Multiple scattering measurement with laser events

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Abstract: The Fluorescence Detector of the Pierre Auger Observatory performs a calorimetric measurement of the primary energy of cosmic ray showers. The level of accuracy of this technique is determined by the uncertainty in several parameters, including the fraction of the fluorescence and Cherenkov light reaching the detector after being scattered in the atmosphere through Rayleigh and Mie processes. A new method to measure this multiple scattering is presented. It relies on the analysis of the image of laser tracks observed by the fluorescence telescopes at various distances to characterize the scattering of light and its dependence on the atmospheric conditions. The laser data was systematically compared with a dedicated Geant4 simulation of the laser light propagation, allowing for any number of scatterings due to both Rayleigh and Mie processes, followed by a detailed simulation of the telescopes optics also based on Geant4.

Keywords: Laser; Multiple Scattering; Pierre Auger Observatory; Fluorescence detector

1 Introduction

The Pierre Auger Observatory [1] in Argentina has 1660 surface detectors in a $3000\ \mathrm{km}^2$ array that is overlooked by 27 fluorescence telescopes at four locations on its periphery. The Fluorescence Detector (FD) [2] telescopes measure the shower development in the air by observing the fluorescence light. The FD offers optical shower detection in a calorimetric way and can be calibrated with very little dependence on shower models.

The accuracy of the fluorescence technique is determined by the uncertainty in several parameters [3], among them, the fraction of shower light (both from fluorescence and Cherenkov processes) that reaches the detector after being multiply scattered in the atmosphere. The multiple scattering (MS) component, which has to be estimated and included in the reconstruction analysis to correctly derive the cosmic ray properties, depends on the atmospheric conditions, in particular on the Rayleigh and Mie scattering processes.

The atmospheric conditions at the Auger site are monitored by several devices [4]. In particular, the observatory is equipped with a set of laser systems that can shoot laser pulses into the atmosphere to be seen by the FD, allowing us to measure atmospheric conditions and monitor the performance of the telescopes. One of them is the Central Laser Facility (CLF) [5], a unit placed about $30\ \mathrm{km}$ from the FD sites emitting energy calibrated pulses of wavelength $\lambda = 355\ \mathrm{nm}$. In addition, a roving laser system, emitting vertical laser pulses at $\lambda = 337\ \mathrm{nm}$, can be positioned in front of the telescopes at distances of a few km.

Using the large amount of laser data and profiting from the negligible width of the beam we have developed a method to extract the transverse distribution of light in the FD cameras, from which it is possible to access the MS parameters. Data is compared to a dedicated Geant4 simulation of light propagation in the atmosphere.

2 Extraction of the transverse light profile

The emitted laser pulses propagate upwards in the atmosphere. The direct light seen by the telescopes results from a first Rayleigh scattering, as illustrated in figure 1. The light from the first scattering can suffer additional scatterings and contribute to the signal recorded at large angles with respect to the direct light component. The method employed to extract this transverse light profile from laser data relies on the principle that identical laser events can be averaged to extract information inaccessible on an event-by-event basis.

For each acquisition time slot, the recorded image is translated into a distribution of the number of detected photons as a function of the angular distance, ζ, to the direction of the direct light.

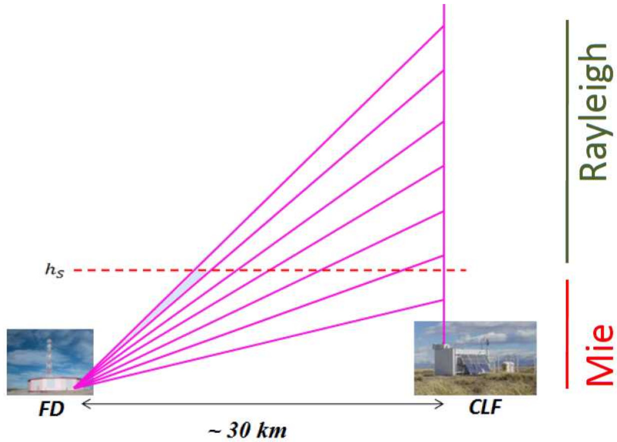

Figure 1: Schematic representation of the propagation of laser photons from the CLF to the FD site. In this model, there is an aerosol band in the area below the h_S horizontal line. Rayleigh and Mie scattering dominated regions are, respectively, above and below the scale height parameter, h_S.

