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Raman Lidar observations of the vertical profiles of aerosol optical properties and water vapour at the Pierre Auger Observatory

E Avocone^{1,2} **for the Pierre Auger Collaboration**^{3} **and M Iarlori**^{2}

[1]INFN Laboratori Nazionali del Gran Sasso, Assergi (L'Aquila), Italy
[2]CETEMPS/DSFC, Università degli Studi dell'Aquila, via Vetoio, 67100, L'Aquila, Italy
[3]Observatorio Pierre Auger, Av. San Martin Norte 304, 5613 Malargue, Argentina
Full author list: http://www.auger.org/archive/authors_2024_07.html
E-mail: spokespersons@auger.org

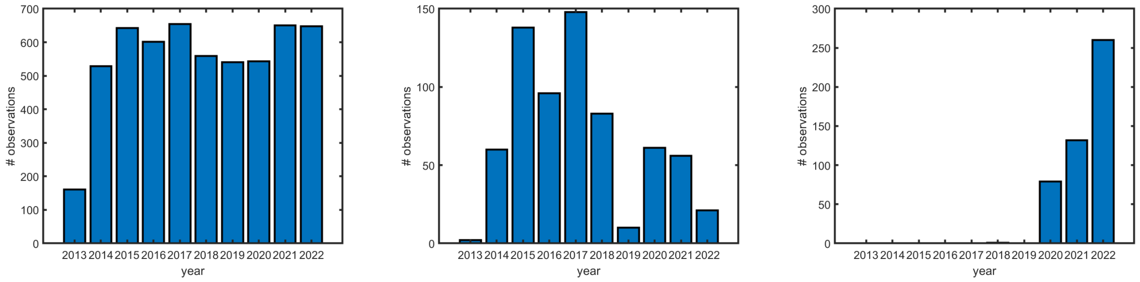
E-mail: emanuele.avocone@univaq.it

Abstract. The observations of a Raman Lidar at the Pierre Auger Observatory in the Argentinian Pampa are reported. The Raman Lidar is utilized for real-time atmospheric monitoring associated with the detection of cosmic-ray air showers. The vertical profiles of aerosol optical depth and aerosol backscatter are presented and discussed for an observation period ranging from 2013 to 2022. Meanwhile, the water vapour profiles are analyzed for the period from 2016 to 2022. The results could give insights into regional climate dynamics over the Argentinian Pampa.

1 Introduction

At the Pierre Auger Observatory [1] for Ultra-High Energy Cosmic Rays (UHECRs), a Raman lidar has been employed for aerosol and water vapour monitoring, continuously collecting data since September 2013. Since the detected fluorescence light associated with an Extensive Air Shower (EAS) depends on the atmospheric optical transparency, the atmosphere above the observatory needs to be continuously monitored to obtain reliable calorimetric information from the Fluorescence Detectors (FD) [2]. Despite the Vertical Aerosol Optical Depth (VAOD) being smaller than the corresponding molecular optical depth profile, due to the greater temporal variability of aerosols, attenuation caused by aerosols should be monitored on an hourly basis. While not directly utilized for correcting atmospheric shower parameters, lidar measurements are of fundamental importance for climatological studies of aerosols and serve as a cross-reference to determine the night with the least aerosol load.

In this contribution we briefly describe the Auger Raman lidar and its performance (section 2). In section 3 the time-series of the aerosol optical properties are shown and discussed, and in section 4 a simple model to describe the aerosol vertical distribution is presented.



(a) **(b)** **(c)**

Figure 1: Raman lidar observations over the years: (a) nitrogen channel observations before filtering; (b) distribution of observations after filtering for clear sky and low aerosol load; (c) distribution of failures of the single board computer.

2 Technical specifications and functionality of the Auger Raman lidar

The Auger Raman Lidar, situated at the Central Laser Facility (CLF), operates autonomously, conducting acquisitions before, during, and after the FD (Fluorescence Detector) shift. This system operates without affecting the FD duty cycle, although lidar operations impact only four fluorescence telescopes for approximately twenty minutes each night.

The lidar system comprises three channels: an elastic channel at 354.7 nm (Rayleigh-Mie scattering), a Raman channel at 386.7 nm (molecular nitrogen Raman scattering), and a Raman channel at 407.6 nm (water vapor Raman scattering). The laser operates at a wavelength central to the nitrogen fluorescence spectrum, specifically at 354.7 nm. It produces pulses with a duration of 7 ns, an output energy of 6 mJ, and a repetition rate of 100 Hz.

