PROCEEDINGS OF SCIENCE

Correcting for atmospheric variations in IACT data analyses

Tim Lukas Holch[a,*]

[a] *Deutsches Elektronen-Synchrotron DESY, Platanenallee 6, 15738 Zeuthen, Germany*

E-mail: tim.lukas.holch@desy.de

A fundamental concept of atmospheric Cherenkov detectors is the use of the Earth's atmosphere as calorimeter. Apart from the advantages of employing this large existing air volume as part of a detector, this implies an accurate characterisation of the atmospheric conditions to correctly interpret the collected data. As extensive Monte Carlo simulations form the basis for common data analyses of such instruments, it can be unpractical and computationally expensive to adequately cover the full phase space of possible conditions under which measurements are performed. Often, this is resolved by excluding data that was taken under non-favourable conditions from an analysis. To avoid discarding valuable data, a scheme to correct for deviations between simulated and actual atmospheric conditions is presented in this contribution. The proposed scheme employs atmospheric data from various sources to build refined atmospheric models. The transmission profile used in MC simulations is then compared to a range of transmission profiles for conditions under which observations were conducted. By applying parametrised air-shower profiles, event-wise zenith and energy dependent correction factors can be determined to refine particle energies and instrument response functions without the need to rerun the full MC simulation chain. A proof of concept is shown on the example of observations of the Crab Nebula with the imaging atmospheric Cherenkov telescopes (IACTs) of the H.E.S.S. experiment with a focus on varying aerosol levels. The scheme can, however, be adapted to correct for the influence of various atmospheric parameters.

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*Speaker

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1. Introduction

Parameters like pressure, temperature and humidity as well as wind, particulate matter and molecular content influence the properties of the Earth's atmosphere as an optical system with altitude dependent refraction, scattering and absorption of photons. As atmospheric Cherenkov detectors like imaging atmospheric Cherenkov telescopes (IACTs) incorporate the atmosphere as a calorimeter, atmospheric variations can impact the accuracy and precision with which the properties of detected air-showers are reconstructed. Common air-shower reconstruction pipelines rely on detailed Monte Carlo (MC) simulations of the detector's response to air-showers under given conditions. Observational data are then compared to these simulations to estimate the properties of detected air-showers. If the atmospheric conditions assumed in these MC simulations do not correspond to the actual observation conditions, the properties of the observed air-showers are systematically misreconstructed. While a constant monitoring of the full atmospheric profile for all parameters of interest is very difficult and expensive to realise, it is also computationally very expensive to take all detailed conditions under which observations are conducted into account in MC simulations, as a full set of simulations with sufficient statistics has to be generated for each set of conditions. A common approach is therefore to produce simulations with a limited number of average atmospheric profiles and discard observations which were conducted under conditions that deviate significantly from these averages. While this approach is well feasible for observations of steady sources, this is not the case for time-domain astronomy where transient phenomena are of high interest and a source simply cannot be observed again under better conditions. In these cases, atmospheric variations need to be compensated[1].

In the following, a procedure is presented with which air-shower data, reconstructed with a default atmosphere model, can be refined to better fit specific observation conditions. After a brief outline of the effect of atmospheric variations on IACT data, the scheme is introduced and a proof-of-concept is presented using Crab Nebula observations by the H.E.S.S. telescope array. This correction procedure has already been applied in the analysis presented in [2].

2. Atmospheric variations in IACT data analyses

MC simulations form the basis for common IACT data analysis. They are used to generate the so-called instrument response functions (IRFs) which characterise the energy- and direction dependent sensitivity/effective collection area of the instrument as well as the errors on reconstructed air-shower directions and energies. By applying a reconstruction algorithm to simulated air-shower data and comparing the simulation input with the results of the reconstruction, a reconstruction algorithm can be tuned and the corresponding IRFs can be generated. This reconstruction algorithm is then also used to determine the properties of *observed* air-showers. By combining the properties reconstructed from observed air-showers with the corresponding IRFs, it is finally possible to convert observational data to physical entities such as energy-dependent gamma-ray flux. If the MC simulations, however, do not match a specific observation condition, the air-showers from this observation are mis-reconstructed and the IRFs are wrongly assigned, yielding additional systematics on the final result.

