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# Techniques for Measuring Aerosol Attenuation using the Central Laser Facility at the Pierre Auger Observatory

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## The Pierre Auger Collaboration\*

**ABSTRACT:** The Pierre Auger Observatory in Malargüe, Argentina, is designed to study the properties of ultra-high energy cosmic rays with energies above  $10^{18}$  eV. It is a hybrid facility that employs a Fluorescence Detector to perform nearly calorimetric measurements of Extensive Air Shower energies. To obtain reliable calorimetric information from the FD, the atmospheric conditions at the observatory need to be continuously monitored during data acquisition. In particular, light attenuation due to aerosols is an important atmospheric correction. The aerosol concentration is highly variable, so that the aerosol attenuation needs to be evaluated hourly. We use light from the Central Laser Facility, located near the center of the observatory site, having an optical signature comparable to that of the highest energy showers detected by the FD. This paper presents two procedures developed to retrieve the aerosol attenuation of fluorescence light from CLF laser shots. Cross checks between the two methods demonstrate that results from both analyses are compatible, and that the uncertainties are well understood. The measurements of the aerosol attenuation provided by the two procedures are currently used at the Pierre Auger Observatory to reconstruct air shower data.

**KEYWORDS:** Ultra-high energy cosmic rays, atmospheric monitoring, aerosols.

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- 53 *Universidad Michoacana de San Nicolas de Hidalgo, Morelia, Michoacan, Mexico*
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## 1. Introduction

Direct measurements of primary cosmic rays at ultra-high energies (above  $10^{18}$  eV) above the atmosphere are not feasible because of their extremely low flux. The properties of primary particles – energy, mass composition, arrival direction – are deduced from the study of cascades of secondary particles of Extensive Air Showers (EAS), originating from the interaction of cosmic rays with air molecules. The Pierre Auger Observatory [1] in Argentina (mean altitude about 1400 m a.s.l.) combines two well-established techniques: the Surface Detector, used to measure photons and charged particles produced in the shower at ground level; the Fluorescence Detector, used to measure fluorescence light emitted by air molecules excited by secondary particles during shower development. The Fluorescence Detector (FD) [2] consists of 24 telescopes located at four sites around the perimeter of the Surface Detector (SD) array. It is only operated during clear nights with a low illuminated moon fraction. The field of view of a single telescope is  $30^\circ$  in azimuth, and  $1.5^\circ$  to  $30^\circ$  in elevation. Each FD site covers  $180^\circ$  in azimuth. The hybrid feature and the large area of  $3000 \text{ km}^2$  of the observatory enable the study of ultra-high energy cosmic rays with much better precision and much greater statistics than any previous experiment.

The fluorescence technique to detect EAS makes use of the atmosphere as 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 towards the FD telescopes. The molecular and aerosol scattering processes that contribute to the overall attenuation of light in the atmosphere can be treated separately. In particular, 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 [3]. 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%. Dedicated instruments are used to monitor and measure the aerosol parameters of interest: the aerosol extinction coefficient  $\alpha_{\text{aer}}(h)$ , the normalized differential cross section – or phase function –  $P(\theta)$ , and the wavelength dependence of the aerosol scattering, parameterized by the Ångström coefficient  $\gamma$ .

At the Pierre Auger Observatory, molecular and aerosol scattering in the near UV are measured using a collection of dedicated atmospheric monitors [3]. One of these is the Central Laser Facility (CLF) [4] positioned close to the center of the array, as shown in Fig. 1. A newly built second laser station, the eXtreme Laser Facility (XLF), positioned north of the CLF, has been providing an additional test beam since 2009. The two systems produce calibrated 355 nm vertical and inclined laser shots during FD data acquisition. These laser facilities are used as test beams for various applications: to calibrate the pointing direction of telescopes, for the determination of the FD/SD time offset, and for measuring the vertical aerosol optical depth  $\tau_{\text{aer}}(h)$  and its differential  $\alpha_{\text{aer}}(h)$ . An hourly aerosol characterization is provided in the FD field of view with two independent approaches using the same CLF vertical laser events. In the near future, those approaches will be applied to XLF vertical events. The FRAM robotic telescope is used for a passive measurement of the total optical depth of the atmosphere, the horizontal attenuation monitors (HAM) at two of the FD sites are used to characterize the optical properties of the atmosphere close to the ground.



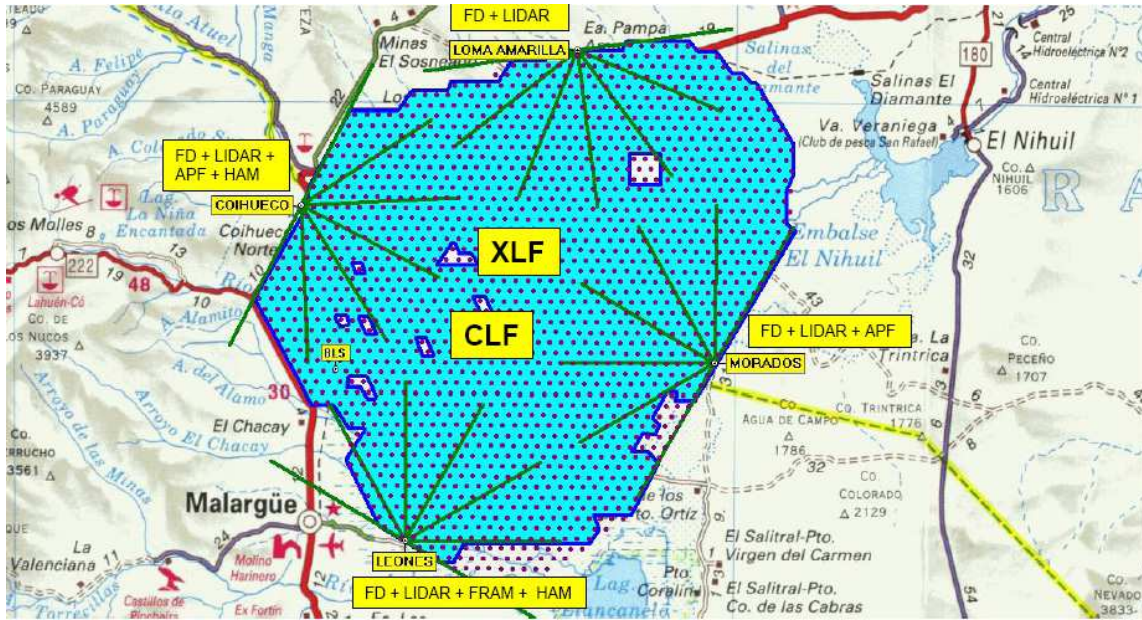


Figure 1: Map of the Pierre Auger Observatory in Argentina. Dots represent SD stations, which are separated by 1.5 km. The green lines represent the field of view of the six telescopes of each of the four fluorescence detectors at the periphery of the SD array. The position of the atmospheric monitoring devices is shown.

43 In addition to the CLF and XLF, four monostatic LIDARs [5] and four Infrared Cloud Cam-  
 44 eras [6] – one at each FD site – are devoted to cloud and aerosol monitoring. During FD data  
 45 acquisition, the LIDARs continuously operate outside the FD field of view and detect clouds and  
 46 aerosols by analyzing the backscatter signal of a 351 nm pulsed laser beam. The cloud cameras use  
 47 passive measurements of the infrared light and provide a picture of the field of view of every FD  
 48 telescope every 5 minutes.

49 To measure the Aerosol Phase Function (APF), a Xenon flash lamp at two of the FD sites  
 50 fires a set of five shots with a repetition rate of 0.5 Hz once every hour [7]. The shots are fired  
 51 horizontally across the field of view of five out of the six telescopes in each building. The resulting  
 52 angular distribution of the signal gives the total scattering phase function  $P(\theta)$  as a function of the  
 53 scattering angle  $\theta$ .

54 In this paper, we will describe the analysis techniques used to estimate aerosol attenuation from  
 55 CLF laser shots. In Sec. 2 we will review atmospheric attenuation due to aerosols and molecules.  
 56 In Sec. 3, we will discuss the setup, operation and calibration of the CLF. Sec. 4 contains the  
 57 description of the two analysis methods used to estimate the aerosol attenuation. Comparisons  
 58 between the two methods and conclusions follow in Sec. 5 and 6.

## 59 2. Atmospheric Attenuation

60 Molecules in the atmosphere predominantly scatter, rather than absorb, fluorescence photons in the

61 UV range<sup>1</sup>. Molecular and aerosol scattering processes can be treated separately. In the following,  
 62 the term “attenuation” is used to indicate photons that are scattered in such a way that they do not  
 63 contribute to the light signal recorded by the FD. The molecular and aerosol attenuation processes  
 64 can be described in terms of atmospheric transmission coefficients  $T_{\text{mol}}(\lambda, s)$  and  $T_{\text{aer}}(\lambda, s)$ , indi-  
 65 cating the fraction of transmitted light intensity as a function of the wavelength  $\lambda$  and the path  
 66 length  $s$ . The amount of fluorescence light recorded at the FD aperture  $I(\lambda, s)$  can be expressed in  
 67 terms of the light intensity at the source  $I_0(\lambda, s)$  as

$$I(\lambda, s) = I_0(\lambda, s) \cdot T_{\text{mol}}(\lambda, s) \cdot T_{\text{aer}}(\lambda, s) \cdot (1 + \text{H.O.}) \cdot \frac{d\Omega}{4\pi}, \quad (2.1)$$

68 where H.O. are higher order corrections due to multiple scattering and  $d\Omega$  is the solid angle sub-  
 69 tended by the telescope aperture as seen from the light source.

70 An accurate measurement of the transmission factors during data acquisition is necessary for  
 71 a reliable reconstruction of the shower and for proper measurements of the physical properties  
 72 of the primary particle (energy, mass composition, etc). While the molecular transmission factor  
 73  $T_{\text{mol}}(\lambda, s)$  can be determined analytically once the vertical profiles of atmospheric temperature,  
 74 pressure, and humidity are known, the aerosol transmission factor  $T_{\text{aer}}(\lambda, s)$  depends on the aerosol  
 75 distribution  $n_{\text{aer}}(r, h)$ , where  $r$  is the aerodynamic radius of the aerosols and  $h$  is the height above  
 76 the ground.