The receiver consists of a parabolic mirror with a diameter of 50 cm and a focal length of 150 cm. Photons collected by the mirror are transported via a fiber optic guide to the detector box. Within the detector box, the signal is split into three wavelength channels using beam splitters, interference filters, and notch filters. Field lenses are employed to collimate the beam. The light is then converted into electrical signals by three photomultiplier tubes and recorded using an FPGA card. Data acquisition is carried out in both photon counting (PC) mode and analog (AD) mode.

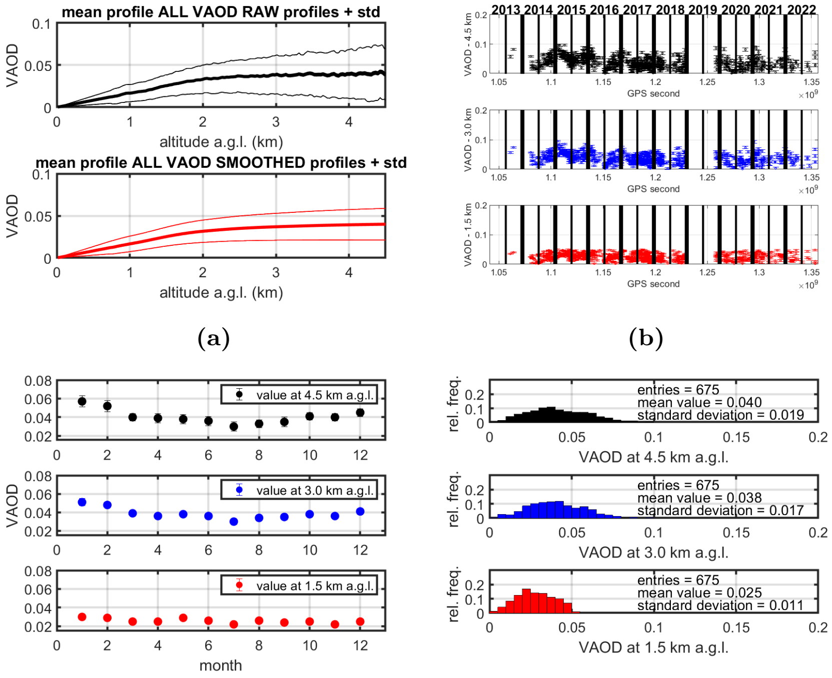
Before inversion, lidar signals undergo preprocessing. PC signals are corrected for dead time, while background and dark signals are subtracted. Bin-shifting is performed, and finally, PC and AD signals are combined.

3 Aerosol optical properties at the Pierre Auger Observatory

The Auger Raman lidar can measure vertical aerosol optical depth, aerosol backscatter coefficient, and water vapor mixing ratio. Additionally, it allows for the calculation of the aerosol extinction coefficient and the lidar ratio.

To investigate the average atmospheric conditions during "clear nights" in which light extinction is dominated by molecular Rayleigh scattering, profiles free from clouds and high aerosol content were selected. From a total of 5433 observations, distributed over time as shown in Figure 1a, 675 observations met the selection criteria, with their distribution depicted in Figure 1b. In 2019, the number of selected observations was notably low, coinciding with a "bad period" characterized by suboptimal lidar performance due to optical misalignment. Furthermore, in recent years, the single-board computer responsible for managing the automatic operation of the lidar has begun to show malfunctions. The frequency of these malfunctions, which has increased over time, is illustrated in Figure 1c. For the water vapour mixing ratio, lidar signals acquired between 2016 and 2022 are considered and are filtered only for clouds.

The Raman lidar technique for retrieving aerosol optical properties is well-established [3]. The Vertical Aerosol Optical Depth (VAOD) τ can be directly estimated from the nitrogen Raman lidar signal. These values are subject to statistical uncertainty from photon detection and systematic uncertainties related to the estimation of molecular number density, Rayleigh scattering cross section, the Ängstrom exponent (which describes the wavelength dependence of aerosol scattering), and uncertainties in the numerical algorithms used. The molecular contribution is computed from monthly average profiles from GDAS data [4] using Rayleigh scattering theory and a 5-component atmosphere model (N_2, O_2, Ar, CO_2, and H_2O) [5], with the Ängstrom exponent k set to 0.7 [6].



(a) (b)

(c) (d)

Figure 2: The vertical aerosol optical depth retrieved with the Auger Raman lidar: (a) overall mean profile; (b) time sequence of VAOD values at 1.5 km, 3.0 km, and 4.5 km; (c) monthly average values of VAOD at 1.5 km, 3.0 km, and 4.5 km; (d) histograms of VAOD values at 1.5 km, 3.0 km, and 4.5 km.

