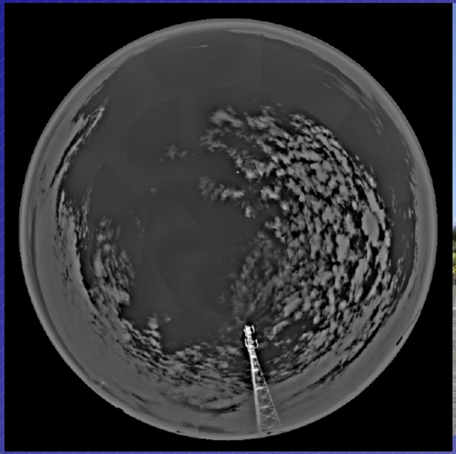
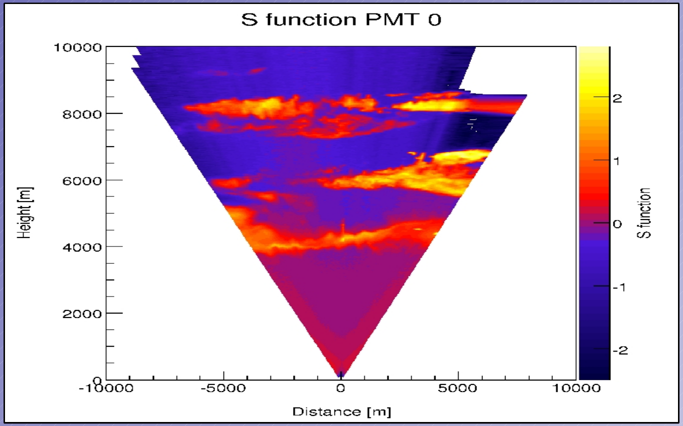
PIERRE
AUGER
OBSERVATORY



Atmospheric monitoring systems for the AUGER Observatory

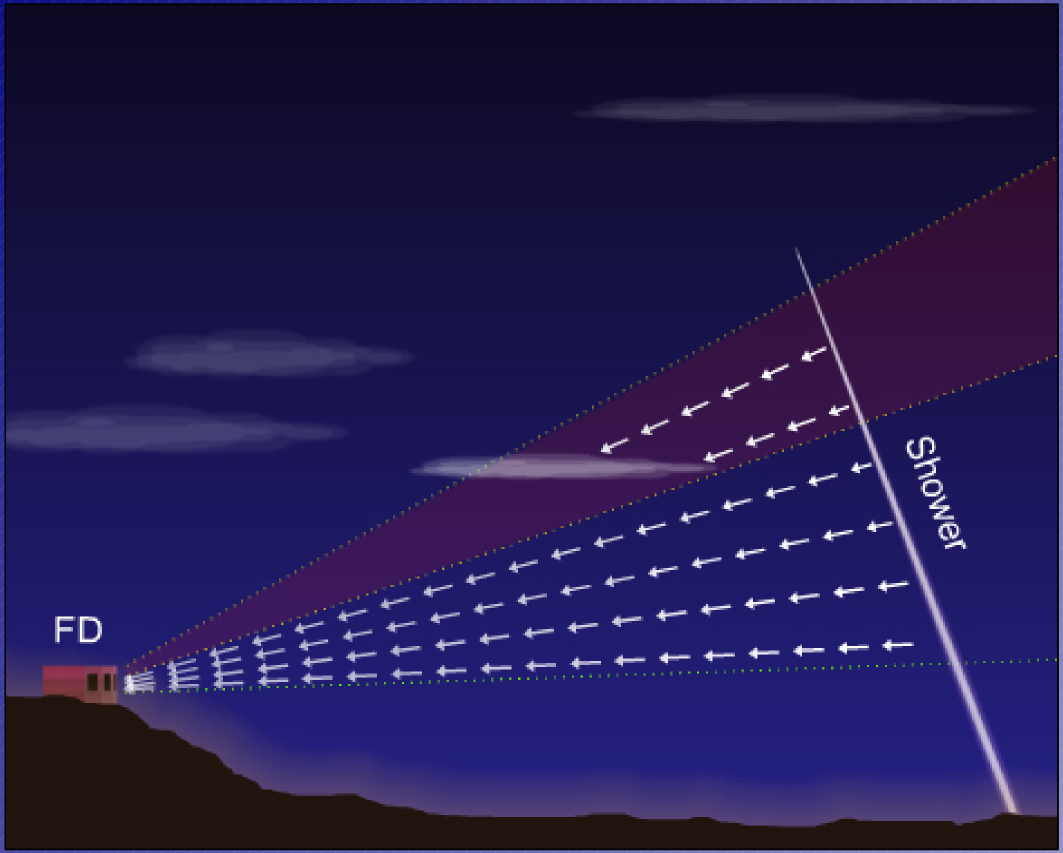
Roberto Mussa - INFN Torino

3) Aerosols detection



III School on Cosmic Rays and Astrophysics – Arequipa - 9/2008

Atmospheric optical properties



Photons emitted at the passage of the shower:

$$\frac{dN_{em}}{dX} = Y(P,T,h)\frac{dE}{dX}$$

Y(P,T,h) : Fluorescence Yield (see Arqueros)