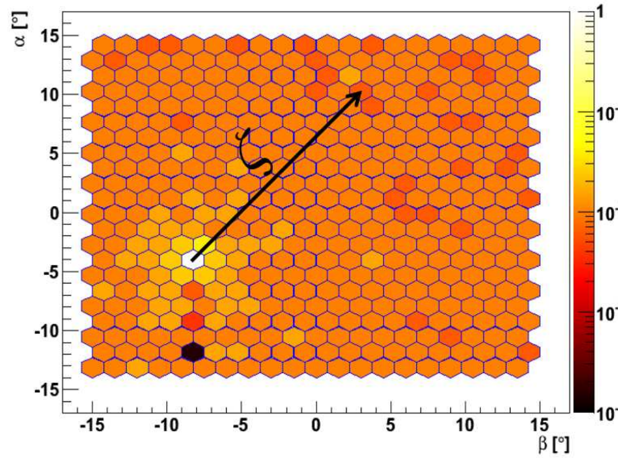

Figure 2: Camera image for a single time bin built by averaging over several CLF shots seen at Los Leones FD site with a full camera acquisition. Colors represent the accumulated charge normalized to the maximum.

In figure 2, a single time bin (100 ns) from the average of several CLF shots (almost one thousand) seen at Los Leones with a full camera acquisition is shown, for the case when the laser spot is at $\alpha \sim -4.9°$ and $\beta \sim -8°$, where α and β are, respectively, the elevation and azimuthal angle in the camera coordinates. Here the full FD camera is represented by the 440 hexagonal pixels and the color scale represents the number of photons detected during this time period, normalized to the maximum signal value at the spot centre. Additional structures are observed surrounding the hottest pixel: a first crown of (yellow/light-orange) pixels followed by second crown made of a bigger group of (orange) pixels, and an almost flat distribution for the rest of the camera with an intensity of $\sim 10^{-3}$ with respect to the maximum. The first crown is connected with the detector point spread function (PSF) while the farther regions are dominated by multiple scattered light. Another feature in the image are the darker pixels (corresponding to fewer detected photons) just below the spot centre. These are the first pixels crossed by the laser, for which the signal attained the largest values, and were removed from the analysis. The small signal in these pixels, some time bins after being hit by the laser direct light, is consistent with an undershoot effect: large signals affect the baseline (pulling it down), which then takes a few μs to recover. Clouds can cause serious distortions to the light profile. Therefore, events in which clouds are identified during the reconstruction are removed from the analysis.

To build the ζ profile, $\frac{dN}{d\Omega}(\zeta)$, the number of photons in pixel i and in time bin j, $\Delta N_{i,j}$, corrected by the pixel solid angle $\Delta\Omega_i$ is obtained as a function of ζ and averaged according to

$$\frac{dN}{d\Omega}(\zeta) = \frac{\sum_{j=1}^{N_t}\sum_{i=1}^{N_p}\frac{\Delta N_{i,j}}{\Delta\Omega_i}(\zeta)}{N_t \cdot N_p} \ ,$$

where N_t is the number of time bins and N_p is the number of acquired pixels in the camera (440 for a full camera acquisition). This method allows us to obtain transverse light profiles, as shown in figure 3.

The observed transverse light profile is the convolution of those of the light source (point-like at the current distances), the multiple scattering in the atmosphere and the detector PSF. The direct light convoluted with the detector PSF is expected to dominate at small ζ angles, while the multiply scattered light should dominate at large ζ (especially for a far away source like the CLF). Although some runs were performed with full camera acquisition, as in the example shown in figure 2, most available CLF data were taken with partial camera acquisition. In this case, data are taken for a small group of pixels neighbouring the pixels triggered by the laser. For vertical CLF shots the data available are contained within a band of pixels with approximately 8 degrees in β. Even in this case, the described method can be used up to values of $\zeta = 15°$.

3 Geant4 laser simulation

A realistic simulation capable of reproducing the features of the multiply scattered photons from production to detection was developed to support the data analysis presented in this paper. This simulation is based on Geant4[6] and performs the tracking of photons in the atmosphere. Simulation of both Rayleigh and Mie scattering processes were implemented according to [4]. Photons are individually

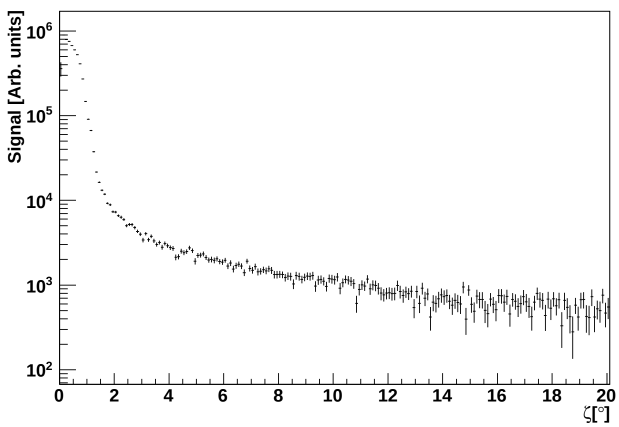

Figure 3: Transverse light profile seen at Los Lones FD site using CLF shots (full camera acquisition runs).

