Systematic study of atmosphere-induced influences and uncertainties on shower reconstruction at the Pierre Auger Observatory

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Abstract: A wide range of atmospheric monitoring instruments is employed at the Pierre Auger Observatory : two laser facilities, elastic lidar stations, aerosol phase function monitors, a horizontal attenuation monitor, star monitors, weather stations, and balloon soundings. We describe the impact of analyzed atmospheric data on the accuracy of shower reconstructions, and in particular study the effect of the data on the shower energy and the depth of shower maximum ($X_{\rm max}$). These effects have been studied using the subset of "golden hybrid" events — events observed with high quality in the fluorescence and surface detector — used in the calibration of the surface detector energy spectrum.

Introduction

The Pierre Auger Observatory in Malargüe, Argentina is a hybrid facility that uses its atmospheric fluorescence detector (FD) to obtain calorimetric estimates of shower energies. The atmosphere acts both as a calorimeter and a scintillator. It affects the fluorescence yield of showers and attenuates light between showers and the FD. The atmosphere over the observatory is also dynamic. Therefore, the state of the atmosphere must be continuously monitored to ensure reliable energy estimates.

To an excellent approximation, the molecular and aerosol scattering processes that contribute to the overall attenuation and scattering of light in the atmosphere can be treated separately. In Malargüe, the molecular component is determined by regular measurements of several macroscopic parameters, including altitude profiles of air temperature, pressure, and density. It has been shown that daily variations in these parameters have a small impact on shower energy estimates ($\Delta E/E < 1\%$) and the depth of shower maximum ($\Delta X_{\rm max} \simeq 6$ g cm^{-2}); hence, the observations have been incorporated into monthly models for use in the FD reconstruction [1]. A more important factor is the effect of humidity on the fluorescence yield, because the yield provides a scaling factor for the energy. Preliminary estimates suggest a $5-10\%$ effect on the fluorescence yield near the ground, and $< 3\%$ at 4 km above sea level [2]. This effect has been incorporated into the reported uncertainty of the fluorescence yield [8]. Aerosols, unlike the molecular component of the atmosphere, are much more variable, and can change significantly in the course of a few hours. Therefore, aerosols are systematically measured at all FD sites, and the parameters most important for the FD reconstruction are recorded hourly. The aerosol data and the facilities used to collect them are described in detail elsewhere [3]. In this paper, we discuss the effect of aerosol measurements on energy and $X_{\rm max}$ for an important subset of observed showers.

Aerosol Measurements

The presence of aerosols does not influence the air fluorescence yield, so their primary effect on the shower reconstruction comes from their role in light attenuation and scattering. Fluorescence light is emitted isotropically, so a detector with a field of view $\Delta\Omega$ observing shower light of intensity I_0 will observe a light level

$$I = I_0 \cdot T_m \cdot T_a \cdot (1 + H.O.) \cdot \frac{\Delta\Omega}{4\pi} \qquad (1)$$

In this expression, T_m is the transmission factor due to molecular scattering; T_a is the transmission due to aerosol scattering; and $H.O.$ is a higher-order correction that accounts for the single and multiple scattering of photons into (or out of) the detector field of view. Ignoring multiple scattering effects, T_a and $H.O.$ may be fully characterized using three independent measurements: the height profile of the vertical aerosol optical depth (VAOD) $\tau(h)$; the wavelength dependence of the VAOD; and the normalized aerosol differential scattering cross-section, or phase function, $P(\theta)$.

The VAOD primarily affects light attenuation. It is defined for each height above the ground level, so that aerosol transmission $T_a(h)$ between the ground and height h is

$$T_a(h) = e^{-\tau(h)}. \tag{2}$$

The height profile $\tau(h)$ is measured independently by three elastic backscatter lidar stations and FD-reconstructed laser tracks provided by the Central Laser Facility (CLF) [3, 4, 5]. With a typical measurement uncertainty of ± 0.01, the CLF measurements are currently used for shower reconstructions. However, both the lidars and the CLF use monochromatic light sources, so the wavelength dependence of the VAOD is measured by two other independent instruments: the Horizontal Attenuation Monitor (HAM) and the robotic astronomical telescope FRAM [6, 7]. This wavelength dependence can be parametrized in terms of the so-called Angstrom exponent γ:

$$\tau(\lambda) = \tau_0 \cdot \left(\frac{\lambda_0}{\lambda}\right)^{\gamma}, \tag{3}$$

where τ_0 is measured at a reference wavelength $\lambda_0 = 355$ nm. Observations made between June and December 2006 indicate a typical value $\gamma = 0.7 \pm 0.5$ for the observatory location.

