Early attempts at atmospheric simulations for the Cherenkov Telescope Array

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Abstract: The Cherenkov Telescope Array (CTA) will be the world’s first observatory for detecting gamma-rays from astrophysical phenomena and is now in its prototyping phase with construction expected to begin in 2015/16. In this work we present the results from early attempts at detailed simulation studies performed to assess the need for atmospheric monitoring. This will include discussion of some analysis methods with a view to determining a range resolved atmospheric transmission profile. We find that under increased aerosol density levels, simulated gamma-ray astronomy data is systematically shifted leading to softer spectra. With lidar data we show that it is possible to fit atmospheric transmission models needed for generating lookup tables, which are used to infer the energy of a gamma-ray event, thus making it possible to correct affected data that would otherwise be considered unusable.

Keywords: monitoring, calibration, lidar, aerosols, gamma-rays, shower reconstruction and analysis, Cherenkov telescopes

1 Introduction

The Cherenkov Telescope Array (CTA) aims to increase its flux sensitivity by an order of magnitude compared to existing ground-based gamma-ray telescopes \cite{1}. This will be achieved using Cherenkov telescopes of 3 different sizes, a large size telescope (LST) $\sim 23$ m diameter, a medium size telescope (MST) $\sim 12$ m diameter and a small size telescope (SST) $\sim 4$ m diameter. In order to achieve such sensitivity gains it is important to minimise the systematic uncertainty in derived flux and energy resolution. Imaging atmospheric Cherenkov telescopes are calorimetric by nature and as such a good knowledge of atmospheric conditions is required at the telescope site. Atmospheric quality affects both shower development and the Cherenkov yield in two ways. Firstly, in the production of Cherenkov light atmospheric quality affects the vertical profile of the refractive index of the air and hence shower development. This variation is seasonal, and effects mid-latitudes worse than the tropics. However, the profile can be measured using radiosondes for example and any seasonal variation that might exist can be accounted for. It is also possible for high-level aerosols (e.g. clouds) to occur around shower maximum and so affect Cherenkov yield and image shape.

Secondly, poor atmospheric quality can also result in the loss of Cherenkov light. For example atmospheric quality affects Cherenkov light propagation through Rayleigh & Mie scattering of the Cherenkov light, which can lower the brightness of an image in the camera for a shower of given energy and core distance. However, by using lidar measurements it is possible to derive a range-resolved probability of transmission (at the lidar wavelength) and adjust atmospheric models, needed in simulations used to reconstruct gamma-ray spectra, accordingly \cite{8}.

This work highlights an early simulation study conducted using a hypothetical 97 telescope array to illustrate the effects of atmospheric quality on a reconstructed gamma-ray spectrum.

Finally, another motivational factor for a large observatory like CTA is the desire to maximise the duty cycle of the instrument. Thus being able to resurrect otherwise unusable data due to relatively poor atmospheric conditions becomes important.

2 Technique

For this work measurements of the atmosphere were recorded using an Easy-Lidar ALS450XT developed with and manufactured by Leosphere France. The Easy-Lidar ALS450XT was a monostatic bi-axial lidar that is now defunct. Table\textsuperscript{1} highlights the specifications of the lidar used for this research.

| Wavelength | Frequency | Pulse Width | Energy/Pulse | Range | Resolution |
|------------|-----------|-------------|--------------|-------|------------|
| 355 nm     | 10 Hz     | 5 ns        | 20 mJ        | 15 km | 1.5 m      |

Table 1: Specifications of the Leosphere Easy-Lidar ALS450XT.

The approach adopted for acquiring data involved pointing the lidar toward zenith and firing the laser to acquire a single atmospheric profile averaged over 600 laser shots. The transmission profile was derived from the lidar data using the Klett inversion method \cite{2} and the multangle method \cite{3}. Using lidar data recorded on 15th August 2008 at the H.E.S.S. site (23°16.28’S/16°30’E), when the atmospheric quality was perceived to be visibly poor, the range-resolved atmospheric transmission was derived as shown in Figure\textsuperscript{1}.