followed through the atmosphere, allowing for any number of scatterings from both processes. The atmosphere was parametrized in layers of constant depth, 20 g cm^{-2}, and different atmospheric profiles can be selected. In order to simulate the camera aperture and inclination, and to improve the efficiency of the simulation, the detector was implemented as a full 2π, 2 meter high cone section. The laser photons are generated at the centre of the cone section with the cone radius corresponding to the distance between the laser and the detector.

The contribution to the light transverse profile from the detector was evaluated by using a full simulation of the fluorescence telescopes [2] based on Geant4. To reduce computation time maps of the optical spot at several positions on the camera were produced with this simulation. The direction of each photon at the entrance window of the telescope was smeared according to these maps.

4 Dependence on aerosol concentration

The multiple scattering processes occur in the interaction of photons with the atmosphere and therefore depend on the atmospheric conditions. In particular these processes depend on atmospheric depth but also on the quantity of aerosols. The latter is quantified in terms of the Vertical Aerosol Optical Depth profile, VAOD(h, t), which is measured using CLF shots [4]. In this work the VAOD will be evaluated at a fixed reference height ($h = 3$ km, above ground level), allowing the event characterization with a single number.

To access the parameters characterizing multiple scattering processes, two distributions were considered: the total light detected by the FD as a function of α and the transverse light profile. The distributions were obtained with the method described in section 2, using 18 months of CLF shots recorded at the Coihueco FD site.

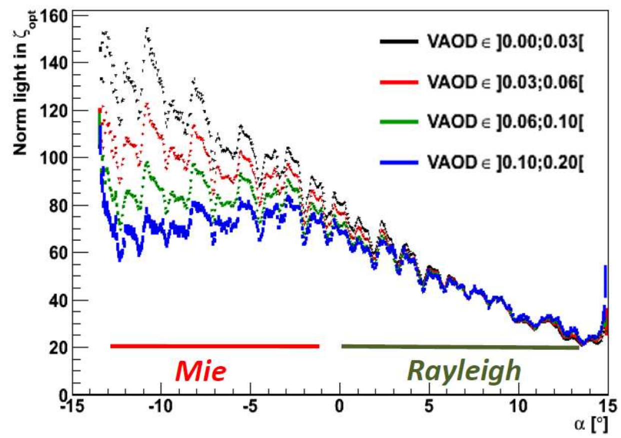

Figure 4: Average light measured at Coihueco FD site as a function of α for different VAOD ranges. The Mie and Rayleigh dominated regions are labeled.

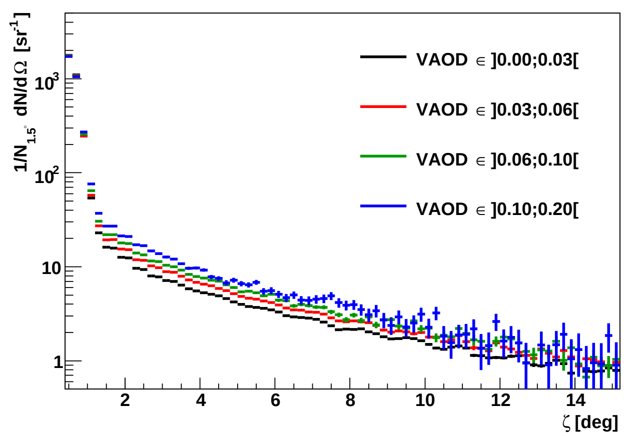

Figure 5: Average transverse light profile seen at Coihueco FD site as a function of ζ for different VAOD ranges.

