Atmospheric Monitoring and its Use in Air Shower Analysis at the Pierre Auger Observatory

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***Abstract*. For the analysis of air showers measured using the air fluorescence technique, it is essential to understand the behaviour of the atmosphere. At the Pierre Auger Observatory, the atmospheric properties that affect the production of UV light in air showers and the transmission of the light to the fluorescence telescopes are monitored regularly. These properties include the temperature, pressure, and humidity as a function of altitude; the optical depth and scattering behaviour of aerosols; and the presence of clouds in the field of view of the telescopes. The atmospheric measurements made at the observatory describe a detector volume in excess of 30,000 cubic km. Since 2004, the data have been compiled in a record of nightly conditions, and this record is vital to the analysis of events observed by the fluorescence telescopes. We will review the atmospheric monitoring techniques used at the observatory and discuss the influence of atmospheric measurements on estimates of shower observables using real and simulated data.**

***Keywords*: ultra high-energy cosmic rays, air fluorescence technique, atmospheric monitoring**

I. Introduction

The Pierre Auger Observatory comprises two cosmic ray extensive air shower detectors: a Surface Detector Array (SD) of 1600 water Cherenkov detectors, and a Fluorescence Detector (FD) of 24 telescopes at four sites overlooking the array. Observations carried out with the FD yield nearly calorimetric measurements of the energy of each primary cosmic ray. The FD telescopes are also used to observe the slant depth of shower maximum (X_{max}), which is sensitive to the mass composition of cosmic rays. Simultaneous shower measurements with the SD and FD (hybrid events) provide high-quality data used in physics analysis and in the calibration of the SD energy scale.

The crucial roles of hybrid calibration and shower measurement performed by the FD depend on detailed knowledge of atmospheric conditions. Light from extensive air showers is produced in the atmosphere, and it is transmitted through the air to the observing telescopes. The production of fluorescence and Cherenkov photons in a shower depends on the temperature, pressure, and humidity of the air. Moreover, as the light travels from the shower axis to the fluorescence telescopes, it is scattered from its path by molecules and aerosols. Therefore, atmospheric conditions have a major impact on shower energies and shower maxima estimated using the fluorescence technique.

To characterise the behaviour of the atmosphere at the Pierre Auger Observatory, extensive atmospheric monitoring is performed during and between FD shifts. Fig. 1 depicts the instruments used in the monitoring program. Atmospheric state variables such as pressure, temperature, and humidity are recorded using meteorological radio soundings launched from a helium balloon station [1], and conditions at ground level are recorded by five weather stations. Aerosol conditions are measured using central lasers, lidars, and cloud cameras [2], [3], [4], as well as optical telescopes and phase function monitors [5], [6]. The atmospheric data have been incorporated into a multi-gigabyte database used for the reconstruction and analysis of hybrid events. We describe the use of these data in estimates of shower light production (Section II) and atmospheric transmission (Section III), and in Section IV we summarise systematic uncertainties in the hybrid reconstruction.

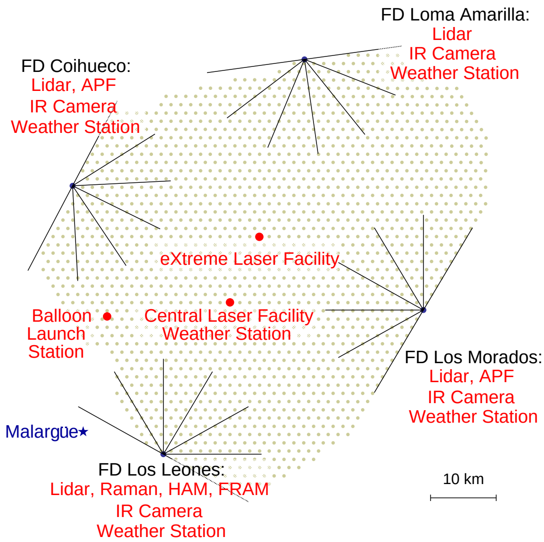

Fig. 1: Atmospheric monitors at the Pierre Auger Observatory include two central lasers, four elastic lidar stations, one Raman lidar, four IR cameras, five weather stations, a balloon launch facility, two aerosol phase function (APF) monitors, and two optical telescopes (HAM, FRAM).