The standard “desert-dust” transmission model \cite{4} is widely used to characterise the measurement site. For convenience this is referred to as the normal aerosol density model in this work. The normal aerosol density transmission model (dashed blue line) shown in Figure\textsuperscript{1} is for a
Atmospheric air shower simulations were conducted using CORSIKA and the telescope simulations were conducted using the singlearray software package \cite{5}. 20 million gamma-ray showers between 5 GeV and 2 TeV, with a differential power-law spectrum with slope $E^{-2}$ at zenith were produced. A hypothetical CTA telescope array comprising two different telescope types. This includes 12 large-sized parabolic dish telescopes each with a mirror area of $\sim 600 \text{ m}^2$, 4093 pixels at their primary focus and a 5 degree field of view. In addition, there are 85 medium-sized Davies-Cotton dish telescopes each with a mirror area of $\sim 100 \text{ m}^2$, 1735 pixels at their primary focus and a 7 degree field of view. It should be noted that such a telescope array is unlikely to be built for the CTA and that it would be too costly and does not necessarily provide optimal sensitivity performance of the broadband energy range from 10 GeV to above 100 TeV. Furthermore, the photomultiplier quantum efficiency for both of the simulated telescopes was increased by 50% compared to the Photonis XP2960, and a 3 pixel trigger threshold was set requiring a minimum signal of 5.3 photoelectrons (within a given sector of the camera). Events which failed to meet this criteria were discarded from the analysis.

Figure 5 (Left panel) shows the effective areas folded with a power-law spectrum whose slope is $E^{-2.45}$ (a Crab-like spectrum), to indicate the threshold energy of the system\cite{4}. For the normal aerosol density dataset, the triggering threshold energy is 10 GeV, rising to 20 GeV post the loose cuts.

Whereas for the increased aerosol density dataset the minimum triggering threshold is 20 GeV rising to 30 GeV post the loose cuts. Initially it appears that such a change in atmospheric quality has little effect on the simulation, but this

\begin{table}
\begin{tabular}{|c|c|}
\hline
\textbf{Energy} & \textbf{Threshold} \\
\hline
10 GeV & 10 GeV \\
20 GeV & 20 GeV \\
30 GeV & 30 GeV \\
\hline
\end{tabular}
\end{table}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure1}
\caption{The derived range-resolved atmospheric transmission up to 20 km above sea level (a.s.l.) recorded at the H.E.S.S. site (1800 m a.s.l.) in Namibia on 15th August 2008. The pink triangles show the transmission derived using the multiangle method, the grey circles show the transmission derived using the Klett method and the blue dashed line shows the normal aerosol density transmission model widely used to characterise the measurement site.}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure2}
\caption{The derived range-resolved atmospheric transmission up to 20 km above sea level (a.s.l.) recorded at the H.E.S.S. site (1800 m a.s.l.) in Namibia on 15th August 2008. The pink triangles show the transmission derived using the multiangle method, the grey circles show the transmission derived using the Klett method and the blue dashed line shows the newly derived best-fit aerosol model found using MODTRAN.}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure3}
\caption{The derived range-resolved atmospheric transmission up to 20 km above sea level (a.s.l.) recorded at the H.E.S.S. site (1800 m a.s.l.) in Namibia on 15th August 2008. The pink triangles show the transmission derived using the multiangle method, the grey circles show the transmission derived using the Klett method and the blue dashed line shows the newly derived best-fit aerosol model found using MODTRAN.}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure4}
\caption{The derived range-resolved atmospheric transmission up to 20 km above sea level (a.s.l.) recorded at the H.E.S.S. site (1800 m a.s.l.) in Namibia on 15th August 2008. The pink triangles show the transmission derived using the multiangle method, the grey circles show the transmission derived using the Klett method and the blue dashed line shows the newly derived best-fit aerosol model found using MODTRAN.}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure5}
\caption{The derived range-resolved atmospheric transmission up to 20 km above sea level (a.s.l.) recorded at the H.E.S.S. site (1800 m a.s.l.) in Namibia on 15th August 2008. The pink triangles show the transmission derived using the multiangle method, the grey circles show the transmission derived using the Klett method and the blue dashed line shows the newly derived best-fit aerosol model found using MODTRAN.}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure6}
\caption{The derived range-resolved atmospheric transmission up to 20 km above sea level (a.s.l.) recorded at the H.E.S.S. site (1800 m a.s.l.) in Namibia on 15th August 2008. The pink triangles show the transmission derived using the multiangle method, the grey circles show the transmission derived using the Klett method and the blue dashed line shows the newly derived best-fit aerosol model found using MODTRAN.}
\end{figure}
3 Results

