Analysis of CLF data for the Pierre Auger Observatory

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Abstract

The Central Laser Facility at the Pierre Auger Observatory calculates the vertical aerosol optical depth (VAOD) for collected data of the number of photons detected as a function of altitude in relation to a reference "clear day" profile. Previously, the fitting procedure experienced edge effects on very clear days, so some of the code was rewritten such that the fits for the VAOD plots were recalculated and now represent a more physical situation.

1 Introduction

The Pierre Auger Observatory is a hybrid detector composed of a combination of 1600 surface detectors and 4 fluorescence detectors used to study high energy cosmic rays, particularly those with energies in the range of 10^{20} eV.

The surface detectors are water Cherenkov tanks that detect the Cherenkov light produced when a particle strikes the water. The fluorescence detectors measure the energy of the particles in the air by detecting the ultraviolet fluorescence produced when the particles interact with the air's nitrogen [1]. By combining the data from both types of detectors, the air shower of particles produced when the incident particle enters the Earth's atmosphere can be reconstructed.

Because the atmosphere is used as a calorimeter in detecting these particles, it is necessary to measure the daily atmospheric conditions to accurately characterize the data. A program called CLFatmos.cc then plots daily profiles of photons detected versus height above ground and compares the measured profile to a reference profile. The program then calculates and plots the vertical aerosol optical depth (VAOD) of the atmosphere for that particular day. One of the problems with the program was that the fits applied to the VAOD plot were not very physical at higher altitudes on very clear days.

2 Central Laser Facility

The Central Laser Facility is located approximately equidistant from the fluorescence detectors at Coihueco, Los Morados, and Los Leones, and it serves to take measurements of the atmospheric conditions that affect the scattering of particles in the air shower. There are two types of scattering: Rayleigh (molecular) which is due to the presence of atmospheric particles such as nitrogen and oxygen, and Mie (aerosol) scattering which results from the presence of aerosols, particulate matter such as dust or water vapor, in the atmosphere [1].

The Central Laser Facility consists of an ultraviolet laser that pulses 50 "fixed-direction vertical shots" into the sky every 15 minutes [2]. The fluorescence detectors then detect the amount of laser light scattered from interactions with molecules and aerosols in the atmosphere[2].

3 Calculation of Vertical Aerosol Optical Depth

Generally, optical depth is a measurement of the transparency of the atmosphere. Roughly, it is defined as:

$$\tau = -ln(I/I_o)$$

where I is the measured intensity, and I_o is the reference intensity.

Transmission through the atmosphere is dependent on both the optical depth due to the atmosphere's molecular components (τ_M) and on the aerosol optical depth due to the aerosols present (τ_A). Mathematically, transmission "through a vertical column of atmosphere" is expressed as [3]:

$$T = exp(-\tau_M - \tau_A)$$

In fact, the molecular optical depth is about four to five times larger than the aerosol optical depth, but the scattering due to the molecular part of the atmosphere can be well modeled whereas the scattering due to aerosols cannot be modeled easily since aerosols themselves are not uniformly shaped or distributed. The Central Laser Facility attempts to carefully measure the atmospheric profile and calculate the VAOD every quarter hour.

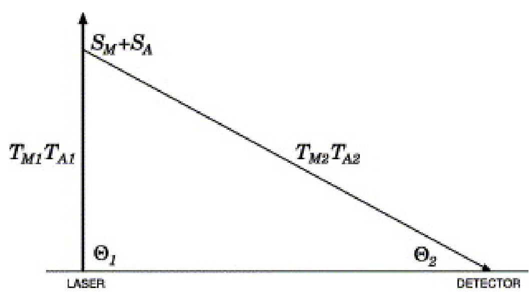
The geometry of the system between the laser and the fluorescence detector is shown in *Figure 1* where T_{M1} and T_{A1} are the molecular and aerosol transmissions for the path from the laser to the point where the scattering took place, and T_{M2} and T_{A2} are similarly the molecular and aerosol transmissions for the path from the scattering point to the detector [3].

From the geometry of the system, the vertical aerosol optical depth (ie. $\theta_1 = 90^o$) can be calculated as:

$$\tau_A = -\frac{ln(\frac{N_{obs}}{N_{mol}})}{1 + csc\theta_2}$$

where N_{obs} is the number of observed photons, and N_{mol} is the number of photons in the reference profile, a clear day where the atmosphere was very

Figure 1: Geometry of Laser Relative to Fluorescence Detector [3]



similar to being purely molecular [4]. Ref[3] shows a derivation of this formula for τ_A.

