Atmospheric Aerosol Characterization using the Central Laser Facility at the Pierre Auger Observatory

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Abstract

The Fluorescence Detector of the Pierre Auger Observatory uses the atmosphere as a huge calorimeter that needs continuous monitoring to ensure unbiased physics results. The Central Laser Facility (CLF), a calibrated laser source located near the centre of the Observatory, is used to measure the light attenuation due to aerosols, highly variable even on time scales of one hour. Two independent, fully compatible procedures based on the analysis of CLF vertical events have been developed. Five years of hourly aerosol characterization are provided.

Key words: cosmic rays, aerosols, central laser facility

1. Introduction

Primary cosmic rays at ultrahigh energies (E > 10^{18}eV) cannot be observed directly because of their extremely low flux. The properties of primary particles (energy, mass composition, arrival direction) are deduced from the study of the cascade of secondary particles (EAS) originating from their interaction with air molecules. The Pierre Auger Observatory in Malargüe, Argentina, is a hybrid detector with an array of more than 1600 surface detectors overlooked by 24 fluorescence telescopes grouped in 4 sites positioned at the array periphery. Each site is composed by 6 telescopes with a field of view of $30° \times 30°$. The Fluorescence Detector (FD) is designed to perform a nearly calorimetric measurement of the energy of cosmic ray primaries. Due to the constantly changing properties of the calorimeter (i.e. the atmosphere), in which the light is both produced and through which it is transmitted, a complex system with several instruments has been set up to perform a continuous monitoring of its properties. A map of the Pierre Auger Observatory together with the atmospheric monitoring system is shown in fig. 1. Atmospheric aerosols are highly variable on a time scale of one hour : if not properly taken into account, these dynamic conditions can bias the showers reconstruction. Therefore, continuous measurements of the aerosol parameters of interest are performed : the aerosol extinction coefficient $\alpha(h)$, the vertical aerosol optical depth $\tau_a(h)$, the normalised differential cross section $P(\theta)$ (or phase function), and the wavelength dependence of the aerosol scattering parametrised by the Ångstrom coefficient γ. The phase function and the Ångstrom coefficient are nearly constant in time [1]. The aerosol optical depth $\tau_a(h)$ is highly variable and contributes to the uncertainty in energy from 3.6% at E = $10^{17.5}$ eV to 7.9% at E = 10^{20} eV, and to the uncertainty in Xmax from 3.3 $\text{g} \cdot \text{cm}^{-2}$ to 7.3 $\text{g} \cdot \text{cm}^{-2}$ [2].

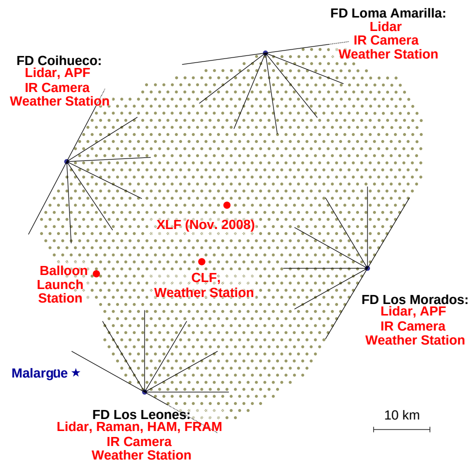

Figure 1: Atmospheric monitoring devices map. In the centre of the array are positioned the Central Laser Facility and the newly built eXtra Laser Facility (November 2008).

2. Atmospheric Attenuation Mechanisms

Light extinction in atmosphere is mainly due to molecular and aerosol scattering: both molecules and aerosols in the atmosphere predominantly scatter, rather than absorb, fluorescence photons. In the following, the term "attenuation" is used to indicate photons that are scattered in such a way that they do not contribute to the light signal recorded by FD. All attenuation processes are usually described in terms of atmospheric transmission coefficients $T^{\lambda}_{mol}(s)$ and $T^{\lambda}_{aer}(s)$, indicating the fraction of transmitted light intensity as a function of the wavelength λ and of the distance to the emission point s . The amount of fluorescence light collected at the FD aperture $I^{\lambda}(s)$ is expressed in terms of the light intensity at the source $I^{\lambda}_0(s)$ as :

$$I^{\lambda}(s) = I^{\lambda}_0(s) T^{\lambda}_{mol}(s) T^{\lambda}_{aer}(s)(1 + f)\frac{d\Omega}{4\pi}$$

where f are higher order corrections due to multiple scatterings and $d\Omega$ is solid angle to the FD.

