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Measurement of Aerosols at the Pierre Auger Observatory

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Abstract:

The air fluorescence detectors (FDs) of the Pierre Auger Observatory are vital for the determination of the air shower energy scale. To compensate for variations in atmospheric conditions that affect the energy measurement, the Observatory operates an array of monitoring instruments to record hourly atmospheric conditions across the detector site, an area exceeding 3,000 km^2. This paper presents results from four instruments used to characterize the aerosol component of the atmosphere: the Central Laser Facility (CLF), which provides the FDs with calibrated laser shots; the scanning backscatter lidars, which operate at three FD sites; the Aerosol Phase Function monitors (APFs), which measure the aerosol scattering cross section at two FD locations; and the Horizontal Attenuation Monitor (HAM), which measures the wavelength dependence of aerosol attenuation.

Introduction

The Pierre Auger Observatory in Malargüe, Argentina employs four fluorescence detector (FD) telescopes to obtain calorimetric estimates of air shower energies. The atmosphere, which acts as the calorimeter, is constantly in flux, so aerosol conditions are measured hourly at each FD location and stored in an offline database for use in the reconstruction of showers.

The aerosol parameters of interest are those that affect light attenuation and scattering: $\alpha(h)$, the aerosol extinction coefficient, and $\tau(h)$, the vertical aerosol optical depth (VAOD), which is the integral of $\alpha(h)$ from the ground to altitude h; $P(\theta)$, the normalized differential scattering cross section, or phase function, as a function of scattering angle θ; and the wavelength dependence of aerosol scattering. We describe measurements of $\tau(h)$ and its wavelength dependence by the CLF, lidars, and HAM, and observations of $P(\theta)$ by the APFs.

Optical Depth Measurements

Central Laser Facility

The CLF produces calibrated laser "test beams" from its location in the center of the Auger surface detector [4, 9]. Located between 26 and 39 km from the FDs, the CLF uses a pulsed laser operating at 355 nm. The atmosphere scatters nearly equal amounts of laser light toward each FD eye, where it is recorded by the FDs. With a nominal energy of 7 mJ per pulse, the light produced is roughly equal to the amount of scintillation light generated by a 10^{20} eV shower.

Among the many measurements provided by the CLF test beams are hourly observations of $\alpha(h)$ and $\tau(h)$. The laser fires sets of 50 shots every quarter-hour, and the track profiles are averaged to obtain hourly aerosol measurements. The CLF estimates the aerosol content using an iterative procedure that does not require absolute photometric

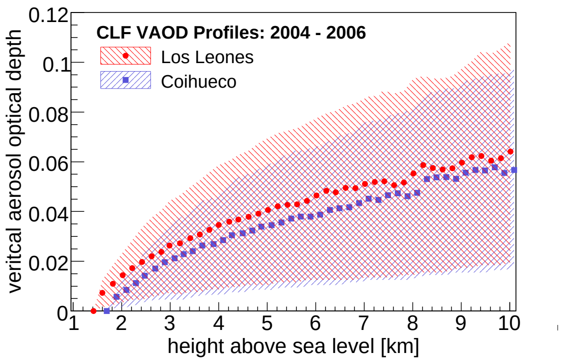

Figure 1: CLF VAOD measurements at Los Leones and Coihueco, 2004 - 2006, showing mean VAOD profiles and their 68% confidence limits.

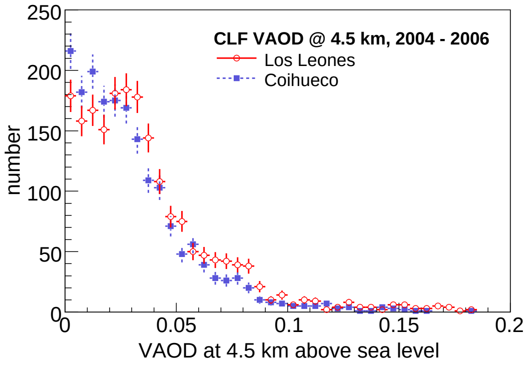

Figure 2: VAOD at 4.5 km. Los Leones, at an altitude ~ 280 m below Coihueco, observes a systematically larger VAOD.

calibrations of the FD or laser. The procedure begins by normalizing hourly average laser profiles $L(h)$ by an "aerosol-free" reference profile $L_{\text{ref}}(h)$ measured during extremely clear conditions. The initial VAOD estimate is then

$$\tau_i(h) = -\frac{\ln L(h) - \ln L_{\text{ref}}(h)}{1 + \csc \epsilon(h)} \qquad (1)$$

where ϵ is the elevation angle to the track point at altitude h. An estimate $\alpha_i(h)$ comes from the slope of the VAOD, and is used to iteratively correct the light profile for aerosol scattering. At the end of the calculation, the final $\alpha(h)$ is normalized by the VAOD at a height h_c above the bulk of aerosols:

$$\int_{h_{\text{ground}}}^{h_c} \alpha(h) dh = \tau_i(h_c) \qquad (2)$$

The final VAOD is found by integrating $\alpha(h)$. Figures 1 and 2 depict the VAOD distribution recorded at Los Leones and Coihueco between 2004 and 2006. Typically, the VAOD at 4.5 km is 0.03, with statistical uncertainties of ~ 0.01.

