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Estimation of the atmospheric transmission profile with the IACT background data

Mario Pecimotika¹, Julian Sitarek², Natalia Żywucka²,
Dorota Sobczyńska², Abelardo Moralejo³, Dario Hrupec⁴

¹Ruđer Bošković Institute, Zagreb, Croatia

²Department of Astrophysics, University of Łódź, Łódź, Poland

³Institut de Física d'Altes Energies, Barcelona, Spain

⁴Department of Physics, J. J. Strossmayer University of Osijek, Osijek, Croatia

E-mail: mario.pecimotika@cta-consortium.org, jsitarek@uni.lodz.pl

Abstract. We present a novel method to determine the atmospheric transmission profile from the isotropic background events detected by the Imaging Atmospheric Cherenkov Telescopes. We construct a longitudinal distribution of the observed Cherenkov light by relating its emission height to a specific pixel in the camera. For this, we use a simple geometric model based on the parameters of the air shower. By comparing this distribution between cloudless and cloudy atmospheres, we were able to obtain the transmission profile during data acquisition. Using Monte Carlo simulations of a subarray of four Large-Sized Telescopes of the upcoming Cherenkov Telescope Array Observatory, we have evaluated the performance of the proposed method and tested a number of possible systematic errors that could influence the method. The proposed method achieves typical systematic accuracy within a few per cent. The aggregated profiles of the observed Cherenkov light can be reconstructed with a statistical accuracy of $\lesssim 5\%$ with only a 5-minute exposure.

1 Introduction

This conference paper presents the findings of a study previously published in [1], which investigates the performance of a novel method for estimating the atmospheric transmission profile using Imaging Atmospheric Cherenkov Technique (IACT) background data. In the field of very-high-energy gamma-ray astronomy ($\gtrsim 100$ GeV), IACT [2,3] has become a crucial method for the indirect detection of gamma-ray sources. This technique is based on the detection of short flashes of Cherenkov light. Namely, when a primary gamma ray interacts with atmospheric nuclei, a cascade of secondary particles (the so-called extensive air shower) is initiated. These secondary charged particles may travel faster than light in the atmosphere, causing an asymmetric polarisation of nearby electric dipoles. When the excited atmospheric molecules return to their ground state, they emit excess energy in the form of Cherenkov radiation, which is then gathered by large mirrors and focused onto a camera equipped with light detectors.

The atmosphere acts as the medium where Cherenkov light is both generated and propagated. Consequently, variations in atmospheric conditions, such as the presence of clouds, can have a notable impact on the detected Cherenkov light yield in the camera and the interpretation of gamma-ray signals. However, clouds are geometrically thin compared to the longitudinal development of extensive air showers that span several kilometres, impacting only a segment of the shower developed above or within the cloud. The observations can still be conducted under such conditions, but at the cost of an increased



energy threshold and reduced performance. The effects of clouds on IACT have been studied in detail and various correction methods have been proposed [4–12].

Cherenkov light is emitted at different altitudes above the telescope, and most correction methods rely on atmospheric transmission profiles obtained from auxiliary atmospheric monitoring devices [10,13–15], in particular LIght Detection And Ranging (LIDAR) systems. LIDARs reconstruct these profiles by analysing the backscattered light from laser sources. However, this analysis is complicated and requires additional calibrations and assumptions, especially for single-wavelength devices. In contrary, Raman LIDARs in particular use strong laser pulses that can interfere with observations, limiting their use to certain periods between the telescope repositioning and requiring interpolation of the transmission profiles in the meantime. Therefore, we propose a novel method for estimating atmospheric transmission profiles based solely on the observed IACT background data presented in [1].

2 Methodology

2.1 Derivation of the atmospheric transmission profile

The proposed method for evaluating the transmission profile of clouds from background observations involves constructing a sum of the longitudinal distributions of the observed Cherenkov light. These aggregated distributions can then be compared between clear atmosphere and cloud-affected observations, where their ratio directly indicates the transmission of the cloud.

