The expected Cherenkov light density and its fluctuations for a large detector

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***Abstract*. The Imaging Air Cherenkov Telescopes (IACT) are used to search and study γ-ray sources. The number of detected photoelectrons (so called SIZE) is proportional to the detector area and the photon density on the ground if the limited telescope field of view is taken into account in the density calculation. The energy reconstruction in IACTs is based on the image SIZE and DIST measurement. The energy resolution is by that strongly correlated with relative fluctuations of the Cherenkov light density. The results presented in this paper were obtained by Monte Carlo simulations for vertical primary γ-rays and protons. The photon density and its fluctuations were calculated for the detector area of 240 m^2 with the FOV of 5 deg. (MAGIC) which is located on 2.2 km and 4 km above see level. It is shown that fluctuations of the density are dominated by shower development. The lower primary energy is the higher relative fluctuations are, as expected. Similar study has been done for larger detectors to check if enlargement of the mirror size results in an improvement of the energy resolution. As the relative fluctuations of the density are the reflector size independent (while size range changed from 240 m^2 up to 960 m^2) than a single telescope with a mirror area larger than that of the MAGIC cannot achieve better energy resolution than estimated and presented in this paper.**

***Keywords*: VHE γ-astronomy, EAS, Cherenkov photon density**

I. Introduction

The photon density on the ground is a fundamental quantity in all experiments based on Cherenkov light measurements. In the experiments with Imaging Air Cherenkov Telescope (IACT), it is very important how many Cherenkov photons are collected by the telescope. Events containing not enough light cannot trigger the telescope and they are not registered. The larger the area of the telescope mirror, the more Cherenkov photons from the same shower can be focused onto the camera. The expected image SIZE depends also on the telescope field of view and the altitude of the telescope [1], [2], [3]. The primary energy reconstruction is based on the measured image SIZE and the DIST parameter (DIST is the distance between the camera and image centres) or on the measured image SIZE and the reconstructed distance between the shower core and the telescope (so called impact parameter)[4], [5], [6], [7].

The Cherenkov photon density on the ground (ρ) is (due to all those reasons) a physical quantity, which is especially worth to investigate. Several publications have focused on this subject. Fluctuations of the Cherenkov light density on the ground have been studied in [2], [8], [9], but they were calculated for smaller telescopes than the currently used and planned detectors. The results presented in [3] were obtained for a large telescope's mirror, but Cherenkov light densities were calculated from all simulated events (no cuts on the number of photons hitting a telescope dish has been applied). The results presented in this paper has been calculated only from detectors which were hit by more than 100 Cherenkov photons.

In this paper the expected Cherekov light densities, which may be measured by a large detector with limited FOV located at the altitude of 2.2 km and 4 km a.s.l., are presented for the primary γ-rays and protons. The relative fluctuations of the density are also shown. Additionally similar fluctuations of the Cherenkov light density were obtained and they are presented for even larger detectors - 480 and 960 m^2 to check if enlargement of the mirror results in an improvement of the energy resolution.

II. Monte Carlo Simulations

The CORSIKA code version 6.023 [10], [11] with GHEISHA and VENUS as low and high energy (primary momentum above 80 GeV/c) interaction models for the primary protons has been used for the Monte Carlo simulations. All simulations were done using the US standard atmosphere model. The MC simulations have been done for the MAGIC site [12], [13], [14], that is 2200 m above sea level (around 800 g/cm^2) and for the altitude of 4000 m a.s.l. The Cherenkov photons with zenith angle below 2.5 ^{o} have been counted because real Cherenkov telescopes have a limited FOV. The effect of light absorption in the atmosphere (Rayleigh and Mie scattering according to the Sokolsky formula [15]) was taken into account for both investigated altitudes. Neither NSB nor trigger conditions were taken incto account in the simulations.

The numbers of produced Cherenkov photons (wavelength between 290 and 600 nm) hitting the detectors area of $240m^2$ in each shower have been used to calculate the Cherenkov photon densities as well as their fluctuations. The expected densities and fluctuations for two and four times larger detectors were also calculated because the simulated detectors covers completely the area on the ground (see details in [3]). As it was pointed out in the introduction the densities and their fluctuations were calculated from the detectors which were hit by more than 100 Cherenkov photons. The fixed primary energies of 20, 50, 100, 200 and 500 GeV were simulated for the vertical γ- cascades. In the case of the primary proton energies of 100, 200, 500 and 1000 GeV have been chosen. Overviews of the number of simulated events are presented in Table 1.

