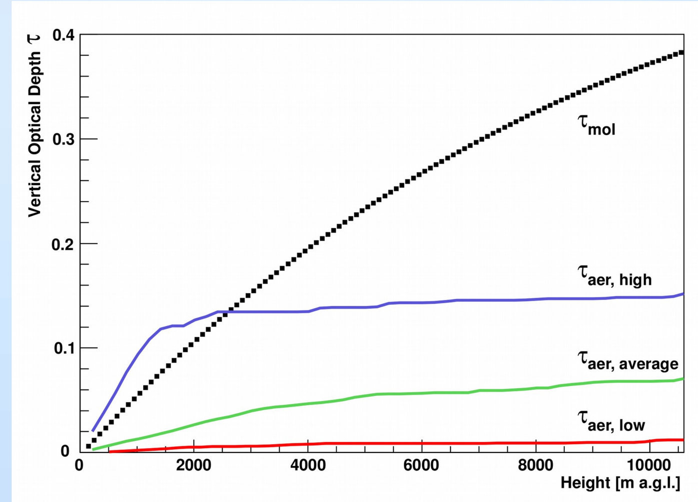
Atmospheric Aerosol Effect on FD data analysis at the Pierre Auger Observatory

L. Valore[1] for the Pierre Auger Collaboration[2]
[1] University of Naples Federico II and INFN Naples, Italy
[2] Observatorio Pierre Auger, Av. San Martín Norte 304, 5613 Malargüe, Argentina
Full author list : http://www.auger.org/archive/authors_2018_09.html

The Pierre Auger Observatory Aerosol Monitoring System

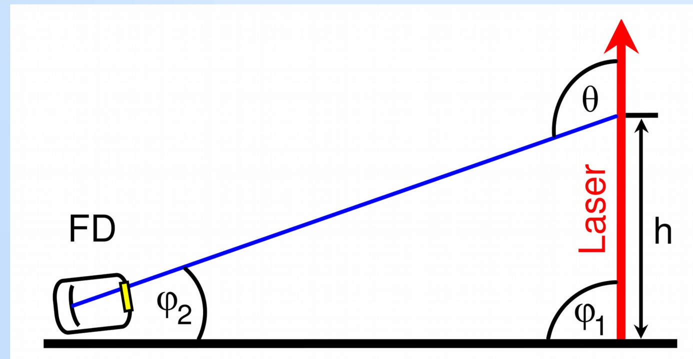
In the fluorescence band of nitrogen, aerosol and molecular scattering are the main mechanisms for the attenuation of light on its path from the point of emission to the detector. Aerosol (Mie) scattering, altought less attenuating than molecular (Rayleigh) scattering, has a non negligible effect on the Fluorescence Detector (FD) data analysis. Moreover, the vertical aerosol distribution is highly variable with time and affects directly the shape of the longitudinal profile.



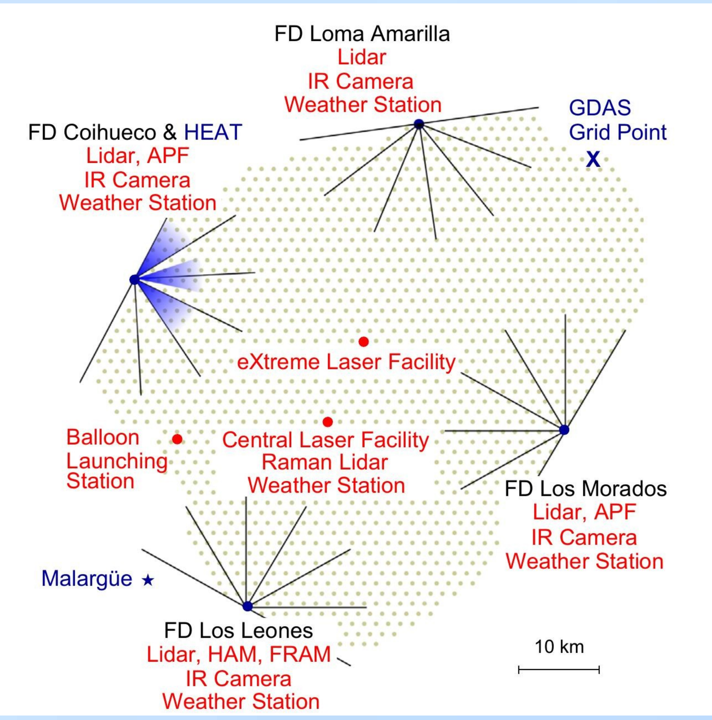
The intensity of fluorescence light that is reaching the FD depends on the transmission factors T_{mol} and T_{aer} :

