Measuring Atmospheric Aerosol Attenuation at the Pierre Auger Observatory

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Abstract: The Fluorescence Detector (FD) of the Pierre Auger Observatory provides a nearly calorimetric measurement of the primary particle energy, since the fluorescence light produced is proportional to the energy dissipated by an Extensive Air Shower (EAS) in the atmosphere. For this reason, the FD is used to calibrate the absolute energy scale of the Surface Detector (SD) by means of hybrid events. Of the major correction terms applied to the FD, atmospheric transmission through aerosols has the largest time variation. The corresponding correction to an EAS energy can range from a few percent to more than 40%, depending on the aerosol attenuation conditions, the distance of the shower, and the energy. We report on 9 years of hourly aerosol optical depth profile measurements, including revised statistical and systematic error estimates, that are propagated through EAS reconstruction. To accumulate these hourly aerosol optical depth profiles, the Central Laser Facility (CLF) and the eXtreme Laser Facility (XLF) of the Auger Observatory generated more than 4 million laser tracks that were recorded by the FD telescopes. Finally we describe major upgrades in progress to the CLF and to the elastic LIDAR stations at the Pierre Auger Observatory. The main features of these complementary upgrades are discussed together with the expected results of their applications.

Keywords: ultra-high energy cosmic rays, aerosol attenuation, laser facilities, lidars

1 Atmospheric Aerosol Attenuation

Ultra High Energy particles entering the atmosphere produce a cascade of secondary particles, the Extensive Air Shower (EAS). During the development of an EAS, fluorescence light in the range 300–420 nm is emitted isotropically by excited air molecules. The Pierre Auger Observatory combines two well-established techniques to detect EAS, the detection of secondary particles at the ground (Surface Detector, SD) and the detection of fluorescence light emitted in the atmosphere (Fluorescence Detector, FD)[1]. The FD is composed of 24 telescopes positioned at 4 sites[1] overlooking the 1660 stations composing the SD covering an area of 3000 km^2. The FD provides a direct estimate of the energy of the primary particle without the need for simulations, therefore FD data are used to calibrate the absolute energy scale of the SD by means of hybrid events.

The direct measurement of the energy is possible since the amount of fluorescence light produced during the development of an EAS is proportional to the energy dissipated in the atmosphere by the EAS. The atmosphere is therefore comparable to a giant calorimeter, whose properties must be continuously monitored to ensure a reliable energy estimate. Atmospheric parameters influence both the production of fluorescence light and its attenuation to the FD telescopes. The molecular and aerosol scattering processes that contribute to the overall attenuation of light in the atmosphere can be treated separately. The molecular scattering is calculated once temperature, pressure and humidity are known from balloon and weather station measurements or model data[2]. The aerosol attenuation of light is the largest time dependent correction applied during air shower reconstruction, as aerosols are subject to significant variations on time scales as little as one hour. If the aerosol attenuation is not taken into account, the shower energy reconstruction is biased by 8 to 25% in the energy range measured by the Pierre Auger Observatory. On average, 20% of all showers have an energy correction larger than 20%, 7% of showers are corrected by more than 30% and 3% of showers are corrected by more than 40% [3]. Hourly vertical aerosol optical depth profiles are produced for each FD site for a correct reconstruction of FD events. 9 years of aerosol attenuation profiles, from January 2004 to December 2012, have been measured.

2 Laser Facilities

The Pierre Auger Observatory has a huge atmospheric monitoring system. Two laser facilities, the Central Laser Facility (CLF) and the eXtreme Laser Facility (XLF), both positioned nearly equidistant from three out of four of the FD sites (see figure 1), have been in operation for many years and provide vertical and inclined calibrated test beams. Sets of 50 vertical shots are produced every 15 minutes during FD data acquisition. The CLF [4], built in late 2003, operational since January 2004, is located at an altitude of 1416 m above sea level. The XLF was installed north of the CLF during 2008, closer to Loma Amarilla, at an altitude of 1397 m and has been producing stable laser shots since January 2010. Each facility uses a pulsed frequency tripled Nd:YAG laser (355 nm), whose wavelength is near the center of the spectrum of the fluorescence light, firing with an average energy of 6.5 mJ. A depolarizer is used to randomly polarize the laser light, to simulate the isotropic emission of the fluorescence light. CLF and XLF events are recorded by the FD telescopes and a specific GPS timing is used to distinguish laser from