TABLE I
NUMBER OF SIMULATED EVENTS

primary particle	primary energy in GeV	altitude 2.2 km	altitude 4 km
γ	20	20000	20000
γ	50	20000	20000
γ	100	20000	20000
γ	200	10000	10000
γ	500	5000	5000
proton	100	40000	40000
proton	200	20000	20000
proton	500	20000	20000
proton	1000	10000	10000

III. RESULTS AND DISCUSSION

A. *The lateral density distribution of the Cherenkov light*

Figure 1 shows the average lateral density distribution for the primary γ-ray at energy 100 GeV. The distribution is not symmetrical due to the Earth's magnetic field influences the shower development [16], [17], [3]. The largest differences in lateral distributions are expected between the North-South (N-S) and East-West (E-W) directions. Electrons and positrons in the γ-cascade are shifted by the magnetic field towards west and east directions, respectively. As a result, the hump is more pronounced in the N-S direction. For proton induced showers, the asymmetry still exists in the electromagnetic sub-showers, but it is washed out since a typical hadronic interaction produces a number of pions at large transverse momentum, and contains a number of electromagnetic sub-showers as well as contributions from single muons that are less deflected by the magnetic field. All the results presented below were calculated for the N-S direction.

Figures 2a and 2b show the comparison between the lateral distributions calculated for two different observational heights - 2.2 km (solid lines) and 4 km (dashed lines) above sea level. The so called hump observed in the γ-rays (figure 2a) is closer to the core axis for observation levels of 4 km due to a geometrical effect. At this level, also higher densities are observed for the same primary energy close to the core axis as shown in [1], [2], [3]. The expected density at 4 km decreases faster than at the altitude of 2.2 km for impact parameters beyond the hump position for primary energies above 100 GeV. The differences between expected densities above the hump at 2.2 km and 4 km become lower as

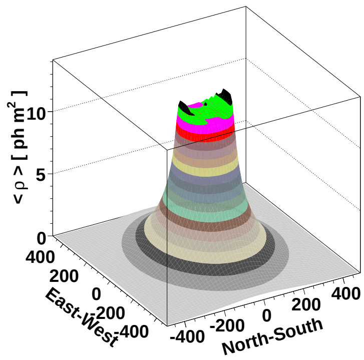


Fig. 1. The mean density of Cherenkov light for all produced photons in γ cascades - primary energy of 100 GeV

the primary energy decreases. Practically no differences are observed at the γ primary energy of 20 GeV. Taking into account only detectors which are hit by more than 100 Cherenkov photons results in this feature (which was not observed in [3] where no limits on the amount of light was applied).

The same dependence on the observation altitude occurs in a proton shower. The average density close to the core axis is higher at 4 km than at 2.2 km and the differences between densities at two levels decreases with primary energy for higher impact parameters.

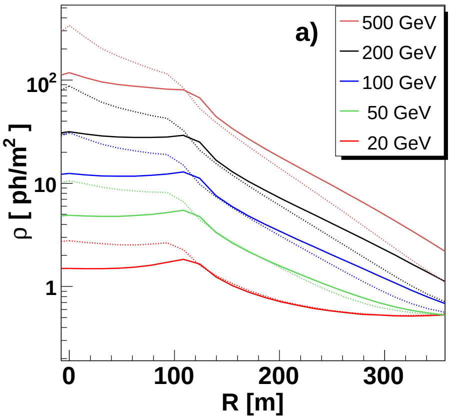
B. *Fluctuations of the Cherenkov light density for a fixed detector size*

The relative fluctuations of the Cherenkov light density (which is define as the ratio of the dispersion of the density to its mean) obtained from the MC simulation are presented in figure 3a and 3b for primary γ-ray and proton, respectively. The results presented in this subsection were calculated for detector area of 240 m^2. The presented ratio was calculated for two different observation levels 2.2 km and as solid and dashed lines, respectively. The relative dispersion of the density decreases with increasing primary energy for both simulated primary energies. This fluctuations are relatively large at small impact parameters where one may expect some charged particles in the shower which reach the observation level.