$$I(\lambda,s) = I_0(\lambda,s)\cdot T_{\rm mol}(\lambda,s)\cdot T_{\rm aer}(\lambda,s)\cdot(1+\mathrm{H.O.})\cdot\frac{\mathrm{d}\Omega}{4\pi} \longrightarrow T_{\rm aer}(\lambda,h) = \exp\left(-\int_0^h \alpha_{\rm aer}(z)\mathrm{d}z/\sin\varphi_2\right) = \exp\left[-(\tau_{\rm aer}(h)/\sin\varphi_2)\right]$$

under the assumption of horizontal uniformity of the atmosphere



To fully determine the vertical aerosol optical depth τ_{aer} it is necessary to measure :
- the vertical height profile of the optical depth *τ(h)*
- the wavelength dependence of the optical depth *τ(λ)*
- the angular distribution of light scattered from aerosols or phase function *P(θ)*

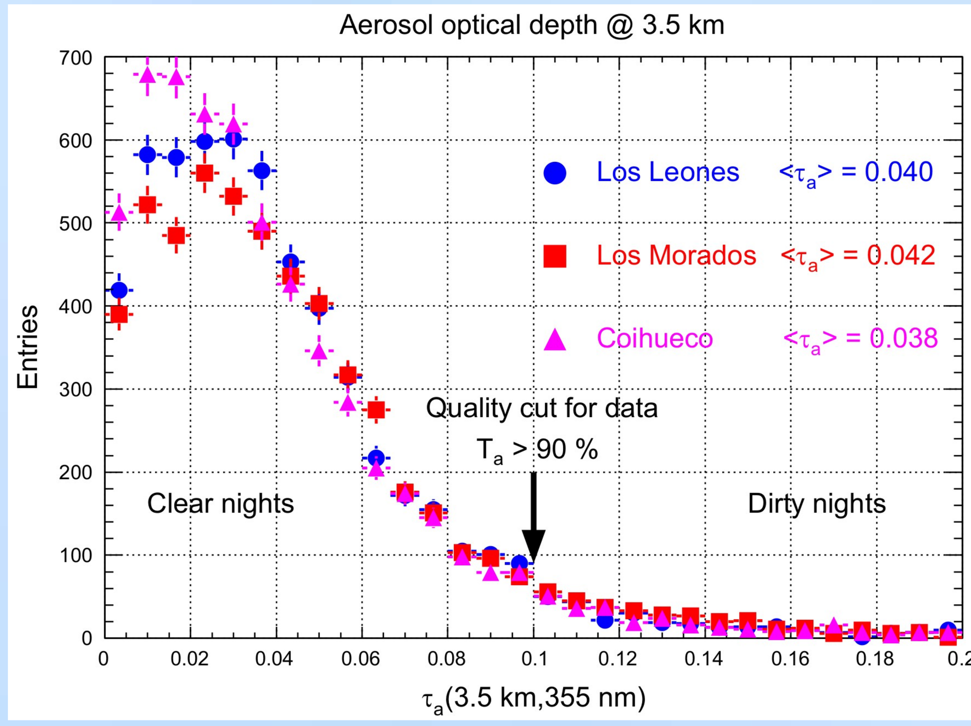


Measurement of the vertical height profile of the optical depth

Two laser facilities have operated smoothly for many years : the Central Laser Facility (2004) and the eXtreme Laser Facility (2010), each firing sets of 50 laser shots 4 times per hour during FD shifts.

