Analysis of Uncertainties Due to Aerosols at the Pierre Auger Observatory

Jeremy P. Lopez
Advisor: Prof. Stefan Westerhoff

August 3, 2007

Abstract

The atmospheric monitoring systems of the Pierre Auger Observatory measure the vertical air optical depth, the aerosol phase function, and the wavelength dependence of the optical depth in order to calibrate the Observatory's fluorescence detector systems. These measurements introduce a statistical uncertainty on measured energy of $\sim$5%. A statistal uncertainty of $\sim$4 g cm^2 was also introduced on the slant depth of the shower maximum. The assumption of horizontal uniformity of aeresols introduces systematic errors on the energy of no more than $\sim$2% and on the slant depth of no more than 2 g cm^{-2}. A simple parametric model of atmospheric aerosols that avoids such extensive monitoring introduces a systematic error of $\sim$4%. However, the root mean square of these errors was nearly 10%, much larger than the statistical errors from the measurements. Similarly, the slant depth showed a systematic shift of 0.3% with an RMS of 1.3%, larger than the statistical uncertainties from the measurements.

1 Introduction

The Pierre Auger Observatory, located near Malargüe, Argentina, is designed to study the origin of ultra-high energy cosmic rays, with energies greater than 10^{18} eV. The Auger Observatory is a hybrid detector, consisting of a surface detector (SD) array of water Cherenkov tanks as well as four fluorescence detectors (FD). When a cosmic ray particle enters the atmosphere, its interactions with the atmospheric molecules produce a shower of new particles. The air shower particles excite atmospheric nitrogen molecules, which emit UV light, while muons in the shower may reach the ground. Most of the particles created in the air shower do not continue on to reach the ground, so the intensity of the energy released into the atmosphere reaches a maximum at a certain height and decreases as it gets closer to the ground. The atmospheric slant depth of this maximum is known as X_{max} and helps to identify the composition of the incoming particle. At the Auger Observatory, the SD array detects the muons in the air shower. The FDs measure the UV fluorescence in order to reconstruct the energy of the original particle, treating the atmosphere as a calorimeter. As a result, extensive monitoring of atmospheric conditions is necessary in order to properly calibrate the FDs.

The measurements of the FDs must take into account attenuation of the UV fluorescence as it travels through the atmosphere. This attenuation is caused by scattering from both molecular and aerosol components in the atmosphere. Molecular scattering is caused by atmospheric nitrogen and oxygen molecules and is described by Rayleigh scattering. The Rayleigh phase function is well-known and such scattering may be described analytically.

Aerosol scattering is be caused by the presence of particulates in the atmosphere such as dust, smoke and fog. Because of the many different possible sizes and shapes of such matter, aerosol scattering is much more complicated and generally cannot be treated analytically. However, if aerosols are spherical and if their composition and size distribution are known, aerosol scattering is described analytically by Mie scattering [1]. Although the molecular component of light attenuation is about four times as great as the aerosol component at altitudes of 3-10 km, it is still important to measure aerosols due to their greater variability.

Several measurements of the properties of atmospheric aerosols must be made in order to properly account for the effects of aerosol scattering, and facilities have been built at the Pierre Auger Observatory to monitor these properties at the FD sites. The use of these measurements and the assumption of horizontal uniformity of aerosols implicit in taking measurements only at a small number of sites introduce some statistical uncertainty into the reconstruction of cosmic ray events. Section 2 of this paper describes the measurement of aerosol parameters. Section 3 describes the error analysis of these parameters as well as the errors introduced with the assumption of horizontal atmospheric uniformity and the use of a simple parametric aerosol model. Section 4 provides a discussion of the results.

2 Measurement of Atmospheric Conditions

Several measurements of the properties of atmospheric aerosols must be made in order to properly account for the effects of aerosol scattering, and facilities have been built at the Pierre Auger Observatory to monitor these properties at the FD sites. At each of the four FD locations, there is an aerosol phase function (APF) light source, used to make measurements of the differential cross section of atmospheric aerosols. This is needed to determine the distribution of scattering angles of the UV fluorescence due to aerosols. The cross section as a function of scattering angle may be approximated by

$$P(\theta) = \frac{1-g^2}{4\pi}\left(\frac{1}{(1+g^2-2g\cos\theta)^{3/2}} + f\frac{3\cos^2\theta - 1}{2(1+g^2)^{3/2}}\right) \tag{1}$$

The APF light sources are used to determine the values of the parameters f and $g = \langle\cos\theta\rangle$, related to the geometry of the scattering [2]. For a more detailed description of the APF light sources, see [1].