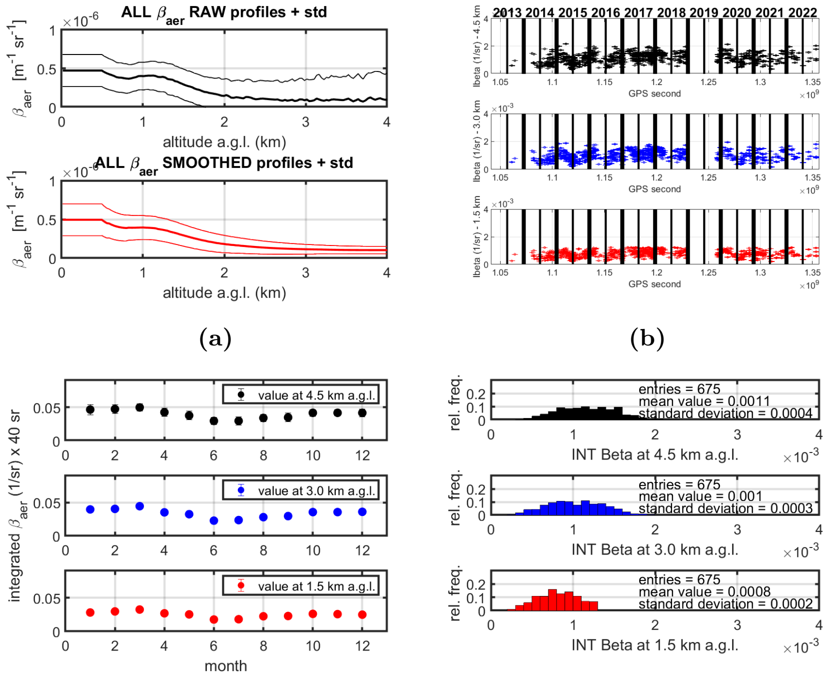
The aerosol backscatter coefficient β_{aer} is obtained instead from the ratio between the elastic and nitrogen Raman signals, normalized to a reference range assumed to be free of aerosols. This calibration procedure represents a further source of uncertainty.

The water vapour mixing ratio is obtained from the ratio of the water vapour Raman signal with the nitrogen Raman signal. A calibration constant needs to be determined by comparing the lidar water vapor mixing ratio with that measured by another technique, such as radiosondes.

The overall mean profile of the vertical aerosol optical depth is reported in Figure 2a. The plot shows a linear behavior of τ for small ranges (within the planetary boundary layer) and above this region an asymptotic growth towards the total VAOD. The complete temporal sequence of τ at three different heights, 1.5 km, 3.0 km, and 4.5 km above ground level, is shown in Figure 2b. The seasonal variability at 3.0 km and 4.5 km is clearly visible, highlighted more prominently in Figure 2c, where the monthly average values are shown, with lower values in the winter months. Furthermore, periods when the lidar performed poorly are also identifiable. In 2015, the average VAOD is larger when compared to that of other years, and the temporal sequence shows a negative trend over the years. The VAOD values at the three reference heights are, however, within the estimated standard deviation, and the observed trend is due to the increased number of failures of the single board computer over the last three years, to the "bad periods" 2015 and 2019, and to the profile selection. Finally, in Figure 2d, the histograms of these quantities are shown. The average value of the vertical aerosol optical depth found analysing the Raman lidar data at 4.5 km is 0.040 with a standard deviation of 0.019. At 3 km above ground level, the mean VAOD is 0.038 with a standard deviation of 0.017 and at 1.5 km it is 0.025 with a standard deviation of 0.011.

In Figure 3a the mean profile of the aerosol backscatter coefficient is shown. To make the results comparable with those of the vertical aerosol optical depth, the statistical analysis was performed on the integrated backscatter coefficient:

$$\mathrm{int}\beta(R, \lambda_{\mathrm{L}}) = \int_0^R \beta_{\mathrm{aer}}(R', \lambda_{\mathrm{L}}) dR'.$$



(a) (b)

(c) (d)

Figure 3: (a) overall mean profile of the aerosol backscatter coefficient; (b) time sequence of integrated aerosol backscatter coefficient at 1.5 km, 3.0 km, and 4.5 km; (c) monthly average values of intβ at 1.5 km, 3.0 km, and 4.5 km; (d) histograms of intβ values at 1.5 km, 3.0 km, and 4.5 km.