77 The molecular transmission factor  $T_{\text{mol}}(\lambda, s)$  is a function of the total wavelength-dependent  
 78 Rayleigh scattering cross section  $\sigma_{\text{mol}}(\lambda)$  and of the density profile along the line of sight  $s$  in  
 79 atmosphere  $n_{\text{mol}}(s)$ ,

$$T_{\text{mol}}(\lambda, s) = \exp\left(-\int \sigma_{\text{mol}}(\lambda) n_{\text{mol}}(s) ds\right). \quad (2.2)$$

80 The Rayleigh scattering cross section  $\sigma_{\text{mol}}(\lambda)$  is

$$\sigma_{\text{mol}}(\lambda) = \frac{24\pi^3}{N_s^2 \lambda^4} \cdot \left(\frac{n_{\text{air}}^2 - 1}{n_{\text{air}}^2 + 2}\right) \cdot F_{\text{air}}(\lambda), \quad (2.3)$$

81 where  $N_s$  is the atmospheric molecular density, measured in molecules per  $\text{m}^{-3}$ ,  $n_{\text{air}}$  is the refrac-  
 82 tive index of the air, and  $F_{\text{air}}$  is the King factor that accounts for the anisotropy in the scattering  
 83 introduced by the non-spherical  $\text{N}_2$ ,  $\text{O}_2$  molecules [8].

84 The atmospheric density profile along the line of sight  $n_{\text{mol}}(s)$  is calculated using altitude-  
 85 dependent temperature and pressure profiles,

$$n_{\text{mol}}(s) = \frac{N_A}{R} \cdot \frac{p(h)}{T(h)}, \quad (2.4)$$

86 where  $N_A$  is Avogadro’s number and  $R$  is the universal gas constant.

87 Temperature, pressure and humidity vertical profiles of the atmosphere were recorded from  
 88 August 2002 to December 2010 by performing an intensive campaign of radiosonde measurements  
 89 above the site of the Pierre Auger Observatory [9]. A set of data was taken about every 20 m

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<sup>1</sup>The most absorbing atmospheric gases in the atmosphere are ozone and  $\text{NO}_2$ . In the 300 to 400 nm range, the contribution of their absorption to the transmission function is negligible [3].

90 during the ascent. The balloons were able to reach altitudes of 25 km a.s.l. on average. Vertical  
 91 profiles are complemented by temperature, pressure and humidity data from five ground-based  
 92 weather stations. The measured profiles from these launches have been averaged to form monthly  
 93 mean profiles (Malargüe Monthly Models) which can be used in the simulation and reconstruction  
 94 of showers [9, 3]. Currently, the Global Data Assimilation System (GDAS) is used as a source  
 95 for atmospheric profiles. GDAS combines measurements and forecasts from numerical weather  
 96 prediction to provide data for the whole globe every three hours. For the location of the Pierre  
 97 Auger Observatory, reasonable data have been available since June 2005. Comparisons with on-  
 98 site measurements demonstrate the applicability of the data for air shower analyses [10].

99 Aerosol scattering can be described by Mie scattering theory. However, it relies on the assump-  
 100 tion of spherical scatterers, a condition that is not always fulfilled. Moreover, scattering depends  
 101 on the nature of the particles. A program to measure the dimensions and nature of aerosols at  
 102 the Pierre Auger Observatory is in progress and already produced first results, but more study is  
 103 needed [11]. Therefore, the knowledge of the aerosol transmission factor  $T_{\text{aer}}(\lambda, s)$  depends on  
 104 frequent field measurements of the vertical aerosol optical depth  $\tau_{\text{aer}}(h)$ , the integral of the aerosol  
 105 extinction  $\alpha_{\text{aer}}(z)$  from the ground to a point at altitude  $h$  observed at an elevation angle  $\varphi_2$ , assum-  
 106 ing a horizontally uniform aerosol distribution (cf. Fig. 4),

$$T_{\text{aer}}(\lambda, h) = \exp\left(-\int_0^h \alpha_{\text{aer}}(z) dz / \sin \varphi_2\right) = \exp[-(\tau_{\text{aer}}(h) / \sin \varphi_2)]. \quad (2.5)$$

107 Hourly measurements of  $\tau_{\text{aer}}(h)$  are performed at each FD site using the data collected from the  
 108 CLF.

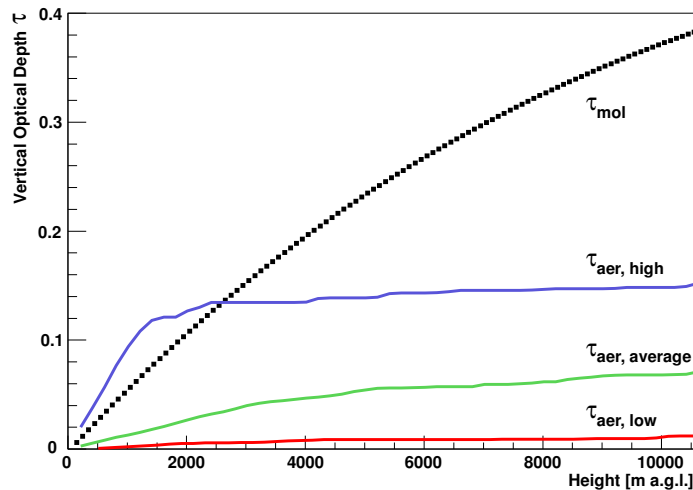


Figure 2: The vertical profile of the molecular optical depth at 355 nm (dots), shown together with the measured vertical profiles of the aerosol optical depth in case of high, average, and low aerosol attenuation of the light. Height is measured above the ground.

109 Similar to the aerosol transmission factor, the molecular transmission factor for UV light at

110 355 nm can be calculated using the same geometry,

$$T_{\text{mol}}(h) = \exp[-(\tau_{\text{mol}}(h)/\sin \phi_2)]. \quad (2.6)$$

111 In Fig. 2, the vertical profile of the molecular optical depth  $\tau_{\text{mol}}(h)$  is compared with measured  
 112 aerosol profiles  $\tau_{\text{aer}}(h)$  (Eq. 2.5) in case of high, average and low aerosols attenuation of light  
 113 in the air. We define “high” aerosol attenuation when  $\tau_{\text{aer}}(5\text{km}) > 0.1$ , “average” when  $0.04 <$   
 114  $\tau_{\text{aer}}(5\text{km}) < 0.05$  and “low” when  $\tau_{\text{aer}}(5\text{km}) < 0.01$ . Considering an emission point P1 at an alti-  
 115 tude of 5 km and a distance on ground of 30 km from the FD, the quoted high, average and low  
 116 values correspond to transmission factors of  $T_{\text{aer}} < 0.54$ ,  $0.73 < T_{\text{aer}} < 0.78$  and  $T_{\text{aer}} > 0.94$ , respec-  
 117 tively. The steps seen in the  $\tau_{\text{aer}}$  profiles are due to multiple aerosol layers at different altitudes.  
 118 For the calculation of the molecular optical depth profile, monthly averaged temperature, pressure,  
 119 and humidity profiles for the location of the Observatory were used. The 12 resulting  $\tau_{\text{mol}}$  profiles  
 120 were averaged, the fluctuations introduced by the varying atmospheric state variables throughout  
 121 the year are very small, comparable to the size of the points in Fig 2. On the other hand, the aerosol  
 122 attenuation can vary between clear and hazy conditions within a few days, making the constant  
 123 monitoring of the aerosol optical depth necessary.

### 124 3. The Central Laser Facility

125 The Central Laser Facility, described in detail elsewhere [4], generates an atmospheric “test beam”.  
 126 Briefly, the CLF uses a frequency tripled Nd:YAG laser, control hardware and optics to direct a  
 127 calibrated pulsed UV beam into the sky. Its wavelength of 355 nm is near the center of the main  
 128 part of the nitrogen fluorescence spectrum [12]. The spectral purity of the beam delivered to the  
 129 sky is better than 99%. Light scattered from this beam produces tracks in the FD telescopes. The  
 130 CLF is located near the middle of the array, nearly equidistant from three out of four of the FD  
 131 sites, at an altitude of 1416 m above sea level. The distances to the Los Leones (located 1416.2 m  
 132 above sea level), Los Morados (1416.4 m), Loma Amarilla (1476.7 m) and Coihueco (1712.3 m)  
 133 FD sites are 26.0 km, 29.6 km, 40 km, and 30.3 km, respectively. In Fig. 3, a picture (left) of the  
 134 CLF is shown. The CLF is solar-powered and operated remotely.

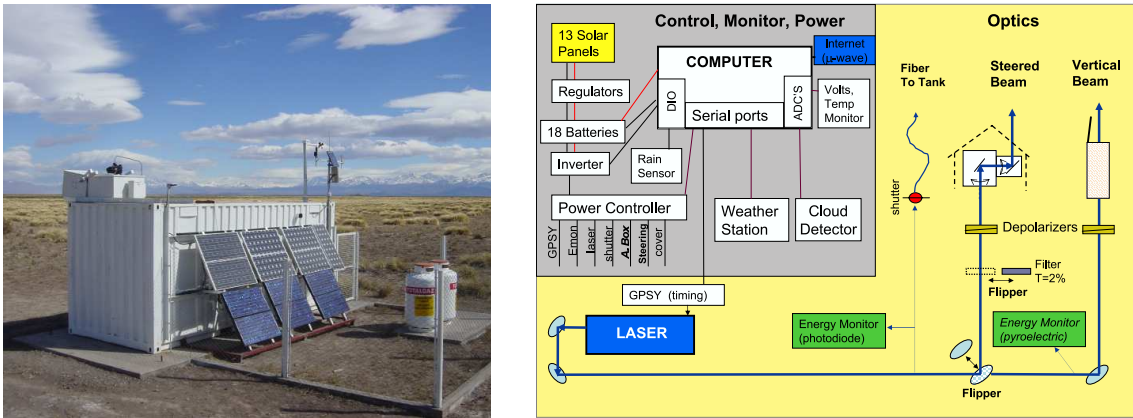


Figure 3: Left: The Central Laser Facility. Right: A schematic of the Central Laser Facility.

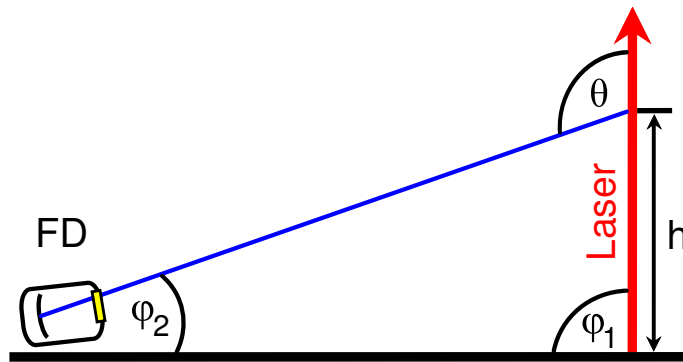


Figure 4: Laser-FD geometry. The light is scattered out of the laser beam at a height  $h$  at an angle  $\theta$ .