At the FD sites there are Lidar stations, used to measure the aerosol extinction coefficient, α_{aer}, and its integral, the vertical aerosol optical depth (VAOD), τ [3]. These parameters describe the transmission factor of light through a vertical column of air due to aerosols as a function of height,

$$T_{aer}(h) = e^{-\tau(h)} \tag{2}$$

Three Lidar stations are currently operating while the fourth, at Loma Amarilla, is under construction. The VAOD measurements are also made by the Central Laser Facility (CLF), located between the four FD sites, near the center of the detector array. Every fifteen minutes, the CLF fires a series of vertical test beams which are observed by the FD sites. The data is then used to reconstruct an initial estimate of τ. Given an averaged hourly measurement of the number of photons to reach the FD $N(h)$ and a reference value $N_{ref}(h)$, measured on clear nights with no aerosols, the VAOD is estimated to be

$$\tau(h) = -\frac{\ln N(h) - \ln N_{ref}(h)}{1 + \csc\epsilon(h)} \tag{3}$$

where ϵ is the elevation angle at height h [2]. For further explanation and derivation of the VAOD estimate see [4]. Currently, the software used to analyze the CLF data includes a method to differentiate this initial estimate of $\tau(h)$ to obtain $\alpha_{aer}(h)$. The aerosol extinction coefficient is then smoothed and integrated to obtain a new estimate of the VAOD. The final results of the aerosol measurements are then stored in a MySQL database. The aerosol information is retrieved by the event reconstruction software. For a more detailed explanation of the CLF, see [5].

The VAOD is dependent on the wavelength of light. This dependence is described by

$$\tau(\lambda) = \tau_0 \left(\frac{\lambda_0}{\lambda}\right)^{\gamma} \tag{4}$$

where τ_0 and λ_0 are reference values. Measurements have shown that $\gamma = 0.7 \pm 0.5$. [6] This is much less variable than the molecular optical depth wavelength dependence, where $\gamma = 4$.

3 Analysis

3.1 Data Reconstruction

All of the following analyses were conducted using the Golden Hybrid dataset, which includes data taken between January 2004 to April 2007. This set includes only high quality events, where sufficient measurements were recorded by both the FD and SD systems to be able to reconstruct the event independently. Only events with measured energy greater than 10^{18} eV were reconstructed. Further quality cuts were used on event profiles and geometrical fits, and events contaminated by Cherenkov light were removed. Once events of interest were identified, they were reconstructed using the full Auger event reconstruction.

3.2 Comparison to Parametric Atmospheric Model

Although systems are in place to directly measure the VAOD and aerosol extinction coefficient, it is also possible to create a simple atmospheric model for these using only two parameters. In this model, the VAOD and extinction coefficient are assumed to be of an exponential form:

$$\begin{aligned} \tau(h) &= \frac{H}{L}(e^{-h_0/H} - e^{-h/H}) \\ \alpha(h) &= \frac{1}{L}e^{-h/H} \end{aligned} \tag{5}$$