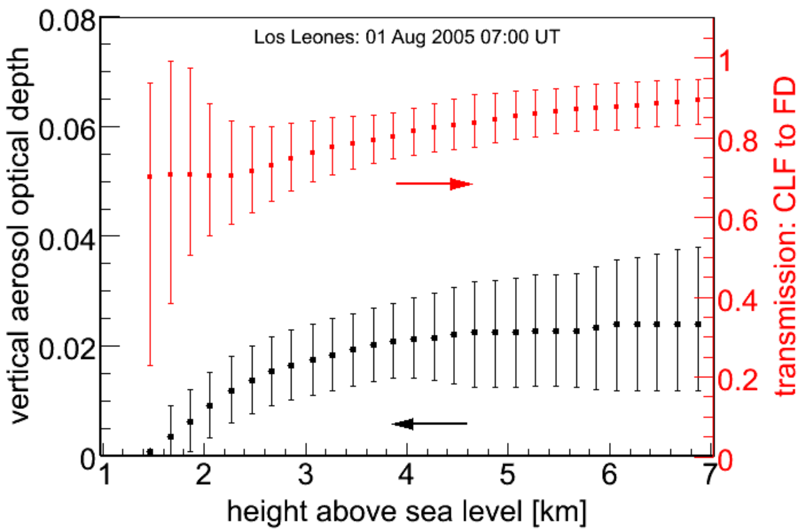
VAOD can also be calculated from the scattering coefficient, α(h), which is defined as "the differential of VAOD" [4]. CLFatmos.cc uses this parameter to achieve a more refined calculation of the VAOD.

An example of the relationship between VAOD and transmission through the atmosphere in relation to height is shown in *Figure 2*. The black curve shows the expected shape for the VAOD in this experiment with the highest acceptable VAOD around 0.1. The red curve shows that the transmission of light through the atmosphere is generally around about 80% at higher altitudes, but the large error bars at lower altitudes indicate that the amount of transmitted light can vary a great deal there. Thus, *Figure 2* indicates that the aerosols are mostly concentrated at lower altitudes as expected.

4 Explanation of Program

The program CLFatmos.cc plots profiles of the numbers of scattered photons detected at the fluorescence detector versus the altitude from ground level to 14 km. The measured profile is composed of the average of the four quarter

Figure 2: VAOD and transmission through the atmosphere as a function of height.



hour measurements, and it is plotted on the same graph as a reference profile that represents a nearly pure molecular atmosphere. If the measured profile is very close to the reference profile, then that particular hour is considered to be clear and mostly free of aerosols. As the distance between the measured profile and the reference profile increases, the amount of aerosols in the atmosphere has increased, and more light is being attenuated.

To ensure that the reference profile truly represents the current atmospheric conditions of that season, a very clear day is chosen as a new reference profile every four months. This recalibration also regularly corrects any "drift" in the laser equipment that occurs over time.

Clouds are evident on some of the profiles as green spikes that extend above the reference profile, and CLFatmos.cc has functions that cut these out of the blue "measured" profile so as to not affect the VAOD calculations.

The code then calculates the VAOD, τ_A, as above using the photon count of the measured profile as N_{obs} and the photon count of the reference as N_{mol}. To ensure that the effect of aerosol scattering from the cross-section of the laser beam on the VAOD calculation is minimized, the slope of the VAOD curve is measured over intervals of altitudes, a "sliding window" of sorts. This slope is fit to both a linear and an exponential fit, and the lowest associated chi-squared value determines which fit is ultimately used for that interval. An integration of this value of α(h) then returns a refined VAOD value that is used as a fit to the original VAOD data [4].

For each VAOD plot, a maximum and a minimum VAOD is calculated according to the calculated RMS, and their fits are calculated in the same way as the median VAOD.

The profiles labeled in *Figure 3* and *Figure 4*, 20AUG200604 and 20SEP200602, are examples of good profiles generated by this code. They both have a measured profile with no clouds. Their associated VAOD plots show that the calculated fits approximate the data and do not shoot up at the higher altitudes.