The FD measures these UV laser tracks, and the analysis yields hourly measurements of the aerosol attenuation loads, expressed as Vertical Aerosol Optical Depth VAOD - or $\tau_{aer}(h)$ - profiles. The hourly VAOD profiles are used to correct the observed longitudinal UV light profiles of the Extensive Air Shower tracks detected by the FD.

Two fully compatible analysis techniques are used to obtain the VAOD profiles.



Distribution of VAOD at 3.5 km above ground level

Measurement of the wavelength dependence of the optical depth

$$\tau_a(h,\lambda) = \tau(h,\lambda_0)\cdot\left(\frac{\lambda_0}{\lambda}\right)^{\gamma}$$

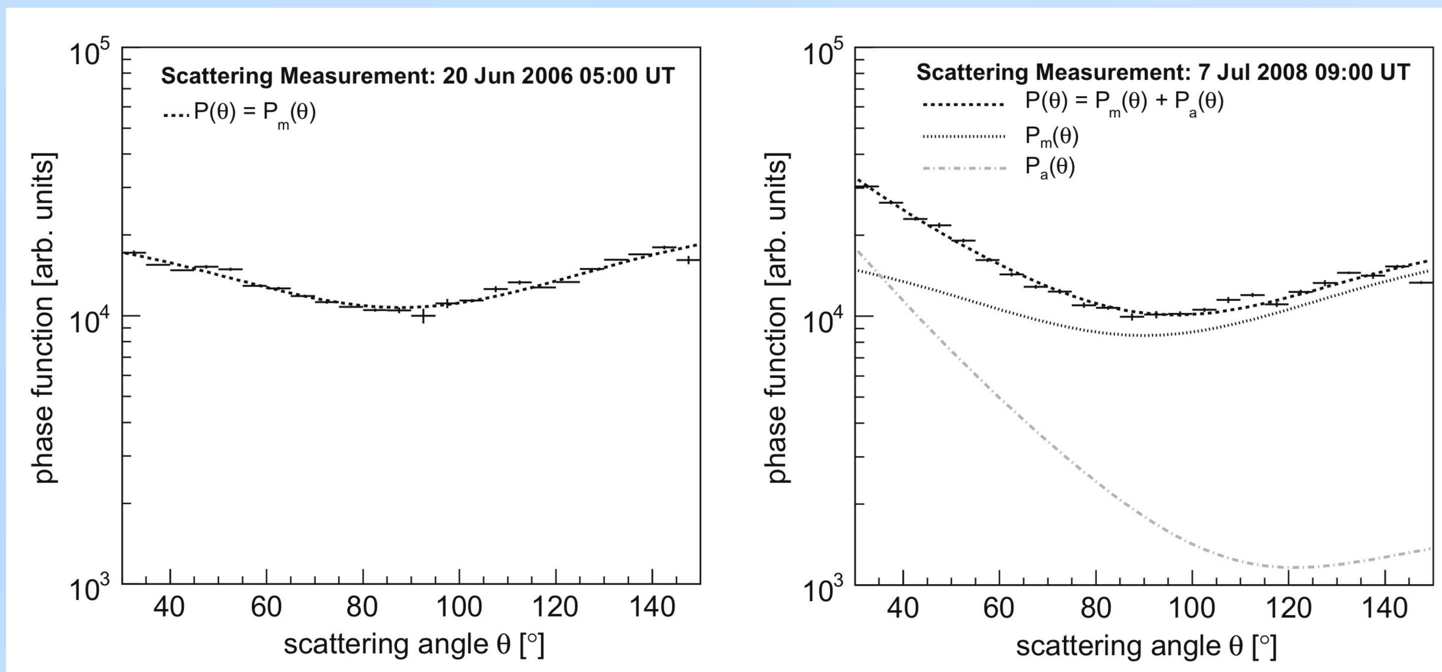
The wavelength dependence of the aerosol optical depth has been measured using the Horizontal Aerosol Monitor (HAM) and confirmed by further measurements taken with the FRAM (F/(Ph)otometric Robotic Atmospheric Monitor). The measured Angstrom coefficient is **ϒ = 0.7** (fixed value used in the FD data analysis) corresponding to a weak dependence on the wavelength as expected for desert-like sites.