1. in addition to the four FD sites, 3 high elevation telescopes (H.E.A.T.) are operating at a fifth site close to Coihueco

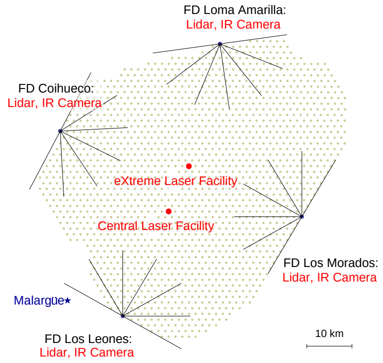

Figure 1: Map of the Pierre Auger Observatory. Some of the atmospheric monitoring devices are shown. The CLF and XLF are marked. The solid lines indicate the field of view of individual fluorescence telescopes.

EAS events. The amount of light scattered out of a 6.5 mJ laser beam by the atmosphere is roughly equivalent to the amount of fluorescence light produced by an EAS of 5×10^{19} eV at a distance to the telescope of about 16 km, as shown in figure 2.

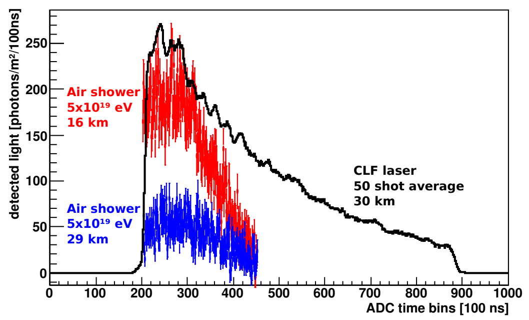

Figure 2: Comparison between a 50 shot average of vertical 6.5 mJ UV laser shots from the CLF and near-vertical cosmic ray showers measured with the FD. The cosmic ray profile has been flipped in time.

The laser energy of the CLF is monitored by a pyroelectric probe receiving a fraction of the laser beam for a relative calibration of each laser shot. Additionally, absolute calibrations are performed periodically, capturing the entire laser beam with an external radiometer before sending the laser light to the sky. The periodic absolute calibration permits to correct the sky energy for the effects related to dust accumulation on some of the optics of the laser bench. The XLF is equipped with a combined system of a pick-off probe for relative calibration, together with an automated calibration system which performs absolute calibrations on a nightly basis using a robotic arm moving a calibration probe in the beam path of the XLF laser.

3 Hourly aerosol optical depth profiles

Laser light is attenuated in the same way as fluorescence light as it propagates towards the FD. Therefore, analysis of the amount of laser light that reaches the FD as a function of time can be used to infer the attenuation due to aerosols between the position of the laser and each FD building. Two independent analyses have been developed to provide hourly aerosol characterization in the FD field of view using vertical laser shots : the Data Normalized Analysis and the Laser Simulation Analysis (more details can be found in [5]).

- The Data Normalized Analysis (DN) is based on the comparison of measured laser profiles with a reference clear night profile in which the light attenuation is dominated by molecular scattering.
- The Laser Simulation Analysis (LS) is based on the comparison of measured laser light profiles to simulations generated in various atmospheres in which the aerosol attenuation is described by a parametric model.

To minimize fluctuations, both analyses make use of average light profiles measured at the aperture of the FD buildings normalized to a fixed reference energy. Using measurements recorded on extremely clear nights where molecular Rayleigh scattering dominates, laser observations can be normalized without the need for absolute photometric calibrations of the FD or laser. These “reference clear nights” are identified using a procedure looking for profiles with maximum photon transmission and maximum compatibility with the shape of a profile simulated in conditions with negligible aerosol attenuation. One reference clear night per year is selected.