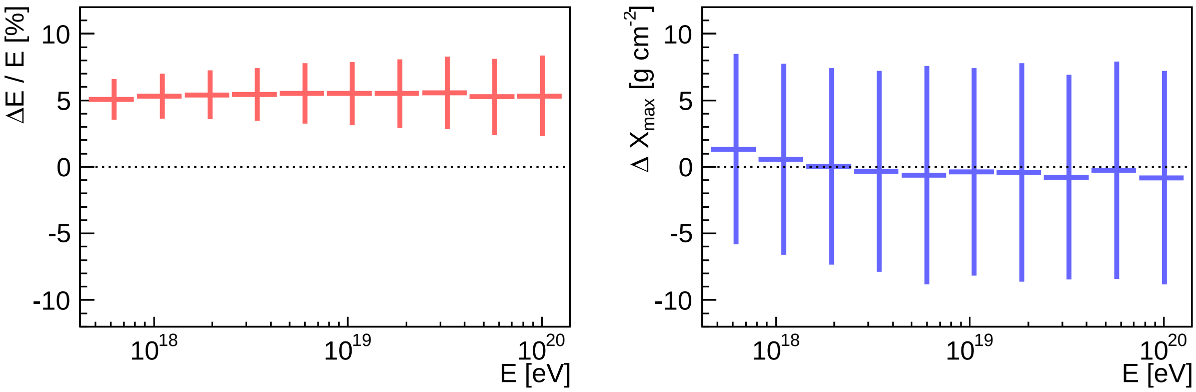

Fig. 2: Combined effects of collisional quenching and atmospheric variability. *Left:* Comparison of reconstructed energies of simulated showers using fluorescence models from AIRFLY [7] and Keilhauer et al. [8]. The uncertainties refer to RMS variations. The AIRFLY model was applied using monthly averages for p and T, constant collisional cross sections, and no water vapour quenching; the Keilhauer model was applied using balloon data, T-dependent collisional cross sections, and water vapour quenching. *Right:* Comparison of X_{max} using the two models.

II. Ultraviolet Light Production

Cherenkov and fluorescence production at a given wavelength λ depend on the pressure p, temperature T, and vapour pressure e of the air. The Cherenkov light yield can be determined from the index of refraction of air, but the weather-dependence of the fluorescence yield is considerably more difficult to calculate. This is due to quenching of the radiative transitions of excited N_2 by collisions between N_2 molecules, collisions between N_2 and O_2, and collisions between N_2 and water vapour. The collisional cross sections depend on temperature and must be determined experimentally [7], [9]. Estimates of these effects in the field are further complicated by significant daily and seasonal variability in the concentration of water vapour.

In Malargüe, the altitude dependence of air pressure, temperature, and relative humidity are measured up to about 23 km above sea level using balloon-borne radio soundings. Balloon launches are performed roughly every five days, and as of this writing there have been 287 successful launches since 2003. Due to the limited measurement statistics, the balloon data were used to create monthly models of atmospheric state variables for use in shower analysis. The models, first introduced in 2005, have recently been updated to include more radiosonde data and humidity profiles [1].

The use of monthly models in the reconstruction provides a significant reduction in systematic uncertainties with respect to the use of a global, static atmospheric model. For example, reconstructing air showers with the 1976 U.S. Standard Atmosphere rather than local monthly models shifts X_{max} by 15 g cm^{-2}, on average [10]. When the monthly models are used, a small systematic uncertainty remains due to the daily variability of the atmosphere. We estimate the size of the effect using simulated proton and iron showers between $10^{17.7}$ and 10^{20} eV. The showers were reconstructed with monthly average profiles and compared to a reconstruction using 109 cloud-free radio soundings. We find that the monthly models introduce minor systematic shifts into the reconstructed energy ($\Delta E/E = -0.5\%$) and shower maximum ($\Delta X_{\text{max}} = 2$ g cm^{-2}).