The uncertainties in each VAOD measurement are dominated by statistical fluctuations in the hourly average light profiles, although systematic effects due to the FD and laser relative calibrations and the choice of aerosol-free reference nights are also present. The last effect has been checked with a separate analysis method that uses CLF laser simulations and a simple two-parameter exponential model of the aerosol density. The results, which are independent of clear-night calibrations, closely match the standard CLF estimates (Figure 3).

The CLF can also detect clouds, which appear as sharp steps in the VAOD profile. When a cloud is present, the lowest base height h_{base} is recorded. For heights $h \leq h_{\text{base}}$, $\alpha(h)$ and $\tau(h)$ are considered valid for air shower analysis.

Elastic Backscatter Lidars

In addition to the CLF, the observatory employs three scanning elastic lidar stations, with a fourth under construction, to record $\alpha(h)$ and $\tau(h)$ at every FD site [2]. Each station has a steerable frame mounted with a pulsed 351 nm laser, three parabolic mirrors, and photomultiplier recorders. The station at Los Leones also includes a separate, vertically-staring Raman lidar test system, which can detect aerosols and the relative concentration of N_2 and O_2 in the atmosphere. Since the lidar hardware and measurement techniques are independent of the CLF, the two systems have essentially uncorrelated systematic uncertainties.

Every hour, each lidar sweeps the sky in a set pattern, pulsing the laser at 333 Hz and observing the backscattered light with its optical receivers. The sweeps occur outside the FD field of view to avoid triggering the detector. By observing the backscattered light, the lidar can determine $\alpha(h)$ and $\tau(h)$ using a straightforward numerical inversion [5]. As

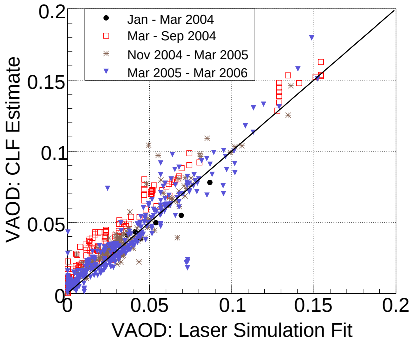

Figure 3: VAOD at 4.5 km from the CLF in different calibration epochs, compared to laser simulations.

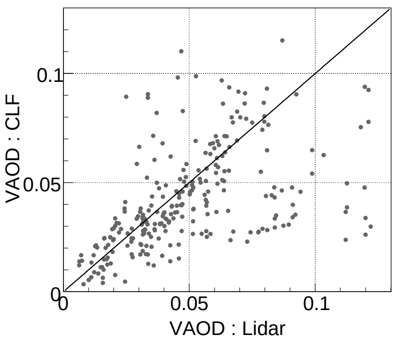

Figure 4: VAOD at 4.5 km at Coihueco, Oct 2006 – Jan 2007, observed by the CLF and Lidar.

shown in Figure 4, the lidar and CLF results are in reasonable agreement, despite large differences in operation, analysis, and viewing regions.

The lidar is also well suited to detect cloud layers, which create significant echoes in the backscattered light signal; these can be automatically detected by a simple gradient/threshold algorithm. Under certain circumstances, the lidar can also estimate cloud optical depths [2]. The lidar is currently accumulating an extensive hourly database of cloud height, sky coverage, and optical depth.

Scattering Measurements

The FD reconstruction must not only correct for the attenuation of scintillation light, but also subtract Cherenkov light scattered into the FD field of view. Therefore, the scattering properties of the atmosphere should be well-understood. Aerosol scattering is highly nontrivial and depends on the physical properties of the aerosols, but its distribution as a function of scattering angle θ can be approximated by the simple parameterization

$$P(\theta) = \frac{1-g^2}{4\pi}\cdot \left(\frac{1}{(1+g^2-2g\cos\theta)^{3/2}} + f\,\frac{3\cos^2\theta-1}{2(1+g^2)^{3/2}}\right) \qquad (3)$$

where $g = \langle\cos\theta\rangle$ measures the asymmetry of scattering and f determines the relative strength of forward and backward scattering. The quantities f and g determine $P(\theta)$, and are affected by local aerosol characteristics.