The Data Normalized Analysis is an iterative procedure that compares hourly average profiles to reference clear night profiles. The first step is to build the hourly profile, starting from the 4 sets of 50 shots. During this procedure, clouds positioned above the vertical laser beam are identified and the height of the lower layer of the cloud is set. Assuming that the atmosphere is horizontally uniform, the Vertical Aerosol Optical Depth $\tau_{aer}^{DN}(h)$ is measured as

$$\tau_{aer}^{DN}(h) = \frac{\ln N_{mol}(h) - \ln N_{obs}(h)}{1 + \mathrm{cosec}(\theta)}$$

where $N_{mol}(h)$ is the number of photons from the reference clear profile as a function of height, $N_{obs}(h)$ is the number of photons from the observed hourly profile as a function of height and θ is the elevation angle of each laser track segment. This calculation does not take into account the scattering of the laser beam itself due to aerosols. To overcome this, $\tau_{aer}^{DN}(h)$ is differentiated to calculate the aerosol extinction coefficient $\alpha(h)$ over short intervals in which the aerosol scattering conditions change slowly. The final $\tau_{aer}^{DN}(h)$ is estimated by re-integrating $\alpha(h)$ (figure 3). The aerosol attenuation profile is calculated from the FD site altitude up to the cloud lower layer height or the highest point in the FD field of view.

The Laser Simulation Analysis is based on a comparison of light profiles from 50 shots every quarter-hour to simulations generated varying the aerosol attenuation conditions. The aerosol attenuation is described by two parameters, the aerosol horizontal attenuation length L_{aer} and the aerosol scale height H_{aer}. The former describes the light attenuation due to aerosols at ground level, the latter accounts for its dependence on the height. With this parameterization, the expression of the vertical aerosol optical depth $\tau_{aer}^{LS}(h)$ between points at altitude h_1 and h_2 is :

$$\tau_{aer}^{LS}(h_2 - h_1) = -\frac{H_{aer}}{L_{aer}}\left[\exp\left(-\frac{h_2}{H_{aer}}\right) - \exp\left(-\frac{h_1}{H_{aer}}\right)\right]$$

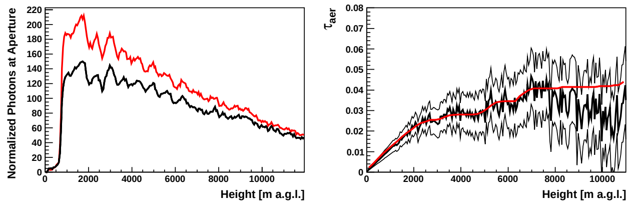

Figure 3: Light profiles (in red the reference clear profile, in black the measured one) and vertical aerosol optical depth measured using the Data Normalized Analysis with the FD at Los Morados during an average night.

A grid of 1540 profiles is simulated for each FD site, each month and at a reference energy, to normalize the measured profiles. Each measured profile is compared to the grid and the simulated profile closest to the measured event is identified and its associated parameters are used to calculate $\tau_{aer}^{LS}(h)$ (figure 4). During the procedure, clouds are identified and the aerosol attenuation profile is measured up to the cloud lower layer height.

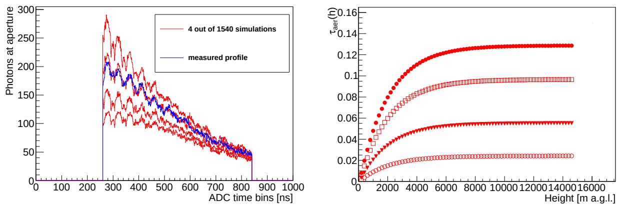

Figure 4: Left : four out of the 1540 simulated profiles of a monthly grid (red), superimposed on a measured profile (blue). Right : the four $\tau_{aer}^{LS}(h)$ profiles corresponding to the simulated CLF profiles.