Finally, aerosols not only attenuate light from air showers, but also scatter Cherenkov light into the FD field of view, contaminating the fluorescence signal. The angular distribution of aerosol-scattered light is given by the aerosol phase function, which we model using two free parameters (see [3]). The parameter f is sensitive to the relative strength of forward and backward scattering and g, the mean cosine of the scattering angle, is the measure of the asymmetry of scattering. Aerosol Phase Function monitors (APFs) perform hourly measurements of these aerosol scattering properties at two FD locations [3].

Analysis

The showers of greatest importance to Auger are those measured with high quality in both the FD and the surface detector (SD), because these are used to set the energy scale of the overall detector. For the analysis presented here, the set of events passing strong quality cuts presented in [8, 9] are used to determine the effect of aerosol measurements on energy and $X_{\max}$ estimated by the FD reconstruction. Only cloud-free measurements, identified by a strict quality cut on the FD longitudinal profile, were used in this study.

Several different studies are of interest:

1. The use of aerosols in the reconstruction, compared to the use of a pure molecular atmosphere.

2. The propagation of measurement uncertainties in VAOD, γ, f, and g in the FD reconstruction, and in particular their effect on energy and $X_{\max}$.

3. A test of the assumption of atmospheric horizontal uniformity used in the FD reconstruction.

(1) Effects of the Presence of Aerosols on Air Shower Detection

We have compared the reconstruction of showers using real-time aerosol measurements with the same events reconstructed using a purely molecu-

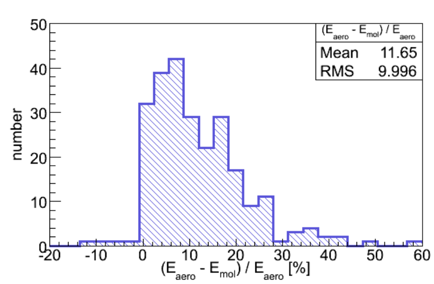

Figure 1: Energy difference for events reconstructed with measured aerosol parameters (E_{aero}) and with assumption of no aerosols (molecular atmosphere; E_{mol}).

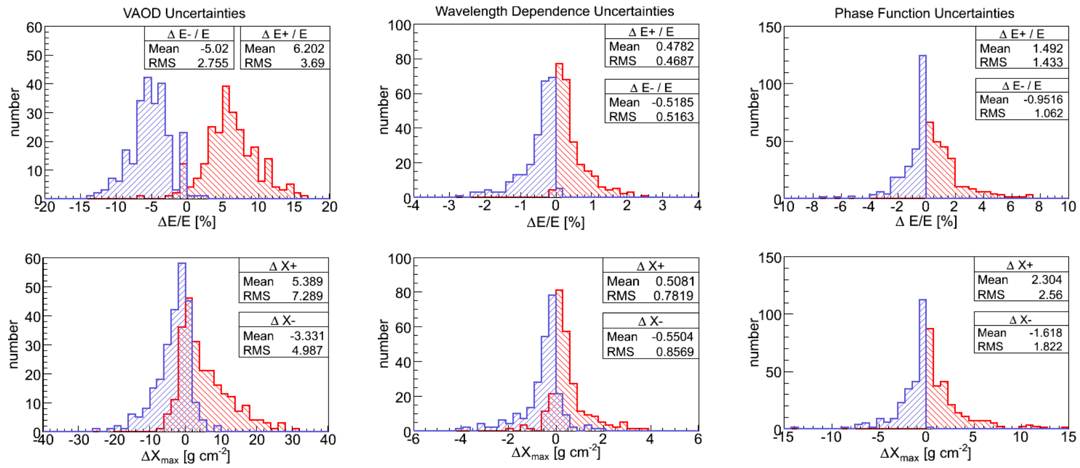

Figure 2: Spread in E and $X_{\rm max}$ due to statistical fluctuations in aerosol measurements. ΔE_+ and ΔX_+ are calculated using the +1 σ uncertainty (on aerosol measurement), ΔE_- and ΔX_- using the $-1\,\sigma$ uncertainty.

lar atmosphere. As shown in Figure 1, neglecting the presence of aerosols causes, on average, a 12% underestimate in shower energies. Moreover, the long tail in the distribution indicates the enormous effect of aerosol attenuation on the reconstruction of a significant fraction of all showers: 15% of the showers have an energy correction greater than 25%; 6.5% of events more than 30%; and 3% more than 40%. Especially for the highest energy events, where the statistics are poor, real-time atmospheric calibration is essential.

Having established the significant influence of aerosols on the reconstruction, we can also ask if simple parametric models of the aerosol content are sufficiently accurate. For example, a two-parameter exponential aerosol density profile, characterizing conditions at the site, has been considered. Preliminary studies indicate that this parameterization leads to a 4% overestimate in shower energies (with a large spread of 10%) compared to reconstructions performed with true aerosol measurements.