An estimate of $T^{\lambda}_{mol}(s)$ can be obtained once density, temperature and pressure of the atmosphere are known. Since 2002 these quantities are sistematically measured on site with meteorological radiosondes and ground based weather stations. Data have been parametrized and organized in monthly profiles (Malargüe Monthly Models, [4]) which are employed in the simulation and reconstruction of showers.

The factor $T^{\lambda}_{aer}(s)$ depends on the aerosol distribution in dimension and height, a component with significant variations in a time scale of one hour. A continuous monitoring of the aerosol attenuation is mandatory; as an example, an underestimation of the attenuation of the fluorescence light due to aerosols leads to an underestimation of the primary energy. Assuming an horizontally uniform aerosol distribution, $\mathrm{T}^{\lambda}_{aer}(\mathrm{s})$ can be defined as a function of the aerosol extinction coefficient $\alpha(h)$ from the ground h_0 to a point at altitude h_1 observed at an elevation angle ψ:

$$\mathrm{T}^{\lambda}_{\mathrm{aer}}(\mathrm{s}) = \exp\left(-\int_{\mathrm{h0}}^{\mathrm{h1}} \alpha(\mathrm{h})\mathrm{dh}/\sin\psi\right) = \exp\left[-(\tau_{\mathrm{a}}(\mathrm{h})/\sin\psi)\right]$$

In this paper the two techniques developed in the Pierre Auger Experiment to measure $\tau_{\mathrm{a}}(\mathrm{h})$ are described.

3. The Central Laser Facility

The Central Laser Facility (CLF) [3] is an independent, fully automated and self-powered facility housed within a container which is nearly equidistant (~ 30km) from three out of four FD buildings, and is operated remotely during FD data acquisition.

Figure 2: The Central Laser Facility of the Pierre Auger Observatory

A frequency tripled Nd:YAG laser, control hardware and optics direct a calibrated and steerable pulsed UV beam into the sky. The laser head is mounted on an enclosed optical table that also houses most of the other optical components. An electric heater protects the laser head from freezing, in the event that the main propane heater fails. The steering mechanism consists of two mirrors on rotating orthogonal axes, which can direct the beam towards any direction above the horizon. The wavelength is 355 nm, near the middle of the nitrogen fluorescence spectrum produced by air showers, with a spectral purity better than 99%. The relative energy of each shot is monitored by two probes (one photo-diode probe and one pyroelectric probe): the nominal energy per pulse is 7 mJ and the pulse width is 7 ns. Variations in beam energy are tracked to an accuracy of 2%. The nominal energy of 7 mJ per pulse is approximately equivalent to the amount of fluorescence light produced by a 10^{20} eV shower. The net polarization of the fixed-direction vertical beam is maintained within 3% of random. Within this uncertainty, equal amounts of light are scattered out of the vertical beam in the direction of each FD telescope. The beam direction is maintained within 0.04 degrees of vertical. The full-width beam divergence is less than 0.05 degrees.

During each hour of FD operation, 50 vertical laser tracks are generated every 15 minutes. FD telescopes record light from the CLF exactly as they record light from EASs, as shown in figure 3. The direction, time and relative energy of each laser pulse is recorded at the CLF and later matched to the corresponding trigger in the FD data. A specific timing is used to distinguish laser from shower events.