4 Statistical and systematic error estimates

Various uncertainties were indentified in the methods for the determination of $\tau_{aer}(h)$ profiles. The uncertainties have been recently re-estimated and are now separated into systematic and statistical contributions. These assignments were based on whether the effect of the uncertainty would be correlated over the EAS data sample, or would be largely uncorrelated from one EAS to the next (see table 1). For more discussion see [6]. Since each method is based

	Correlated	Uncorrelated
Relative FD Calibration	2%	4%
Relative Laser Energy (CLF)	1–2.5%	2%
Relative Laser Energy (XLF)	1%	2%
Reference Clear Night	3%	-
Atmospheric Fluctuations	-	$\sim 3\%$

Table 1: List of uncertainties in the determination of the $\tau_{aer}(h)$ profiles (see text).

on the use of ratios of FD events, it is not sensitive to the absolute photometric calibration of either the laser or the FD. Consequently, the calibration correlated uncertainties in table 1 are those that describe how accurately drifts in the FD and laser energy calibrations were tracked over the period between reference nights. These nights are typically a year apart. For the CLF, the 1-2.5% value corresponds to different epochs over the 10 year life of the system and depends on how well the effect of dust accumulation on the optics downstream of the monitor probe was tracked. An estimate of the stability in the net depolarization of the laser beam is included in these numbers. The corresponding term for the XLF (1%) reflects the fact that this system has an automated calibration system that tracks beam energy and polarization. The uncorrelated error of the relative FD calibration was estimated to be 4%. It includes an estimate of the variability in FD calibration during the night. A 3% correlated uncertainty was estimated as due to the choice of the reference clear night. Finally the uncorrelated error due to the atmospheric fluctuations within the hour is estimated on a event-by-event basis and is about 3%. These errors are estimated for each of the two methods described. In the Laser Simulation Analysis a 2% uncorrelated uncertainty is added to take into account how well the parametric model used describes the real aerosol attenuation conditions. A study was performed on hybrid events to estimate the effect on reconstructed EAS energy and Xmax when moving $\tau_{aer}(h)$ up or down by its systematic uncertainty. It was found that the energy varies from +2.4% to -2.5%, and Xmax from 0.8 to -1.2 $g \cdot cm^{-2}$.

5 2004–2012 Aerosol Attenuation Profiles

The hourly aerosol attenuation profiles over 9 years (from January 2004 to December 2012) have been measured using the two analyses described.

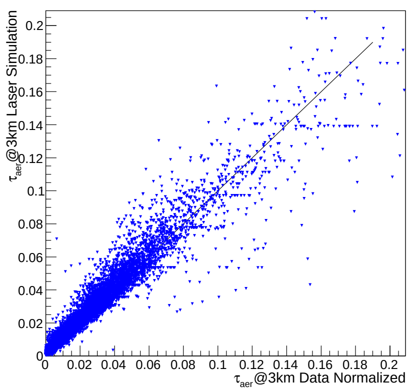

Figure 5: Comparison of Vertical Aerosol Optical Depth at 3 km above ground measured with the two analyses for the Coihueco site. 9 years of data are shown.

Due to the distance, XLF events were used to produce aerosol profiles for Loma Amarilla and CLF events were used for Los Leones, Los Morados and Coihueco. Results from the two analyses were compared and are fully compatible. In figure 5, the correlation of τ_{aer}^{DN} versus τ_{aer}^{LS} measured at 3 km above the ground level is shown for the Coihueco site for the period January 2004 to December 2012. Hourly profiles measured with the two analyses together with correlated and uncorrelated error bands in average aerosol attenuation conditions are shown

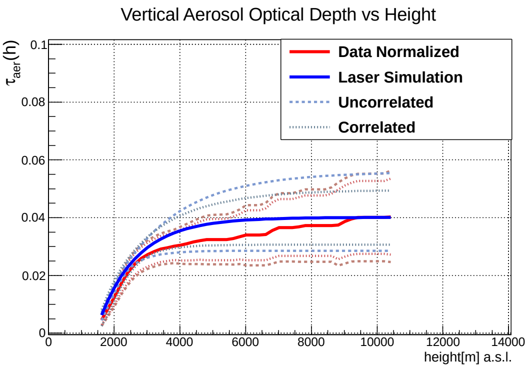

Figure 6: Hourly aerosol profiles measured with the Data Normalized (red) and Laser Simulation (blue) analyses in average conditions. Correlated and uncorrelated uncertainties are shown.

in figure 6. The aerosol profiles measured are stored in the Pierre Auger Observatory Aerosol Database for the reconstruction of EAS data. The database is filled with results obtained with the Data Normalized analysis, while results from Laser Simulation analysis are used to fill gaps. A total of 10430 hours are stored in the aerosol database for the Los Leones site, 9302 for Los Morados, 2270 for Loma Amarilla and 10430 for Coihueco. In figure 7 τ_{aer} measured at 3 km above ground as a function of time is shown for each FD site.