More significant systematic shifts are caused by the collisional cross sections $\sigma_{\text{NN}}(T)$ and $\sigma_{\text{NO}}(T)$ and the water vapour cross section $\sigma(e)$. We have calculated the effect using simulated showers with UV light generated according to fluorescence models published by AIRFLY [7] and Keilhauer et al. [8]. The addition of T-dependent collisional cross sections and water vapour quenching systematically increases the energy by 5.5% and decreases X_{max} by 2 g cm^{-2}, partially offsetting the uncertainties due to atmospheric variability. The combined effects of quenching and variability are shown in Fig. 2. The uncertainties RMS($\Delta E/E$)= $1.5\%-3.0\%$ and RMS(ΔX_{max})= $7.2 - 8.4$ g cm^{-2}, which increase in the energy range $10^{17.7} - 10^{20}$ eV, are caused by the variability of atmospheric conditions.

III. Ultraviolet Transmission

When the light from an air shower travels to an FD telescope, it is absorbed and scattered by molecules and aerosols. The attenuation of light is given by the optical transmittance $\mathcal{T}$. In a horizontally uniform atmosphere, the transmittance from an altitude h to the ground through a slanted path of elevation φ is

$$\mathcal{T}(h, \lambda, \varphi) = e^{-\tau(h,\lambda)/\sin\varphi} \cdot (1 + H.O.), \tag{1}$$

where the exponential term is the Beer-Lambert law, $\tau(\lambda, h)$ is the total vertical optical depth between the ground and altitude h, and $H.O.$ is a higher-order single and multiple scattering correction. The total optical depth is simply the sum of the molecular and aerosol optical depths, which must be either estimated or measured.

A. Molecular Attenuation

In the lower atmosphere, the attenuation of near-UV light by molecules is predominantly due to scattering. Hence, the vertical molecular optical depth between the ground and altitude h can be calculated from

$$\tau_m(\lambda, h) = \int_{h_{\text{gnd}}}^{h} N(h')\ \sigma_R(\lambda, h')\ dh', \qquad (2)$$

where N is the number density of scatterers and σ_R is the Rayleigh scattering cross section [11]. The altitude profiles of pressure, temperature, and vapour pressure can be used to calculate $N(h)$ and $\sigma_R(\lambda, h)$; hence, data from radio soundings or monthly average profiles completely describe molecular scattering. Transmission uncertainties due to the use of monthly models are included in the values reported in Section II.

B. Aerosol Attenuation

Aerosol attenuation does not have a general analytical solution, and so knowledge of aerosol transmission requires direct field measurements of the aerosol optical depth. To estimate the transmission, we assume the form

$$\tau_a(\lambda, h) = \tau_a(\lambda_0, h) \cdot (\lambda_0/\lambda)^{\gamma}, \qquad (3)$$

where $\tau_a(\lambda_0, h)$ is the vertical aerosol optical depth profile recorded at a single wavelength λ_0, and the wavelength dependence of $\tau_a(\lambda, h)$ is parameterised by the exponent γ [6], [12]. Hourly measurements of the vertical aerosol optical depth profile are carried out using two central lasers [2] ($\lambda_0 = 355$ nm) and four lidar stations [3] ($\lambda_0 = 351$ nm). As shown in Table I, more than 13 000 site-hours of aerosol data have been collected since 2004 using the Central Laser Facility. The data are required inputs to the hybrid physics analysis, and roughly 80% of hybrid events can be reconstructed using aerosol measurements.

We have propagated the measurement uncertainties in the hourly aerosol data into the reconstruction of real hybrid events observed since 2004. Over the energy range $10^{17.7} - 10^{20}$ eV, the average systematic uncertainties in energy increase from $\Delta E/E = ^{+3.6}_{-3.0}\%$ to $^{+7.9}_{-7.0}\%$, and the uncertainties in X_{max} increase from $\Delta X_{\text{max}} = ^{+3.3}_{-1.3}$ g cm^{-2} to $^{+7.3}_{-4.8}$ g cm^{-2}. For the RMS, we make the preliminary estimates RMS($\Delta E/E$)=$1.6(1 \pm 1)\%$ to $2.5(1 \pm 1)\%$ and RMS(ΔX_{max})=$3.0(1 \pm 1)$ g cm^{-2} to $4.7(1 \pm 1)$ g cm^{-2}. The uncertainties are dominated by the aerosol optical depth, with minor contributions from the exponent γ and the aerosol phase function. The use of hourly aerosol data offers a significant improvement over a static aerosol model, which if used would increase the systematic uncertainties by a factor of two.