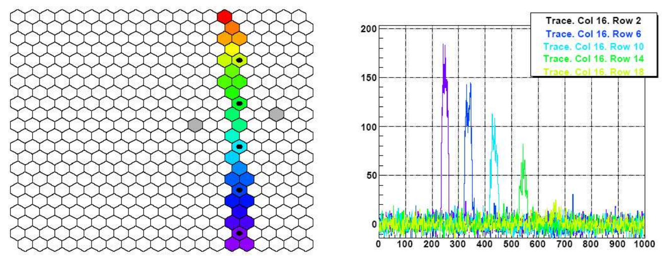

Figure 3: Left : the CLF light recorded by telescope 4 of Los Leones FD building. Right : ADC traces corresponding to the selected pixels on the left.

4. Aerosol Optical Depth Measurements

The light emitted by the Central Laser Facility, isotropically diffused towards each FD building, is scattered and attenuated by the molecular and aerosol components in the atmosphere in the travel towards FD buildings exactly as the fluorescence light emitted by a shower.

The analysis of the amount of CLF light that reaches the FDs as a function of time is used to infer the aerosol attenuation, once the laser energy is known. To minimize fluctuations, average quarter hour profiles (photons collected at the aperture of the FD building as a function of ADC time bins) normalized to a fixed reference energy E_{ref} are computed. Two independent analyses of vertical laser events have been developed to provide an hourly aerosol charaterization in the FD field of view: the Laser Simulation and the Data Normalized analyses. Both analyses use as a reference an extremely clear night in which the aerosol contribution to the light attenuation can be neglected (Rayleigh Night). A procedure to identify these extremely clear conditions in real data has been developed: for each coherent data set the shape of CLF profiles is compared to the one of a Rayleigh Night simulated profile using a Kolmogorov test that checks their compatibility. The profile with the highest probability is chosen as the reference. Rayleigh nights occur more frequently during austral winter.

4.0.1. Laser Simulation Analysis

This procedure is based on the comparison of CLF laser light profiles with those obtained by a grid of simulated profiles generated in different aerosol attenuation conditions. The atmospheric model adopted in this analysis is based on the assumption that the aerosol attenuation in the atmophere can be reasonably described by a two parameters model: the Aerosol Horizontal Attenuation Lenght (L_{mie}) and the Aerosol Scale Height (H_{mie}). The first parameter describes the aerosol attenuation at ground level, the second accounts for its dependence on the height. Horizontal uniformity is assumed. With this parametrization the Aerosol Transmission Factor is:

$$T_{aer}(s) = \exp\left(\frac{H_{mie}}{L_{mie}\cos\theta}\left[\exp\left(-\frac{h_2}{H_{mie}}\right) - \exp\left(-\frac{h_1}{H_{mie}}\right)\right]\right)$$

where h1, h2 are the altitudes above sea level of the first and second observation levels respectively, and θ is the zenith angle of the light path. The Vertical Aerosol Optical Depth τ_a(h) is :

$$\tau_a(\mathrm{h}) = -\frac{H_{mie}}{L_{mie}}\left[\exp\left(-\frac{h_2}{H_{mie}}\right) - \exp\left(-\frac{h_1}{H_{mie}}\right)\right]$$

The grid of simulated profiles is generated fixing the energy at the value E_{ref} and the nominal geometry of the laser event, varying only the atmospheric conditions. In this approach, atmosphere is defined once the parametric Monthly Density Profiles and the parameters L_{mie} and H_{mie} are set. The aerosol parameters space is defined varying L_{mie} from 5 to 150 km in steps of 2.5 km and H_{mie} from 0.5 km to 5 km in steps of 0.25 km. A total of 1121 profiles x 12 months are generated for this analysis.