135 The laser is mounted on an optical table that also houses most of the other optical components.  
 136 The arrangement is shown in Fig. 3 (right). Two selectable beam configurations – vertical and  
 137 steerable – are available. The steering mechanism consists of two mirrors on rotating, orthogonal  
 138 axes which can direct the beam in any direction above the horizon. The inclined laser shots can  
 139 be used to calibrate the pointing and time offsets of the fluorescence telescopes. For the aerosol  
 140 analyses described in this paper, only the vertical beam is used. For this configuration, the beam  
 141 direction is maintained within  $0.04^\circ$  of vertical with full-width beam divergence of less than  $0.05^\circ$ .

142 The Nd:YAG laser emits linearly polarized light. To perform the aerosol measurements de-  
 143 scribed in this paper, it is convenient, for reasons of symmetry, to use a vertical beam that has no  
 144 net polarization. In this case equal amounts of light are scattered in the azimuthal directions of  
 145 each FD site. Therefore, the optical configuration includes depolarizing elements that randomize  
 146 the polarization by introducing a varying phase shift across the beam spot. The net polarization of  
 147 the fixed-direction vertical beam is maintained within 3% of random.

148 The nominal energy per pulse is 6.5 mJ and the pulse width is 7 ns. Variations in beam  
 149 energy are tracked to an estimated accuracy of 3%. The relative energy of each vertical laser shot  
 150 is independently measured by a photodiode and a pyroelectric probe. The CLF laser energy is  
 151 periodically calibrated and optics are cleaned. For each of these periods a new coherent data set is  
 152 defined and the corresponding period referred to as a *CLF epoch*. The length of an epoch varies  
 153 between a few months and one year.

154 The CLF fires 50 vertical shots at 0.5 Hz repetition rate every 15 minutes during the FD  
 155 data acquisition. Specific GPS timing is used to distinguish laser from air shower events. The  
 156 direction, time, and relative energy of each laser pulse is recorded at the CLF and later matched to  
 157 the corresponding laser event in the FD data.

158 An upgrade [13] to the CLF is planned for the near future. This upgrade will add a backscatter  
 159 Raman LIDAR receiver, a robotic calibration system, and replace the current flash lamp pumped  
 160 laser by a diode pumped laser.

161 **4. CLF Data Analysis**

162 The light scattered out of the CLF laser beam is recorded by the FD (see Fig. 4 for the laser-FD  
 163 geometry layout). The angles from the beam to the FD for vertical shots are in the range of  $90^\circ$   
 164 to  $120^\circ$ . As the differential scattering cross section of aerosol scattering is much smaller than the  
 165 Rayleigh scattering cross section in this range, the scattering of light is dominated by well-known  
 166 molecular processes. Laser tracks are recorded by the telescopes in the same format used for air  
 167 shower measurements. In Fig. 5, a single 7 mJ CLF vertical shot as recorded from the Los Leones  
 168 FD site is shown. In the left panel of Fig. 6, the corresponding light flux profile for the same event  
 169 is shown. In Fig. 6, right panel, an average profile of 50 shots is shown.

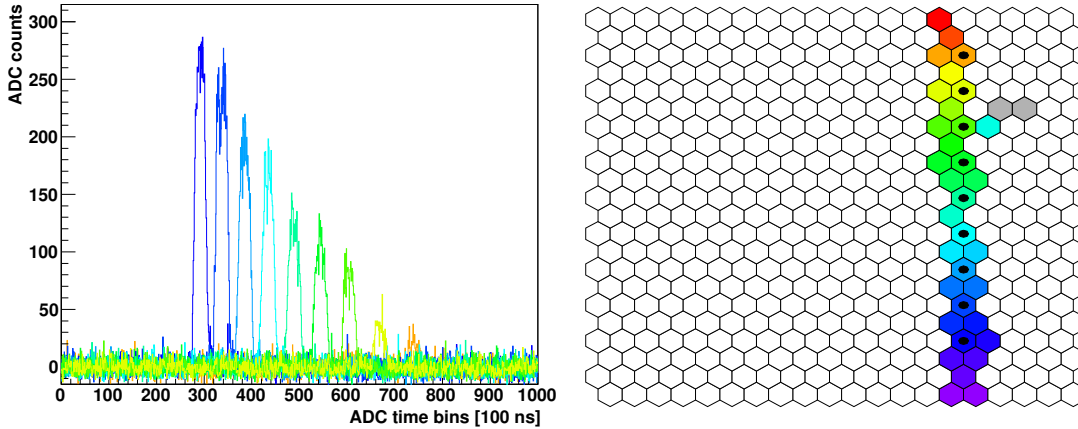


Figure 5: A 7 mJ CLF vertical event as recorded by the Los Leones FD site (distance 26 km). Left panel: ADC counts vs. time (100 ns bins). The displayed data are for the marked pixels in the right panel. Right panel: Camera trace. The color code indicates the sequence in which the pixels were triggered.

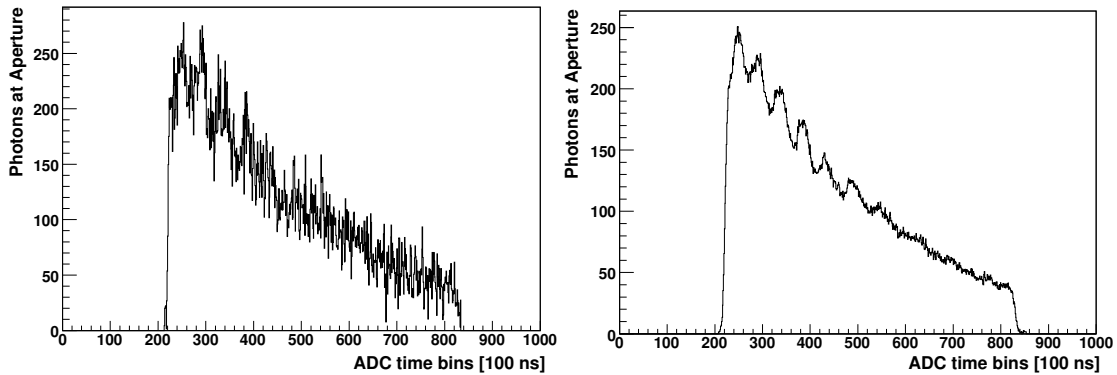


Figure 6: Left: The light flux profile of a single CLF vertical shot seen from the Los Leones FD site. The same event as shown in Fig. 5 is used. Right: 50 shots average profile.

170 Laser light is attenuated in the same way as fluorescence light as it propagates towards the  
 171 FD. Therefore, the analysis of the amount of CLF light that reaches the FD can be used to infer  
 172 the attenuation due to aerosols. The amount of light scattered out of a 6.5 mJ laser beam by the  
 173 atmosphere is roughly equivalent to the amount of UV fluorescence light produced by an EAS of

174  $5 \times 10^{19}$  eV at a distance to the telescope of about 16 km, as shown in Fig. 7. Also shown is the  
175 more attenuated light profile of an almost identical shower at a larger distance.

176 Besides determining the optical properties of the atmosphere, the identification of clouds is  
177 a fundamental task in the analysis of CLF laser shots. Clouds can have a significant impact on  
178 shower reconstruction.

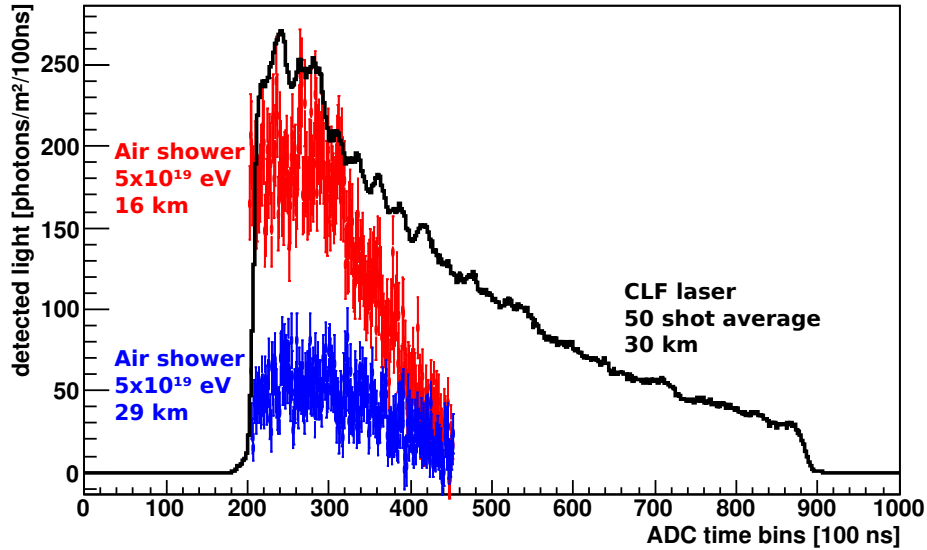


Figure 7: Comparison between a 50 shot average of vertical 6.5 mJ UV laser shot from the CLF and near-vertical cosmic ray showers measured with the FD. The cosmic ray profile has been flipped in time so that in both cases the left edge of the profile corresponds to the bottom of the FD field of view.

179 In Fig. 8, examples of various hourly profiles affected by different atmospheric conditions are  
180 shown. The modulation of the profile is due to the FD camera structure, in which adjacent pixels are  
181 complemented by light collectors. A profile measured on a night in which the aerosol attenuation  
182 is negligible is shown in panel (a). Profiles measured on nights in which the aerosol attenuation  
183 is low, average and high, are respectively shown in panels (b), (c) and (d). As conditions become  
184 hazier, the integral photon count decreases. The two bottom profiles (e) and (f) represent cloudy  
185 conditions. Clouds appear in CLF light profiles as peaks or holes depending on their position. A  
186 cloud positioned between the CLF and the FD can block the transmission of light in its travel from  
187 the emission point towards the fluorescence telescopes, appearing as a hole in the profile (e). The  
188 cloud could be positioned anywhere between the CLF and the FD site, therefore its altitude cannot  
189 be determined unambiguously. A cloud directly above the CLF appears as a peak in the profile,  
190 since multiple scattering in the cloud enhances the amount of light scattered towards the FD (f).  
191 In this case, it is possible to directly derive the altitude of the cloud from the peak in the photon  
192 profile since the laser-detector geometry is known.