Grammage : $X(h) = \int_h^\infty \rho(z)dz$

Photons arriving at FD window:

$$\frac{dN_{FD}(x)}{dX} = \frac{dN_{em}}{dX} T(x) \frac{A_{FD}}{|x|^2}$$

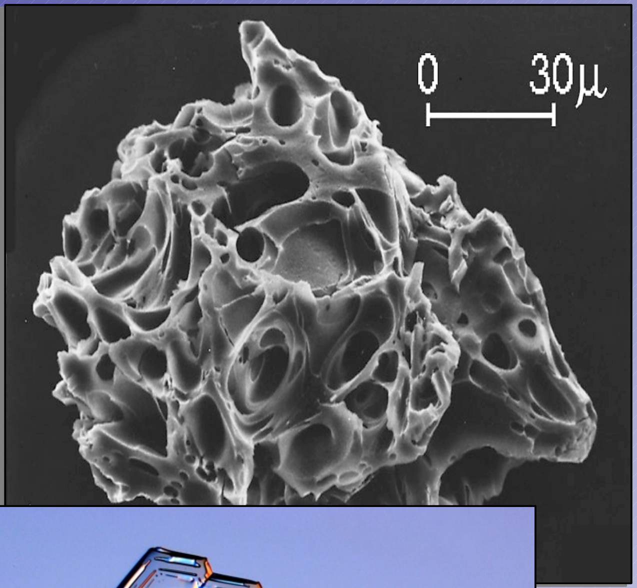
Transmission: $T(x) = e^{-\tau}$

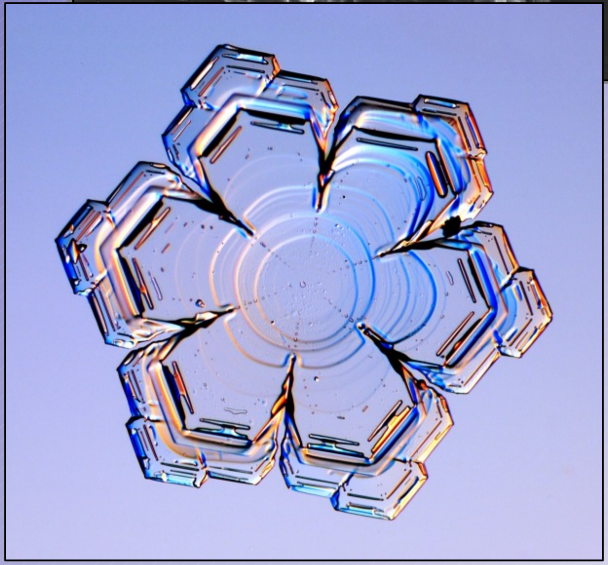
Optical Depth (OD): $\tau = \int_0^X \alpha(r)\, dr = \tau_{molec} + \tau_{clouds} + \tau_{aerosol}$

Attenuation coefficient: $\alpha = \sigma * N(x)$

Attenuation Length: $\Lambda = 1/\alpha$

Light scattering by particulate





The intensity of light scattering by particulates depends on:

- the geometric **size** and **shape** of the scattering particle
- the **refractive index** of the particle
- the **wavelength** of the incident light
- the particulate number **density**

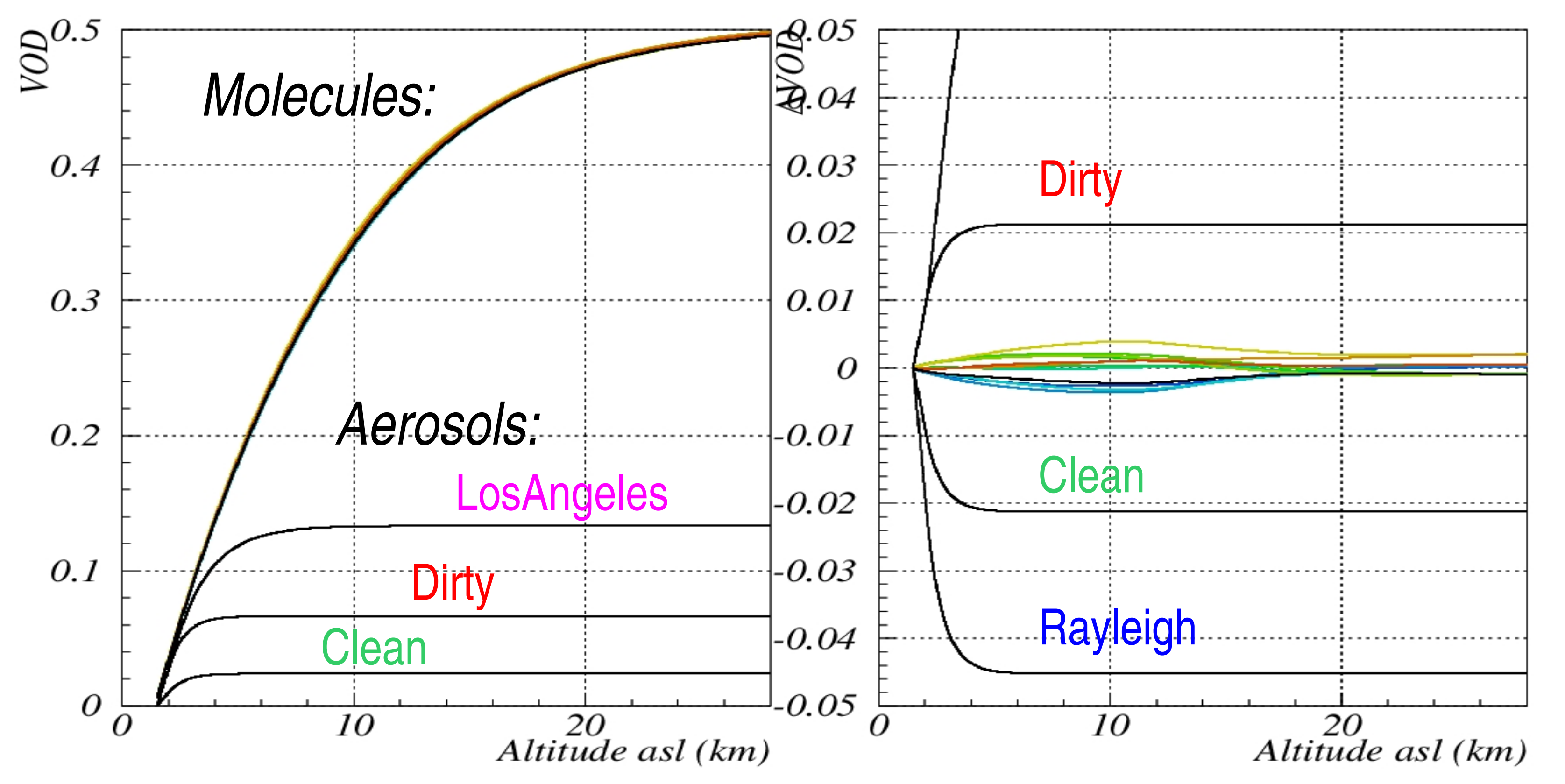
Very difficult to model :

