The use of aerosol data in Auger Fluorescence Detector analysis

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Pierre Auger Collaboration

About 500 members from 19 countries

Argentina, Bolivia*, Australia, Romania*, Brazil, Vietnam*, Croatia, Czech Republic, France, Germany, Italy, Mexico, Netherlands, Poland, Portugal, Slovenia, Spain, United Kingdom, USA

*Associated

Full members
Associate members
Auger site
Pierre Auger Observatory

Fluorescence Detector
UV light from excited $N_2$
4 x 6 telescopes, 30° x 30°
+ 3 high-elevation telescopes

Surface Detector Array
charged particle + photon detector
1500 m grid: 1700 stations (3000 km$^2$)
+ 750 m grid: 71 stations, (25 km$^2$)
The Pierre Auger Observatory

Coihueco
Loma Amarilla
Los Morados
Los Leones
XLF
CLF
BLF

3000 km²

MALARGÜE

Los Leones

Los Morados

[km]
The Pierre Auger Observatory

Coihueco
Loma Amarilla
Los Morados
Los Leones
HEAT
XLF
CLF
BLF

24 km²

3000 km²

MALARGÜE

Los Leones

24 km

3000 km

0 10 20 30 40 50 60 70 [km]
Auger is a Hybrid detector - FD calibrates SD energy scale

\[ E_{\text{cal}} = \int \frac{dE}{dX} \, dX \]

\[ \sigma_{E/X} \lesssim 20 \, \text{g/cm}^2 \]

\[ \Delta_{\text{sys}} \lesssim 10 \, \text{g/cm}^2 \]

\[ \sigma_{X_{\text{max}}} \lesssim 20 \, \text{g/cm}^2 \]

\[ \Delta_{\text{sys}} \approx 15 \% \]

\[ E_{\text{surface}} = f(S_{1000}, \theta) \]

\[ S_{1000} \]
Energy Spectrum

\[ E^3 J(E)/(eV^2 \text{ km}^2 \text{ sr}^{-1} \text{ yr}^{-1}) \]

- SD-1500 vertical
- SD-750 vertical
- Hybrid
- SD-1500 m inclined

F. Fenu [Auger Collab.], ICRC2017
Combined Energy Spectrum

$E^3 J(E) / (\text{eV}^2 \text{ km}^{-2} \text{ sr}^{-1} \text{ yr}^{-1})$

Auger (ICRC 2017)

F. Fenu [Auger Collab.], ICRC2017
Mean $X_{\text{max}}$ and fluctuations in $X_{\text{max}}$
Aerosols

- Shower light transmission to the FD (sensitivity 300-400nm):
  - no major absorption (though we account for O$_3$)
  - scattering (Rayleigh and aerosol) determines transmission

\[
\tau(3\text{km}) = \text{VAOD}(3\text{km}) = 0.04
\]
Measuring Aerosols

See talks at this meeting about these instruments and analysis!
B. Keilhauer, L. Valore, V. Rizi, J. Ebr, P. Janecek

Central Laser Facility (CLF)

Laser: 355nm, 6.5 mJ per pulse to sky
Measuring Aerosols

Our standard method: bi-static lidar
(currently cross-checked with Raman lidar, FRAM...)

\[ \text{VAOD}(h) = \frac{-1}{1 + 1/\sin \phi_2} \ln \left( \frac{N_{\text{aer}}}{N_{\text{ref}}} \right) \]

Measured light flux relative to that on a nominally aerosol free reference night

Note: VAOD often denoted by \( \tau \)

M. Malacari [Auger Collab.], ICRC2017
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).
Measuring Aerosols  Laser Simulation (LS) method

![Graph of measured and simulated aerosol profiles](image1)

- **Left**: Four out of 1121 simulated profiles of a monthly grid. Right: The four aerosol profiles in black, the measured one (blue), and the four aerosol profiles of a reference night in red.

![Graph of optical depth determination and cloud identification](image2)

- **Left**: The four profiles of a simulation for each month and at a reference energy, to normalize the measured profiles. Each measured profile is compared to the corresponding term for the XLF (1%) reflects the fact that the energy varies from +2.4% to -2.5%.

![Graph of correlation of aerosol profiles](image3)

- **Right**: The correlation of aerosol profiles is shown for different epochs over the 10 year life of the system and is calculated with the dependence on FD or CLF absolute calibration. The correlation for the Coihueco site for the period January 2004 to December 2012 is shown.

![Graph of laser simulation](image4)

- **Right**: The laser simulation (LS) method is used for Los Leones, Los Morados and Coihueco. Results are consistent within the hour and between measured and simulated profiles computed for each bin between the measured profile under study and the corresponding epoch before measuring the aerosol attenuation at the Pierre Auger Observatory.