5 Problems with Program

The fits calculated by CLFatmos.cc generally followed the plotted profiles well; however, on very clear days when the measured profile was very close to the reference profile, the fits would sometimes fail by increasing very rapidly at high altitudes as shown in *Figure 5* and *Figure 6*. These failures occured because the program was not designed to handle the very clear days in which the measured profile happened to be larger than the reference profile in some places. These edge effects of the VAOD fit skyrocketing at higher altitudes is unphysical since the higher altitudes have very few aerosols.

The sliding window used to calculate the original VAOD fits took intervals of 1.2 km widths up to 14 km, the maximum altitude measured, while fitting to the VAOD every 200 m. Because the problems with the fits occured on very clear days, the assumption was made that it was not necessary to fit all the way to 14 km. According to *Figure 2*, the amount of aerosols present in the atmosphere

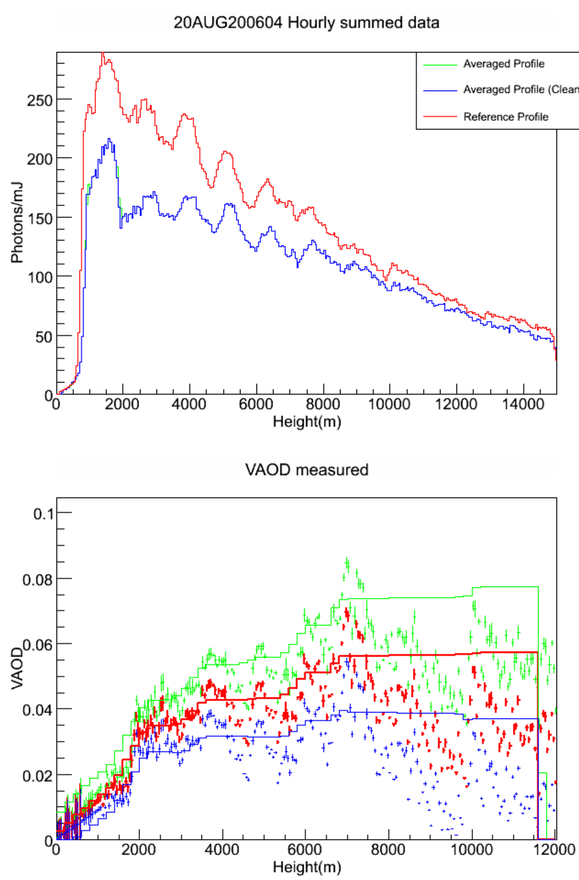


Figure 3: Good VAOD fits

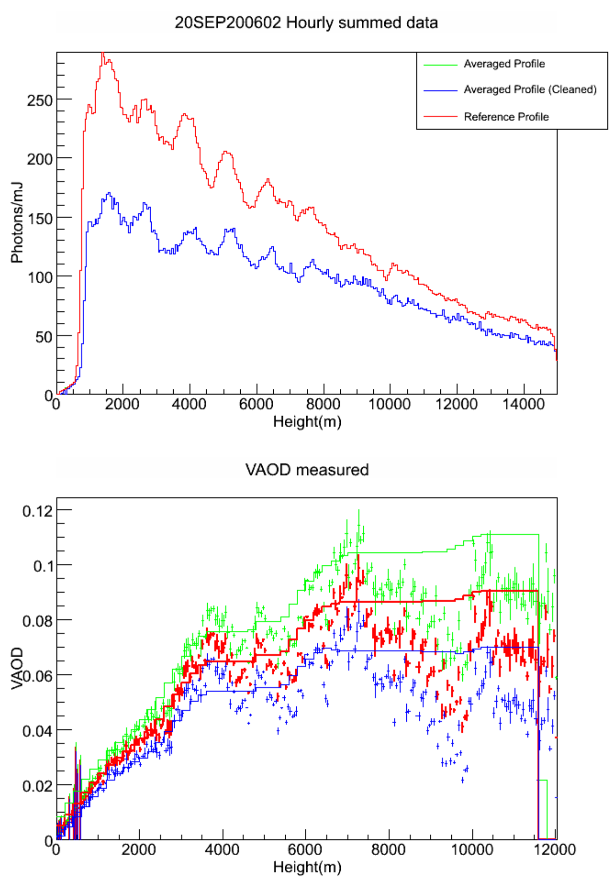


Figure 4: Good VAOD fits