193 Two independent analyses have been developed to provide hourly aerosol characterization in  
194 the FD field of view using CLF laser shots from the fixed-direction vertical configuration. To  
195 minimize fluctuations, both analyses make use of average light flux profiles normalized to a fixed

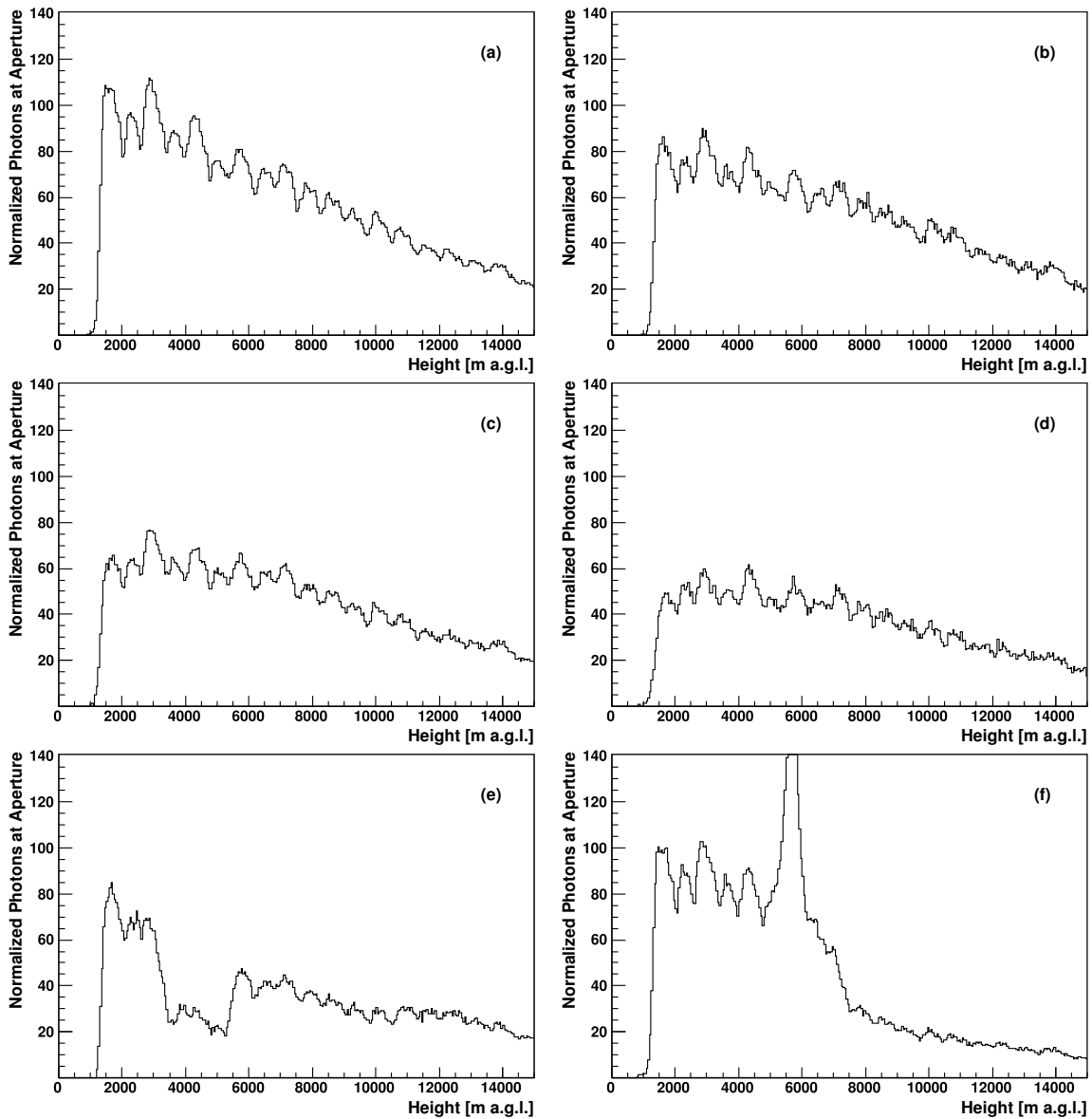


Figure 8: Examples of light profiles measured with the FD at Coihueco under various atmospheric conditions. The height is given above the FD. The number of photons at the aperture of the FD is normalized per mJ of laser energy. Shown are a reference clear night (a); low (b), average (c) and high aerosol attenuation (d); cloud between FD and laser (e); laser beam passing through cloud (f).

196 reference laser energy.

197 • The *Data Normalized Analysis* is based on the comparison of measured profiles with a refer-  
 198 ence clear night profile in which the light attenuation is dominated by molecular scattering.

199 • The *Laser Simulation Analysis* is based on the comparison of measured light flux profiles to  
 200 simulations generated in various atmospheres in which the aerosol attenuation is described  
 201 by a parametric model.



202 Measured profiles are affected by unavoidable systematics related to the FD and laser calibra-  
203 tions. Simulated profiles are also affected by systematics related to the simulation procedure. Using  
204 measurements recorded on extremely clear nights where molecular Rayleigh scattering dominates,  
205 CLF observations can be properly normalized without the need for absolute photometric calibra-  
206 tions of the FD or laser. We will refer to these nights as *reference clear nights*. At present multiple  
207 scattering effects are not included in the laser simulation code, however the aforementioned nor-  
208 malization includes this effect for Rayleigh scattering, allowing to take it into account in the Laser  
209 Simulation Analysis.

#### 210 **4.1 Reference clear nights**

211 In *reference clear nights*, the attenuation due to aerosols is minimal compared to the uncertainty  
212 of total attenuation, the scattering is dominated by the molecular part. In such a clear night, the  
213 measured light profiles are larger than profiles affected by aerosol attenuation, indicating maximum  
214 photon transmission. Those profiles have shapes that are compatible with a profile simulated under  
215 atmospheric conditions in which only molecular scattering of the light is used. Reference clear  
216 night profiles are found by comparing measured profiles to simulated average profiles of 50 CLF  
217 shots in a purely molecular atmosphere at an energy of 6.5 mJ. Using the Malargüe Monthly Models  
218 described in section 2, the procedure is repeated 12 times using the appropriate atmospheric density  
219 profiles.

220 The method chosen for the comparison is the unnormalized Kolmogorov-Smirnov test. This  
221 test returns a pseudo-probability<sup>2</sup>  $P_{KS}$  that the analyzed profile is compatible with the clear one on  
222 the basis of shape only, without taking into account the normalization. For each profile,  $P_{KS}$  and  
223 the ratio  $R$  between the total number of photons of the measured profile and the simulated clear  
224 one is calculated. In each CLF epoch, the search for the reference clear night is performed among  
225 profiles having high values of  $P_{KS}$  and  $R$ . A search region is defined by extracting the mean values  
226  $\mu_{P_{KS}}$ ,  $\mu_R$  and the RMS  $\sigma_{P_{KS}}$ ,  $\sigma_R$  of the distribution of each parameter. Both parameters are required  
227 to be above their average  $\mu + \sigma$ . Profiles belonging to the search region are grouped by night,  
228 and nightly averages for the two parameters are computed  $\langle P_{KS} \rangle$  and  $\langle R \rangle$ . A list of candidate clear  
229 nights with associated pseudo-probabilities and number of profiles is produced. The night with the  
230 highest  $\langle P_{KS} \rangle$  is selected and – if available – at least 4 candidate profiles are averaged to smooth  
231 fluctuations. Once identified, the associated  $\langle R \rangle$  is the normalization constant that fixes the energy  
232 scale between real and simulated profiles needed in the Laser Simulation Analysis. We estimated  
233 the uncertainty introduced by the method chosen to identify the reference clear night by varying  
234 the cuts that determine the list of candidate clear nights and the selection criteria that identify the  
235 chosen reference night in the list. The normalization constant used to fix the energy scale between  
236 real and simulated CLF profiles changes by less than 3%.

237 As a final check to verify that the chosen nights are reference clear nights we analyze the  
238 measurement of the aerosol phase function (APF) [7] for that night, measured by the APF monitor  
239 (see Sec. 1). The molecular part of the phase function  $P_{mol}(\theta)$  can be calculated analytically from  
240 temperature, pressure and humidity at ground provided by weather stations. After subtraction of the

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<sup>2</sup>the Kolmogorov-Smirnov test calculates probabilities for histograms containing counts, therefore here the returned value is defined as a pseudo-probability.

241 molecular phase function, the aerosol phase function remains. In a reference clear night, the total  
242 phase function is dominated by the molecular part with almost no contribution from aerosols. Since  
243 the APF light source only fires approximately horizontally, this method to find the reference nights  
244 is insensitive to clouds, so it can only be used as a verification of reference nights that were found  
245 using the procedure described in this section. After verification, the reference night is assumed to  
246 be valid for the complete CLF epoch. In Fig. 8, panel (a), an averaged light profile of a reference  
247 night is shown.

## 248 4.2 Data Normalized Analysis

### 249 4.2.1 Building hourly laser profiles and cloud identification

250 Using the timing of the event, the time bins of the FD data are converted to height at the laser  
251 track using the known positions of the FD and CLF. The difference in altitude between telescope  
252 and laser station and the curvature of the Earth, which causes a height difference on the order of  
253 50 m, are taken into account. The number of photons is scaled to the number of photons of a  
254 1 mJ laser beam (the normalization energy is an arbitrary choice that has no implications on the  
255 measurements). The CLF fires sets of 50 vertical shots every 15 minutes. For each set, an average  
256 profile is built.

257 Clouds are then marked by comparing the photon transmission  $T_{\text{aer}}$  (see Eq. 2.5) of the quarter  
258 hour profiles  $T_{\text{quarter}}$  to the clear profile  $T_{\text{clear}}$  bin by bin. A ratio  $T_{\text{quarter}}/T_{\text{clear}}$  of less than 0.1  
259 indicates a hole in the profile that is caused by a cloud between the laser beam and the FD. A  
260 ratio larger than 1.3 indicates that the laser beam passed through a cloud directly above the CLF  
261 causing a spike in the profile. In both cases, the minimum cloud height  $h_{\text{cloud}}$  is set to the height  
262 corresponding to the lower edge of the anomaly. Only bins corresponding to heights lower than this  
263 cloud height are used for the optical depth analysis. Hours are marked as cloudy only if clouds are  
264 found in at least two quarter hour sets, see Fig. 9. If there are no such discontinuities, then  $h_{\text{cloud}}$  is  
265 set to the height corresponding to the top of the FD camera field of view.