As expected, the same seasonal behaviour has been found: the aerosol integrated backscatter coefficient shows smaller values in the winter months (Figures 3b and 3c). In Figure 3d the distributions of the mean values of the integrated aerosol backscatter coefficient at 1.5 km, 3.0 km, and 4.5 km are reported. The average value of intβ at 4.5 km is 0.0011 sr^{-1} with a standard deviation of 0.0004 sr^{-1}. At 3 km above ground level, the mean $int\beta$ is 0.0010 sr^{-1} with a standard deviation of 0.0003 sr^{-1} and at 1.5 km it is 0.0008 sr^{-1} with a standard deviation of 0.0002 sr^{-1}.

The monthly average vertical profiles of the water vapour mixing ratio are reported in Figure 4. Larger values are recorded close to the ground and during summer months. The highest water vapor content occurs in the month of March, with an average mixing ratio at ground level $\chi \approx 4.22$ g/kg, while the smallest value occurs in June and July with $\chi \approx 1.67$ g/kg. In any case, the measured mixing ratio values are relatively small, at the limit of the instrument's sensitivity.

4 Aerosol vertical profile: a simple model

At the Pierre Auger Observatory, two independent techniques have been developed to provide the atmospheric aerosol load using CLF laser shots [8]:

- the Data Normalized Analysis;
- the Laser Simulation Analysis.

The Data Normalized Analysis compares measured profiles with a clear night profile in which molecular Rayleigh scattering dominates, while the Laser Simulation Analysis compares measured profiles with simulated profiles under varying atmospheric conditions.

In these simulations, aerosol attenuation is described using two parameters, the aerosol horizontal attenuation length $L_{\rm aer}$ and the aerosol scale height $H_{\rm aer}$:

$$\alpha_{\rm aer}(R) = \frac{1}{L_{\rm aer}} e^{-\frac{R}{H_{\rm aer}}} \qquad (1)$$

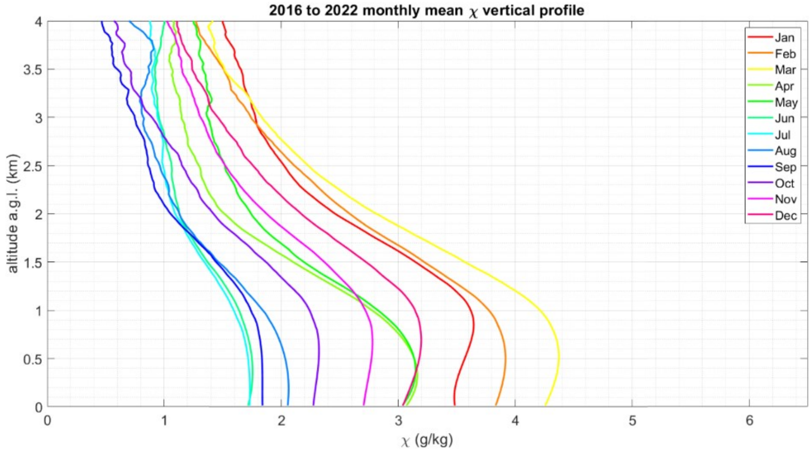


Figure 4: Monthly average vertical profile of the water vapour mixing ratio. From [7].

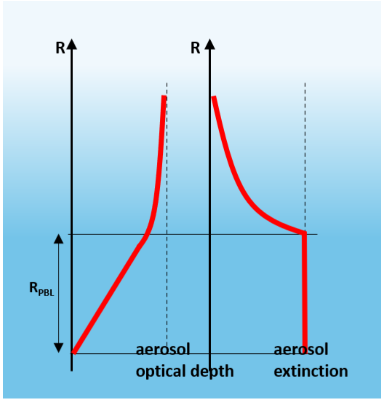


Figure 5: The three parameter model for aerosol modeling. On the left the vertical aerosol optical depth, on the right side the aerosol extinction coefficient.

and

$$\tau(R) = \frac{H_{\text{aer}}}{L_{\text{aer}}}\left(1 - e^{-\frac{R}{H_{\text{aer}}}}\right) \tag{2}$$

This model has been tested to describe the lidar data in comparison with an alternative model based on three parameters, depicted in Figure 5, and described by:

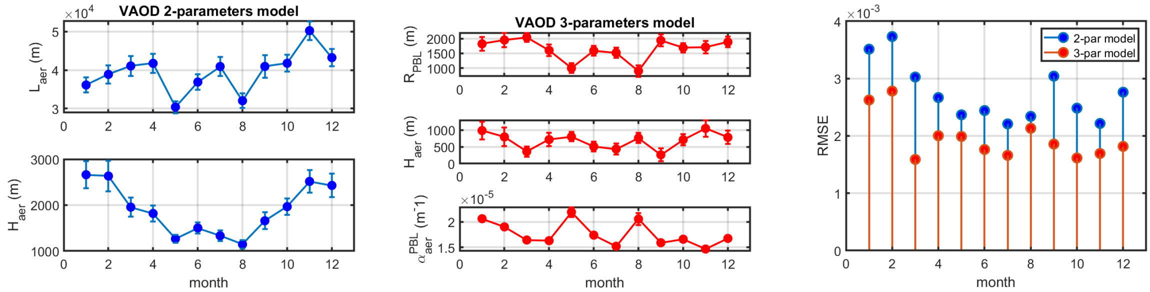
$$\alpha_{\text{aer}}(R) = \begin{cases} \alpha_{\text{aer}}^{\text{PBL}} & \text{if } R < R_{\text{PBL}} \\ \alpha_{\text{aer}}^{\text{PBL}} e^{-\frac{(R-R_{\text{PBL}})}{H_{\text{aer}}}} & \text{if } R \geq R_{\text{PBL}} \end{cases} \tag{3}$$

and

$$\tau(R) = \begin{cases} \alpha_{\text{aer}}^{\text{PBL}} \cdot R & \text{if } R < R_{\text{PBL}} \\ \alpha_{\text{aer}}^{\text{PBL}} R_{\text{PBL}} - \alpha_{\text{aer}}^{\text{PBL}} H_{\text{aer}} \left(e^{-\frac{(R-R_{\text{PBL}})}{H_{\text{aer}}}} - 1\right) & \text{if } R \geq R_{\text{PBL}} \end{cases} \tag{4}$$

with R_{PBL} the PBL height, $\alpha_{\text{aer}}^{\text{PBL}}$ the aerosol extinction coefficient into the well-mixed PBL, and H_{aer} the entrainment zone thickness. This means that the extinction coefficient takes constant values within the PBL and then exponentially decreases above this layer.

To evaluate which model is more accurate, we fitted the monthly averaged profiles obtained from lidar measurements using both models. Fit results are shown in Figure 6. Figures 6a and 6b show the parameters obtained from the fit. They exhibit a pronounced seasonal variability for the two-parameter



(a) **(b)** **(c)**

Figure 6: Results obtained fitting the vertical aerosol optical depth: (a) parameters obtained using the two-parameter model; (b) parameters obtained using the three-parameter model; (c) Root Mean Squared Error of the fit.

model.
The overall mean values for the two-parameter model are (with their standard deviation): $L_{\mathrm{aer}} = (40 \pm 5) \times 10^3\,\mathrm{m}$ and $H_{\mathrm{aer}} = (19 \pm 5) \times 10^2\,\mathrm{m}$. For the three-parameter model: $R_{\mathrm{PBL}} = (16 \pm 4) \times 10^2\,\mathrm{m}$, $H_{\mathrm{aer}} = (7 \pm 2) \times 10^2\,\mathrm{m}$ and $\alpha_{\mathrm{aer}}^{\mathrm{PBL}} = (18 \pm 2) \times 10^{-6}\,\mathrm{m}^{-1}$.
For each month, lidar measurements at the Pierre Auger Observatory are better described by the three-parameter model. Figure 6c shows the Root Mean Squared Error, defined as $RMSE = \sqrt{\frac{SSE}{\nu}}$, where ν is the residual degrees of freedom and SSE is the summed squared of residuals. A value close to zero indicates a fit that is more useful for prediction.

5 Conclusions

For the reconstruction of atmospheric showers, knowledge of the state of the atmosphere is fundamental. Within the Pierre Auger Observatory, an important program for atmospheric monitoring has been developed, with particular attention to the aerosol component. At the CLF, a Raman lidar has been installed, whose observations, although not directly used for the correction of FD observations, are important for a climatological study of aerosols. In particular, the observations from the Raman lidar have been used to test a three-parameter model for describing the vertical distribution of aerosols.

These Raman lidar data were also used to derive the aerosol scale height (two-parameter model) of the reference night. In [9], a model for the upper limit on the possible bias in the measured VAOD is developed. In the Data Normalized Analysis, the clearest night of the year is assumed as night without aerosol content. The method is therefore sensitive to how good, for this reference night, the approximation of aerosol absence is. Using the stereo energy balance technique, an underestimation of VAOD has emerged. At the reference height of 4.5 km above sea level, a VAOD correction of 0.005 with an aerosol scale height $H_{\mathrm{aer}} = 1.5\,\mathrm{km}$ was found. This new VAOD systematic uncertainty translates to an uncertainty in energy between 2 % and 4 %, lower than the previous values.

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