In the Auger Observatory, f and g are measured by Aerosol Phase Function monitors (APFs) located several km from the FDs at Coihueco and Los Morados [3]. Using a collimated xenon flash lamp, each APF fires an hourly sequence of 350 nm shots horizontally across the FD field of view, covering $30°$ to $150°$ in azimuth. The scattering parameters f and g can be determined simply by fitting the horizontal light track recorded by the FD.

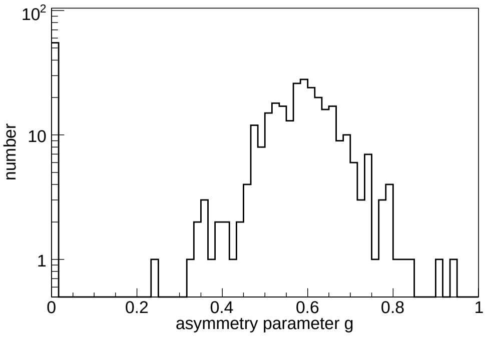

Figure 5: Scattering parameter g measured at Coihueco between June 2006 and March 2007.

Ten months of APF measurements at Coihueco have yielded a site average of $g = 0.59 \pm 0.08$ for the local asymmetry parameter, excluding clear nights when $g = 0$. The distribution of g, shown in Figure 5, is comparable to measurements reported in the literature for similar climates [1].

Wavelength Dependence

The attenuation of light by aerosols is expected to have some wavelength dependence, and this is typically parameterized by a power law

$$\tau(\lambda) = \tau_0 \cdot \left(\frac{\lambda_0}{\lambda}\right)^{\gamma} \qquad (4)$$

In this expression, τ_0 is the optical depth measured at the reference wavelength $\lambda_0 = 355$ nm, and γ is the so-called Angstrom exponent of the dependence ($\gamma \approx 4$ for molecular scattering).

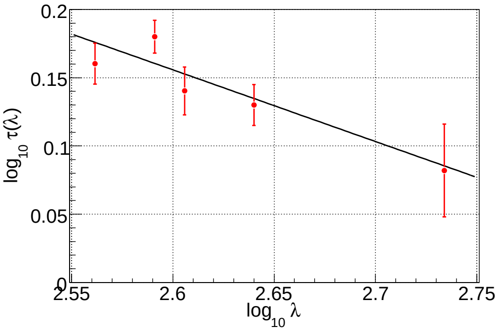

Figure 6: HAM fit to CCD response after molecular subtraction for one measurement set.

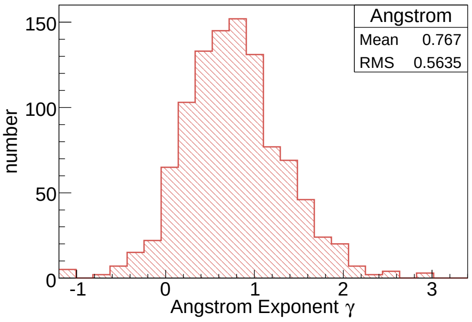

Figure 7: Distribution of the Angstrom exponent observed by the HAM, July 2006 - February 2007.

At the Auger Observatory, measurements of γ are performed by two instruments: the robotic telescope FRAM, described in detail in [8]; and the Horizontal Attenuation Monitor (HAM). The HAM consists of a high intensity discharge lamp located at Coihueco, viewed by a CCD camera placed ~ 45 km away at Los Leones. Using a filter wheel, the camera records the aerosol extinction coefficient, and hence the aerosol optical depth between the two sites, at five different wavelengths.

Figure 6 shows a typical HAM fit used to estimate γ. The uncertainties are dominated by measurement fluctuations, and include a systematic effect due to subtraction of the estimated molecular optical depth between Los Leones and Coihueco. The distribution of observed γ values, plotted in Fig. 7, is consistent with other measurements and physical expectations [8, 6].

Impact of Aerosols on Shower Measurements

The measurement uncertainties in the VAOD, phase function, and wavelength dependence of aerosol attenuation have been propagated in the reconstruction of a select number of high-quality air showers [7]. The dominant uncertainty comes from the VAOD, which contributes 5.5% to the uncertainty in shower energy, while the phase function and wavelength dependence both contribute $\sim 1\%$ to the uncertainty in the energy. The effect of VAOD observations on X_{max}, the depth of shower maximum, is $4\ \mathrm{g\ cm^{-2}}$, while the wavelength dependence and the phase function contribute uncertainties of 1 and $2\ \mathrm{g\ cm^{-2}}$, respectively.

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