266 After  $h_{\text{cloud}}$  is determined, a preliminary full hour profile is made by averaging all the available  
267 quarter hour profiles. One or more quarter hour profiles can be missing due to the start or stop of FD  
268 data taking, heavy fog, or problems at the CLF. Only one quarter hour profile is required to make  
269 a full hour profile. Outlying pixels that triggered randomly during the laser event are rejected and  
270 a new full hour profile is calculated. To eliminate outliers in single bins that can cause problems  
271 in the optical depth analysis, the quarter hour profiles are subjected to a smoothing procedure by  
272 comparing the current profile to the preliminary full hour profile. After multiple iterations of this  
273 procedure, the final full hour profile is constructed.

274 The maximum valid height  $h_{\text{valid}}$  of the profile is then determined. If there is a hole in the  
275 profile of two bins or more due to the rejection of outliers or clouds,  $h_{\text{valid}}$  is marked at that point.  
276 As with  $h_{\text{cloud}}$ , if no such holes exist, then  $h_{\text{valid}}$  is set to the height corresponding to the top of the  
277 FD camera field of view. If  $h_{\text{valid}}$  is lower than  $h_{\text{cloud}}$ , the minimum cloud height is set to be the  
278 maximum valid height. Points above  $h_{\text{valid}}$  are not usable for data analysis.

### 279 4.2.2 Aerosol optical depth calculation

280 Using the laser-FD viewing geometry shown in Fig. 4, and assuming that the atmosphere is hori-

281 zontally uniform, it can be shown [14] that the vertical aerosol optical depth is

$$\tau_{\text{aer}}(h) = -\frac{\sin \varphi_1 \sin \varphi_2}{\sin \varphi_1 + \sin \varphi_2} \left( \ln \left( \frac{N_{\text{obs}}(h)}{N_{\text{mol}}(h)} \right) - \ln \left( 1 + \frac{S_{\text{aer}}(\theta, h)}{S_{\text{mol}}(\theta, h)} \right) \right), \quad (4.1)$$

282 where  $N_{\text{mol}}(h)$  is the number of photons from the reference clear profile as a function of height,  
 283  $N_{\text{obs}}(h)$  is the number of photons from the observed hourly profile as a function of height and  
 284  $\theta$  is defined in Fig. 4.  $S_{\text{aer}}(\theta, h)$  and  $S_{\text{mol}}(\theta, h)$  are the fraction of photons scattered out of the  
 285 laser beam per unit height by aerosols and air molecules, respectively.  $S(\theta, h)$  is the product of  
 286 the differential cross section for scattering towards the FD multiplied by the number density of  
 287 scattering centers. For vertical laser shots ( $\varphi_1 = \pi/2$ ),  $S_{\text{aer}}(\theta, h)$  is small compared to  $S_{\text{mol}}(\theta, h)$   
 288 because typical aerosols scatter predominately in the forward direction. Thus the second term in  
 289 Eq. 4.1 can be neglected to first order and Eq. 4.1 becomes

$$\tau_{\text{aer}}(h) = \frac{\ln N_{\text{mol}}(h) - \ln N_{\text{obs}}(h)}{1 + \text{cosec } \varphi_2}. \quad (4.2)$$

290 With these simplifications, the CLF optical depth measurements depend only on the elevation angle  
 291 of each laser track segment and the number of photons from the observed track and the reference  
 292 clear profile. The aerosol optical depth may be calculated directly from Eq. 4.2.

293  $\tau_{\text{aer}}$  is calculated for each bin in the hourly profile. The optical depth at the altitude of the  
 294 telescope is set to zero and is interpolated linearly between the ground and the beginning of  $\tau_{\text{aer}}^{\text{meas}}$   
 295 corresponding to the bottom of the field of view of the telescope. This calculation provides a  
 296 first guess of the measured optical depth  $\tau_{\text{aer}}^{\text{meas}}$ , assuming that aerosol scattering from the beam  
 297 does not contribute to the track profile. While this is true for regions of the atmosphere with low  
 298 aerosol content,  $\tau_{\text{aer}}^{\text{meas}}$  is only an approximation of the true  $\tau_{\text{aer}}$  if aerosols are present. To overcome  
 299 this,  $\tau_{\text{aer}}^{\text{meas}}$  is differentiated to obtain an estimate of the aerosol extinction  $\alpha_{\text{aer}}(h)$  in an iterative  
 300 procedure.

301 It is possible to find negative values of  $\alpha_{\text{aer}}$ . They are most likely due to statistical uncertainties  
 302 in the fit procedure, or can be due to systematic effects. As the laser is far from the FD site, the  
 303 brightest measured laser light profile, after accounting for relative calibrations of the FD and the  
 304 laser, occurs during a clear reference night. However, there are uncertainties (see Sec. 4.2.3) in  
 305 the calibrations that track the FD PMT gains and the CLF laser energy relative to the reference  
 306 period. Therefore, in some cases it is possible that parts of a laser light profile recorded during a  
 307 period of interest can slightly exceed the corresponding profile recorded during a reference period.  
 308 Typically, these artifacts occur during relatively clear conditions when the aerosol concentration is  
 309 low. The effect could also happen if a localized scattering region, for example a small cloud that  
 310 was optically too thin to be tagged as a cloud, remained over the laser and scattered more light out  
 311 of the beam. However, since negative values of  $\alpha_{\text{aer}}$  are unphysical, they are set to zero. Since the  
 312 integrated  $\alpha_{\text{aer}}$  values are renormalized to the measured  $\tau_{\text{aer}}^{\text{meas}}$  profile, this procedure does not bias  
 313 the aerosol profile towards larger values. The remaining values of  $\alpha_{\text{aer}}$  are numerically integrated  
 314 to get the fit optical depth  $\tau_{\text{aer}}^{\text{fit}}$ . The final values for  $\alpha_{\text{aer}}$  and  $\tau_{\text{aer}}^{\text{fit}}$  can be used for corrections in light  
 315 transmission during air shower reconstruction.

316 In Fig. 9, examples of laser and  $\tau_{\text{aer}}$  profiles are displayed from an average night and from

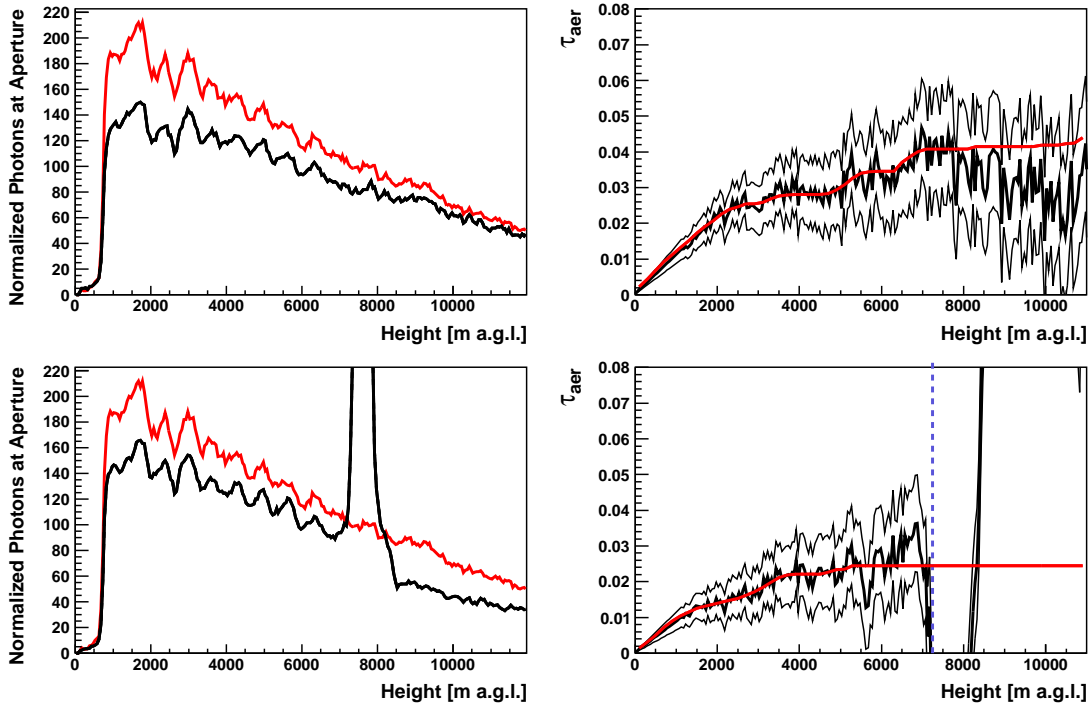


Figure 9: Examples of light profiles and vertical aerosol optical depth  $\tau_{\text{aer}}$  measured with the FD at Los Morados during an average night (top) and with the laser passing through a cloud (bottom). The height is given above the FD, the light profile was normalized to a laser shot of 1 mJ. The black traces in left panels represent the hourly profiles, the red traces the reference clear nights. In the right panels, the thick black line represents  $\tau_{\text{aer}}^{\text{meas}}$ , the red line  $\tau_{\text{aer}}^{\text{fit}}$ . The upper and lower traces correspond to the uncertainties. In the bottom right panel, the estimated cloud height is indicated by the vertical blue dotted line.

317 a cloudy night when the laser pulse passed through a cloud. In the left panels the black traces  
 318 represent the hourly profiles and the red traces represent the reference clear nights. In the right  
 319 panels  $\tau_{\text{aer}}^{\text{meas}}$  and  $\tau_{\text{aer}}^{\text{fit}}$  measurements as a function of height are shown. The black curve is  $\tau_{\text{aer}}^{\text{meas}}$   
 320 and  $\tau_{\text{aer}}^{\text{fit}}$  is overlaid in red. The upper and lower traces correspond to the uncertainties. In the  
 321 cloudy night, a large amount of light is scattered by a cloud starting from a height of approximately  
 322 7000 m. In the bottom right panel, the minimum height at which a cloud was detected is indicated  
 323 by a vertical blue line.

### 324 4.2.3 Determination of Uncertainties

325 Systematic uncertainties are due to uncertainty in the relative calibration of the FD ( $\sigma_{\text{cal}}$ ), the rela-  
 326 tive calibration of the laser ( $\sigma_{\text{las}}$ ), and the relative uncertainty in determination of the reference clear  
 327 profile ( $\sigma_{\text{ref}}$ ). A conservative estimate for each of these is 3%. These uncertainties are propagated  
 328 in quadrature for both the hourly profile ( $\sigma_{\text{sys},\text{hour}}$ ) and the clear profile ( $\sigma_{\text{sys},\text{clear}}$ ). The systematic  
 329 uncertainty strongly depends on the height. Thus, the viewing angle from the FD to the laser must  
 330 be taken into account. The final systematic uncertainty on  $\tau_{\text{aer}}^{\text{meas}}$  is calculated by adding  $\sigma_{\text{sys},\text{hour}}$

331 and  $\sigma_{\text{sys},\text{clear}}$  in quadrature, along with the height correction,

$$\sigma_{\text{sys}} = \frac{1}{1 + \csc \varphi_2} \sqrt{(\sigma_{\text{sys},\text{hour}})^2 + (\sigma_{\text{sys},\text{clear}})^2}. \quad (4.3)$$

332 Two separate profiles are then generated corresponding to the values of  $\tau_{\text{aer}}^{\text{meas}} \pm \sigma_{\text{sys}}$ , as shown on  
 333 the right panels of Fig. 9.