[1]Recent examples are the H.E.S.S. observations of the recurrent Nova RS Ophiuchi [1] and GRB 221009A [2].

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The energy reconstruction is thereby especially affected, as the detected Cherenkov light is proportional to the energy of a primary air-shower particle. Any change in atmospheric transmission directly impacts the amount of Cherenkov photons that reach an IACT and thus also impacts the reconstructed energy. As an example, if the true atmospheric transmission is lower than assumed in MC simulations, less Cherenkov photons reach the detector than expected and the energy reconstructed for each individual air-shower is consequently too low. Furthermore, the energy dependency, i.e. the *true energy-axis* of the IRFs, is misaligned accordingly towards lower energies. A specific sensitivity is then assumed for a too low energy range, yielding an overall shift of the reconstructed gamma-ray flux towards lower energies. In combination with power-law type spectra as common in gamma-ray astronomy, this results in an effective underestimation of reconstructed gamma-ray flux. More specifically, for an atmospheric transmission which is lower by a factor of two than assumed in MC simulations, only half of the Cherenkov photons reach the detector and, assuming a linear dependency, the air-shower energies are underestimated by a factor of two. The reconstructed flux of a source at e.g. 1 TeV then actually corresponds to the flux at 2 TeV.

For higher-level IACT data analyses, reconstructed air-showers are commonly binned in space, energy and time to form a combined histogram-like data structure. By combining data from multiple observations that were conducted under different atmospheric conditions without taking these differences into account in the reconstruction (i.e. in the underlying MC simulations), individual air-showers can end up in the "wrong" bins, effectively introducing an additional smearing to the binned data. The impact of this smearing on the final result can thereby depend on a combination of multiple aspects such as the binning resolution, the true physical properties and distribution of the observed air-shower events as well as the specific differences between the actual and simulated observing conditions. The final effect on the results can thereby vary from higher fluctuations in the binned data and thus larger statistical uncertainties up to systematic shifts.

3. An a posteriori correction scheme for atmospheric variations

By generating atmospheric transmission profiles for specific observation conditions, it is possible to estimate the amount of Cherenkov photons which is expected to reach an IACT from a given air-shower. This can then be compared to the amount of Cherenkov photons that is expected for this air-shower under the simulated conditions to generate correction factors by which the reconstructed air-shower energies and corresponding IRFs have to be shifted to better match the actual observation conditions. For the presented study, atmospheric transmission profiles are generated by performing radiative transfer simulations using the software package `Py6S` [3, 4]. The atmospheric profiles used for these simulations are generated with data from the In-Aircraft for a Global Observing System (IAGOS) [5, 6], the Integrated Global Radiosonde Archive (IGRA) [7] and the Aerosol Robotic Network (AERONET) [8] station located on the H.E.S.S. site in combination with the biomass-burning aerosol model provided via `Py6S`. To generate energy-dependent correction factors, the parametrisation of gamma-ray induced air-shower profiles as presented in [9] is used. A more detailed description of the approach can be found in [10].

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4. Proof of concept – Correcting Crab Nebula observations affected by biomass burning

As a proof of concept, H.E.S.S. observations of the Crab Nebula are analysed. The regarded observations were conducted during a period in which the atmospheric transmission was strongly influenced by frequently elevated aerosol levels. As aerosols have a particularly strong impact on the atmospheric transmission at the wavelengths of the Cherenkov light emitted by air-showers, this dataset is well suited for a proof of concept. The applied correction is therefore designed to correct for deviations in aerosol levels (for technical reasons defined via the AOD_{550}, which is the aerosol optical depth at 550 nm) and assumes all other atmospheric parameters to be constant at the average obtained from the data sources listed above in Sec. 3.

4.1 The H.E.S.S. experiment and the annual biomass-burning season

The H.E.S.S. telescope array[2] is an array of five IACTs operating in the GeV to TeV energy range located in the Khomas Highland in Namibia at about 1800 m above sea level. This region is impacted by the annual biomass-burning season with rising aerosol levels from around August to October, caused by an overabundance of fires during the dry winter months in sub-Saharan Africa [11]. The effect can be nicely seen in the data from the AERONET station operated on the H.E.S.S. site as e.g. shown in Fig. 1 in [10].