Small horizontal nonuniformities in the vertical aerosol distribution also introduce energy-dependent uncertainties into the reconstruction. The contribution to the average uncertainties is negligible, but over the same energy range, we estimate the effect of the uniformity to be RMS($\Delta E/E$)= $3.6\% - 7.4\%$ and RMS(ΔX_{max})= $5.7 - 7.6$ g cm^{-2}.

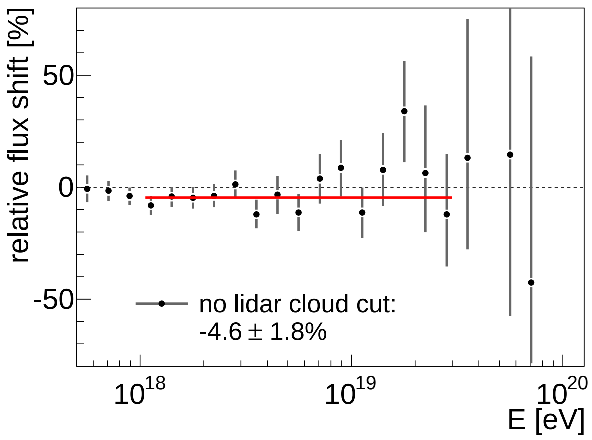

Fig. 3: Relative shift in the flux of events detected in hybrid mode when the lidar cloud coverage cut is not applied. The shift between 10^{18} and $10^{19.5}$ eV is indicated by a solid line.

C. Multiple Scattering Corrections

While molecular and aerosol scattering primarily attenuate shower light as it propagates to an FD telescope, it will also increase the detected signal by scattering photons into the telescope. This causes a systematic overestimate of the shower signal, particularly at low altitudes where the density of scatterers is greatest.

Several Monte Carlo studies have been carried out to parameterise the multiply-scattered component of shower light as a function of optical depth [13], [14]. Using real hybrid events, we have found that a failure to account for multiple scattering will cause overestimates of $2\% - 5\%$ in shower energies and $1 - 3$ g cm^{-2} in X_{max}, where the overestimates increase with energy. Once multiple scattering is included in the reconstruction, the systematic differences between various multiple scattering parameterisations are $\Delta E/E < 1\%$ and $\Delta X_{\text{max}} \approx 1$ g cm^{-2} for all energies.

D. Attenuation by Clouds

Clouds strongly attenuate UV light, and therefore have a major influence on FD measurements. By blocking the line of sight to high altitudes, cloud layers can bias a fluorescence telescope toward the detection of deep showers and alter the effective aperture of the FD. To monitor clouds and correct for these effects, cloud layers are tracked using the elastic lidar stations and four IR cloud cameras [3], [4]. Data from these instruments are stored in an hourly database of cloud height and coverage above each FD site, up to an altitude of 12 km.

The lidar cloud database has been used to analyse the cloud conditions in Malargüe [3], and the data indicate clear conditions during 50% of measured hours, and $< 25\%$ coverage in 60% of measured hours. The remaining hours are affected by moderate to heavy cloud coverage; $> 80\%$ sky coverage occurs in 20% of the lidar measurements.

TABLE I: Statistics of hourly cloud and aerosol measurements collected at the Pierre Auger Observatory and analysed as of this writing.