To obtain these distributions, we correlate the pixel position in the camera with the specific emission height following the approach described in [12]. For each event, we perform a preliminary stereoscopic direction reconstruction using the crossing point method. The distance from each pixel to the crossing point is projected along the line connecting the reconstructed position of the source to the centre of gravity of the image. Finally, a geometric formula is used to convert the distance in the camera into the emission height [1] (Fig. 1):

$$\xi = \frac{0.85}{\cos \theta} \cdot \arctan \left(\frac{I \cos \theta}{H} \right). \quad (1)$$

For a shower with an impact parameter I and a zenith angle θ , Cherenkov photons emitted at height H will be detected by the telescope at an angular distance ξ from the primary particle direction. The term $0.85/\cos \theta$ was introduced as a phenomenological correction for better agreement between the data and the model, as the model does not contain any information about the lateral and the angular distribution of the charged particles in the cascade.

In the presence of clouds, the effective collection area decreases [5, 11, 12], leading to degraded event reconstruction. To address this event selection bias, we renormalize the transmission profile in the 3–4 km above ground level (a.g.l.) range.

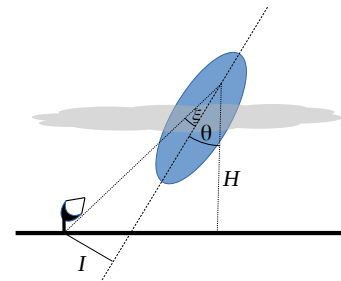


Figure 1: The model geometry [12].

2.2 Monte Carlo simulations and data analysis

To evaluate the performance of the proposed method, we analysed dedicated Monte Carlo simulations of the telescope array of the future Cherenkov Telescope Array Observatory¹ consisting of four Large-Sized Telescopes (see Fig. 1 in [12]). We used the code CORSIKA 7.7410 [13, 14] to simulate the evolution of air showers and the emission of Cherenkov light with the included package ATMO/IACT. The `sim_telarray` [15] code was used to simulate the atmospheric effects on the propagation of the Cherenkov light and the response of the detector to the recorded Cherenkov photons. Atmospheric transmission profiles, including clouds, were simulated using the MODerate resolution atmospheric TRANsmission (MODTRAN) band model algorithm version 5.2.2. [16, 17]. For technical details on the simulations, please refer to [1].

Data analysis was conducted using `ctapipe`² and `lstchain`³. For stereoscopic reconstruction, we selected only images consisting of a single island with at least 20 pixels. Images with an absolute time gradient⁴ of less than 1 ns/m were excluded to avoid single muon-dominated images. Additionally, events

¹<https://www.ctao.org>

²<https://github.com/cta-observatory/ctapipe>

³<https://github.com/cta-observatory/cta-lstchain>

⁴The time gradient describes the rate of change of the arrival time along the major axis of the ellipse.

