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Multiple scattering measurement with laser events

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Abstract. The Pierre Auger Observatory Fluorescence Detector (FD) 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, among them the fraction of shower light (both from fluorescence and Cherenkov light) that reaches the detector after being multiply scattered (MS) in the atmosphere. This component depends on atmospheric conditions, namely on Rayleigh and Mie scattering processes. Using laser events it is possible to study these processes and deconvolute them from the shower's electromagnetic lateral distribution.

We propose a new method to measure the Rayleigh and Mie MS components seen in laser events, and correlate them with atmospheric conditions. In order to study in detail the effect of such conditions in the scattering of photons, a Geant4 dedicated laser simulation was developed. This combination of a MS dedicated data analysis with a realistic laser simulation enables to explore MS characteristics, in particular the evolution with time, altitude and distance from the FD.

1 Introduction

The Pierre Auger Observatory, in Argentina, studies cosmic rays with energies above $\sim 5\times10^{17}$ eV. Having four Fluorescence Detectors (FD) (Abraham et al., 2010a) overlooking the array it can perform a *quasi*-calorimetric measurement of the primary energy cosmic ray showers by detecting the fluorescence light produced by the shower secondary particles as they travel through the atmosphere. This is a nearly model independent measurement allowing not only to calibrate the Surface Detector (SD), which has a 100% duty cicle, while the FD only works in moonless nights, but also to study the shower longitudinal profile that contains in itself variables sensitive to the primary composition (Abraham et al., 2010c; Andringa et al., 2011).

The accuracy of this technique is determined by the uncertainty in several parameters (Unger et al., 2008), among them, the fraction of shower light (both from fluorescence and Cherenkov processes) that reaches the detector after being multiply scattered (MS) in the atmosphere. The MS component which has to be estimated and included in the reconstruction analysis to correctly access the cosmic ray properties, depends on the atmospheric conditions, in particular on the Rayleigh and Mie scattering processes. The atmospheric conditions in the Auger site are monitored by several devices (Abraham et al., 2010b). One of them is the Central Laser Facility (CLF) (Fick et al., 2006), an unit placed about 30 km from the FD sites that emits laser shots into the atmosphere. These energy calibrated shots, of wavelength $\lambda = 355$ nm, are seen by the FD allowing to measure atmospheric conditions, in particular its transparency. Using the large amount of CLF data and negligible width of the CLF beam, unlike the showers, which yield an electromagnetic lateral distribution, we propose a method to extract the transverse distribution of light in the FD cameras, from which it is possible to access the MS parameters (see Fig. 1). The method is described in Sect. 2. A dedicated simulation of light propagating in the atmosphere, including multiple scattering of light, has been developed and is introduced in Sect. 3. The sensitivity of the method to multiscattering parameters is shown in Sect. 4 using data. Finally, in Sect. 5, some first results of the method applied on data are compared to the simulation, and followed by the conclusions.

2 Extraction of the transverse light profile

The method employed to extract the transverse light profile from laser shots data relies on the principle that CLF events,

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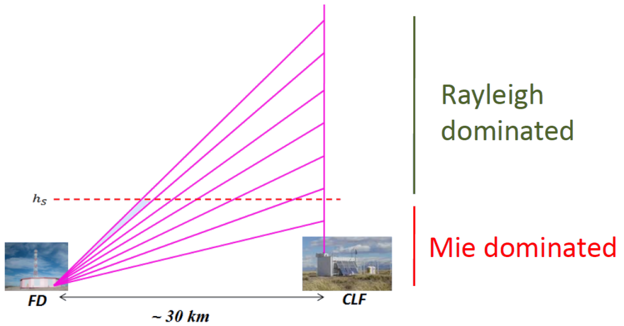

Fig. 1. Schematic representation of the propagation of laser photons from the CLF to the FD site. In this model, there is an aerosol band which is the area below the h_S horizontal line. Rayleigh and Mie scattering dominated regions are, respectively, above and below the height scale parameter, h_S.

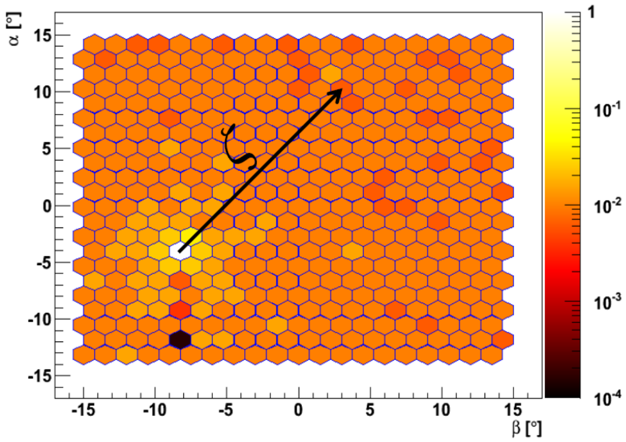

Fig. 2. Camera image for a single timeslot build by averaging over several CLF shots seen at Los Leones with a full camera acquisition. Colors represents the accumulated charge, normalized to the maximum.

being similar, can be averaged in order to extract information inaccessible in an event-by-event basis.