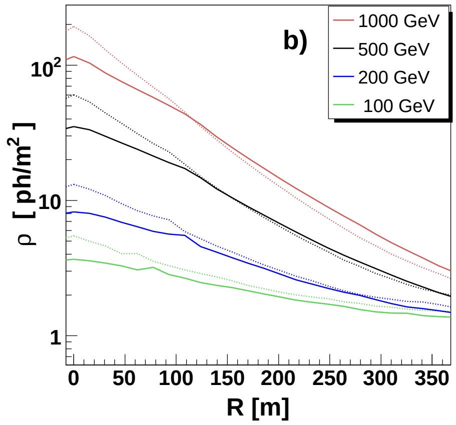
The local maximum of the presented in figure 3a ratio pronounces the hump position for primary energies of γ below or equal to 200 GeV. This feature disappears for higher energies.

For the primary γ ray the relative dispersions are smaller at a height of 4 km (dotted lines) than at 2.2 km (solid lines) only at distances between 30 m and 100 m from the shower axis at γ-ray energies above 100 GeV. The relative fluctuations of the density are higher at an observation level of 4 km (dotted lines) than at 2.2 km (solid lines) at impact parameters above 100 m.

It has been checked that the number of photons within each detector does not have a Poissonian distribution in

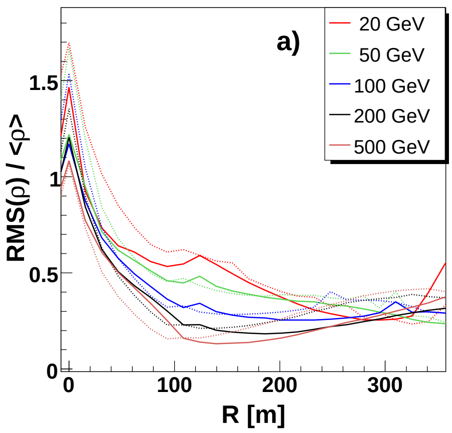


(a) primary γ-ray

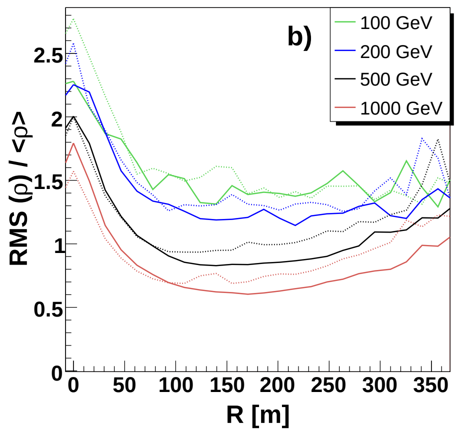


(b) primary proton

Fig. 2. Comparison between the average lateral density distributions obtained at observations levels of 2.2 km (solid lines) and 4.0 km (dotted lines)



(a) primary γ-ray



(b) primary proton

Fig. 3. The expected relative dispersions of the Cherenkov light density on the ground for detector size of $240m^2$; solid and dotted lines correspond to the observation altitude of 2.2 km and 4 km, respectively.

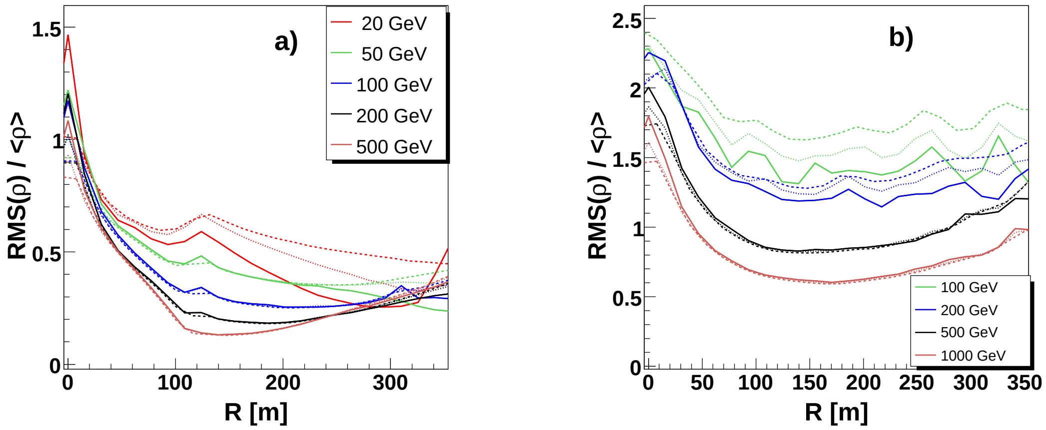
all primary energies and observation levels simulations, regardless of the primary particle type.