Measurement of the aerosol phase function P(ϴ)

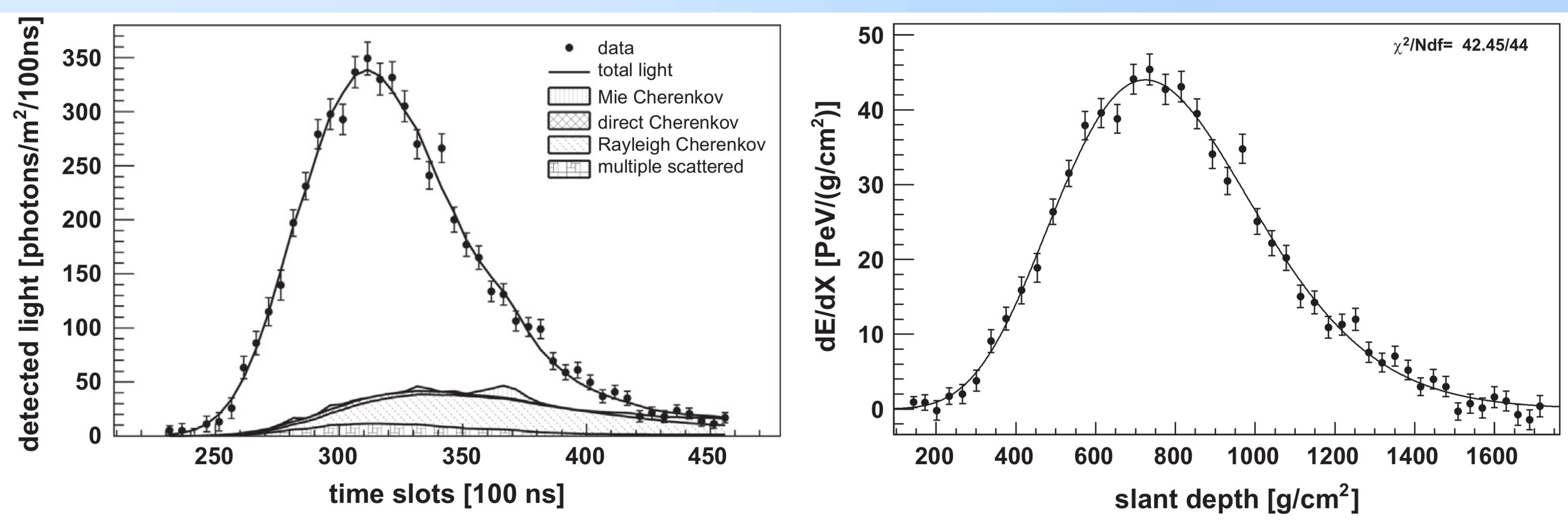
The angular dependence of the aerosol scattering is described by the normalised differential scattering cross section in the form of the modified Henyey-Greenstein function

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

Two Aerosol Phase Function (APF) monitors fire light pulses horizontally in the FOV and the measured data are well fitted by the parametrized phase function. In the FD data analysis we use fixed values of **f = 0.4** and **g = 0.6**, obtained from the mean of the measured distributions.