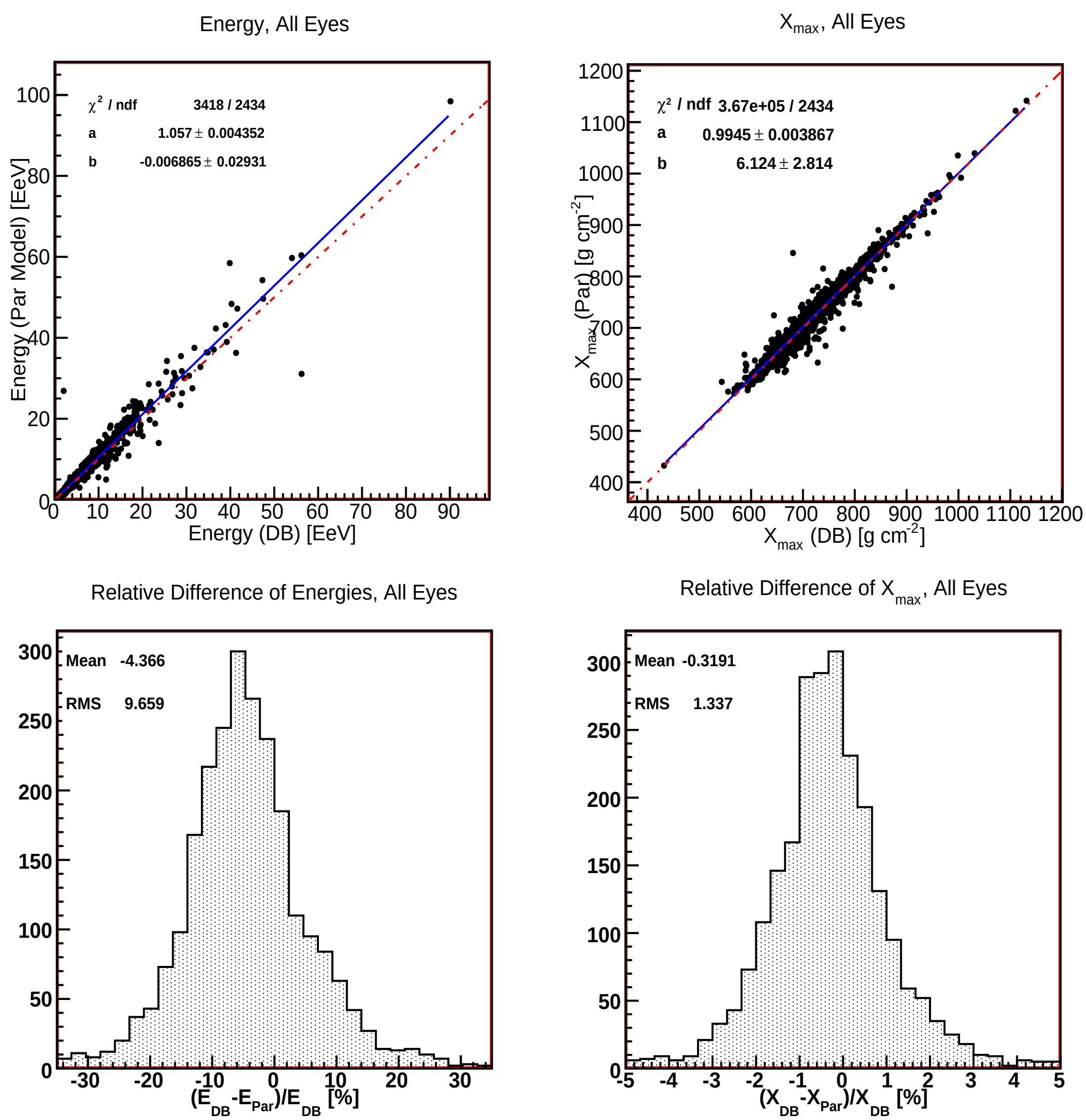

Figure 1: Comparison of reconstructed energy and shower maximum depth using database measurements and parametric model. The blue line shows a linear best-fit curve. The red line shows $E_{Par} = E_{DB}$.

The parameters are H, the exponential scale height, and L, the horizontal attenuation length. The value h_0 is the detector altitude.

Reconstruction of the Golden Hybrid events shows that use of this parametric model compared to the hourly CLF measurements leads to a systematic energy overestimate of more than 4%. The RMS of this shift, however, is nearly 10%, so for many events the parametric model can lead to significant deviations from the results using measured aerosol parameters. The value of X_{max} is overestimated by only 0.3% with an RMS of 1.3%. Figure 1 shows the spread of the differences of the reconstructed energies and slant depths between the two models.

3.3 Determination of Horizontal Uniformity

The software used by the Auger collaboration depends on the assumption of horizontal uniformity of atmospheric aerosols. Measurements are taken only at the four FD sites and the aerosols are assumed to be roughly constant in the area around each FD location. The VAOD and, thus, aerosol transmission coefficient, are measured as a function of height at a single location, while for a sight line at an angle θ above horizontal between two points, the VAOD is assumed to be

$$\tau_{slant}(h) = \frac{\tau(h)}{\sin\theta} \tag{6}$$

which requires horizontal uniformity. However, aerosol conditions are known to be much more variable than molecular atmospheric conditions and are affected by things such as local terrain and ground altitude, so this introduces some errors into the reconstructions. Additionally, at times there will be no MySQL database information available for an FD site for a particular hour. In these cases, the Auger reconstruction software replaces these missing database values with the corresponding values from the nearest FD location. The large distances between FD locations would introduce an even larger error than the assumption of uniformity near the FD site.