Mie approach: scattering on spheres with $r >> \lambda$

OK to describe water droplets or liquid aerosols

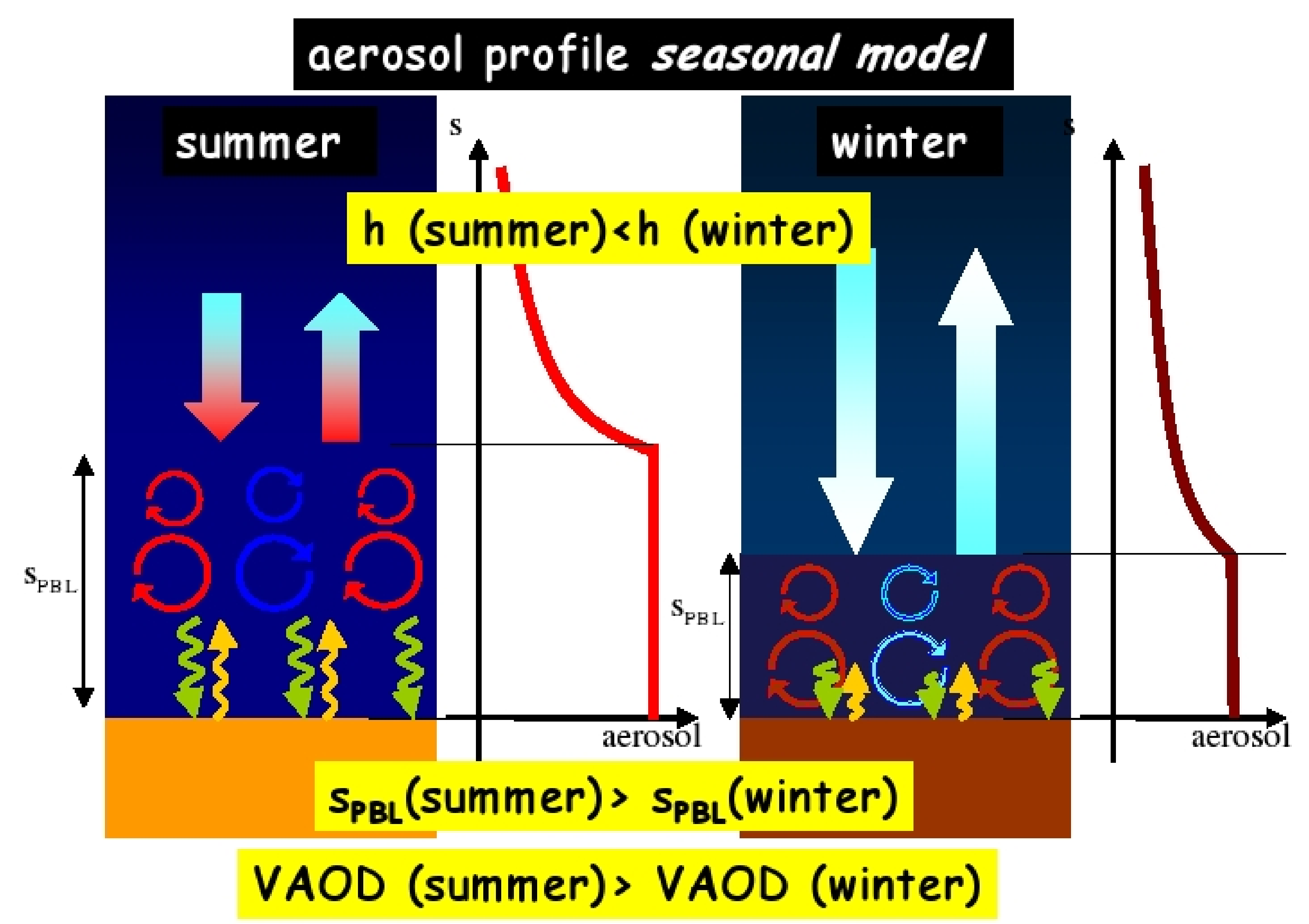
Henyey-Greenstein parametrization: more generic, but OK for typical aerosols in desert areas: sand, dust, ash.

Atmosphere: Optical Depth, molecules vs aerosols



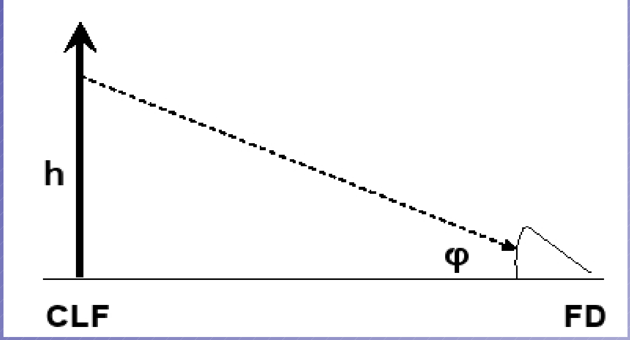
Optical properties show little dependence on molecular density variations and much larger complications from aerosols and clouds