334 The statistical uncertainty  $\sigma_{\text{stat}}$  is due to fluctuations in the quarter hour profiles and is consid-  
 335 ered by dividing the RMS by the mean of all quarter hour profiles at each height. These statistical  
 336 uncertainties are assigned to each bin of the  $\tau_{\text{aer}}^{\text{meas}} \pm \sigma_{\text{sys}}$  profiles. These two profiles are then pro-  
 337 cessed through the same slope fit procedure and integration as  $\tau_{\text{aer}}^{\text{meas}}$  (see Sec. 4.2.2) to obtain the  
 338 final upper and lower bounds on  $\tau_{\text{aer}}^{\text{fit}}$ .

### 339 4.3 Laser Simulation Analysis

#### 340 4.3.1 Atmospheric Model Description

341 The atmospheric aerosol model adopted in this analysis is based on the assumption that the aerosol  
 342 distribution in the atmosphere is horizontally uniform. The aerosol attenuation is described by  
 343 two parameters, the *aerosol horizontal attenuation length*  $L_{\text{aer}}$  and the *aerosol scale height*  $H_{\text{aer}}$ .  
 344 The former describes the light attenuation due to aerosols at ground level, the latter accounts for  
 345 its dependence on the height. With this parameterization, the expression of the aerosol extinction  
 346  $\alpha_{\text{aer}}(h)$  and the vertical aerosol optical depth  $\tau_{\text{aer}}(h)$  are given by

$$\alpha_{\text{aer}}(h) = \frac{1}{L_{\text{aer}}} \left[ \exp\left(-\frac{h}{H_{\text{aer}}}\right) \right], \quad (4.4)$$

$$\tau_{\text{aer}}(h_2 - h_1) = \int_{h_1}^{h_2} \alpha_{\text{aer}}(h) dh = -\frac{H_{\text{aer}}}{L_{\text{aer}}} \left[ \exp\left(-\frac{h_2}{H_{\text{aer}}}\right) - \exp\left(-\frac{h_1}{H_{\text{aer}}}\right) \right]. \quad (4.5)$$

348 Using Eq. 2.5, the aerosol transmission factor along the path  $s$  can be written as

$$T_{\text{aer}}(s) = \exp\left(\frac{H_{\text{aer}}}{L_{\text{aer}} \sin \varphi_2} \left[ \exp\left(-\frac{h_2}{H_{\text{aer}}}\right) - \exp\left(-\frac{h_1}{H_{\text{aer}}}\right) \right]\right), \quad (4.6)$$

349 where  $h_1$  and  $h_2$  are the altitudes above sea level of the first and second observation levels and  $\varphi_2$   
 350 is the elevation angle of the light path  $s$  (cf. Fig. 4).

351 The Planetary Boundary Layer (PBL) is the lower part of the atmosphere directly in contact  
 352 with the ground, it is variable in height and the aerosol attenuation of light can be assumed as  
 353 constant. The PBL is neglected in this two parameters approach. In the near future, the *mixing layer*  
 354 *height* will be introduced as a third parameter to take into account the PBL. In the Data Normalized  
 355 Analysis,  $\tau_{\text{aer}}(h)$  is calculated per height bin in the hourly profile, therefore this analysis is sensible  
 356 to the PBL and takes it into account.

#### 357 4.3.2 Building quarter-hour CLF profiles and generating a grid of simulations

358 As described in section 3, the CLF fires 50 vertical shots every 15 minutes. The profile of each  
 359 individual event of the set is normalized to a reference energy  $E_{\text{ref}}$ , to compute an average profile

360 equivalent to  $E_{\text{ref}}$  for each group of 50 shots. In the following, this average light profile will be  
 361 referred to simply as “profile”. A grid of simulations at the reference energy  $E_{\text{ref}}$  is generated,  
 362 fixing the initial number of photons emitted by the simulated vertical laser source. While energy  
 363 and geometry of the simulated laser event are fixed, the atmospheric conditions, defined by aerosol  
 364 and air density profiles, are variable and described by means of a two parameters models. The  
 365 aerosol attenuation profile in the atmosphere, according to the model adopted, is determined setting  
 366 values for  $L_{\text{aer}}$  and  $H_{\text{aer}}$ . For this analysis, the grid is generated by varying  $L_{\text{aer}}$  from 5 to 150 km  
 367 in steps of 2.5 km and  $H_{\text{aer}}$  from 0.5 km to 5 km in steps of 0.25 km, corresponding to a total of  
 368 1121 profiles. The air density profiles are provided by the Malargüe Monthly Models, as discussed  
 369 in Sec 2. Therefore, a total of 13 452 profiles are simulated to reproduce the wide range of possible  
 370 atmospheric conditions on site. In the left panel of Fig. 10, a measured CLF profile (in blue) is  
 371 shown together with four out of the 1 121 monthly CLF simulated profiles (in red) used for the  
 372 comparison procedure. In the right panel, the four aerosol profiles  $\tau_{\text{aer}}(h)$  corresponding to the  
 373 simulated CLF profiles are shown.

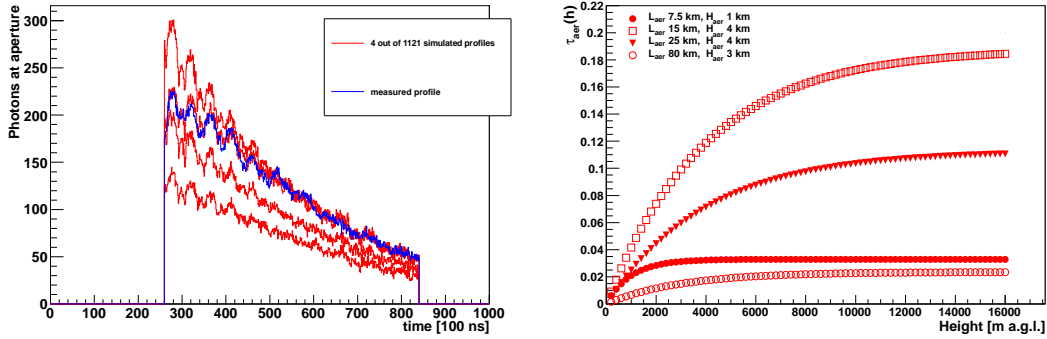


Figure 10: Left: Four out of the 1 121 simulated profiles of a monthly grid (red), superimposed to a measured profile (blue). Right: The four aerosol profiles corresponding to the simulated CLF profiles. In order, from top to bottom,  $\tau_{\text{aer}}(h)$  profiles on the right correspond to CLF profiles on the left from bottom to top.

374 The relative energy scale between measured and simulated laser profiles has to be fixed. The  
 375 amplitude of CLF light profiles from laser shots fired at the same energy depends on the aerosol  
 376 attenuation in the atmosphere and on absolute FD and CLF calibrations, that are known within  
 377 10% and 7%, respectively. The ratio of the amplitudes of the simulated clear night to the measured  
 378 reference clear night  $R$  as defined in Sec. 4.1 returns the normalization constant that fixes the  
 379 relative energy scale between measured and simulated laser profiles. Using this normalization  
 380 procedure, the dependence on FD or CLF absolute calibrations is avoided and only the relative  
 381 uncertainty (daily fluctuations) of the laser probes (3%) and FD calibration constants (3%) must  
 382 be taken into account. This procedure is repeated for each CLF epoch data set. Average measured  
 383 profiles are scaled by dividing the number of photons in each bin by the normalization constant of  
 384 the corresponding epoch before measuring the aerosol attenuation.

### 385 4.3.3 Optical depth determination and cloud identification

386 For each quarter hour average profile, the aerosol attenuation is determined obtaining the pair  
387  $L_{\text{aer}}^{\text{best}}$ ,  $H_{\text{aer}}^{\text{best}}$  corresponding to the profile in the simulated grid closest to the analyzed event. The  
388 quantification of the difference between measured and simulated profiles and the method to identify  
389 the closest simulation are the crucial points of this analysis. After validation tests on simulations  
390 of different methods, finally the pair  $L_{\text{aer}}^{\text{best}}$  and  $H_{\text{aer}}^{\text{best}}$  chosen is the one that minimizes  
391 the square difference  $D^2$  between measured and simulated profiles computed for each bin, where  
392  $D^2 = [\sum_i (\Phi_i^{\text{meas}} - \Phi_i^{\text{sim}})^2]$  and  $\Phi_i$  are reconstructed photon numbers at the FD aperture in each  
393 time bin. In Fig. 11, an average measured profile as seen from Los Leones compared to the simulated  
394 chosen profile is shown. The small discrepancy between measured and simulated profiles,  
395 corresponding to boundaries between pixels, has no effect on the measurements.

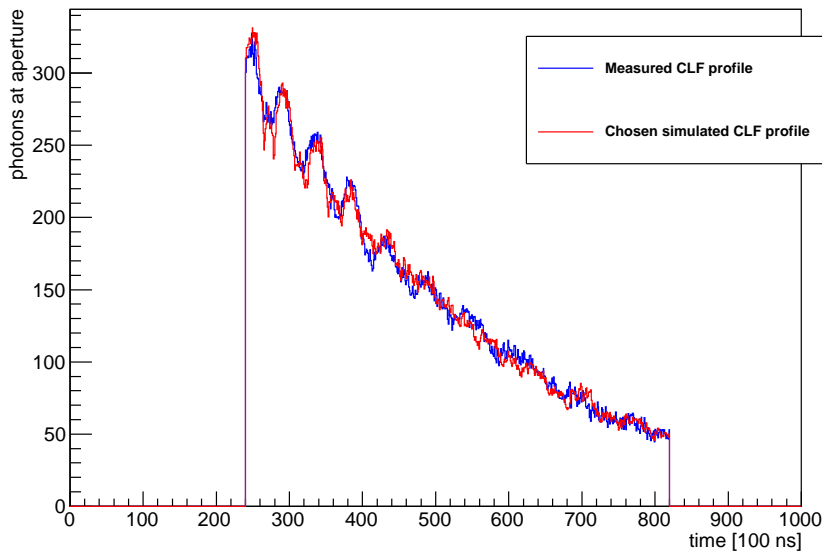


Figure 11: A measured CLF profile (blue) together with the chosen simulated (red).