To estimate the error caused by horizontal nonuniformities in atmospheric aerosols, the Golden Hybrid events for the FD sites at Coihueco and Los Leones were reconstructed first using the original VAOD database values and then after switching the VAOD values of the two FD sites. Of the four sites, the greatest difference in local conditions and terrain is between Coihueco and Los Leones. Thus, the comparison of these two sites is expected to give an upper limit on the errors introduced by the assumption of horizontal

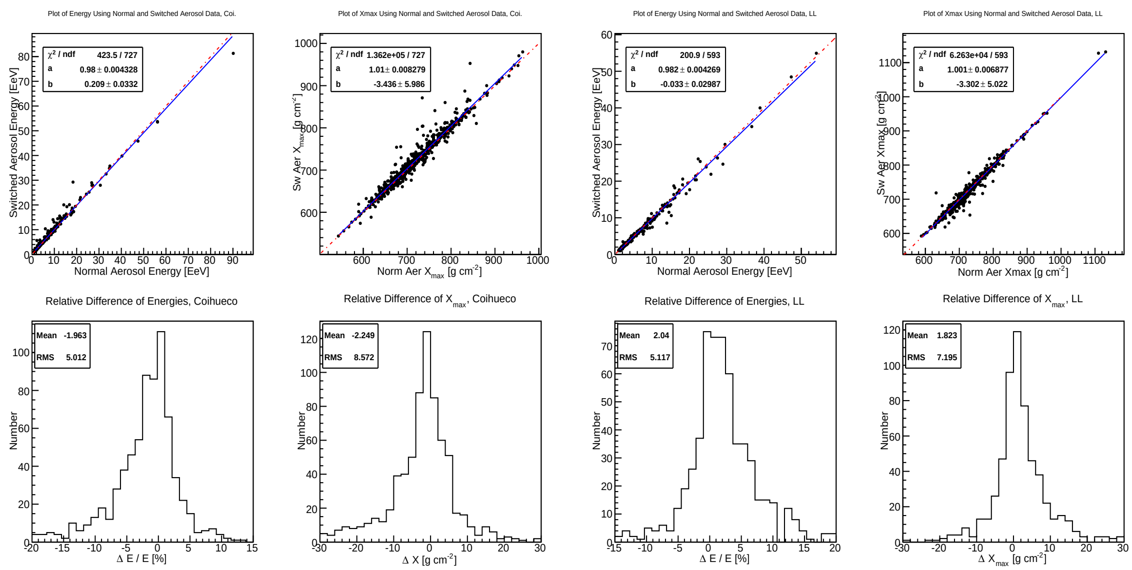

Figure 2: Comparison of event reconstructions at Coihueco and Los Leones using original VAOD database values and switched values.

uniformity of atmospheric aerosols. Figure 2 depicts the resulting changes in energy and X_{max} at both sites.

The reconstructions show a systematic overestimate of the energy at Coihueco of about 2% and of X_{max} by 2 g cm^{-2}. The Los Leones data showed underestimates of both by the roughly the same amounts. For both sites, the RMS of $\Delta E/E$ of about 5%. The RMS values of the changes in X_{max} at Coihueco and Los Leones were 7 g cm^{-2} and 9 g cm^{-2}, respectively.

3.4 Uncertainties Introduced By Aerosol Measurements

As stated previously, there are several parameters needed to account for the effects of atmospheric aerosols. The VAOD, whose errors are dominated by systematic effects, the differential cross section, and the wavelength dependence of the VAOD provide the three main sources of error due to the measurement of atmospheric aerosols. These errors were propogated by varying the different parameters by $\pm 1\sigma$ and reconstructing the Golden Hybrid events. Figure 3 shows both the positive and negative uncertainties for the different parameters. Because the differential cross section depends on two parameters, the positive error was taken to be the variation of those parame-