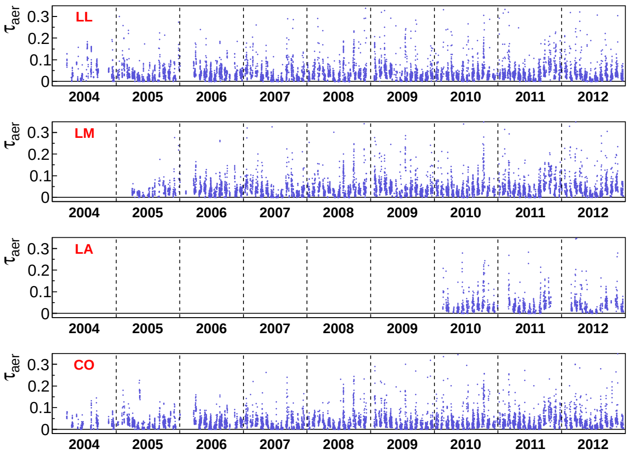

Figure 7: 9 years of τ_{aer} measured at 3km above ground.

6 Upgrades

A major update is in progress at the CLF site. Upgrades include the addition of a Raman LIDAR to the system to perform $\tau_{aer}(h)$ measurements independently of the methods described here, a solid state laser with better shot-to-shot stability, and an automated calibration system similar to the one presently in use at the XLF to improve the laser calibration reliability over long periods. Infrastructure upgrades include a 2000 liter thermal reservoir to reduce temperature fluctuations of the equipment, and a new shipping container shelter with better insulation and dust control. Completion is expected by July 2013.

Figure 8: The new shelter for the upgraded CLF is placed in position at the site.

The atmospheric monitoring system of the Pierre Auger Observatory also includes 4 steerable elastic LIDAR stations[7], one for each FD site. LIDARs provide an independent estimation of the $\tau_{aer}(h)$, but only outside the FOV of the FD due to the high interference with data acquisition, therefore they are used to monitor the cloud cover. A new prototype with improved mechanics and alignment capabilities will be tested at the Loma Amarilla site. The new system has a one-meter-diameter f/1 composite mirror, and the capability of shooting the laser beam coaxially or with a parallax of 1.5 meters. This allows us to extend the sampled atmosphere down to 200 m, and the range up to 40 km. The new LIDAR is expected to provide very precise measurements of the aerosol optical depth. In figure 9, the schema of the full prototype and a picture of the box, the carousel and the mirror are visible. Installation will take place during 2013.

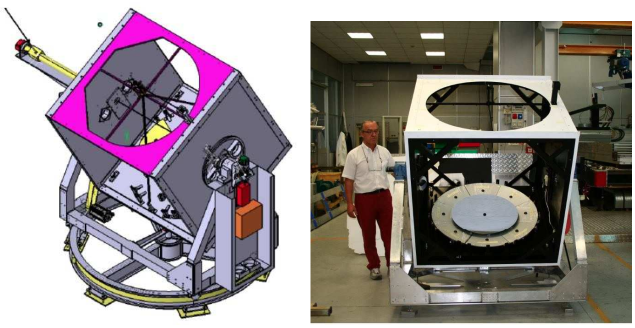

Figure 9: The new prototype of the LIDAR system.

Acknowledgment: The ICRC 2013 is funded by FAPERJ, CNPq, FAPESP, CAPES and IUPAP.

References

[1] The Pierre Auger Collaboration, Nucl. Instr. Meth. **A620** (2010) 227
[2] The Pierre Auger Collaboration, Astropart. P. **35** (2012) 591
[3] The Pierre Auger Collaboration, Astropart. P. **33** (2010) 108
[4] B. Fick et al., JINST **1** (2006) p11003
[5] The Pierre Auger Collaboration, JINST **8** (2013) P04009
[6] V. Verzi, for the Pierre Auger Collaboration, paper 0928, these proceedings
[7] S.Y. BenZvi et al., Nucl. Instr. Meth. **A574** (2007) 171