4.2 Estimating the aerosol optical depth

To apply the proposed correction, it is necessary to know the AOD_{550} during each observation. As the AERONET station on the H.E.S.S. site cannot operate during astronomical darkness, actual AOD measurements concurrent to H.E.S.S. observations are not available. The telescope trigger rates however correlate with the aerosol levels during an observation, which makes it possible to calculate the so-called Cherenkov transparency coefficient (TC) as outlined in [12]. This TC is calculated from observation zenith angle corrected telescope trigger rates, taking into account camera hardware settings as well as the optical efficiency of the telescopes via the so-called muon efficiencies. For the presented study, slight adaptations are made to the TC calculation, e.g. by replacing the observation-wise muon efficiency with a long-term estimate to compensate for variations introduced by changes in atmospheric conditions, and adapting the overall normalisation to reduce the number of values > 1. This adapted TC is referred to here as the *atmospheric* transparency coefficient ATC. To circumvent the lack of concurrency between AERONET and H.E.S.S. measurements, all available AERONET data points and ATC estimates are resampled into 30 min averages and the resampled AERONET data is extrapolated with a third order polynomial over 2.5 h into the gaps of astronomical darkness from both directions. Using orthogonal distance regression (i.e. minimising the distance of the fitted curve to the data points along both axes), these concurrent data points are then fitted with an exponential (due to the relation between optical depth and transparency) that is restricted to have an AOD_{550} of 0 at an ATC of 1 and only exhibit non-negative ATC values. This fitted function is then used to translate an ATC measurement to an AOD_{550} estimate as e.g. done for the data points shown in Fig. 1. An emphasis has hereby

[2]See https://www.mpi-hd.mpg.de/hfm/HESS/ for more details.

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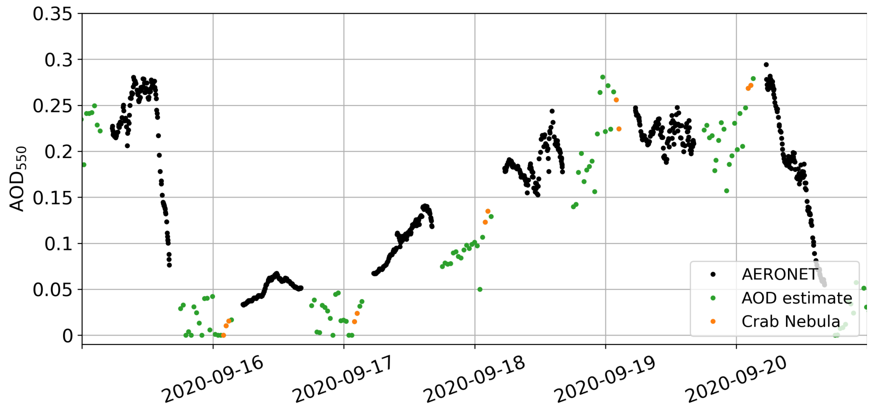

Figure 1: Estimated AOD_{550} for all observations conducted during the five regarded nights shown in green with the here analysed Crab Nebula observations shown in orange. The AERONET measurements over the period are shown in black. It can be seen how the estimated AODs nicely follow the trends in the AERONET data.

to be put on the resulting values being *estimates* as their accuracy is difficult to judge without actual concurrent AOD measurements as reference. The overall AERONET data can be used as a rough guide, however, as also seen in the AERONET data, AOD levels can rapidly change on timescales of hours. Filling the gaps in AERONET data by extrapolating the measurements with a polynomial may therefore not capture the true AOD evolution correctly. Furthermore, the accuracy of the calculated ATC values can be compromised e.g. by technical aspects such as hardware configurations of which potential dependencies on the trigger rates are not taken into account in the ATC calculation.