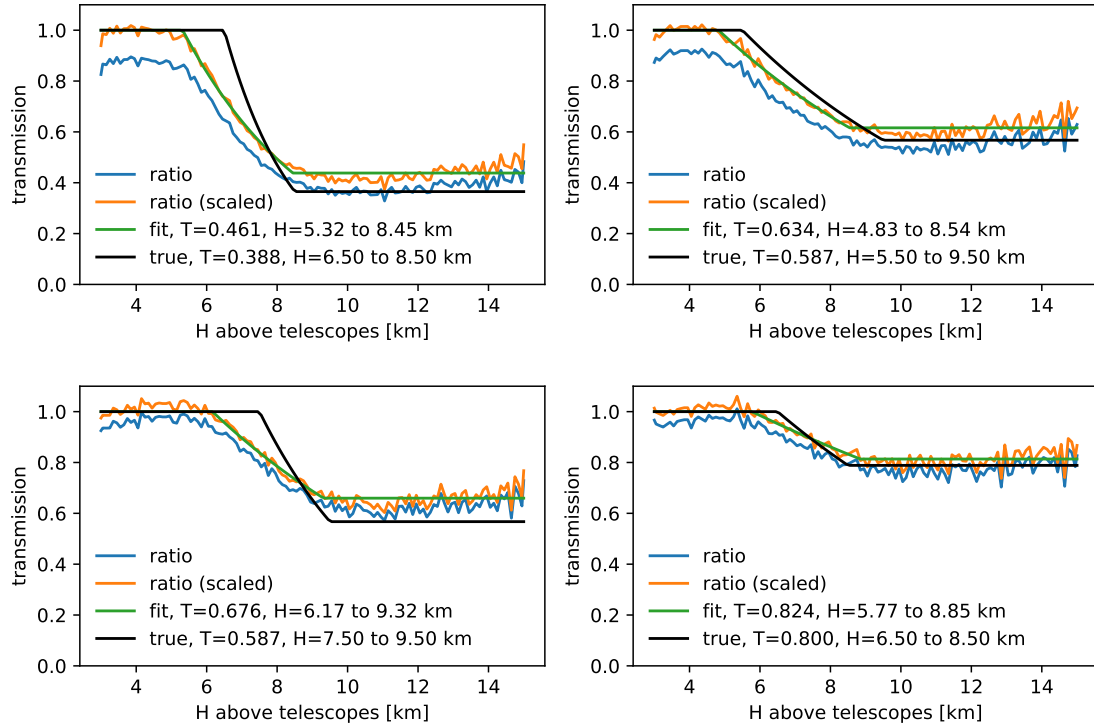


Figure 2: The blue line shows the raw ratio between aggregated distributions for clear atmosphere and cloud-affected observations, while the orange line shows the same ratio renormalised at 3 – 4 km a.g.l. The black line shows the simulated cloud transmission profile, while the green line shows the reconstructed profile from the fit to the orange line [1].

with the centre of gravity outside the cleaned image were also excluded. A multiplicity cut of two was applied, requiring at least two images of the same event to proceed with stereo reconstruction.

Next, we applied a second set of conditions to each image that passed the initial reconstruction. To avoid nearby events with roundish images lacking a clear height profile, we excluded events with an absolute time gradient below 5 ns/m. Additionally, to exclude events with very large impact parameters that are cut at the edge of the camera and do not follow the geometrical model, we retained only events with an absolute time gradient below 15 ns/m. The decision to cut based on the time gradient is supported by its minimal susceptibility to cloud presence compared to, for example, cuts based on the intensity parameter [12].

3 Results

The results for the selected clouds are shown in Fig. 2. For further details, please refer to [1]. The method can reconstruct the total cloud transmission with a high degree of accuracy, typically within a few per cent of the absolute value, although it tends to overestimate it slightly. However, the height of the cloud is underestimated in all simulated cases. In particular, the method often reconstructs the cloud base at lower heights, while the cloud top is generally reconstructed with an absolute bias of less than half a kilometre. Consequently, the geometric centre of the cloud is reconstructed at a lower height, but this bias is relatively small compared to the total size of the simulated clouds. Furthermore, due to the wide distribution of angular offsets at a given emission height, there is a limitation in the accurate reconstruction of the cloud profile. This leads to a significant overestimation of the cloud thickness, especially for cloud structures narrower than ≈ 3 km. The aggregated profiles of the emitted Cherenkov light can be reconstructed with a statistical accuracy of $\lesssim 5\%$ with only a 5-minute exposure [1].

We also tested a number of possible systematic uncertainties. The study has shown that changes in the optical point spread function up to $\pm 10\%$ compared to the nominal one (cf. Fig. 6 in [1]) and a degradation of the reflectivity of the telescope mirror up to $\pm 8\%$ (cf. Fig. 7 in [1]) do not

significantly affect the method, as the relative differences in the reconstructed transmissions are $\lesssim 5\%$.