Pierre Auger Collaboration, JINST 8, P04009 (2013)
Measuring Aerosols

scattering angular distributions

**Modified Henyey-Greenstein phase function**

\[
\frac{1}{4\pi} \frac{d\sigma}{d\Omega} = \frac{1 - g^2}{(1 + g^2 - 2g \cos \theta)^{3/2}} + f \frac{3\cos^2 \theta - 1}{2(1 + g^2)^{3/2}}
\]

- \(g\) – asymmetry parameter
- \(f\) – backscattering parameter

For aerosols:

\[\chi^2 / \text{ndf} = 5.433 / 18\]

- \(A = 5893 \pm 142.6\)
- \(B = 6283 \pm 141.7\)
- \(g = 0.52 \pm 0.01937\)
- \(f = 0.2496 \pm 0.084\)

[S.Y. BenZvi et al., Astropart. Phys. 28 (2007) 312-320]
Measuring Aerosols

- Scattering Measurements

Scattering Measurement: 20 Jun 2006 05:00 UT

\[ P(\theta) = P_m(\theta) \]

very few or no aerosols

Scattering Measurement: 7 Jul 2008 09:00 UT

\[ P(\theta) = P_m(\theta) + P_a(\theta) \]

\[ P_m(\theta) \]

\[ P_a(\theta) \]
Characteristics of Aerosols at Auger - VAOD(3.5km)

![Graph showing aerosol optical depth at 3.5 km]

- **Los Leones**: $\langle \tau_a \rangle = 0.040$
- **Los Morados**: $\langle \tau_a \rangle = 0.042$
- **Coihueco**: $\langle \tau_a \rangle = 0.038$

Quality cut for data: $T_a > 90\%$

Clear nights

Dirty nights
Characteristics of Aerosols at Auger - seasonal dep.

[The Pierre Auger Collaboration, Atmos. Res. 149 (2014) 120-135]
Improvements to aerosol attenuation measurements at the Pierre Auger Observatory

Varying the asymmetry parameter \((g)\) and the backscattering parameter \((f)\)

\[
\left( \frac{1}{\sigma d\Omega} \right)_A = \frac{1 - g^2}{4\pi} \frac{1}{(1 + g^2 - 2g \cos \theta)^{3/2}} + f \frac{3 \cos^2 \theta - 1}{2(1 + g^2)^{3/2}}
\]
Reconstructing the energy and $X_{\text{max}}$ of an air shower

$E_{\text{cal}} = \int \frac{dE}{dX} \, dX$

$\sigma_{X_{\text{max}}} \leq 20 \, \text{g/cm}^2$

$\Delta_{\text{sys}} \leq 10 \, \text{g/cm}^2$

$\sigma_E/E \sim 8\%$

$\Delta_{\text{sys}} \approx 15\%$

$E_{\text{surface}} = f(S_{1000}, \theta)$
Reconstructing the energy and Xmax of an air shower

- isotropic fluorescence emission
- forward beamed direct Cherenkov light
- Rayleigh- and Mie-scattered Cherenkov light

![Graph showing the detected light over time slots and elevation/azimuth angles.](image)
Complication: light received at detector is...

- fluorescence light
- direct and scattered Cherenkov light

Improvements to aerosol attenuation measurements at the Pierre Auger Observatory

Figure 1: (a) Example of a measured laser trace (black). In red is the associated nominally clear reference trace. (b) The V AOD as derived from this measurement. The central black profile is the raw V AOD, and in red is a smoothed version. The upper and lower black profiles denote the raw upper and lower uncertainty bounds on the V AOD.

Here $N_{aer}$ and $N_{ref}$ are the photon fluxes originating from height $h$ (on the night of measurement and the reference night respectively), $f_2$ is the elevation of the laser track segment with respect to the detector, and $S_A$ and $S_M$ describe the fraction of the laser beam scattered towards the detector from that height by aerosols and molecules respectively. Terms (1) and (2) of Eq. 2.1 both encode separate pieces of information about the aerosol attenuation properties of the atmosphere, with the first part representing the transmission of laser light along the laser beam to height $h$, and from that point to the aperture of a fluorescence detector, and the second representing the scattering of laser light out of the beam and towards the detector. Traditionally the analysis operates under an additional assumption; that the density of molecular scattering centres in the atmosphere is much greater than that of aerosols. This, coupled with the fact that the aerosol scattering phase function is strongly forward peaked and the vertical laser beam is always viewed nearly side on, means that the $S_A$ term is much smaller than the $S_M$ term. In this case, term (2) $\rightarrow 0$ and the V AOD at a given height depends only on the ratio of the measured light flux originating from that height relative to that measured on the reference night. An example of a measured averaged laser trace, along with a reference trace, is shown in Fig. 1a. In Fig. 1b is the corresponding reconstructed V AOD determined using the DN technique. The average V AOD at 3 km above ground level (above the planetary boundary layer) measured at the Observatory site is approximately 0.04.
Reconstructing the energy and Xmax of an air shower

- isotropic fluorescence emission
- forward beamed direct Cherenkov light
- Rayleigh- and Mie-scattered Cherenkov light
Cherenkov light is also a signal
- reconstruct $w = dE/dX$ profile by matrix method