(2) Uncertainties Introduced by Aerosol Measurements

We have propagated the measurement uncertainties in the VAOD, phase function, and wavelength dependence in the hybrid reconstruction. Figure 2 depicts the contribution of each measurement to the uncertainty in energy and shower maximum. The VAOD provides the dominant contribution to the shower uncertainties: 5.5% for the statistical uncertainty in energy and 4 g cm^{-2} for $X_{\rm max}$. The wavelength dependence and the phase function are significantly less important, contributing 1% and 1.3%, respectively, to the uncertainty of the energy, and $\sim$ 2 g cm^{-2} to the uncertainty in $X_{\rm max}$.

(3) Evaluation of the Horizontal Uniformity of the Atmosphere

The atmospheric measurements at the Auger Observatory, while extensive, are only able to observe conditions at several locations across the site. Therefore, during the reconstruction of events one must assume that these limited measurements characterize broad regions of the atmosphere around each FD, or in other words, that the atmosphere exhibits a large degree of horizontal uniformity.

The assumption of horizontal uniformity and its effect on the reconstruction can be tested for both the molecular and aerosol components of the atmosphere. Molecular conditions are observed by balloon flights and two ground-based weather stations located at Los Leones and the Central Laser Facility. Figure 3 indicates differences in the weather conditions observed at these sites, and the corresponding effect of these differences on shower reconstructions is $< 1\%$ for the shower energy and ~ 1 g cm^{-2} for $X_{\rm max}$.

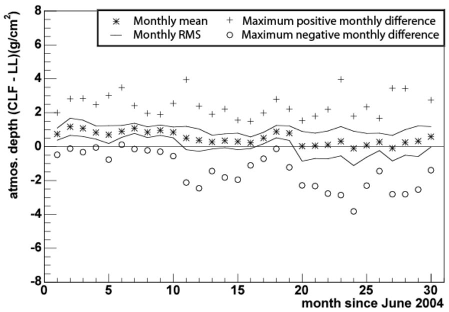

Figure 3: Comparison of monthly atmospheric depth measurements at two sites separated by ∼30 km.

For the aerosol component of the atmosphere, it is possible to estimate the effect of horizontal nonuniformities by reconstructing showers using different sets of aerosol measurements. For this study, we have reconstructed a set of high quality air showers observed by the Coihueco FD using CLF VAOD profiles measured concurrently at Coihueco and Los Leones (the distance between these two FD sites is about 40 km). As shown in Figure 4, the systematic uncertainty on shower energies introduced by the assumption of uniformity is $\sim 2.5\%$, with measurement fluctuations contributing $\sim 7\%$ to the statistical uncertainty. The shower maximum $X_{\max}$ is also shifted by ~ 2.5 g cm^{-2}, with typical statistical uncertainties of ~ 9 g cm^{-2}.

Discussion

The following table summarizes atmosphere-induced uncertainties in the hybrid reconstruction:

Effect	Δ E / E	Δ X_{max}
Molecular:		
Horizontal uniformity	<1 %	1 g cm^{-2}
Variations in air density profile	1 %	6 g cm^{-2}
Aerosols:		
Horizontal uniformity [systematic]	2.5 %	2.5 g cm^{-2}
Horizontal uniformity [statistical]	7 %	9 g cm^{-2}
Vertical Aerosol Optical Depth	5.5 %	4 g cm^{-2}
Wavelength Dependence	1 %	1 g cm^{-2}
Differential Scattering Cross-section	1.3 %	2 g cm^{-2}

Table 1: Summary of atmosphere-induced uncertainties for the set of calibration events

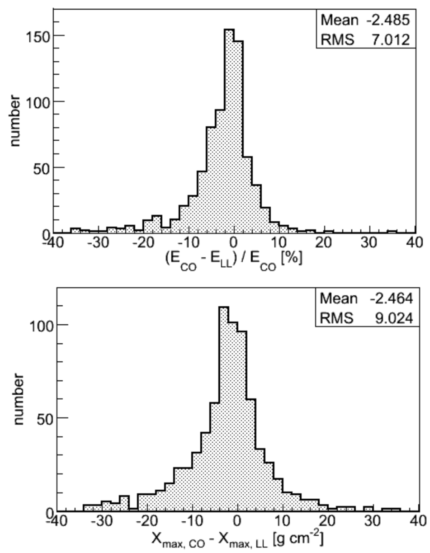

Figure 4: Comparison of energy difference (top) and of shift in position of shower maximum (bottom) due to the use of non-local aerosol atmospheric parameters.

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