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Impact of aerosols and adverse atmospheric conditions on the data quality for spectral analysis of the H.E.S.S. telescopes

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ABSTRACT

The Earth's atmosphere is an integral part of the detector in ground-based imaging atmospheric Cherenkov telescope (IACT) experiments and has to be taken into account in the calibration. Atmospheric and hardware-related deviations from simulated conditions can result in the mis-reconstruction of primary particle energies and therefore of source spectra. During the eight years of observations with the High Energy Stereoscopic System (H.E.S.S.) in Namibia, the overall yield in Cherenkov photons has varied strongly with time due to gradual hardware aging, together with adjustments of the hardware components, and natural, as well as anthropogenic, variations of the atmospheric transparency. Here we present robust data selection criteria that minimize these effects over the full data set of the H.E.S.S. experiment and introduce the *Cherenkov transparency coefficient* as a new atmospheric monitoring quantity. The influence of atmospheric transparency, as quantified by this coefficient, on energy reconstruction and spectral parameters is examined and its correlation with the aerosol optical depth (AOD) of independent MISR satellite measurements and local measurements of atmospheric clarity is investigated.

1. Introduction

During the last decade, imaging atmospheric Cherenkov telescopes (IACTs) have qualified as powerful instruments for astronomy in the very-high-energy (VHE; $E > 0.1$ TeV) regime, and allowed detailed studies of the most violent phenomena known in the Universe.

The flux of VHE gamma rays is very low, so that large effective areas are required. To achieve this, the IACT technique makes use of telescopes on the ground and the Earth's atmosphere acts as the calorimeter of the detector system.

Due to the atmosphere's opacity, VHE photons can be observed only indirectly at ground level: gamma rays penetrating the atmosphere interact with air molecules and give rise to showers of secondary particles (Extensive Air Showers, EAS). Cherenkov telescopes are designed to detect the Cherenkov radiation emitted by these relativistic shower particles. The main strengths of this type of detector, compared to any other ground-based systems, include the good rejection of the background of cosmic-ray initiated showers, the angular and energy resolution, and the low energy threshold.

The energy threshold is directly influenced by the atmospheric absorption, as more absorption leads to a higher threshold.

H.E.S.S. is an array of Cherenkov telescopes situated at Khomas Highland of Namibia (23°16′18″ S, 16°30′00″ E) at 1800 m above sea level. Four telescopes are equipped with a 13 m Davis–Cotton mirror arrangement featuring a focal length of 15 m. They are located at the corners of a square of 120 m side length, optimized for an energy threshold of 100 GeV. Each camera is equipped with an array of 960 photo-multiplier tubes (PMTs) with attached light concentrators, covering a field of view of 5° diameter in the focal plane [2].

In order to reconstruct the energy of the primary particle, shower images are compared to Monte Carlo shower simulations for which nominal hardware parameters and average atmospheric conditions at the H.E.S.S. site are assumed [6]. However, changes in telescope photon detection efficiency as well as atmospheric variations complicate this comparison. In the case of the telescope photon detection efficiency this includes changes in the

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photo-sensor response as well as in the reflectivities and transmissivities of optical components such as the telescope mirrors or the light concentrators.

The hardware changes are taken into account through a detailed calibration of the instrument:

- PMT aging is monitored by a regular measurement of their gain. Adjustments to the high voltage are performed to keep the gain in a region that is compatible with the Monte Carlo simulations [1].
- Changes in telescope photon detection efficiency are measured through the detection of muons during normal data taking. These events allow the determination of the "muon efficiency" μ, which is a telescope-wise quantity and provides a measure of the number of photo-electrons detected per incident photon. Although muons are created at any time during the shower development, only those emitted in the last few hundred meters form a ring-shaped image in the camera. By comparing radii and intensities of these rings to theoretical values, it is possible to measure changes in the optical performance [3]. New Monte Carlo simulations are performed when μ changes by more than ∼10–15%, typically due to changes in mirror reflectivity.

While it is possible to measure the effect of these hardware parameters on the spectral shower reconstruction, the effect of the atmosphere is more difficult to quantify, due to its complexity and our limited knowledge of the atmospheric conditions.

Some atmospheric phenomenon will act as atmospheric light absorbers, attenuating Cherenkov light from EAS particles and therefore reducing the amount of Cherenkov photons that reach the detector. Therefore, it is expected that a reduction of the actual atmospheric Cherenkov light transparency compared to the Monte Carlo model assumptions results in underestimated energies.