396 Before the aerosol optical depth is determined, the average profile is checked for integrity and  
397 for clouds in the field of view in order to establish the maximum altitude of the corresponding  
398 aerosol profile. The procedure for the identification of clouds works on the profile of the difference  
399 in photons for each bin between the measured profile under study and the closest simulated profile  
400 chosen from the grid. With this choice, the baseline is close to zero and peaks or holes in the  
401 difference profile are clearly recognizable. The algorithm developed uses the bin with the highest  
402 or lowest signal and the signal-to-noise ratio to establish the presence of a cloud and therefore  
403 determines its altitude. The quarter hour information on the minimum cloud layer height needed in  
404 the aerosol attenuation characterization is then stored.

405 If the average profile under study shows any anomaly or if a cloud is detected between the laser  
406 track and the FD, it is rejected. If a cloud is detected above the laser track, the profile is truncated  
407 at the cloud base height and this lower part of the profile is reanalyzed, since the first search for

408 clouds only identifies the optically thicker cloud layer. If a lower layer of clouds is detected in the  
 409 truncated profile, or the cloud height is lower than 5500 m a.s.l., the profile is rejected.

410 If no clouds are detected (either in the whole average profile or in the lower part), the pair  $L_{\text{aer}}^{\text{best}}$ ,  
 411  $H_{\text{aer}}^{\text{best}}$ , together with the maximum height of the profile are stored and the procedure is completed.  
 412 The quarter hour  $\tau_{\text{aer}}(h)$  profile is calculated according to Eq. 4.5 together with the associated  
 413 statistical and systematic uncertainties. The information is stored, and the quarter hour  $\tau_{\text{aer}}(h)$   
 414 profiles are averaged to obtain the hourly vertical aerosol optical depth profile and the aerosol  
 415 extinction profile  $\alpha_{\text{aer}}(h)$ .

#### 416 4.3.4 Determination of Uncertainties

417 Uncertainties on the vertical aerosol optical depth  $\tau_{\text{aer}}(h)$  are due to the choice of the reference clear  
 418 night, to the assumption that a parametric model can be adopted to describe the aerosol attenuation,  
 419 to the relative uncertainty of nightly FD calibration constants – converting ADC counts to photon  
 420 numbers – and CLF calibration constants – converting laser probe measurements to laser energy,  
 421 and to the method used to choose the best matching simulated profile.

422 To estimate the total uncertainty, the different contributions mentioned above are evaluated and  
 423 summed in quadrature. The uncertainty on the choice of the reference clear night and the relative  
 424 FD and CLF calibrations directly affect the light profile, therefore they are summed in quadrature to  
 425 estimate their total contribution to the uncertainty on the photon profile, which is then propagated  
 426 to the aerosol profile. The uncertainty introduced by the method used to identify the reference clear  
 427 night is quoted at 3% as described in Sec. 4.1; the contributions arising from the daily variations  
 428 on the FD and CLF calibration constants are both quoted at 3% level [4, 2]. Therefore, the total  
 429 uncertainty of the number of photons in the profile is less than 5.2%. The effect on the aerosol  
 430 profile  $\tau_{\text{aer}}(h)$  of this total uncertainty on the light profile is evaluated by increasing and decreasing  
 431 the number of photons in the current CLF profile by 5.2% and searching for the corresponding  
 432  $\tau_{\text{min}}(h)$  and  $\tau_{\text{max}}(h)$  profiles. At each height, the error bars are given by  $\tau_{\text{best}}(h) - \tau_{\text{min}}(h)$  and  
 433  $\tau_{\text{max}}(h) - \tau_{\text{best}}(h)$ .

434 The contribution due to the parametric description of the aerosol attenuation of light was de-  
 435 termined comparing the hourly vertical aerosol optical depth profiles obtained with the Laser Sim-  
 436 ulation Analysis to the corresponding profiles obtained with the Data Normalized Analysis, which  
 437 is not using a parametric model for the aerosol attenuation. This comparison for each height shows  
 438 that aerosol profiles are compatible within 2% at each altitude.

439 The uncertainty related to the method defined to choose the best matching simulated profile  
 440 as a function of the altitude is also estimated. As described in Sec. 4.3.3, the parameters  $L_{\text{aer}}^{\text{best}}$  and  
 441  $H_{\text{aer}}^{\text{best}}$  minimize the quantity  $D^2 = [\sum_i (\Phi_i^{\text{real}} - \Phi_i^{\text{sim}})^2]$ . The method is repeated a second time in  
 442 order to find the couple  $L_{\text{aer}}^{\text{err}}$  and  $H_{\text{aer}}^{\text{err}}$  corresponding to the quantity  $D^{2'}$  nearest to  $D^2$ . This profile  
 443 is used to estimate  $\tau_{\text{err}}(h)$ , the uncertainty of the aerosol profile. Therefore, the uncertainty related  
 444 to the method  $\sigma_{\text{method}}(h)$  associated with  $\tau_{\text{aer}}(h)$  for each height bin is given by the difference  
 445  $\tau_{\text{best}}(h) - \tau_{\text{err}}(h)$ . This uncertainty is negligible with respect to the previous contributions.

446 The Laser Simulation Analysis extrapolates the aerosol attenuation for each quarter hour CLF  
 447 profile; then the four measured aerosol profiles are averaged to obtain the hourly information  
 448 needed for the air shower reconstruction. The same procedure is adopted to obtain the uncer-



449 tainties related to the hourly aerosol attenuation profile. As a final step, the hourly uncertainty on  
450  $\tau_{\text{aer}}(h)$  is propagated to the aerosol extinction  $\alpha_{\text{aer}}(h)$ .

## 451 5. Comparison of the two analyses

452 The two analyses described in this paper independently produce hourly aerosol profiles. In the Data  
453 Normalized Analysis, measured laser light profiles are compared with an averaged light profile of  
454 a reference clear night. The Laser Simulation Analysis is a procedure based on the comparison of  
455 CLF laser light profiles with those obtained by a grid of simulated profiles in different parameter-  
456 ized atmospheric conditions.

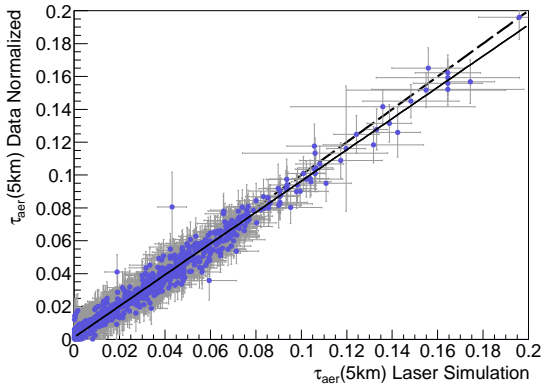
457 Both analyses have been applied to the whole data set of CLF laser shots. A systematic com-  
458 parison of the results shows excellent agreement. Since aerosols are concentrated in the lower  
459 part of the troposphere, we compare the total vertical aerosol optical depth at 5 km above the FD  
460 which includes most of the aerosols. The correlation of  $\tau_{\text{aer}}(5 \text{ km})$  results of the Data Normalized  
461 Analysis and the results of the Laser Simulation Analysis is shown in Fig. 12. The dashed line is  
462 a diagonal indicating perfect agreement between the analyses. The solid line is an actual fit to the  
463 data. It is compatible with the diagonal. The reliability of the parametric aerosol model adopted  
464 and the validity of both methods can be concluded. In high aerosol attenuation conditions, com-  
465 patible with the presence of a high Planetary Boundary Layer, that the Laser Simulation Analysis  
466 does not take into account, the difference between the measured  $\tau_{\text{aer}}(5 \text{ km})$  is within the quoted  
467 systematic uncertainties. Also shown in Fig. 12 are examples for the  $\tau_{\text{aer}}(h)$  profiles estimated with  
468 the two analyses for conditions with low, average and high aerosol attenuation, respectively.

469 The high compatibility of the two analyses guarantees a reliable shower reconstruction using  
470 aerosol attenuation for the highest possible number of hours. Nearly six years of data have been  
471 collected and analyzed (from January 2005 to September 2010). Long term results are shown in the  
472 following figures. In the left column of Fig. 13, the time profile of the vertical aerosol optical depth  
473 measured 5 km above ground using the Los Leones, Los Morados and Coihueco FD sites is shown.  
474 The Loma Amarilla FD site is too far from the CLF to obtain fully reliable results. The XLF is  
475 closer and will produce aerosol attenuation measurements for Loma Amarilla in the near future.  
476 Values of  $\tau_{\text{aer}}(5 \text{ km})$  measured during austral winter are systematically lower than in summer.

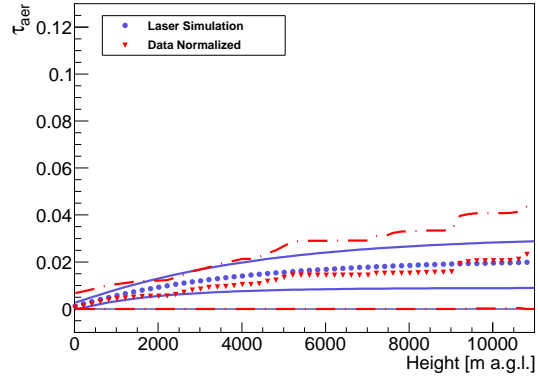
477 In the right column of Fig. 13, the  $\tau_{\text{aer}}(5 \text{ km})$  distribution over six years is shown for aerosol  
478 attenuation measurements using the FD sites at Los Leones, Los Morados and Coihueco. More  
479 than 5000 hours of aerosol profiles have been measured with each FD. The average  $\tau_{\text{aer}}(5 \text{ km})$   
480 measured with different FD sites are compatible. The average value measured above Coihueco is  
481 slightly smaller due to the higher position ( $\sim 300 \text{ m}$ ) of the Coihueco FD site with respect to Los  
482 Leones and Los Morados.