4.3 Analysis and results

For this proof of concept study, H.E.S.S. observations of the Crab Nebula from five consecutive nights in September 2020 are used, for which the AOD measurements from the AERONET station indicate a successive increase in aerosol concentration. This trend is also well captured by the AOD estimates based on telescope trigger rates as seen in Fig. 1. Using a standard Hillas-based H.E.S.S. air-shower reconstruction, a dataset is generated which is then analysed with `gammapy` [13] in version 1.0. A 1D spectral analysis using the reflected background method is performed on the corrected as well as the uncorrected dataset and the results are compared. The AOD level during the regarded five nights increases steadily from a very low value around 0.01 to around 0.27, with the last two nights not meeting the standard H.E.S.S. data quality selection requirements for spectral analyses. In a normal analysis, these two observations would thus be discarded due to low atmospheric transmission.

Analysing the uncorrected dataset yields a spectrum which clearly deviates from the published H.E.S.S. exponential cut-off power law (ECPL) [14], systematically underestimating the flux over the full energy range as seen in Fig. 2 (*left*). The corrected dataset on the other hand shows a much better agreement as seen in Fig. 2 (*right*). Here, a deficit can mainly be seen in the flux points from ~ 4 TeV to ~ 9 TeV.

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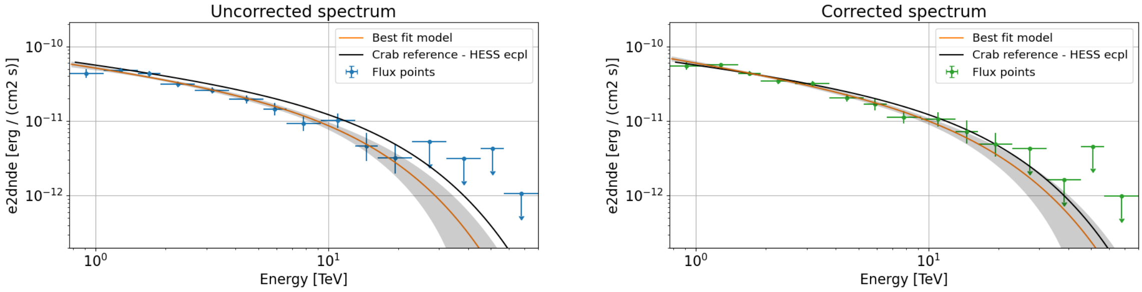

Figure 2: Uncorrected (*left*) and corrected (*right*) best-fit power-law spectra with expnential cut-off and flux points as extracted from the regarded five nights of observations. As a reference, the published H.E.S.S. ECPL spectrum is shown in black. The systematically lower flux can be well seen for the uncorrected dataset.

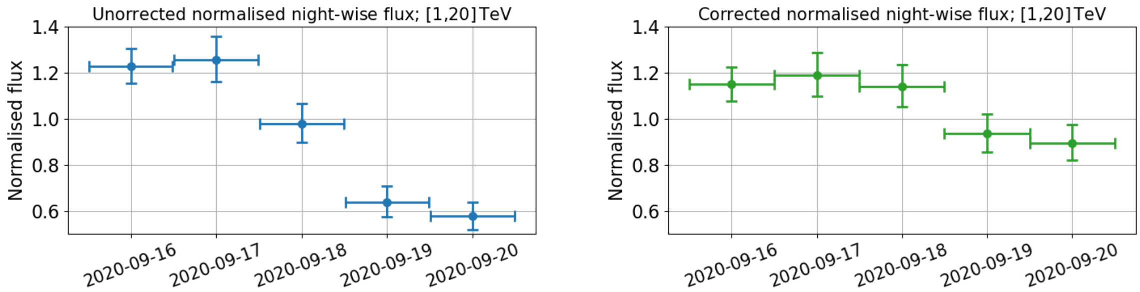

Figure 3: Night-wise lightcurves in [1,20] TeV energy range extracted from the uncorrected (*left*) and corrected (*right*) datasets. The flux points are normalised to the flux of the reference HESS ECPL spectrum shown in Fig. 2, integrated from 1 TeV to 20 TeV. Errorbars depict the statistical errors only. It can be well seen how the correction significantly reduces the spread in the night-wise flux.