In figure 4 the average total light flux as a function of α is shown for different VAOD ranges where the expected laser attenuation dependence on the elevation angle α is observed. The total light flux was obtained integrating the light in $\zeta \in [0°, \zeta_{\rm opt}]$, where $\zeta_{\rm opt}$ is the angle that maximizes the signal to noise ratio. The curves were normalized in the region $\alpha \in [5°, 12°]$ to the one with the lowest VAOD. The oscillations on the light curves are due to the FD camera non-uniformities and, since the curves result from averaging over several hundreds of thousand of laser events, the distributions show structures with high definition and small statistical errors. The normalisation and shape of the curves shows sensitivity to the aerosol content and distribution, allowing us to extract information concerning the Mie scattering process. As illustrated in figure 1, aerosols are mostly concentrated near the ground and their density can be modeled by an exponential function

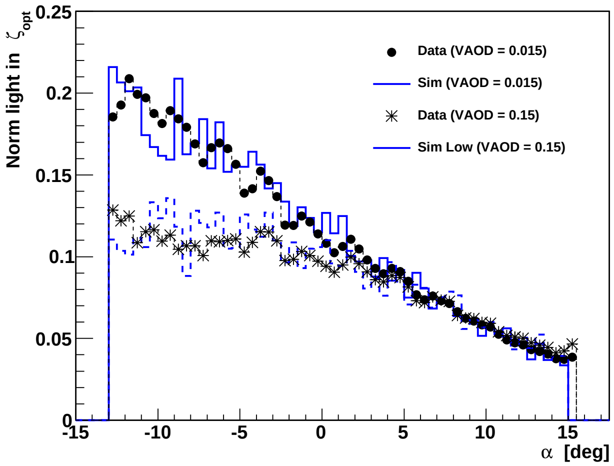

Figure 6: Average light profile seen at Coihueco FD site as a function of α for VAOD = 0.015 and VAOD = 0.15. Comparison between data and simulation.

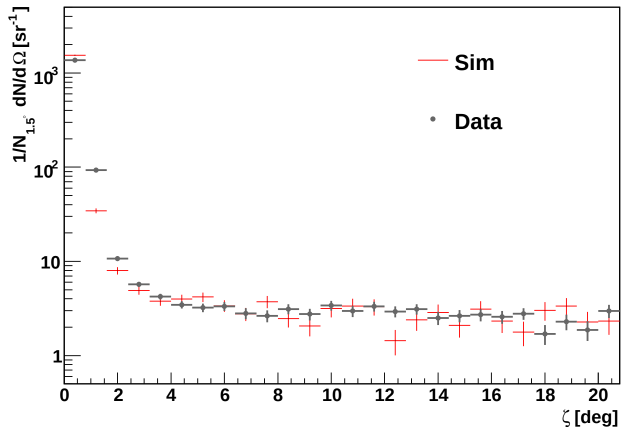

Figure 7: Average transverse light profile from CLF shots seen at FD for low VAOD. Comparison between data and simulation.

decreasing with a vertical scaling factor, h_s. Thus, photons propagating in the lower part of the atmosphere ($\lesssim h_s$) are more likely to suffer from Mie scattering than at higher altitudes. The profiles in figure 4 are in agreement with this model, where the effect of Mie scattering can be observed for low values of α.

The parameters describing Mie scattering can also be constrained by the analysis of the transverse light profile. The transverse light profile distributions corresponding to different VAOD ranges are shown in figure 5. The distributions were normalized to the total signal in $\zeta < 1.5°$ ($\mathrm{N}_{1.5°}$). As described in section 2, the multiple scattering component of the signal should dominate the light transverse profile distribution for values of ζ larger than the size of the direct signal convoluted with the detector PSF ($\zeta \lesssim 1.5°$). Therefore, the dependence of the multiple scattered light component on the atmospheric conditions should be visible in the transverse profile distributions for different VAOD ranges. This is observed in figure 5, where the differences between the profiles for different VAOD ranges are clearly visible for bigger values of ζ. The distributions show, as expected, that the higher the VAOD, the higher is the multiple scattering component.

The available data on the transverse light distribution from laser shots is being explored to assess the MS parameters. Both the total light profile (fig. 6) and the transverse light profile (fig. 7) show a reasonable agreement between data and simulation if the average Auger Mie parameters, which depend on the aerosol type and concentration, are used. The observed effect of higher aerosol concentrations on the light profile is well described by the simulation. For the transverse light profile, a deviation between simulation and data is observed for $\zeta < 2°$. Such effect is expected to arise from the use of a finite set of spot maps, as described in section 3.

5 Conclusions

A method to extract the transverse light profile using CLF laser shots was developed. The method enables the assessment of atmospheric parameters relevant for both Rayleigh and Mie scattering processes. A dedicated laser simulation based on Geant4 was developed to attain a better understanding of multiply scattered light in the atmosphere. A first comparison between data and simulation shows already a reasonable agreement. Further studies exploring the evolution of the multiple scattering component with altitude, time and distance from the FD are in progress.

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