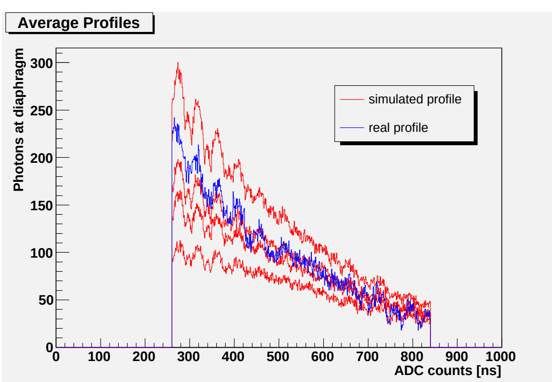

Figure 4: A real CLF profile of light at diaphragm (in blue) compared to an example of four simulated profiles (in red) in different aerosol attenuation conditions.

For each average real profile, the aerosol attenuation is determined choosing the simulated profile, identified by the parameters pair L^{best}_{mie}, H^{best}_{mie}, closest to the real one. The strategy adopted searches for the parameters pair that minimizes the square difference D^2 between real and simulated profiles computed for each bin, where $D^2 = [\sum_i(\Phi^{real}_i - \Phi^{sim}_i)^2]$ and Φ_i are the reconstructed photons at diaphragm in each time bin. In the case of presence of clouds, appearing as spikes/holes in the profiles, the aerosol attenuation is measured from the ground level to the height of the cloud layer. The number of reconstructed photons of the CLF profiles in analysis depends both on the aerosol attenuation and on FD and CLF calibrations, so it is not possible to distinguish the contribution from each factor. To overcome this problem, the procedure makes use of the reference Rayleigh Night. For each coherent data set, the ratio between the reconstructed energy of the Rayleigh Night profile and the nominal energy returns the normalization constant that fixes the energy scale between real and simulated CLF profiles. The normalization constant is then used to scale all CLF profiles before measuring the aerosol attenuation.

The uncertainty on τ_a(h) is calculated taking into account both statistic errors and systematic errors arising from the variables involved in the procedure. The evaluation of the statistic error includes the indetermination due to the comparison algorithm used to determine the aerosol attenuation. The main contribution to systematic errors is due to the indetermination in the choice of the Rayleigh night and to the parametric model adopted.

This procedure provides a measurement of the aerosol attenuation every 15 minutes and results are averaged to fill the hourly aerosol database.

4.0.2. Data Normalised Analysis

The Data Normalised Analysis consists of an iterative procedure that compares hourly average profiles to reference real Rayleigh Night profiles. Using the timing of the events, FADC time bins are converted to height at the laser track using the known positions of FD and CLF. An average profile is built every hour, merging the corresponding four quarter-hour profiles. A procedure is applied to remove inconsistencies between the four quarter hour profiles due to clouds. A cloud is detected in a bin if the ratio of light in the quarter hour profile to that seen in a clear day exceeds a given threshold. In such a case the bin content is not used in the average hour profile. Then more subtle discrepancies are searched for. For each height bin the average and the RMS of quarter hour profiles are computed. Any signal which exceeds the hourly mean by a certain multiple of the RMS is automatically set to zero. The procedure is repeated reducing threshold values at each repetition. If only one quarter hour survives, the corresponding bin is set to zero and discarded for further analysis.

Once the hourly average profile (Ihour) is built, it is compared to the Rayleigh Night profile of the data set (Iaerfree). A first estimate of τ_a(h) is :

$$\tau_a^{\mathrm{first}}(h) = -\frac{\ln\left(I_{\mathrm{hour}}(h)/I_{\mathrm{aerfree}}(h)\right)}{1 + 1/\sin\theta}$$

where I_{hour} is the average hourly laser profile, I_{aerfree} is the reference Rayleigh Night profile and θ is the elevation angle of the laser track point at height h. This calculation does not take into account the laser beam scattering due to aerosols; to overcome this, $\tau_a^{\mathrm{first}}(h)$ is differentiated to calculate the extinction

α(h) over short intervals in which the aerosol scattering conditions change slowly. Finally, $\tau_a(h)$ is estimated re-integrating $\alpha(h)$. An example of a profile in analysis is shown in figure 5.