APF light intensity vs scattering angle : aerosol-free (left) vs typical (right) night



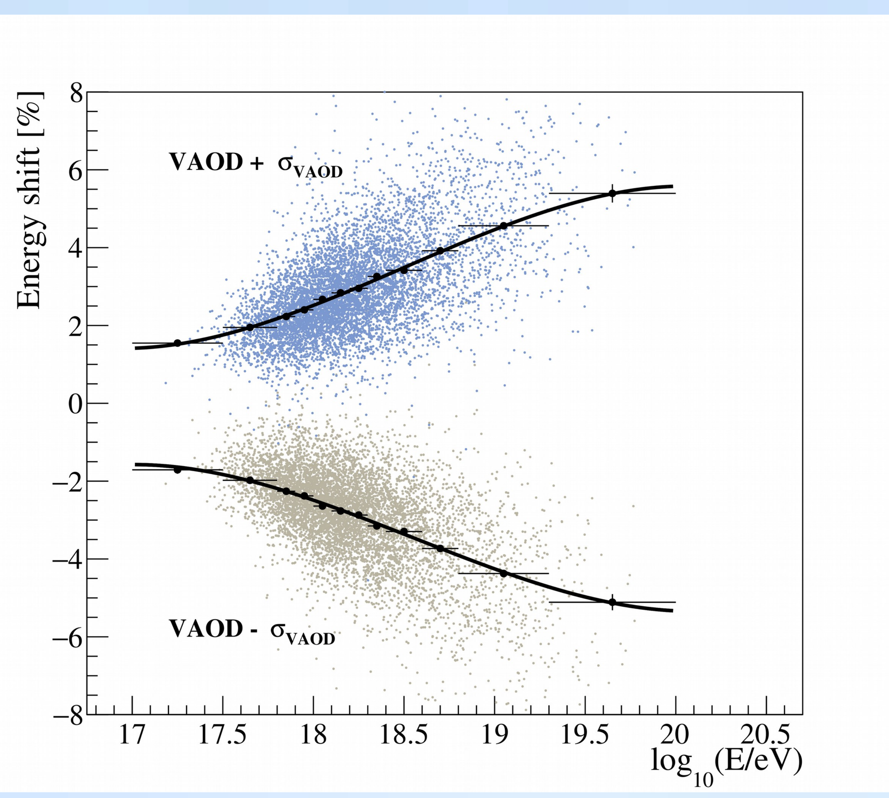
The light received at the telescope with each component (left) and the final dE/dX (right)

How aerosols affect FD events

The longitudinal development of a shower is built using the light detected by the 4 FDs. The components of the UV light collected are Fluorescence, direct Cherenkov, and aerosol + Molecular scattered Cherenkov light. The atmosphere is responsible for both the production and the attenuation of the Fluorescence and Cherenkov light. Aerosols, in particular, scatter light out of the field of view during its travel towards the detector, resulting in an attenuation of the light at the FDs. Also, scattered Cherenkov light may enter the FOV due to aerosol scattering.

All of these contributions are evaluated to build the longitudinal energy deposit profile dE/dX.

How aerosol uncertainties affect FD data analysis



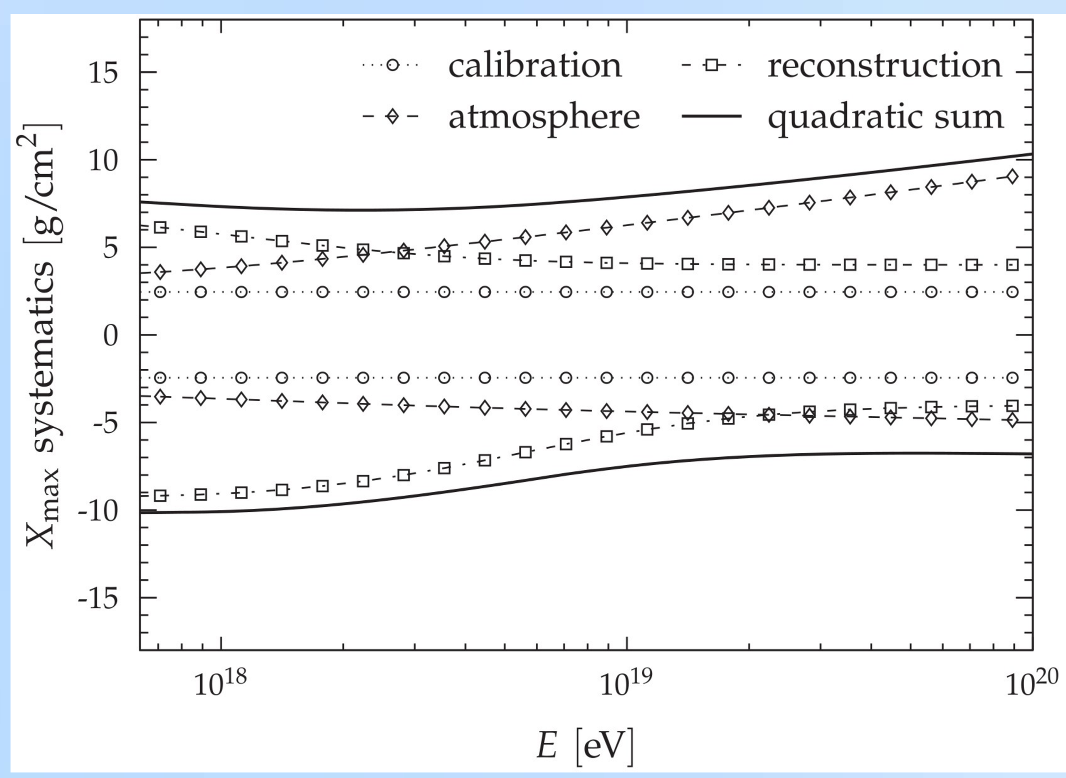
The uncertainties on the measured hourly VAOD profiles are divided into correlated (affecting a sample of EAS) and uncorrelated uncertainties (different from one EAS to the next)