To access the transverse light profile it is useful to introduce the variable ζ, the angular distance between the centre of the spot in the camera for a given time interval and any pixel centre (see example in Fig. 2). For each time interval the corresponding image of the transverse light distribution in the camera, can be translated into a distribution of the number of detected photons as a function of ζ.

In Fig. 2, a single timeslot (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 $\alpha \sim -4.9°$, where α is the elevation 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 timeslot normalized to the maximum signal value, at the spot centre.

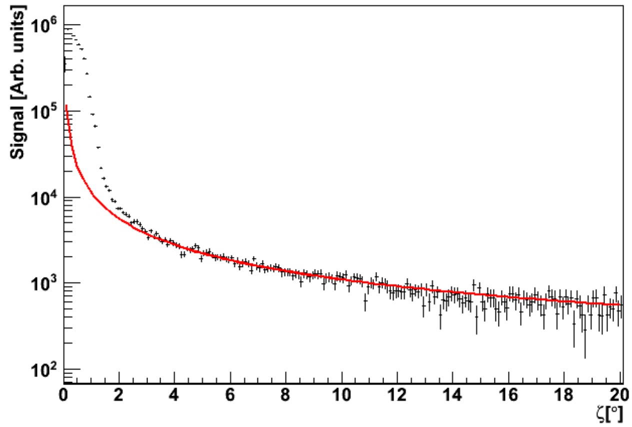

Fig. 3. Transverse light profile seen at Los Leones using CLF shots (full camera acquisition runs). The red curve is a power law fit performed in $\zeta \in [4°, 15°]$.

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 bellow 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 drop down in these pixels, some timeslots 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. CLF events with clouds were discarded to avoid biases to the transverse light profile.

To build the ζ profile one needs to cycle over each camera pixel calculating its angular distance to the spot centre (ζ), and taking the accumulated light in the corresponding timeslot. In order to guarantee that the profile does not get biased, the signal for each pixel and for each timeslot must be normalized to the corresponding pixel solid angle. To obtain the transverse light profile in ζ, the signal in the pixels is averaged as follows,

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

where N_t is the number of timeslots and $N_p = 440$, the total number of pixels in the camera. This method allows to obtain differential light transverse profiles, as in Fig. 3.

The observed transverse light profile is the convolution between the light source (point-like at the current distances), multiple scattering in the atmosphere and the detector PSF. The direct light convoluted with the detector PSF is expected

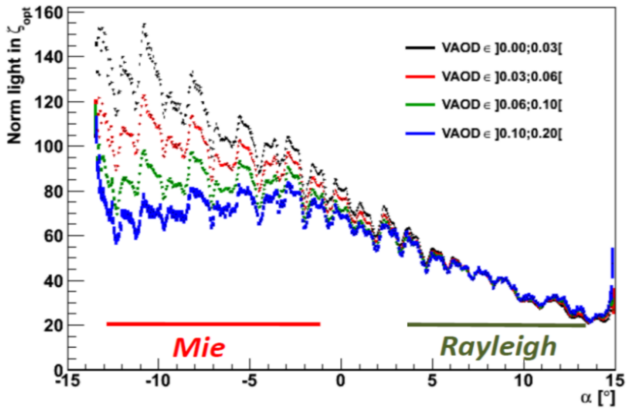

Fig. 4. Average light profile, in data, seen at Coihueco as a function of α for different VAOD ranges. The Mie and Rayleigh dominated regions are labeled.

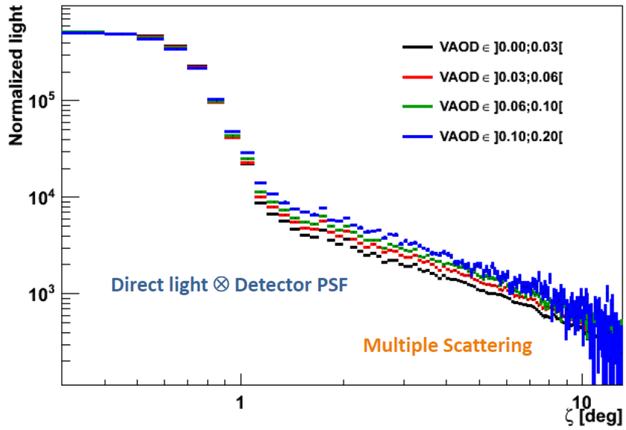

Fig. 5. Average transverse light profile seen at Coihueco as a function of ζ for different VAOD ranges.