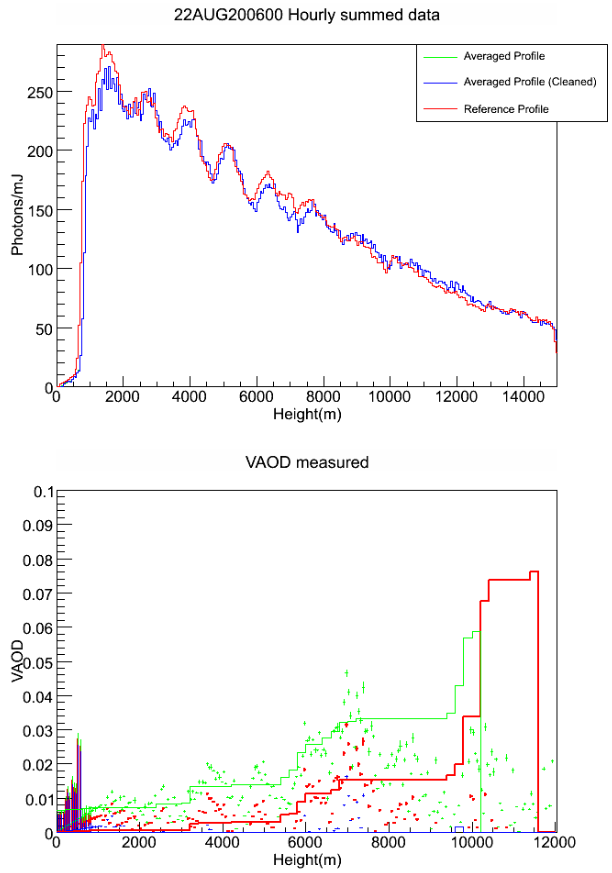


Figure 5: Poor VAOD fits

decreases significantly after about 8 km. Thus, the decision was made to set the upper limit on the fit interval to the minimum of the maximum valid height and the end of the current interval (where the maximum valid height is the highest altitude at which the bin has nonzero data). This step ensures that the sliding window will not blindly calculate VAODs up to 14 km, but will eventually stop at the maximum bin with data available.

Also, when the sliding window hits the end of the measurements, the value of $\alpha(\mathrm{h})$ is set to zero if the altitude is larger than the variable ODmaxHeight which is currently set to 8 km. Thus, the VAOD is set to zero at altitudes greater than 8 km at the end of the measurements since altitudes above 8 km do not usually have aerosols, and an aerosol-free atmosphere has a zero VAOD. This should rid the program of the problem of edge effects of increasing VAOD at higher altitudes because the slope should be set to zero on the fit at those higher altitudes.

These corrections on the fit were also applied to the VAOD maximum and minimum fits.