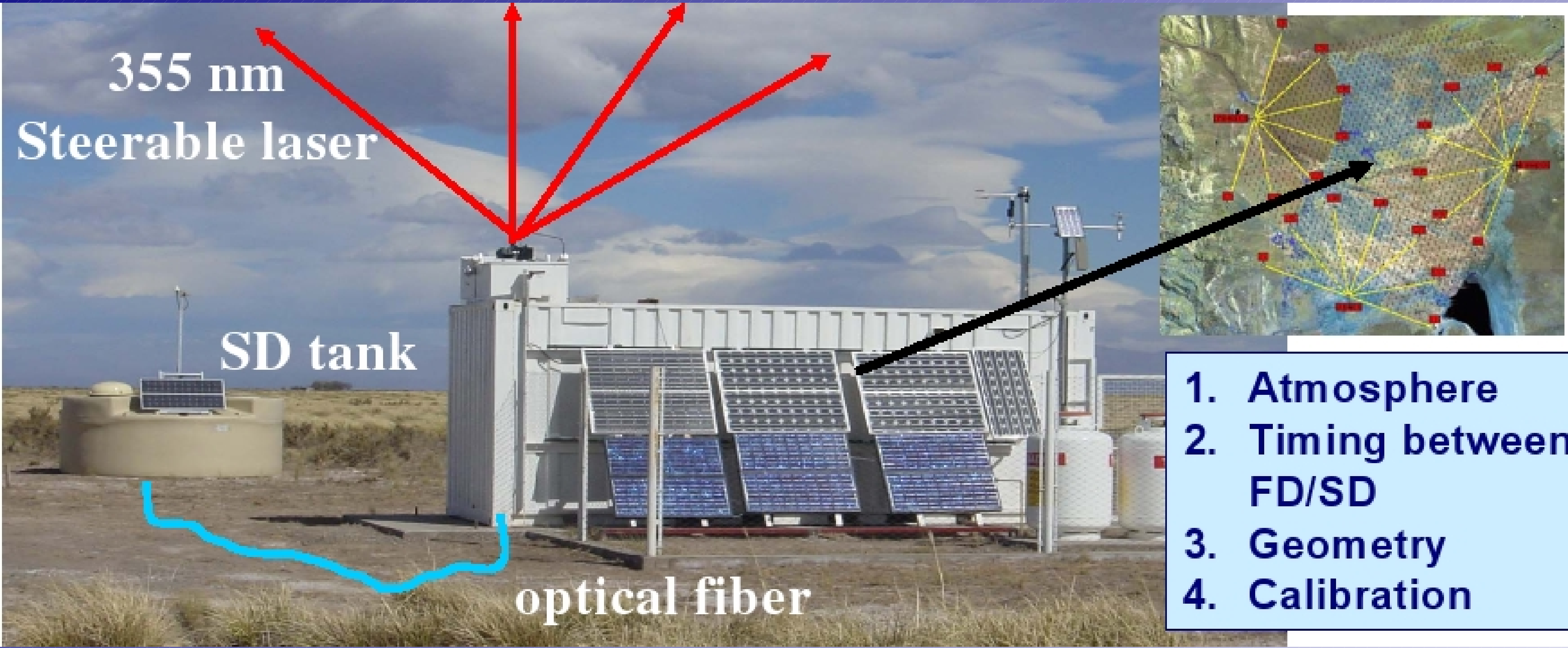
Aerosols: monthly models



CLF+XLF: principles of operation

CLF = Central Laser Facility
XLF = Extended Laser Facility





1. Atmosphere
2. Timing between FD/SD
3. Geometry
4. Calibration

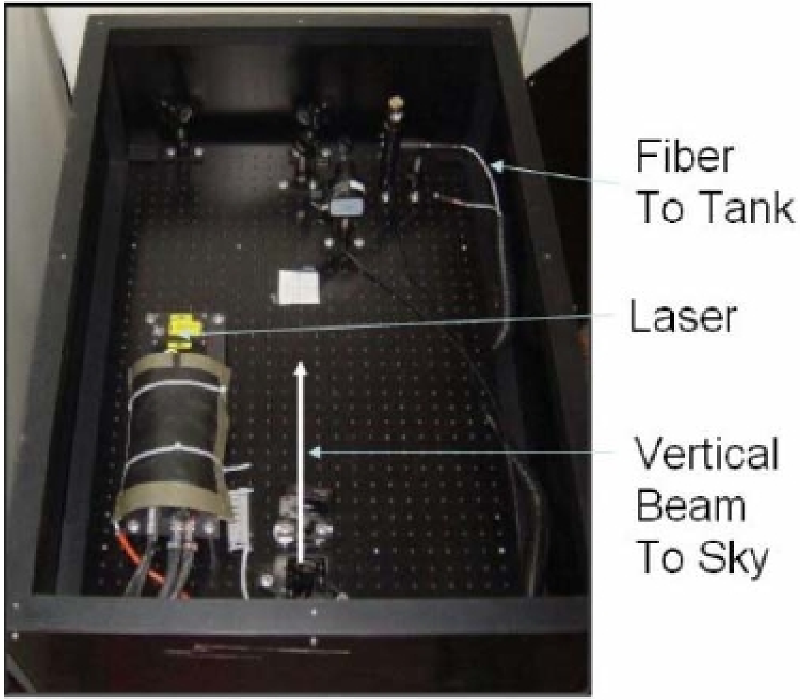
$$P(\varphi_k) = Q_0 \frac{A_{FD}}{R^2} \frac{\beta(h, \pi/2 + \varphi_k)}{1 + tan^2\varphi_k} e^{-\tau(h)(1+1/sin\varphi_k)}$$