## 483 6. Conclusions

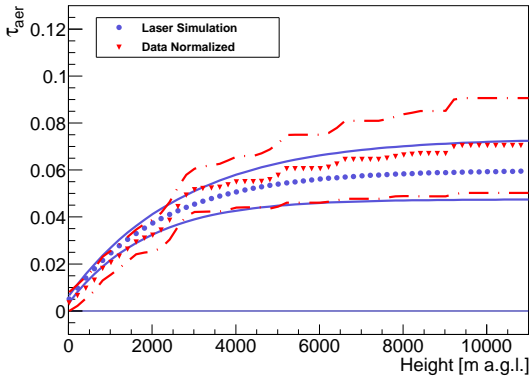
484 Aerosols cause the largest time-varying corrections applied during the reconstruction of extensive  
485 air showers measured with the fluorescence technique. They are highly variable on a time scale  
486 of one hour. Neglecting the aerosol attenuation leads to a bias in the energy reconstruction of air



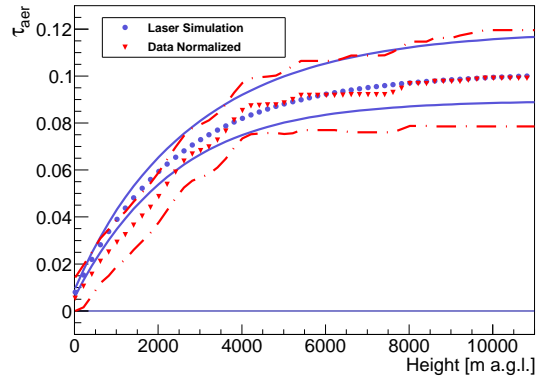
(a) Correlation between the analyses.



(b) Low aerosol attenuation.



(c) Average aerosol attenuation.



(d) High aerosol attenuation.

Figure 12: Correlation between  $\tau_{\text{aer}}(5 \text{ km})$  obtained with the Laser Simulation and the Data Normalized procedures (a) for the year 2008 (compatibility of results is equivalent in the other years). The dashed line is a diagonal indicating perfect agreement, the solid line is a fit to the data. Also shown is the vertical aerosol optical depth profile  $\tau_{\text{aer}}(h)$  above ground from Laser Simulation (blue) and Data Normalized (red) analyses in atmospheric conditions with a low (b), average (c), and high (d) aerosol concentration together with the corresponding uncertainties. The laser data was recorded with the FD at Los Leones on July 8th, 2008 between 8 and 9 a.m., April 4th, 2008 between 4 and 5 a.m., and January 5th, 2008 between 3 and 4 a.m. local time, respectively.

487 showers by 8 to 25% in the energy range measured by the Pierre Auger Observatory. This includes  
 488 a tail of 7% of all showers with an energy correction larger than 30%.

489 To determine the vertical aerosol optical depth profiles for the Pierre Auger Observatory, verti-  
 490 cal laser shots from a Central Laser Facility in the center of the SD array are analyzed. The Central  
 491 Laser Facility fires 50 vertical shots every 15 minutes during the FD data acquisition, covering  
 492 the whole FD data taking period. Two methods were developed to analyze the CLF laser shots.  
 493 The Data Normalized method compares the measured laser light profile to a reference clear night,  
 494 the Laser Simulation method compares the measured profile with a set of simulated profiles. In  
 495 addition, the minimum cloud heights over the central part of the array are extracted from the laser  
 496 data. The two methods are compared and a very good agreement was found. Nearly six years of

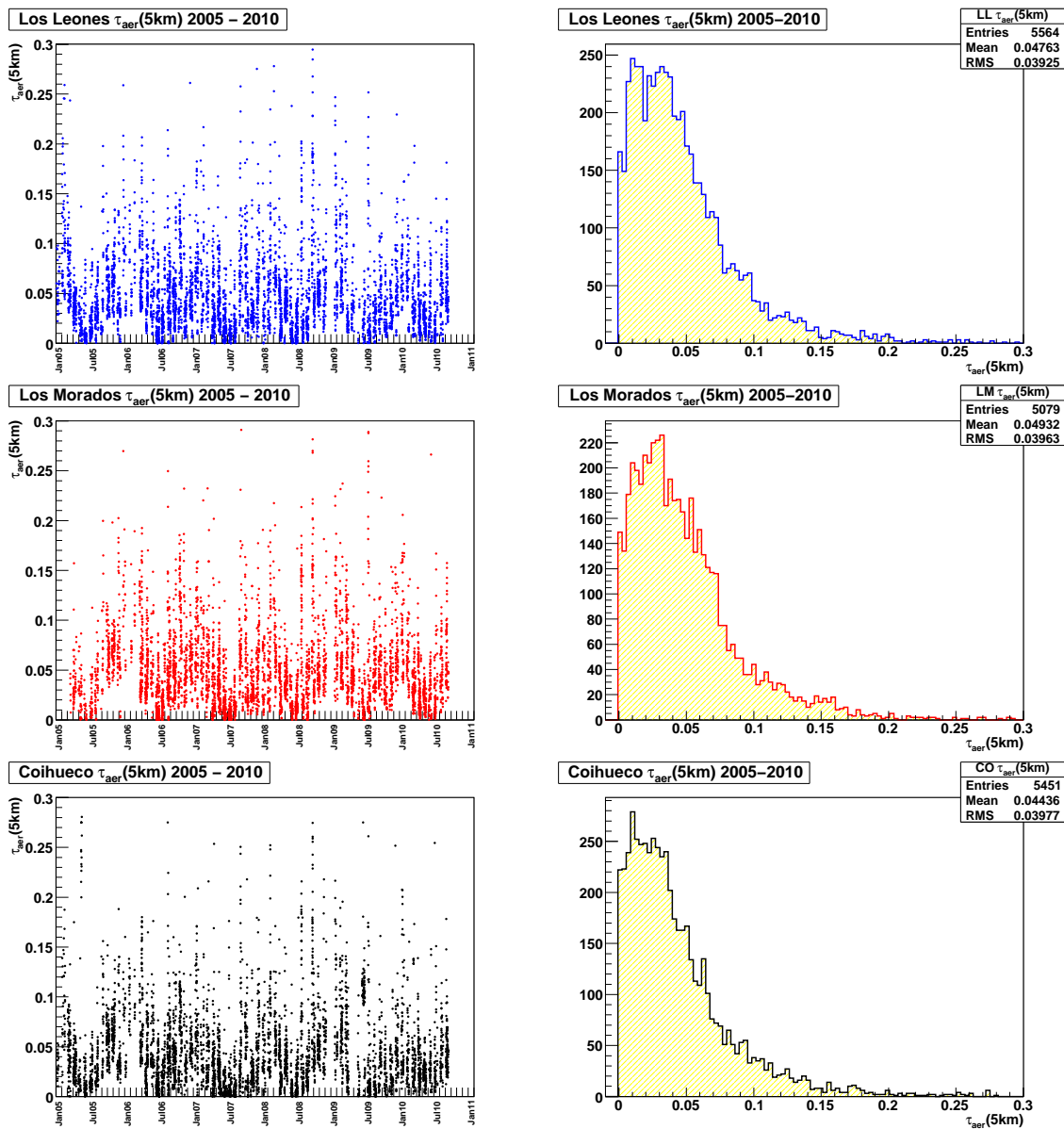


Figure 13: Vertical aerosol optical depth  $\tau_{\text{aer}}$  5 km above the ground, measured with the Los Leones (top), Los Morados (middle) and Coihueco (bottom) FD sites. Left column: Hourly measurements of  $\tau_{\text{aer}}$  versus time. Right column: Distribution of hourly measurements of  $\tau_{\text{aer}}$ . Average values are very similar.

497 data have been analyzed with both methods (from January 2005 to September 2010). In air shower  
 498 reconstructions, mainly the results of the Data Normalized method are used. The data from the  
 499 Laser Simulation method is used to fill holes in the data set where the Data Normalized method is  
 500 not able to produce a result.

## Acknowledgments

The successful installation, commissioning, and operation of the Pierre Auger Observatory including the Central Laser Facility would not have been possible without the strong commitment and effort from the technical and administrative staff in Malargüe.

We are very grateful to the following agencies and organizations for financial support: Comisión Nacional de Energía Atómica, Fundación Antorchas, Gobierno De La Provincia de Mendoza, Municipalidad de Malargüe, NDM Holdings and Valle Las Leñas, in gratitude for their continuing cooperation over land access, Argentina; the Australian Research Council; Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Financiadora de Estudos e Projetos (FINEP), Fundação de Amparo à Pesquisa do Estado de Rio de Janeiro (FAPERJ), Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP), Ministério de Ciência e Tecnologia (MCT), Brazil; AVCR AV0Z10100502 and AV0Z10100522, GAAV KJB100100904, MSMT-CR LA08016, LC527, 1M06002, MEB111003, and MSM0021620859, Czech Republic; Centre de Calcul IN2P3/CNRS, Centre National de la Recherche Scientifique (CNRS), Conseil Régional Ile-de-France, Département Physique Nucléaire et Corpusculaire (PNC-IN2P3/CNRS), Département Sciences de l'Univers (SDU-INSU/CNRS), France; Bundesministerium für Bildung und Forschung (BMBF), Deutsche Forschungsgemeinschaft (DFG), Finanzministerium Baden-Württemberg, Helmholtz-Gemeinschaft Deutscher Forschungszentren (HGF), Ministerium für Wissenschaft und Forschung, Nordrhein-Westfalen, Ministerium für Wissenschaft, Forschung und Kunst, Baden-Württemberg, Germany; Istituto Nazionale di Fisica Nucleare (INFN), Ministero dell'Istruzione, dell'Università e della Ricerca (MIUR), Italy; Consejo Nacional de Ciencia y Tecnología (CONACYT), Mexico; Ministerie van Onderwijs, Cultuur en Wetenschap, Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO), Stichting voor Fundamenteel Onderzoek der Materie (FOM), Netherlands; Ministry of Science and Higher Education, Grant Nos. N N202 200239 and N N202 207238, Poland; Fundação para a Ciência e a Tecnologia, Portugal; Ministry for Higher Education, Science, and Technology, Slovenian Research Agency, Slovenia; Comunidad de Madrid, Consejería de Educación de la Comunidad de Castilla La Mancha, FEDER funds, Ministerio de Ciencia e Innovación and Consolider-Ingenio 2010 (CPAN), Xunta de Galicia, Spain; Science and Technology Facilities Council, United Kingdom; Department of Energy, Contract Nos. DE-AC02-07CH11359, DE-FR02-04ER41300, National Science Foundation, Grant Nos. 0450696, 0855680, The Grainger Foundation USA; NAFOSTED, Vietnam; ALFA-EC / HELLEN, European Union 6th Framework Program, Grant No. MEIF-CT-2005-025057, European Union 7th Framework Program, Grant No. PIEF-GA-2008-220240, and UNESCO.

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