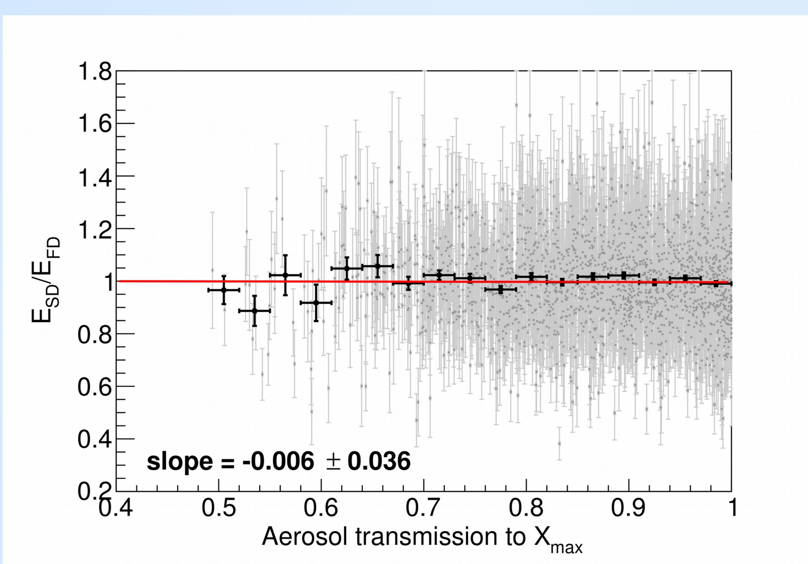
ENERGY

The correlated uncertainties lead to a systematic error in shower energy which is energy dependent, ranging from 3 to 6 % from 10^{18}eV to the highest energies. We quote also a 1% systematic uncertainty related to the shape of the phase function, and another 0.5% related to the aerosol scattering wavelength dependence.

X_{MAX}

All systematic effects due to the atmosphere have been combined and are energy dependent. The vertical aerosol attenuation profile affect the shape of the measured longitudinal profile of showers, affecting the measurement of Xmax. The aerosol errors are the major contribution to the Xmax systematics due to the atmosphere.





Validity of the aerosol attenuation profiles applied to FD event analysis

To confirm the validity of the VAOD profiles applied to the FD event analysis, a useful metric is the flatness of the ratio of the reconstructed SD energy to FD energy as a function of the aerosol transmission to the shower maximum.

We see a slope in this ratio of −0.006 ± 0.036, fully consistent with zero, and this is a strong indication that our VAOD measurements accurately describe the status of the aerosol atmosphere above the array.