\(^{-20}\) | 17.264 | 12.368 | 21.476|

the actual distance of the telescope to the shower axis. The arrival time of Čerenkov photons onto reflector is \(t = t_e + t_\phi\), where \(t_e\) and \(t_\phi\) is accordingly a propagation time of emitting electrons and photons, respectively. Electrons of an energy, which is sufficient for emission of Čerenkov light in the atmosphere, are apparently moving faster than the emitted photons. Thus at relatively small distances of the telescope to the shower axis \((r \leq 120 \text{ m})\) Čerenkov photons, emitted at later stages of the shower development in the atmosphere, are actually arriving earlier than the photons emitted at the beginning of shower development. It swaps over at a large distance from the shower axis, because of the rather long travel path in dense atmosphere for the photons emitted by electrons out of a dying particle cascade\(^2\). Therefore, in general, the larger the distance of the telescope to the shower axis, the broader the corresponding Čerenkov light pulse.

Time pulses of Čerenkov light flashes always show a very steep rising edge, and a slow fall-off. They can be well fitted by

\[ p(t) = C \cdot t^\alpha (1 + (t/t_o)^\beta) \]  

Parameters of the fits of time pulses simulated for two observational levels and for a number of impact distances are given in Table 1. The normalization condition was \(\int_{0}^{50\text{ns}} p(t)\,dt = 1\). The contribution of Čerenkov photons delayed by longer times than 50 ns is negligible.

Shape of time pulse can be characterized by a few parameters, e.g. \(t_1 = t_{10\%} - t_{0\%}\), \(t_2 = t_{50\%} - t_{10\%}\), \(t_3 = t_{90\%} - t_{10\%}\), where \(t_{10\%}\), \(t_{30\%}\), \(t_{50\%}\), and \(t_{90\%}\) give the time tags, which are defined as, e.g. \(\int_{0}^{10\%} p(t)\,dt = 0.1\). Results of calculations are shown in Figure 2. One can see that for a 500 [gr/cm\(^2\)] observational level time pulses are substantially broader at impact distances

\(^2\)This is a well-known effect, sometimes called the "sea-gull" effect, in the shape of Čerenkov light pulses (e.g. see \(5\)).
beyond 100 m. Hereafter we are dealing with Čerenkov light images averaged over a sample of simulated 10 GeV gamma-ray showers. For an impact distance of ca. 250 m, the time pulse of Čerenkov light flash recorded at high altitude in the atmosphere will be a factor of 2 broader than for the same impact distance at a conventional altitude of 2 km above sea level (see Figure 3). Integration over the time pulse yields a total number of Čerenkov photons in a flash. Therefore, for a given flux of night sky background light, a signal-to-background ratio might be correspondingly lower by factor of 2 for a high altitude site. For high energy gamma-ray showers ($E_o \geq 100$ GeV) Čerenkov pulses recorded at 5 km above sea level might be as long as 50 ns. Registration of these pulses will occur in the regime highly dominated by night sky background.

It is worth noting that, at the time of writing, there is no well established altitude dependence of a flux of night sky background light available. In general this parameter is considered to be very specific for each individual observational site. Apparently the high altitude sites provide substantially reduced attenuation and consequently more starlight from the individual stars, which is in fact a background for the Čerenkov telescopes. However, the effect of bright stars might be diminished simply by switching off the high voltage for those camera pixels (PMTs) collecting direct star light. Such procedure usually runs in automatic mode while taking the observational runs. At the same time one might expect a significant increase in flux of background light photons within the UV wavelength range (200-300 nm). However, conven-
Fig. 3. Time profile of Čerenkov light flashes simulated for impact distance of 150 m and two observational levels of 2 (1) and 5 (2) km above the sea. Primary energy of simulated air-showers is 10 GeV. Label a.u. along Y-axis stays for the arbitrary units.

Fig. 3. Time profile of Čerenkov light flashes simulated for impact distance of 150 m and two observational levels of 2 (1) and 5 (2) km above the sea. Primary energy of simulated air-showers is 10 GeV. Label a.u. along Y-axis stays for the arbitrary units.

Even though there are good reasons to believe that this flux will, in fact, be much lower (on average) for high altitude sites, it still needs to be measured at any chosen observational site.

For the sake of thoroughness one should mention that the high altitude sites will noticeably increase the probability that the ionizing particles, such as atmospheric electrons and muons of low energy cosmic rays, can directly hit the camera PMTs. It will lead to some random increase in background light over the camera pixels. However, dedicated calculations are needed in order to quantify this additional component of the background, which fall unfortunately out of the area of this paper.