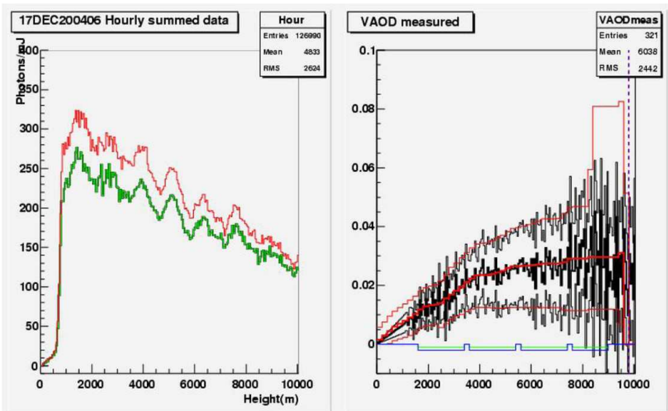

Figure 5: Left : a CLF profile in analysis (lower) compared to the Rayleigh Night profile (upper). Right : the τ_a(h), τ_a^{min}(h), τ_a^{max}(h) profiles with the superimposed fit.

This analysis provides a measurement of the aerosol attenuation every hour.

5. Comparison between the two analyses

The results produced with these two independent analyses are fully compatible, as shown in fig. 6: the average τ_a(3 km) above the detector in the period from January 2005 to December 2008 is 0.04 ± 0.01.

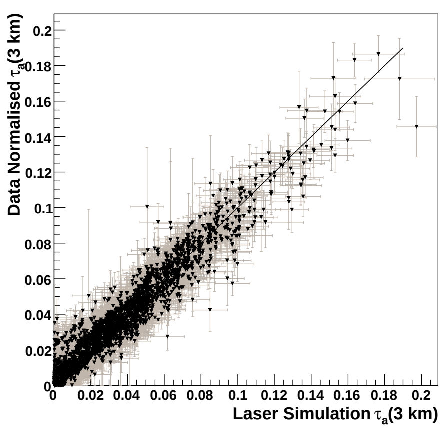

Figure 6: τ_a(h) estimated by CLF analyses

An example of the good agreement between a typical hourly vertical aerosol optical depth profiles measured with the Data Normalised and the Laser Simulation analyses is shown in figure 7.

By studying the vertical aerosol optical depth as a function of time, over a period of 4 years of data, a clear seasonal variation is observed, as shown in figure 8. Austral winter is the season with lower aerosol attenuation.

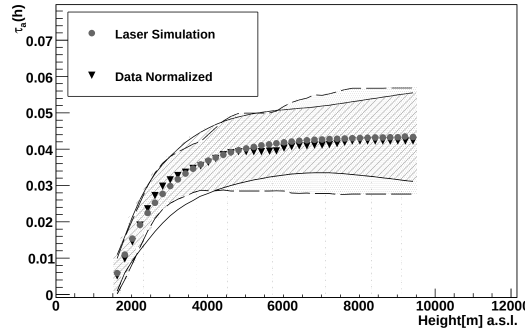

Figure 7: Comparison of a $\tau_a(h)$ profile estimated by the Laser Simulation and the Data Normalised analyses

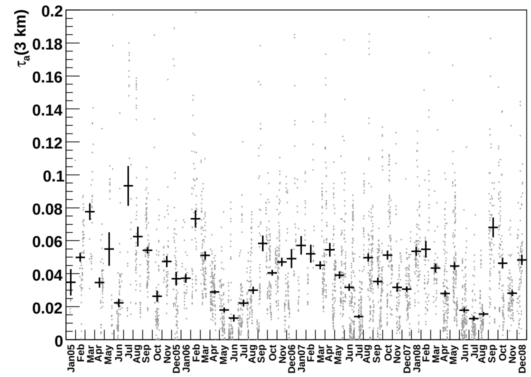

Figure 8: τ_a(3km) as a function of time. Lower values of τ_a(3km) happens in austral winter (June - July)

The official Pierre Auger Observatory aerosol database is filled with hourly measurements of the vertical aerosol optical depth computed with the two described analyses. Five years of hourly aerosol characterization are provided.

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