That effect is especially problematic for spectral analysis since misreconstructed energies shift the entire reconstructed spectrum to lower energies. This results in biased values of the reconstructed flux normalization, and, in particular in the case of non-power law spectra, other spectral parameters.

To limit such effects to a minimum, corresponding monitoring quantities have to be used in the Cherenkov technique in order to detect data that is taken in the presence of clouds and aerosols. In this paper we present a new way to estimate the atmospheric transparency by using only observables and calibration parameters from the Cherenkov data taken with the H.E.S.S. telescope array.

In the first part of this paper we will discuss the most important atmospheric conditions that affect spectral shower reconstruction. A second part will present the new monitoring quantity that estimates the "atmosphere transparency", followed by a short systematic study on the effect of atmospheric transparency, traced by this quantity, on reconstructed spectral parameters. Finally, the last part will contain a detailed comparison of this new monitoring quantity with satellite data that measures the total atmospheric optical depth at different wavelengths and with local radiometer measurements of sky clarity.

2. Origin of atmospheric effects

2.1. Clouds

The maximum of the Cherenkov emission from air showers, developed by primary particles of energies within the H.E.S.S. energy domain ($E \geqslant 300$ GeV), takes place at altitudes between ∼6–11 km (see [6]). Thus, one can assume that thin layers of clouds below those altitudes act as atmospheric light absorbers which may attenuate Cherenkov light from the whole shower or parts of it, resulting in fewer photons reaching the camera and a lower trigger probability. As a result, single telescope trigger rates and consequently the central trigger rate (see [10]) are reduced.[1] The trigger rate can therefore be used to detect data that has been taken in the presence of clouds.

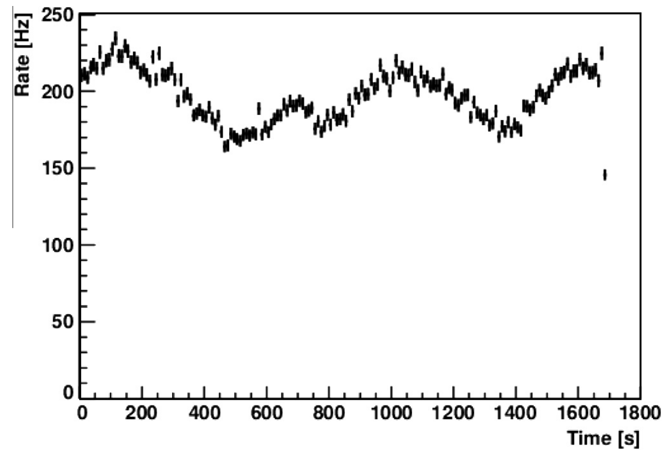

Fig. 1. Fluctuating behavior of the central trigger rate in the presence of clouds moving through the field of view. Fluctuations can be quantified by the RMS of the data points with respect to a linear fit.

For instance, if absorbing structures (local clouds) pass through the field of view, a fluctuating behavior in the central trigger rate on time scales smaller than the standard duration of data sets[2] can be observed, as highlighted in Fig. 1. In order to quantify these fluctuations for each run, the average central trigger rate (coincidence of two or more telescopes) is calculated over 10 s time intervals. The resulting evolution of the trigger rate is fitted by a linear function. Fluctuations in the central trigger rate can be quantified by the R.M.S. of the residuals of the fit. As an atmospheric data monitoring quantity, the R.M.S. value is divided by the time averaged central trigger rate. In the absence of clouds, relative fluctuations in the central trigger rate are smaller then 3%.

However, this quantity is only sensitive to clouds that affect the central trigger rate on time-scales smaller than the run duration. Long-term atmospheric absorbers like aerosol and long-term cloud layers need another quantity to be detected.

2.2. Aerosols

In addition to clouds, there is another phenomenon that might absorb or scatter photons from Cherenkov showers: aerosol particles of human or natural origin. Even though the atmosphere at the H.E.S.S. site features a very low aerosol concentration, seasonal biomass burning to the north-east of the H.E.S.S. site around August and October may lead to a significant increase of the atmospheric aerosol content. These aerosols can be transported over large distances to the H.E.S.S. site resulting in an increase of the aerosol concentration over several kilometers in height at the site (see [6]). The aerosols may also persist in the atmosphere for weeks, affecting the experiment over time scales much larger than that of individual data sets. This makes it difficult to disentangle their effect on the trigger rates from that of instrumental changes,

[1] The trigger rate decreases with the zenith angle even in absence of atmospheric light absorbers due to the increase of the distance of the shower maximum. In this paper, trigger rates are assumed to be corrected for this effect.

[2] In H.E.S.S., observations are performed in so-called runs of 28 min.