Aerosol and Cloud Measurements at the Pierre Auger Observatory (2004–2009)			
Location:	Los Leones	Los Morados	Coihueco
Aerosols (CLF):	4943 hours 15 Jan 2004 – 5 Mar 2009	3760 hours 18 Mar 2005 – 5 Mar 2009	4695 hours 16 Jun 2004 – 5 Mar 2009
Clouds (Lidar):	3784 hours 4 Apr 2006 – 4 Feb 2009	3308 hours 1 Jul 2006 – 4 Feb 2009	4461 hours 1 Nov 2005 – 4 Feb 2009
Clouds (IR Cameras):	4432 hours to May 2008	2681 hours to Jan 2008	4420 hours to Aug 2008

TABLE II: Systematic uncertainties in the hybrid reconstruction due to atmospheric influences on light production and transmission.

Systematic Uncertainties					
Source	$\log(E/\mathrm{eV})$	$\Delta E/E$ (%)	RMS($\Delta E/E$) (%)	ΔX_{max} (g cm^{-2})	RMS(ΔX_{max}) (g cm^{-2})
Molecular Light Transmission and Production					
Horiz. Uniformity	$17.7-20.0$	1	1	1	2
Quenching Effects p, T, e Variability	$17.7-20.0$	+5.5 -0.5	$1.5-3.0$	-2.0 +2.0	$7.2-8.4$
Aerosol Light Transmission					
$\tau_a(\lambda_0, h)$	<18.0 $18.0-19.0$ $19.0-20.0$	$+3.6, -3.0$ $+5.1, -4.4$ $+7.9, -7.0$	1.6 ± 1.6 1.8 ± 1.8 2.5 ± 2.5	$+3.3, -1.3$ $+4.9, -2.8$ $+7.3, -4.8$	3.0 ± 3.0 3.7 ± 3.7 4.7 ± 4.7
γ Exponent	$17.7-20.0$	0.5	2.0	0.5	2.0
Phase Function	$17.7-20.0$	1.0	2.0	2.0	2.5
Horiz. Uniformity	<18.0 $18.0-19.0$ $19.0-20.0$	0.3 0.4 0.2	3.6 5.4 7.4	0.1 0.1 0.4	5.7 7.0 7.6
Scattering Corrections					
Mult. Scattering	<18.0 $18.0-19.0$ $19.0-20.0$	0.4 0.5 1.0	0.6 0.7 0.8	1.0 1.0 1.2	0.8 0.9 1.1

The number of hybrid events affected by cloud obscuration is reduced with strong cuts on the shape of reconstructed shower profiles. Showers must also be reconstructed with an hourly aerosol profile from the Central Laser Facility, weighting the data toward periods with relatively unobstructed views to the center of the SD. For the surviving events, a cut of $<25\%$ lidar cloud coverage has been applied and compared to the dataset with no lidar cuts (Fig. 3). Over the energy range 10^{18} to $10^{19.5}$ eV, a 4% reduction is observed in the flux if no cloud cut is applied. Clouds also increase measurements of $\langle X_{\mathrm{max}}\rangle$ by blocking the upper part of the FD fiducial volume; without the lidar cloud cut, we find a systematic increase in $\langle X_{\mathrm{max}}\rangle$ of 3 g cm^{-2} at all energies.

IV. SUMMARY OF SYSTEMATIC UNCERTAINTIES

The Pierre Auger Observatory has accumulated a large database of atmospheric measurements relevant to the production of light in air showers and the transmission of the light to fluorescence telescopes. We have propagated the uncertainties of the atmospheric data into the reconstruction, and estimated the size of effects such as collisional quenching and multiple scattering. The systematic uncertainties are summarised in Table II.

Aside from large "quenching effects" on the fluorescence yield, the uncertainties are dominated by the variability of the molecular atmosphere and the uniformity and uncertainties of the aerosol optical depth. The combined uncertainties are, approximately, $\Delta E/E \approx 4\%-8\%$, RMS($\Delta E/E$)$\approx 5\pm1\%$ to $9\pm1\%$, $\Delta X_{\mathrm{max}} \approx 4-8$ g cm^{-2}, and RMS(ΔX_{max})$\approx 11\pm1$ g cm^{-2} to 13 ± 1 g cm^{-2}. The atmospheric data provide a significant improvement over static weather models, reducing the systematic uncertainties by approximately a factor of two.

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