The effect of the correction is even better visible when comparing the integrated night-wise flux as shown in Fig. 3. The shown flux measurements are normalised to the flux of the H.E.S.S. ECPL reference model. Looking at the light curve from the uncorrected dataset in Fig. 3 (*left*) shows clearly how the rising aerosol levels (as shown in Fig. 1) over the five nights yield decreasing flux levels. The corrected light curve in Fig. 3 (*right*) shows a different behaviour. While the flux in the first two nights is slightly decreased by the correction (due to higher atmospheric transparency than assumed in the simulations) the flux of the following three nights increases by up to 50%. While the corrected flux of the first three nights is constant within statistical errors, the flux of the last two nights is not. This may be explained by an inaccurate/too low AOD estimate or by a non-optimal aerosol model. As seen in the AERONET data (see Fig. 2 in [10]) the aerosol size distribution at the H.E.S.S. site changes over the year. Such variations can also occur on much shorter timescales. The here assumed constant biomass-burning aerosol profile and its particle size distribution might therefore not be most accurate to represent each observation condition.

Nevertheless, by applying the correction, the spread in integral flux over the five nights is reduced from 31% to 11%. This can also be seen when plotting the nightly flux over the mean estimated AOD as shown in Fig. 4.

In H.E.S.S. data analyses, it is common to assume a systematic error on the flux normalisation of ~ 20% [14] due to uncertainties on the shower interaction and atmospheric models used in MC

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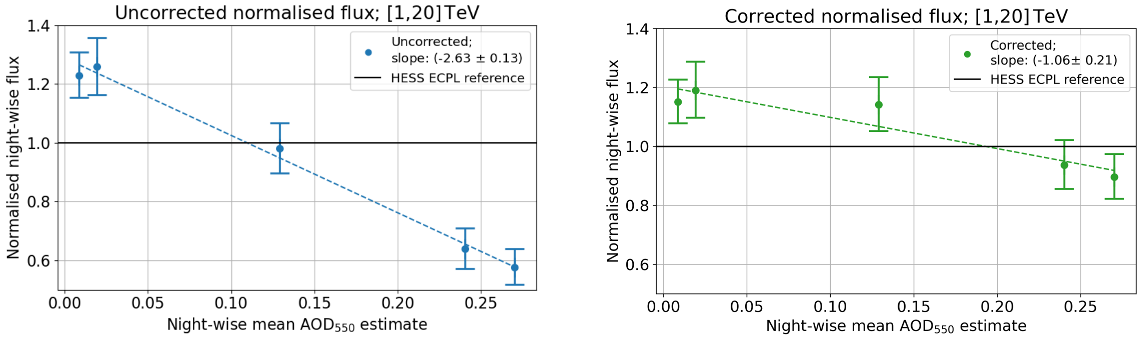

Figure 4: Night-wise integral flux in the [1,20] TeV energy range normalised to the reference ECPL model for the corrected (*left*) and uncorrected (*right*) datasets plotted over the nightly mean AOD estimates. Errorbars show statistical errors only.

simulations. By applying the correction, the flux levels including the observations from the last two nights which would normally be discarded, all agree with the reference flux when taking these additional 20% systematic uncertainty into account. This is not the case for the uncorrected dataset. While the first three nights with AOD levels < 0.2 also agree with the reference when taking the additional systematics into account, the last two nights do not.

5. Conclusion

The correction scheme presented in this contribution could be shown to successfully compensate for aerosol induced errors in a standard Hillas-based H.E.S.S. air-shower reconstruction to a level that results obtained from normally discarded data agree within commonly assumed systematic uncertainties. It should however be noted that the aerosol levels regarded in this study are relatively moderate with values up to an $\mathrm{AOD}_{550} \sim 0.3$ when compared to phases of extremely elevated aerosol levels during the biomass-burning season at the H.E.S.S. site where the AOD_{550} can reach values up to ~ 0.8 and higher. The performance of the correction scheme for such aerosol levels still has to be investigated in detail. Nevertheless, the presented scheme can be used to refine data that was taken under – at least moderately – non-optimal atmospheric conditions and make it useable for further high-level analysis, which is especially helpful for studying transient phenomena where observations cannot be repeated when the conditions are more favourable.

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