C. Fluctuations of the Cherenkov light density for the different detector size

The relative dispersions of the density have been calculated for detectors, which are two and four times larger than 240 m^2, The results are shown in figure 4a for primary γ-rays. Solid, dotted and dashed lines correspond to the telescope area of 240, 480 and 960 ^{2}. As an example the observation level of 2.2 km has been chosen. The ratio of the RMS deviation of the density to the mean density is independent on the detector size for almost all simulated energies (except the lowest 20 GeV and 50 GeV) and impacts parameters larger than 30 m. However, very close to the shower axis, lower relative fluctuations were obtained for larger detectors.

Paradoxically the relative dispersion increases with increasing of the detector size in very low primary energy range (below 50 GeV). This effect has been not found in [3] where any limit on the Cherenkov photons hitting the detector was taken into account. It has been checked, that for larger detector size lower average densities were obtained as well as the lower dispersions of the density. At low energy, the expected density decreases faster than its fluctuations with increasing the size of the telescope mirror. The NSB and even not strict trigger conditions (not simulated here) influence on the density more in the low energy than in the high energy. This may leads to fact that paradoxical feature would not be observed in the real experiment.

The estimated energy resolution (which is approximately proportional to the relative fluctuation of the Cherenkov light density) obtained in this analysis is the same as in [3] except two lowest simulated energies. Worse energy resolution (at 20 and 50 GeV) is expected for larger detectors if the minimal number of photons hitting the detector was required.



(a) primary γ-ray (b) primary proton

Fig. 4. The relative dispersions of the Cherenkov light density obtained for different detector sizes: 240 (solid lines), 480 (dotted lines) and 960 m^2 (dashed lines) at the observation height of 2.2 km

Figure 4b shows the relative dispersion of the Cherenkov light density for the primary proton. In this case the relative dispersion do not depend on the mirror size for impact larger than 40 m and energies larger than 200 GeV. In the low primary energy range, the limit of the number of photons hitting the detector has similar influence on the relative dispersion like for the primary γ-rays.

IV. Conclusions

There are differences in the lateral density distributions obtained from different observation levels at the distances (from the shower core axis) below the hump position. The expected Cherenkov photon density above the hump position do not depend on the observation altitude in the very low energy range. The relative fluctuations of the density decrease as the primary energy increases for both types of simulated primary particles. The low energy showers show larger intrinsic fluctuations than high energy EAS, even as the mirror area is increased and Poissonian fluctuations are reduced.

The fluctuations of the Cherenkov light density are not Poissonian, but rather are dominated by intrinsic shower fluctuations when one considers large mirror areas. The relative dispersions of the density are much more pronounced in proton than γ-ray showers. For γ-rays the relative fluctuations of the Cherenkov light density on the ground are quite large at small impact parameters.

The relative density fluctuations are independent of the detector size (in the investigated range - from 240 m^2 up to 960 m^2) for γ-rays beyond 40 m distance (between the detector and the core axis) and for primary energy of γ-ray above 100 GeV. In the case of protonic showers, a similar independence is observed for energies above 500 GeV. Supposing that the ratio between the RMS deviation of the density to its mean is an estimation of the primary energy resolution, even a four times larger reflector surface than that of the MAGIC telescope, a single telescope cannot achieve a better energy resolution than presented in this paper.

The simulations show that better energy resolution in a single IACT can be achieved by building the experiment at an altitude of 4 km a.s.l., but this only concerns primary energies above 200 GeV at impact parameters between 40 and 100 m. At lower energies the energy resolution should be better on an observation level of 2.2 km. The energy resolution of a single IACT is limited by the fluctuations in the shower development itself which causes the difficulties of the detection of low energy γ-rays.

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