3.3 Images

A two-dimensional distribution of the Čerenkov light intensity in the telescope’s focal plane (image), $q(\theta)$, can be effectively used to derive detailed information about shower orientation and shape. Phenomenology of Čerenkov light images was discussed in [9]. For an ellipsoid-like image, the orientation of its major axis constrains the shower orientation in space with respect to the telescope optical axis. Images recorded at relatively small impact distances from the shower axis ($R \leq 100$ m) have circular shape, and an accurate de-
termination of the major axis is quite difficult. For impact distances beyond 100 m the image ellipsoid has a well defined shape, and the ratio of its angular size measured along a major axis to the corresponding angular size of the image measured along a minor axis is ca. 2 and above. At the same time at large impact distances \((R \gg 200 \text{ m})\) the total number of Čerenkov photons in an image becomes rather low and high fluctuations prevent accurate measurement of the image orientation. Those two effects finally constrain the range of optimum impact distances for effective shower reconstruction. As mentioned above, the advantage of the high altitude site is mainly associated with an enhancement in Čerenkov light density at small distances to the shower axis \((R \leq 100 \text{ m})\). However, in this range of impact distances Čerenkov light images tend to have poorly determined orientation.

Average Čerenkov light images for two observational heights of 2 and 5 km, respectively, are shown in Figure 4. Note that scales used along X- and Y-axis are not identical. Detailed comparison of those images revealed two major differences in their shape.

1. Images of 10 GeV gamma-ray showers recorded at high altitude above sea level are substantially larger in size (see Figure 1 and Table 2). This is mainly because showers are located at a relatively smaller distance to the telescope, than for a conventional observational site of 2 km above the sea. Calculations show that the angular size of an image measured along the major axis, the image length, increases considerably faster with altitude than the angular size of image measured along a minor axis, the image width. This can be easily understood by comparing the ratio of the actual scale of a shower longitudinal development over the distance of shower maximum to the telescope, which is located at two altitudes of 2 and 5 km above the sea, respectively. In a simplified toy model the length of the image will scale with height of observation level above sea level, \(H_o\), as

\[
L \propto (H_{max} - H_o), \quad R << (H_{max} - H_o).
\]  

2. Images recorded at high altitude must have considerably larger displacement from the center of the focal plane. Coming closer to the shower maximum \((H_{max}\) is the height of the shower maximum), the shower will be apparently seen in Čerenkov light at larger angle

\[
\theta \propto \tan^{-1}\left(\frac{R}{H_{max} - H_o}\right)
\]

with respect to the optical axis.

One can see in Figure 1 that the density of Čerenkov photons from a 10 GeV gamma-ray shower is approximately the same at both observational heights for impact distances above 150 m from the shower axis. Thus, at large impact distances, the difference in image shape mentioned above is of
Fig. 4. Images of Čerenkov light calculated at different altitudes above sea level for a number of impact distances of the telescope to the shower axis as indicated in the pictures. Images were averaged over a sample of 10 GeV gamma-ray showers. The contour plots were drawn starting from the position of maximum intensity with the isoline increment of $\ln 2$.

Table 2. Area $A$, $[\text{deg}^2]$ and effective size, $r_o = \sqrt{ab}$ $[\text{deg}]$, (in this Table both values are given in a format of $A/r_o$) of Čerenkov light images calculated for two observational levels of 2 and 5 km, and for a few impact distances.

| H [km] | D [gr/cm$^2$] | R [m]  | 50  | 100  | 150  | 200  |
|--------|---------------|--------|-----|------|------|------|
| 2.2    | 843           | 0.16/0.22 | 0.24/0.27 | 0.31/0.32 | 0.44/0.37 |
| 5      | 500           | 0.40/0.36 | 0.54/0.41 | 0.87/0.53 | 1.27/0.64 |

purely geometrical origin, which is independent of the image size (the total number of photons in the image). At first glance, large images at high altitudes might offer better resolution for a camera of crude pixellation. However,
for a 10 GeV gamma-ray shower images will always be significantly affected by contamination of background light and reduction of background light per camera pixel. Large images recorded at high altitudes yield considerably lower Čerenkov light density per 1 ster for fixed image’s size. For the flux of night sky photons, as measured at conventional observational level of 2 km above the sea, the image of a 10 GeV gamma-ray shower recorded at high altitudes will have higher contamination of background photons per camera pixel of any size.

As mentioned above, the images recorded at high altitudes must have large displacements from the camera center. This issue stringently constrains the design of the camera for the telescope placed at high altitudes, in particular the field of view has to be larger. Cameras of a narrow field of view will be drastically limited in their ability to detect gamma-rays at high energies.

### 3.4 Time-dependent imaging

One can try to suppress contamination of night sky background light in an image by using a very narrow time gate. This may be tuned exactly, for example, to a rising edge, maximum, or tail of a time pulse. However, it leads to a trade off between losing a substantial fraction of Čerenkov photons and on the other hand a severe reduction of night sky background. This approach is illustrated by the images shown in Figure 5. Photons emitted at the very beginning of the shower development in the atmosphere, which are mainly arriving at the front of the time pulse of a flash, form the so-called image ”conk”\(^3\). The image of shower electrons, which propagate further into the atmosphere, shifts further away from the center of telescope’s focal plane. Multiple scattering of low energy cascade electrons at later stages of the shower development becomes very important and it results in a very broad image as shown in Figure 5. One can see also in Figure 5 that Čerenkov light images for such narrow time windows are in fact rather symmetric in shape, and they are not so good for reconstruction of image orientation. At the same time, an image which contains all registered Čerenkov photons (0 ns < \(t\) < 14 ns), has a regular ellipsoid-like shape. Note that photons, which are significantly delayed with respect to the front of time pulse, will be hitting the outer edge of the image, whereas background light photons are apparently dominant.