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 Fig. 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, this 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 (Agostinelli et al., 2003) and it performs the tracking of photons in the atmosphere. Both Rayleigh and Mie physical processes were implemented with steerable parameters, accordingly to (Abraham et al., 2010b). Photons are individually followed through the atmosphere, allowing for any number of scatterings, from both processes. The atmosphere was parametrized in layers of constant depth, $20\,\mathrm{g\,cm^{-2}}$, 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 m high cone section. The laser signal is generated in the geometrical centre of the cone section, the cone radius corresponding to the distance between the CLF and the detector.

4 VAOD dependency

The multiple scattering processes occur in the interaction of photons with the atmosphere and therefore depend on the atmospheric conditions, in particular on the atmospheric depth and the quantity of aerosols. The latter is translated in terms of Vertical Aerosol Optical Depth profile, VAOD(h,t), which is measured using CLF shots (Abraham et al., 2010b). In this work the VAOD will be fixed at a reference height ($h = 3$ km, above ground level), allowing the event characterization with a single number.

In order 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 Sect. 2, using 18 months of CLF shots recorded at the Coihueco FD site.

In Fig. 4 the average total light flux as a function of α is shown for different VAOD ranges, where the expected laser attenuation dependency on the elevation angle α is observed. The oscillations on the light profile are due to the FD camera non-uniformities and, since the profiles result from averaging over several hundreds of thousand of laser events, the distributions show structures with high definition and small statistical errors. The profiles were normalized to the profile with the lowest VAOD (black) in the region $\alpha \in [5°, 12°]$. After the normalization it becomes evident that more information concerning the Mie scattering process can be extracted from the profile shape. This can be understood with the help of Fig. 1, representing the light path from the CLF to the FD site. The aerosols concentrate below h_S (the aerosol vertical scale) and therefore, photons propagating in the atmosphere below that value suffer mainly Mie scattering, while photons traveling above h_S interact mostly via Rayleigh scattering. The profiles in Fig. 4 can thus be interpreted according to this model since the dependency of the shape of the distributions with the aerosol conditions is observed for lower α values, fading out for higher values of α.

The parameters describing Mie scattering can also be constrained by the analysis of the transverse light profile. The

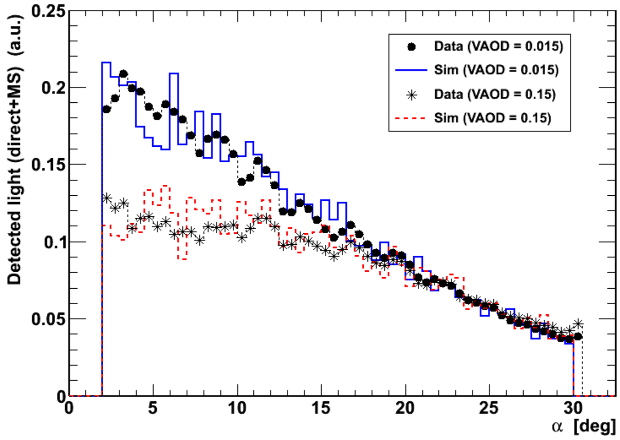

Fig. 6. Average light profile seen at Coihueco as a function of α for VAOD = 0.015 and VAOD = 0.15. Comparison between data and simulation.

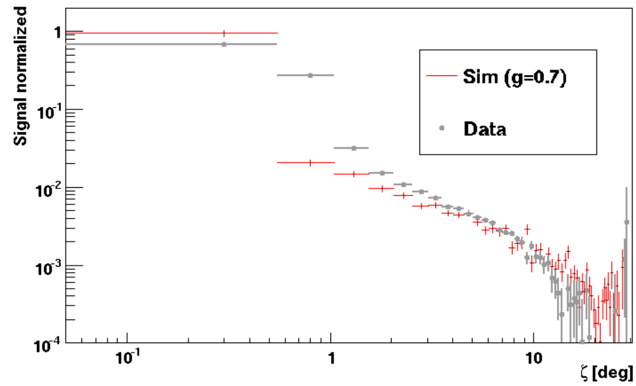

Fig. 7. Average transverse light profile seen at Coihueco as a function of ζ for large VAOD. Comparison between data and simulation.

transverse light profile distributions corresponding to different VAOD ranges, are shown in Fig. 5. The distributions were normalized to the maximum of the profile distribution for the lowest VAOD range. As described in Sect. 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 dependency of the multiple scattered light component with the atmospheric conditions should be visible in the transverse profile distributions for different VAOD ranges. This is observed in Fig. 5, where the differences between the profiles for different VAOD ranges arise for bigger values of ζ. The distributions show, as expected, that the higher the VAOD, the higher is the multiple scattering component.

5 First results

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 are used. The observed effect of higher aerosol concentrations on the light profile is well described by the simulation. There is a good agreement between data and simulation in the transverse light profile for the region dominated by multiple scattering light (large ζ). The poor agreement for low ζ values is due to the fact that the detector PSF component was not included in the simulation.

6 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 multiscattering component with altitude, time and distance from the FD are in progress. The effect of the detector PSF on the transverse light profile is also being investigated.

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