Next, we tested how the presence of heavier nuclei in the background data, such as helium, or change in the Night Sky Background (NSB) affects the proposed method. Including helium nuclei had a negligible effect on the reconstructed transmission profile of the cloud (cf. Fig. 5 in [1]), while for the increase in NSB by 25%, the absolute difference in reconstructed transmission was only 4% (cf. Fig. 11 in [1]).

Finally, we investigated the impact of pointing direction on the performance of our method. The study demonstrated that data taken at different azimuth angles can be reliably used. Comparing cloud-affected south-pointing data with reference cloudless north-pointing data revealed an absolute difference in reconstructed cloud transmission of only 3% (Fig. 3). However, this holds true only for data taken at the same zenith angle. The reconstructed emission height distributions show a strong dependence on the zenith angle due to the increased atmospheric thickness with zenith distance, causing the shower to develop higher in the atmosphere [18]. As long as cloud-affected observations are compared with reference cloudless observations at the same zenith angle, our method can reconstruct cloud transmission with similar accuracy across all pointing angles (Fig. 4).

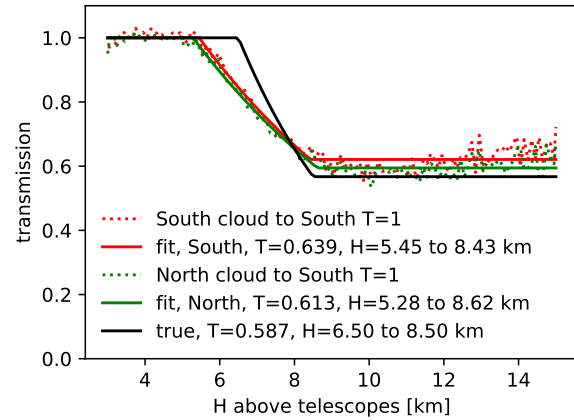


Figure 3: Influence of pointing azimuth angle on the reconstructed cloud transmission profile [1]. The true cloud profile is shown in black. The reconstructed profile for the case of matching pointing azimuth between reference cloudless and cloud-affected observations is shown in red. The green line shows the case in which different pointing azimuth is used for a reference cloudless observations. The reconstructed transmission profiles are shown in dotted lines and their fits by solid lines.