**Production at the shower**

$$N^f_{\gamma}(X_i) = Y^f_i w_i \Delta X_i,$$

$$N^C_{\gamma}(X_i) = Y^C_i N^e_i \Delta X_i$$

$$w_i = N^e_i \int_0^\infty f_e(E, X_i) w_e(E) \, dE$$

$$= dE/dX(X_i)$$

**Light at the FD**

$$y^f_i = d_i Y^f_i w_i \Delta X_i$$

$$y^{C_d}_i = d_i f_C(\beta_i) Y^C_i \Delta X_i N^e_i$$

$$y^{C_s}_i = d_i f_s(\beta_i) \sum_{j=0}^i \mathcal{T}_{ji} Y^C_j \Delta X_j N^e_j$$

$$y_i = y^f_i + y^{C_d}_i + y^{C_s}_i.$$

**Matrix inversion**

$$\hat{w} = C^{-1} y$$
Uncertainties in aerosol measurements

Correlated errors: are correlated across a period of time
   e.g. due to drift in relative calibration of FD or laser since the reference night

Uncorrelated errors: change from hour to hour
   e.g. statistical error on light profiles, and variation within a given hour
Uncertainties in aerosol measurements

|                           | Correlated | Uncorrelated |
|---------------------------|------------|--------------|
| Relative FD calibration   | 2%         | 4%           |
| Relative laser energy (CLF)| 1 – 2.5%   | 2%           |
| Relative laser energy (XLF)| 1%         | 2%           |
| Reference clean night     | 3%         | -            |
| Atmospheric variations    | -          | ~3%          |

Table 1. Errors relevant to the calculation of VAOD from CLF/XLF laser profiles at the FD. See text and [14] for details.

Correlated errors: are correlated across a period of time
   e.g. due to drift in FD or laser relative calibration since reference night

Uncorrelated errors: change from hour to hour
   e.g. statistical error on light profiles, variation within a given hour
VAOD uncertainty propagated to EAS energy

![VAOD correlated uncertainty on E](chart)

- Energy shift [%]
  - VAOD + $\sigma_{VAOD}$
  - VAOD - $\sigma_{VAOD}$

log$_{10}$(E/eV)
VAOD uncertainty propagated to EAS energy

VAOD un-correlated uncertainty on E

Similar method used for uncertainties in shower maximum, $X_{\text{max}}$
Contribution to total uncertainties - energy

Uncorrelated errors on shower energy

| Error Source                                      | Uncertainty |
|--------------------------------------------------|-------------|
| Aerosol optical depth                            | 3%÷6%       |
| Horizontal uniformity                            | 1%          |
| Atmosphere variability                           | 1%          |
| Nightly relative calibration                     | 3%          |
| Statistical error of the profile fit             | 5%÷3%       |
| Uncertainty in shower geometry                   | 1.5%        |
| Invis. energy (shower-to-shower fluc.)           | 1.5%        |
| FD energy resolution                             | 7%÷8%       |

Correlated errors on shower energy

| Error Source                                      | Uncertainty |
|--------------------------------------------------|-------------|
| Absolute fluorescence yield                      | 3.4%        |
| Fluor. spectrum and quenching param.             | 1.1%        |
| Sub total (Fluorescence yield - sec. 2)          | 3.6%        |
| Aerosol optical depth                            | 3%÷6%       |
| Aerosol phase function                           | 1%          |
| Wavelength depend. of aerosol scatt.             | 0.5%        |
| Atmospheric density profile                       | 1%          |
| Sub total (Atmosphere - sec. 3)                  | 3.4%÷6.2%   |
| Absolute FD calibration                          | 9%          |
| Nightly relative calibration                     | 2%          |
| Optical efficiency                               | 3.5%        |
| Sub total (FD calibration - sec. 4)              | 9.9%        |
| Folding with point spread function               | 5%          |
| Multiple scattering model                         | 1%          |
| Simulation bias                                  | 2%          |
| Constraints in the Gaisser-Hillas fit            | 3.5%÷1%     |
| Sub total (FD profile rec. - sec. 5)             | 6.5%÷5.6%   |
| Invisible energy (sec. 6)                        | 3%÷1.5%     |
| Stat. error of the SD calib. fit (sec. 7)        | 0.7%÷1.8%   |
| Stability of the energy scale (sec. 7)           | 5%          |
| Total                                            | 14%         |
**Contribution to total uncertainties - $X_{\text{max}}$**

- **calibration**
- **reconstruction**
- **atmosphere**
- **quadratic sum**

$X_{\text{max}}$ **statistical error (resolution):** atmosphere contributes up to 10 g/cm$^2$ at highest energies (the major contribution to the total uncertainty there, 15 g/cm$^2$)

A. Aab et al. [Pierre Auger Collab.], Phys. Rev. D 90, 122005 (2014)
Figure 5: Ratio of the reconstructed SD to FD energy as a function of the aerosol transmission to the depth of shower maximum. (a) Before the improvements made to aerosol extinction measurements. The negative slope indicates that the aerosol content of the atmosphere has been underestimated. (b) Following the improvements made to aerosol extinction measurements. The slope is fully compatible with zero, demonstrating internal consistency within the data.
Conclusions

• The measurement and treatment of aerosols in Auger’s shower analysis pipeline is well developed and stable.

• However we continue fine tuning and cross checks, and we are in the process of tuning the assignment of uncertainties.

• For more detail on Auger’s atmospheric measurements and analysis, see talks by my colleagues!