Bistatic Lidar Equation: source and receiver **not in the same place**

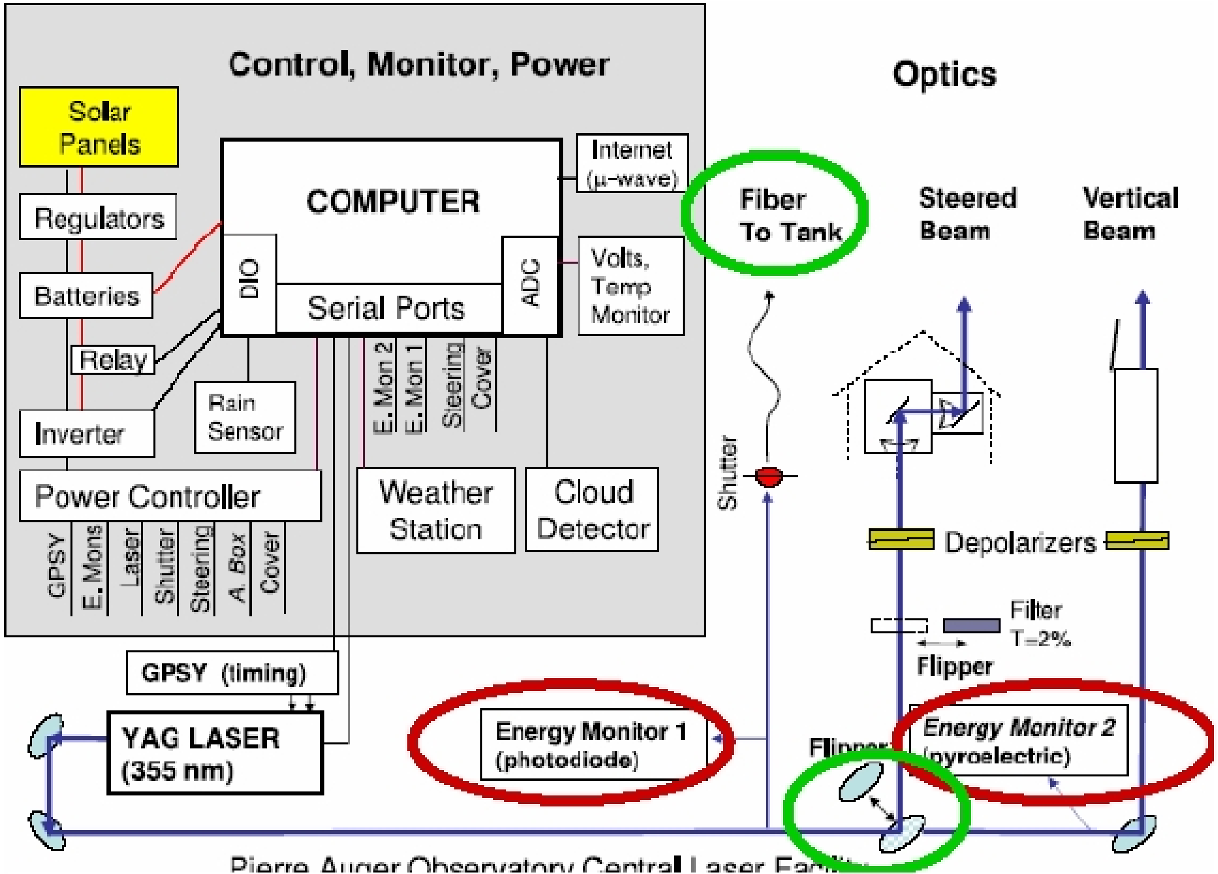
CLF+XLF: more details

1. Nd::YAG laser
    1. harmonic separator mirrors to suppress first two harmonics (1064nm e 534nm)
    2. Depolarizer to randomly polarize the beam
    3. Pulsed beam width 7ns
    4. Average energy per pulse 7mJ (~10^{20} eV)

The laser wavelength is 355 nm, which is near the middle of the nitrogen fluorescence spectrum that is produced by air showers.