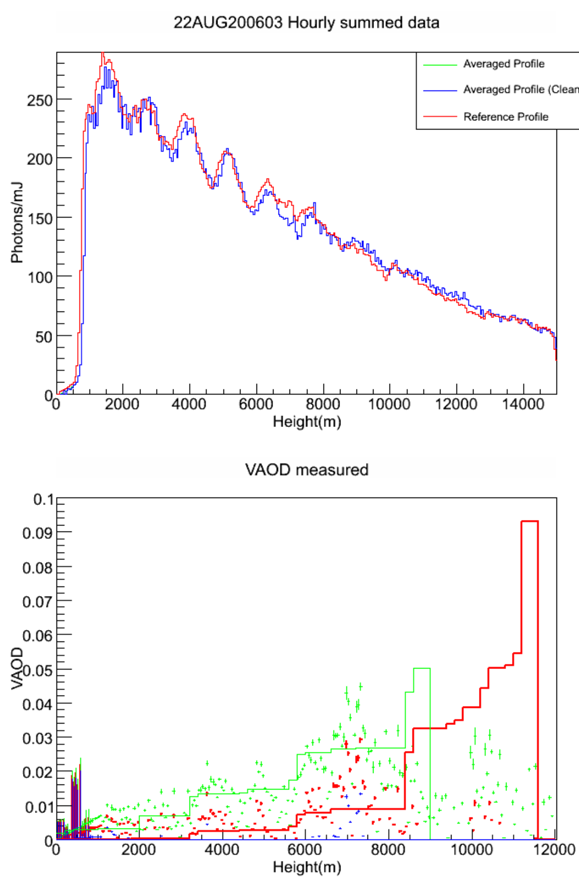


Figure 6: Poor VAOD fits

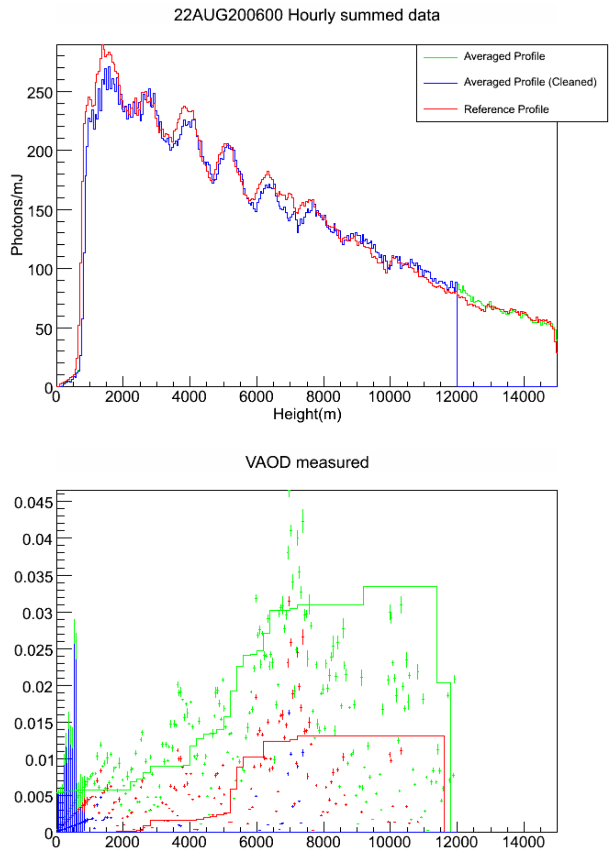


Figure 7: Fixed VAOD fits for 22AUG200600

6 Results

In *Figure 7* and *Figure 8*, the corrected plots for *Figure 5* and *Figure 6* respectively are shown. From these plots, it is apparent that the fits no longer drastically increase at the higher altitudes. Instead, the fits appear to smoothly follow the data and have a nice cutoff at the end of the fit with greatly reduced edge effects.

7 Acknowledgements

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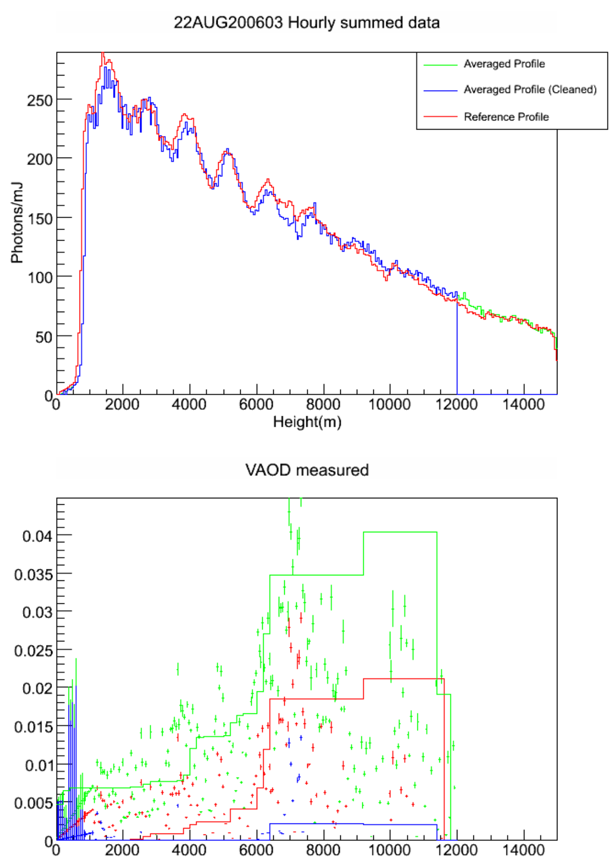

Figure 8: Fixed VAOD fits for 22AUG200603

8 References

[1] S.Y. BenZvi, et. al., *Measurement of the Aerosol Phase Function at the Pierre Auger Observatory*, [arXiv:0704.0303v1, astro-ph].

[2] B. Fick, et. al., *The Central Laser Facility at the Pierre Auger Observatory*, *JINST*, 1:P11003, 2006.

[3] R. Abbasi, et. al., *Techniques for measuring atmospheric aerosols at the High Resolution Fly's Eye experiment*, *Astroparticle Physics*, 25, 2006, 74 - 83.

[4] M.D. Roberts, *Atmospheric aerosol determination using vertical laser tracks from the central laser facility*, *GAP Note* 2006-067.