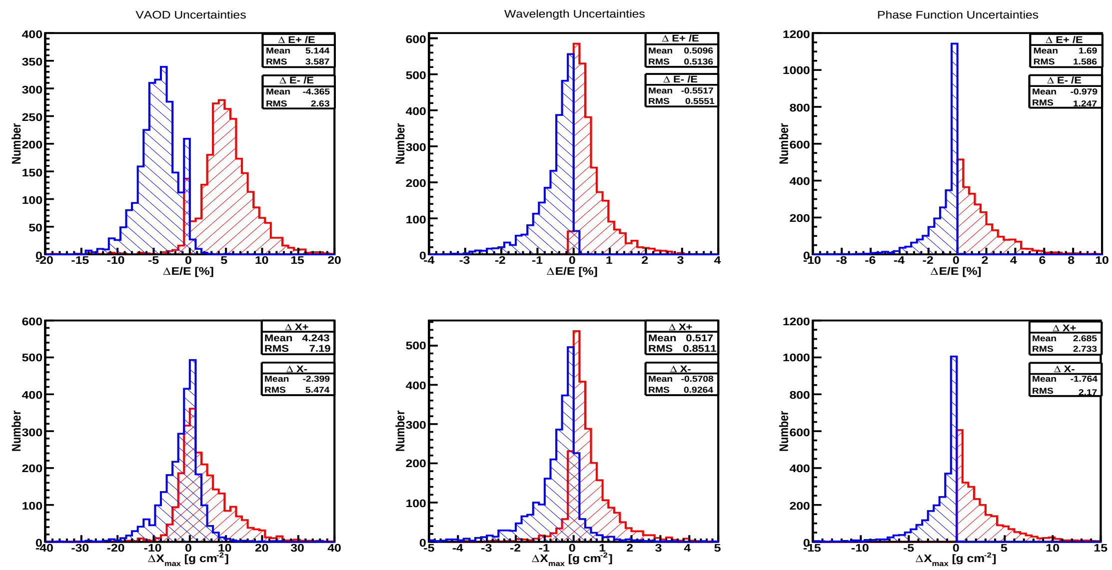

Figure 3: Errors introduced due to statistical uncertainties on aerosol measurements.

ters leading to the greatest positive change in energy or X_{max}. The negative error was calculated similarly.

The statistical uncertainties introduced by the VAOD error propagation were the dominant source of aerosol measurement errors, while the wavelength uncertainties were the smallest. Averaging the positive and negative errors of the three sources and adding them in quadrature shows typical statistical fluctuations of 5.0% for energy and 4.0 g cm^{-2} for X_{max}.

4 Discussion

The statistical uncertainties calculated in this analysis were largely in agreement with the previous estimates found in [6]. Comparing the errors introduced by the aerosol MySQL database to the spread of errors seen in the parametric model, the database leads to much smaller variations. Thus, it appears that the database is, in fact, the better method of the two in minimizing the uncertainties of the FD measurements at the Pierre Auger Observatory. However, the second maximum seen near $\Delta E/E = 0$ in the VAOD energy uncertainty plot (Figure 3) is troubling. Further investigation has shown that this is caused by the presence of non-physical VAOD limits in the database. The database currently uses information obtained by the CLF, so it is clear that in some cases the CLF analysis software fails to properly reconstruct the VAOD errors. Fortunately, the errors only occur on very clean days, where there are few if any aerosols present in the atmosphere. Because of this and because of the relatively small percentage of events affected, it is likely that any changes from the current error estimates will be very small. We have started to correct the problems in the CLF software and, when it is completed, it is still likely necessary to perform the VAOD error analysis once again to confirm that the corrections do not significantly change the errors.

5 Acknowledgements

I would like to thank Prof. Stefan Westerhoff, Segev BenZvi, and Michael Prouza, all of Columbia University for their help during this project. I would also like to thank the National Science Foundation for their support of the Research Experience for Undergraduates program.

References

[1] S.Y. BenZvi et al., Astroparticle Physics, in press (2007).

[2] S.Y. BenZvi et al. (for the Pierre Auger Collaboration), Measurement of Aerosols at the Pierre Auger Observatory, in Proc. 30^{th} Int. Cosmic Ray Conference, Mérida, México (2007).

[3] S.Y. BenZvi et al., Nucl. Instr. Meth. A 574 (2007) 171.

[4] R. Abbasi et al. Astroparticle Phys. 25 (2006) 74.

[5] B. Fick et al., Journal of Instrumentation 1 (2006) P11003.

[6] M. Prouza (for the Pierre Auger Collaboration). Systematic study of atmosphere-induced influences and uncertainties on shower reconstruction at the Pierre Auger Observatory, in Proc. 30^{th} Int. Cosmic Ray Conference, Mérida, México (2007).