Time-dependent imaging seems to be a rather promising approach in improvement of gamma/hadron separation of extremely low energy events. Despite that present analysis does not reveal an evident improvement using time-dependent imaging, it could be perhaps very effective in analysis based on centroid positions in a few triggered telescopes in an array.

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\(^3\)Non-standard definition of a strongly elongated part of the comet like image, which has a relatively high photoelectron density.
Fig. 5. Average images of Čerenkov light from a 10 GeV gamma-ray shower, calculated at an observation level of 2 km above sea level, and for an impact distance of 150 m from the shower axis. An additional selection on arrival time of Čerenkov photons was applied. Corresponding time windows were 7.25-7.5 ns (a); 8.25-8.5 ns (b); 9-9.5 ns (c); 10-12 ns (d). Each of (a)-(d) plots contains approximately the same number of photoelectrons. The image shown in the lower panel was generated without time selection.
4 Conclusions

In this paper we have attempted to perform a comparative analysis of Čerenkov light images simulated for two observational levels of 2 and 5 km above sea level, respectively. We used as the basis of our calculations a 30 m diameter telescope, which is a conceivable size for a future Čerenkov telescope project. The system aspect was not discussed here, but all conclusions are obviously relevant to any telescope of a possible future array. One has to mention that for a future detector, approaching a very low energy threshold of about 10 GeV or even below, a contamination of night sky background in the registered shower images is in fact a very important issue. It might finally constrain the choice of the observational site for such low threshold arrays of Čerenkov telescopes.

Results reported here generally confirm that the observational site at higher altitude provides substantially higher Čerenkov light density. However this enhancement occurs only within the area limited by roughly 100 m from shower axis. Therefore all recorded gamma-ray showers well below 10 GeV (here we assume that the telescope has in fact sufficient area of the reflector, see discussion in Section 3.1) will concentrate in a region of relatively small impact distances. Those images are not so clearly elongated in shape, which makes reconstruction of the image’s orientation rather difficult.

Flashes of Čerenkov light from 10 GeV gamma-ray showers have broader time pulses for the impacts beyond 100 m at higher altitude. Corresponding images are considerably broader as well. Both of these two effects might apparently substantially increase the background light contamination in an image. Images recorded at high altitude must be further displaced from the center of telescope’s focal plane, than for conventional altitude of ca. 2 km above sea level. They also, most probably, require larger field of view.

The time-depending imaging is a very promising approach in further development of advanced analysis for observation of low energy gamma-ray showers, but it might be not very effective in resolving the problem of dominating night sky background light in the recorded images of such low energy gamma-rays.

One can briefly conclude that an observational site at high altitude might provide further modest reduction of the energy threshold of a future detector, even though the shape of time pulses and in particular the topology of the two-dimensional angular distribution of Čerenkov light flashes recorded at extremely high altitudes are palpably less preferable for imaging of gamma-ray showers above 10 GeV.

We hope that the results presented here may help to increase the understanding of changes in topology of Čerenkov light images after an increase in the observational level from its conventional height of ca. 2 km up to 5 km above sea level.

Ultimately, the choice of a site for the next generation of ground-based imaging atmospheric Čerenkov detector, which is widely believed to be a sys-
tem of 30 m class telescopes, will depend on both scientific and political issues relating to funding, international collaboration etc. The move to lower energy threshold is likely to remain a significant drive for the science. However, one has to consider all trade-offs, i.e. reasonable altitude, low level of night sky background, need for the robotic telescopes etc, in selecting candidate sites for such a detector to optimize the scientific goals.

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References

1. T. Weekes: ”Very High Energy Gamma-Ray Astronomy”, IOP Publishing Ltd, Bristol and Philadelphia, Series in Astronomy and Astrophysics (2003)
2. A. Konopelko, A. Plyahsheshnikov: Nuclear Instruments & Methods in Physics Research A 450, 419 (2000)
3. A. Konopelko, et al. (HEGRA Collaboration): Astroparticle Physics 10, Issue 4, 275 (1999)
4. L. Eltermann: Air Force Cambridge Res. Lab. Ref. 40, AFC RL-68-153 (1968)
5. S.L. Valley: Handbook of Geophysics and Space Environments, McGraw-Hill Book Company (1965)
6. W. Hofmann: J. Phys. G: Nuclear and Particle Physics, 27, Issue 4, 933 (2001)
7. F. Aharonian, A. Konopelko, H.J. Völk, H. Quintana: Astroparticle Physics 15, Issue 4, 335 (2001)
8. A. Konopelko: Proc. Kruger Park Workshop on TeV γ-Ray Astrophysics ”Towards a Major Atmospheric Čerenkov Detector -V”, (ed. O.C. de Jager), Kruger Park, Source Africa, August 8-11, 208 (1997)
9. A.M. Hillas: Proc. ”TeV Gamma-ray Astrophysics” (Heidelberg) (Space Sci. Rev. 75) ed H.J. Völk and F.A. Aharonian (Dordrecht: Kluwer), 17 (1996)