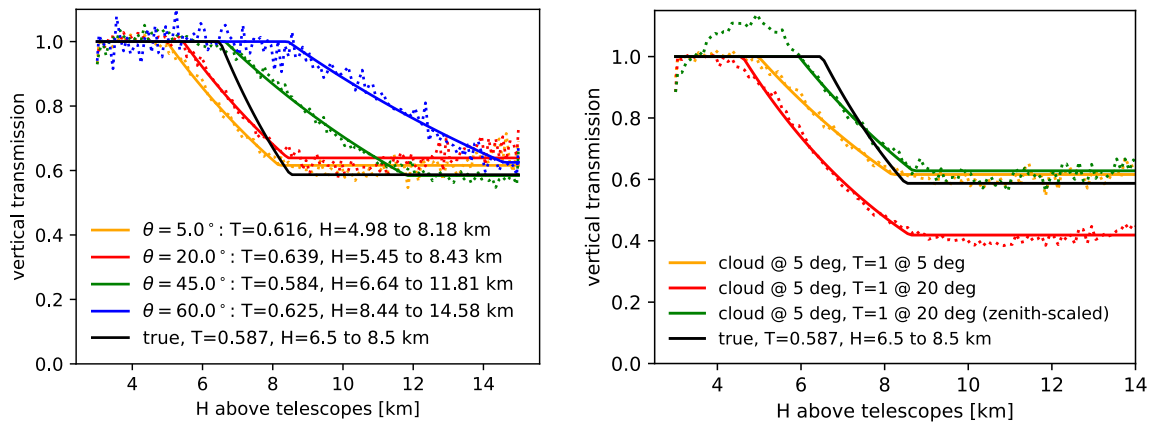


Figure 4: The impact on the pointing zenith angle on the reconstructed cloud transmission profile [1]. The true cloud profile is shown in black. The reconstructed transmission profiles are shown in dotted lines and their fits with solid lines. *Left*: The reconstructed profile for the case of matching pointing between cloudless and cloud observations is shown in red ($\theta = 20^\circ$). Other lines show cases in which different pointing is used for a reference, cloudless observations ($\theta = 20^\circ$ for cloud-affected observations). *Right*: The reconstructed profile for the case of matching pointing between cloudless and cloud observations is shown in yellow ($\theta = 5^\circ$). The red line shows reconstructed profile when cloud-affected data taken at $\theta = 5^\circ$ is compared with reference cloudless data taken $\theta = 20^\circ$. The green line shows the transmission profile after the zenith scaling of the reference data taken at $\theta = 20^\circ$.

At higher zenith distances, the geometric thickness of the cloud and its centre are overestimated. Therefore, in cases where reference good weather observations with the same zenith angle are not available, we propose to use the scaling method described in detail in [1]. Assuming reference observations at zenith angle θ_0 with height distribution $M(h_0; \theta_0)$, the goal is to scale this distribution to the zenith angle θ_c at which cloud-affected data were taken, resulting in the height distribution $M'(h_c; \theta_c)$. We recalculate the heights by assuming that the emission depends only on the atmospheric thickness $D(h)$:

$$D(h_c)/\cos\theta_c = D(h_0)/\cos\theta_0 \quad (2)$$

The density of Cherenkov photons reaching the telescope scales inversely with the area over which the photons are distributed, estimated as $A = \pi(\alpha(h)h/\cos\theta)^2$, where α is the height-dependent Cherenkov angle. The effective collection area scales linearly with A , cancelling out this effect in the aggregated light distribution. Therefore, the distribution $M'(h_s)$ only has to be adjusted by the emission height binning difference induced by Eq. (2):

$$M'(h_c; \theta_c) = M(h_0; \theta_0)\Delta h_0/\Delta h_c. \quad (3)$$

The results of the scaling procedure are shown in Fig. 4 (*right*). The scaling performance degrades at higher zenith distances. In these cases, to maintain data consistency, the reference clear-sky data sample used to estimate atmospheric absorption should cover a zenith range similar to that of the cloud-affected data.

4 Summary and conclusions

The presented novel method for determining the transmission profile with IACTs is based on the summation of the longitudinal distributions of the observed Cherenkov light from the isotropic background. This approach associates pixel positions in the camera with specific emission heights based on air shower parameters. By comparing these reconstructed distributions between cloudless and cloudy atmospheres, the ratio is directly interpreted as a measure of cloud transmission.

We investigated several possible systematic errors that could affect the method. The study confirmed that helium and heavier nuclei, minor changes in optical reflectivity or optical point spread function due to telescope ageing (up to 10% and 8%, respectively), azimuth dependence, and background light levels have negligible effects on the performance of the method and correctly reconstruct the cloud parameters. The main limitation of the method is the zenith angle of the observation. Due to significant variations in the distribution of emission heights of the detected Cherenkov light, only data taken at the same zenith angle can be compared. For cases in which this is not possible, we have proposed a scaling method to mitigate the bias caused by different zenith distributions.

The proposed method achieves typical statistical and systematic accuracy within a few per cent and allows reconstruction of the aggregated profiles of the observed Cherenkov light with a statistical accuracy of $\lesssim 5\%$ with only a 5-minute exposure. Although the method cannot completely replace LIDAR measurements and is unsuitable for measuring the transmission of low layers of increased aerosols (such as Calima), it allows independent and continuous monitoring of atmospheric transmission without the need for additional specialised auxiliary instruments. The obtained transmission profiles can be used directly in the correction method or as input for modelling atmospheric profiles with MODTRAN, which are needed for the data analysis based on dedicated Monte Carlo simulations.

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