In order to test the effect of atmospheric quality on the simulated dataset, a set of lookup tables for the reconstructed energy $E_R(r,S)$ and the reconstructed effective area $A_R(E)$ were generated from the simulation database. This was done for both a normal aerosol density level and an increased aerosol density level. A test spectrum of 100,000 events each with a simulated energy $E$ (following a power-law spectral slope of $E^{-2.3}$) was randomly drawn from each of the databases. Using the lookup tables, the $E_R(r,S)$ and $A_R(E)$ were derived for these events and a reconstructed differential spectrum was generated for three specific combinations of simulation data and lookup tables highlighted in Table 2.

Table 3: Results of fitting a power-law $dN/dE = I_0 E^{-\alpha}$ to the reconstructed spectra for each of the cases highlighted in Table 2. The quoted errors are statistical only.

| Case | $I_0$ events $\text{TeV}^{-1}$ | $\alpha$ |
|------|---------------------------------|----------|
| 1    | 198±5                           | 1.93±0.01|
| 2    | 77±2                            | 2.34±0.01|
| 3    | 210±3                           | 1.91±0.01|

The power-law fit values highlighted in Table 3 show that
Figure 5: Left: The effective area for triggering is shown for a database of gamma-ray showers at zenith folded with a telescope simulation that is computed with different atmospheric models to reflect the real atmospheric quality measured with a lidar. Shown here is the resulting effective area for the normal aerosol density model (filled circles) and the increased aerosol density model (filled squares). In addition a cut of at least 2 triggering telescopes, with a minimum of 4 signal tubes is applied to the data and the resulting effective area after this cut is shown for the normal aerosol density model (open circles) and the increased aerosol density model (open squares). Right: Shown here is the effective area (seen in the Left panel) folded with a power-law spectrum (Crab type slope of $E^{-2.45}$) in order to illustrate the energy threshold of the system, which is located at the peak of each distribution.

Correcting for changing atmospheric quality results in a power-law index similar to what is expected when atmospheric quality at the site is considered to be normal, or at least the aerosol density level is considered to be normal. Thus using a lidar to measure changing aerosol density levels and hence atmospheric quality is a useful tool for correcting data in ground-based gamma-ray astronomy. However, it should be noted that transmission values calculated using a single-scattering lidar like the one used in this work, are reported to have systematic errors of approximately 30% [6]. Thus there is a desire to test whether Raman lidars which have a much lower associated systematic error ($\sim$5%) can be used within CTA for active atmospheric calibration.

5 Conclusion

Currently within the field of ground-based gamma-ray astronomy, atmospheric quality is accounted for by monitoring the background cosmic-ray trigger rates and data with sub-standard atmospheric quality is discarded [8]. This work shows that it is possible to use a lidar to take in-situ atmospheric measurements in order to derive the probability of transmission at a wavelength close to the maximum for Cherenkov light production. A model of atmospheric transmission for a spectrum of wavelengths is then fitted to the lidar data and used within simulations to produce lookup tables that better reflect the actual atmospheric quality. Correcting for changing atmospheric quality in such a way can increase the lifetime of an observatory like CTA. In addition, such an active atmospheric calibration method helps to lower any systematic uncertainty on the derived flux.

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Figure 6: Shown here are the reconstructed differential spectra generated from lookup tables that were created from a random sample of 100,000 events following a spectral slope of $E^{-2.3}$. This has been done for each of the different combinations of simulation data and lookup tables. The open circles show the reconstructed differential spectrum for case 1, the open squares for case 2 and the filled triangles for case 3. By incorporating lidar data into the reconstruction, this allows a corrected spectrum to be formed (case 3) whose slope is very similar to that seen when the atmospheric quality is considered to have a normal aerosol density level (case 1).

| Case | Simulated data derived from | Lookup table derived from |
|------|-----------------------------|----------------------------|
| 1    | Normal aerosol density database | Normal aerosol density database |
| 2    | Increased aerosol density database | Normal aerosol density database |
| 3    | Increased aerosol density database | Increased aerosol density database |

Table 2: Reconstructed differential spectra were generated using the following three specific combinations of simulation data and lookup tables.