Optical Table

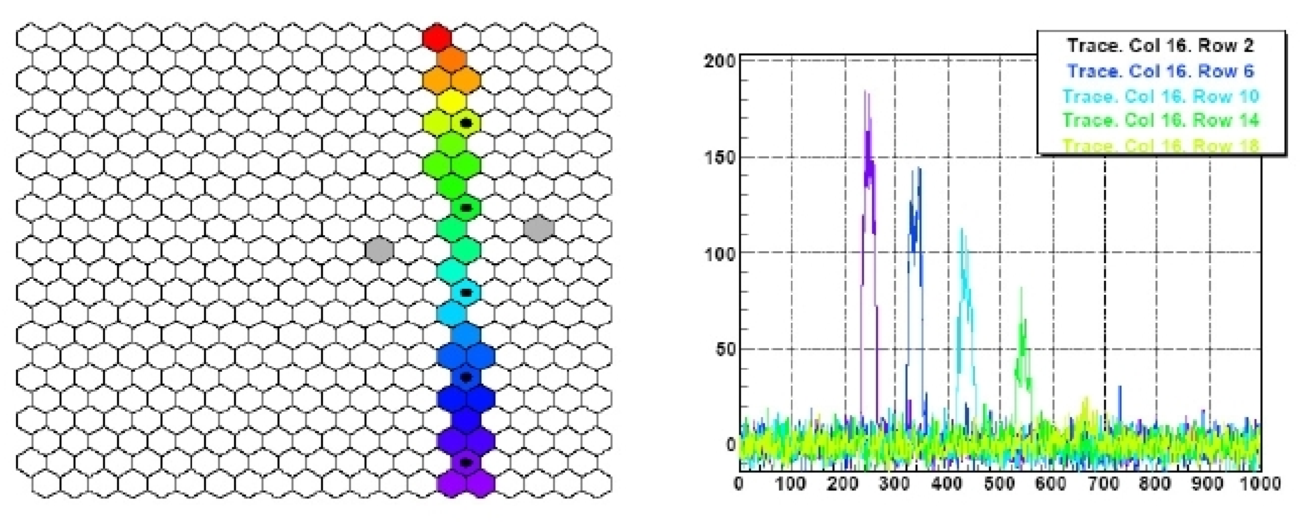


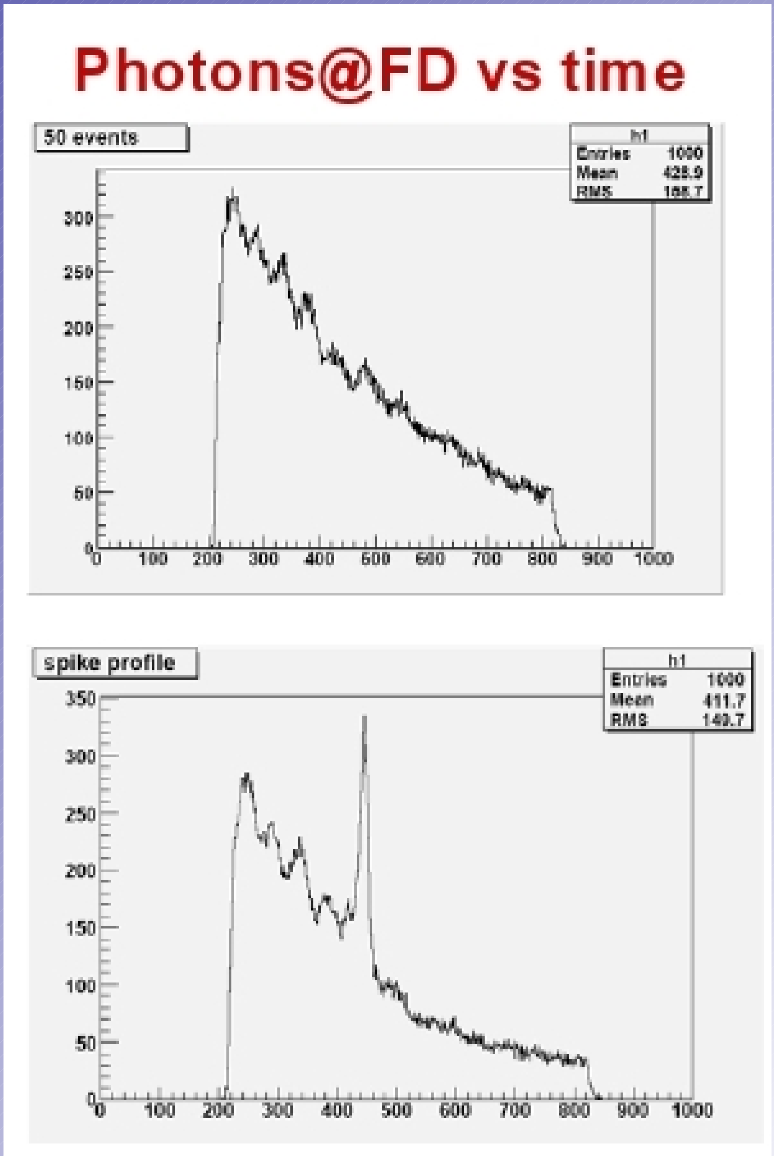
Pierre Auger Observatory Central Laser Fa

CLF+XLF: operating modes, typical signals

- Completely automated operation
- 50 vertical shots every 15 minutes
- 1 shot every 2 seconds
- 1 set of inclined shots every hour

Raw signals on FD camera:




Photons@FD vs time

Clouds on direct laser path produce spikes

Clouds on scattered light path appear as dips
(integral signal: cannot determine their distance)

CLF+XLF: aerosol OD measurement

Normalize fully simulated profiles in Rayleigh nights, when signal is:

$$P_{rn}(\varphi_k) = Q_0 \frac{A_{FD}}{R^2} \frac{3\alpha_m(1+sin^2\varphi_k)}{4\pi(1+tan^2\varphi_k)} e^{-\tau_m(h)(1+\frac{1}{sin\varphi_k})}$$

Caveats:

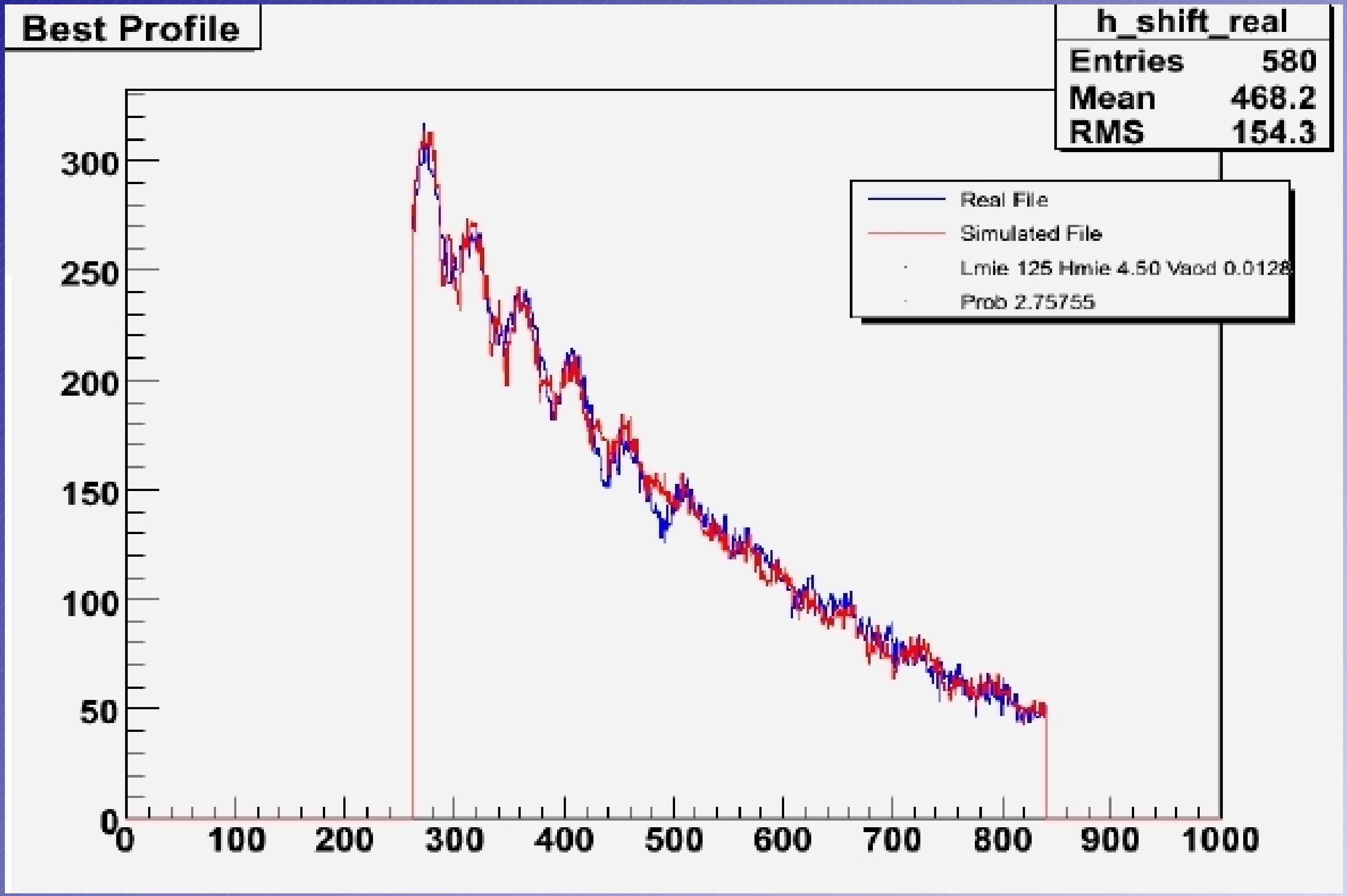
- Energy calibration at few % level is crucial
- VAOD profile measured up to base height of clouds
- Iterative procedure to extract profiles starts with $\beta = \beta_m$

$$ln(P/P_{rn}) = ln\left(\frac{\beta(h,\pi/2+\varphi_k)}{\beta_m(h,\pi/2+\varphi_k)}\right) - \tau_a(h)(1+\frac{1}{sin\varphi_k})$$

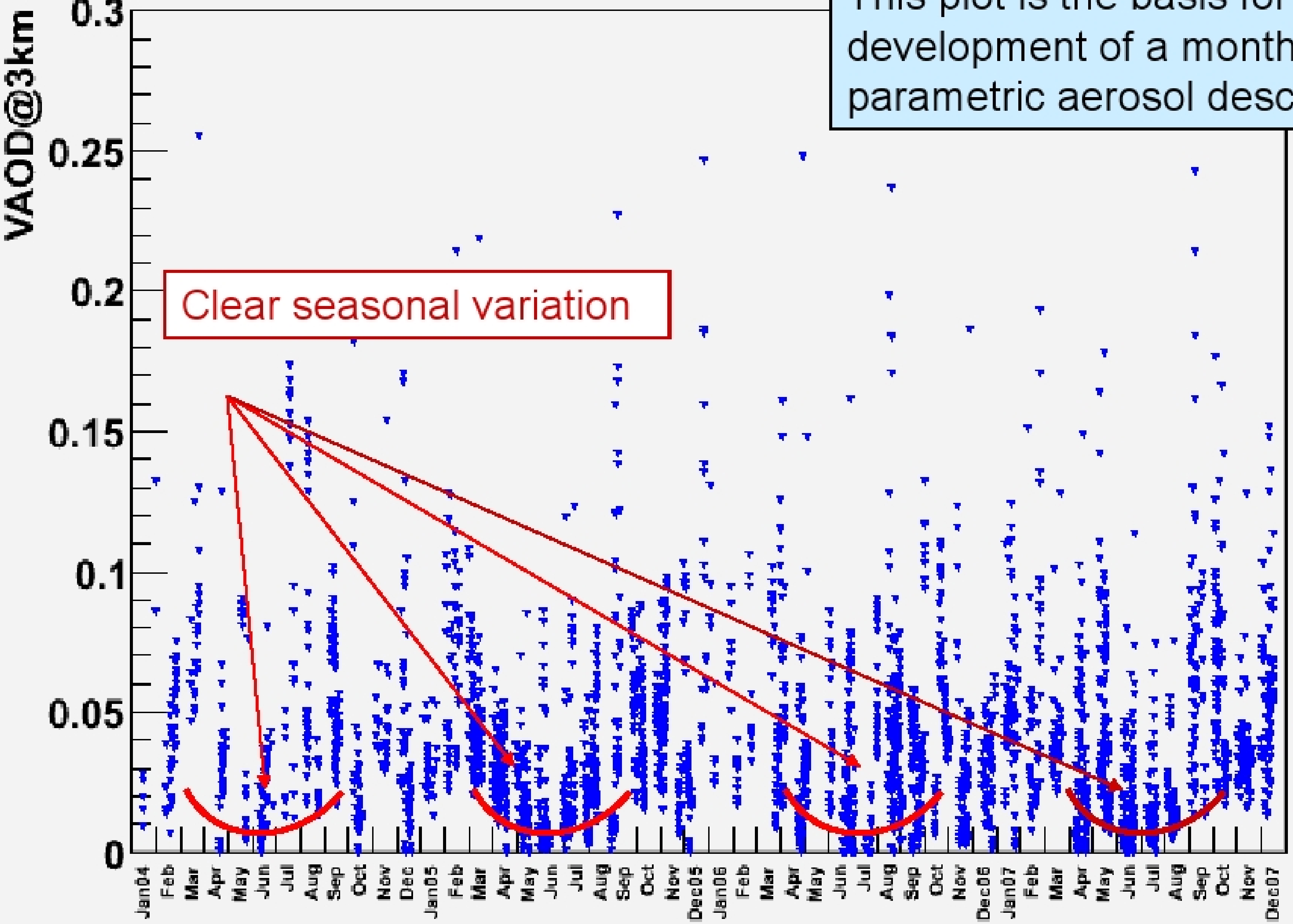
Vertical profiles fitted to a two parameter function for aerosols:

$$\alpha_a = \frac{1}{L_{Mie}} e^{(-h/H_{Mie})}$$

CLF: typical example of best fit



CLF: VAOD vs time, 4 years



Clear seasonal variation

This plot is the basis for the development of a monthly parametric aerosol description

Lidar : scanning patterns

- **Horizontal Shots**

  Horizontal omogeneity

  Aerosol extinction at ground

- **Continuous Scans**

  Cloud coverage

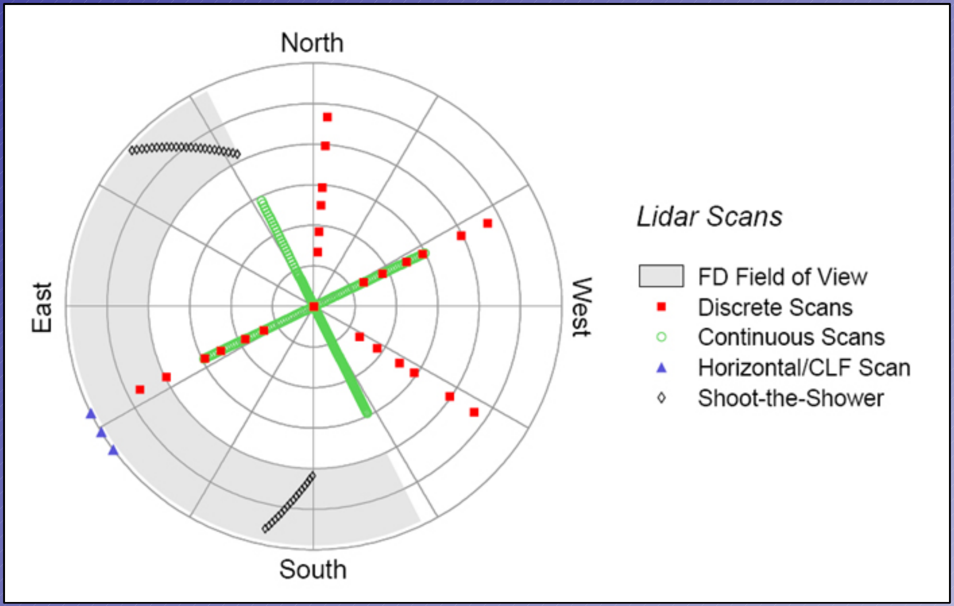
  Cloud characterization

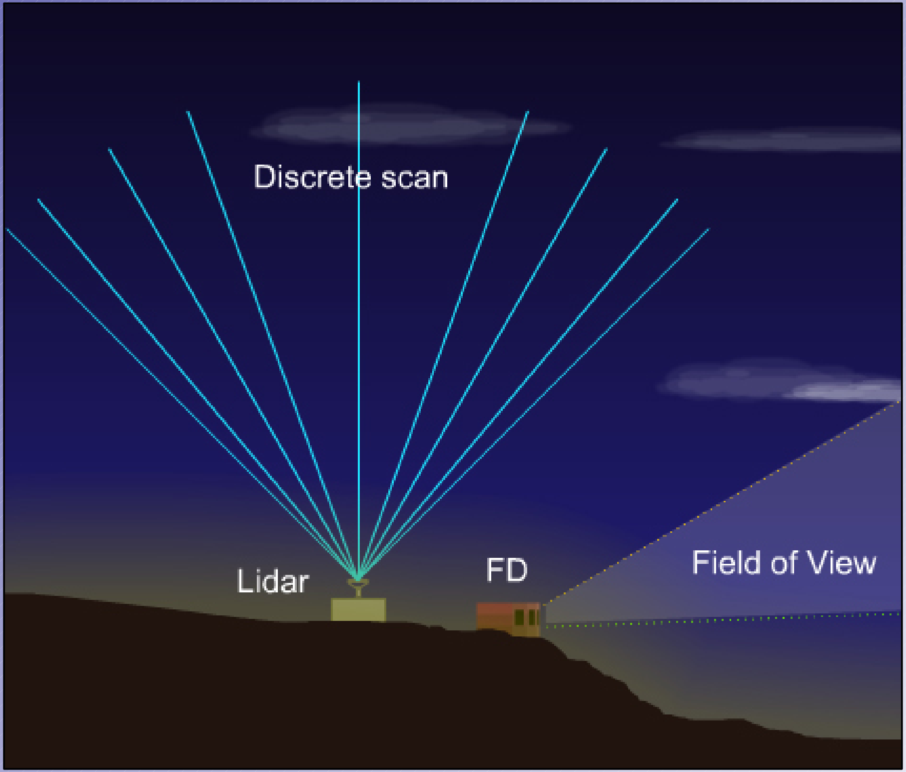
- **Discrete Scans**

  Aerosol optical depth
  with multiangle inversion technique

- **Vertical Shots**

  Aerosol optical depth with Fernald inversion technique





Lidar : horizontal shots

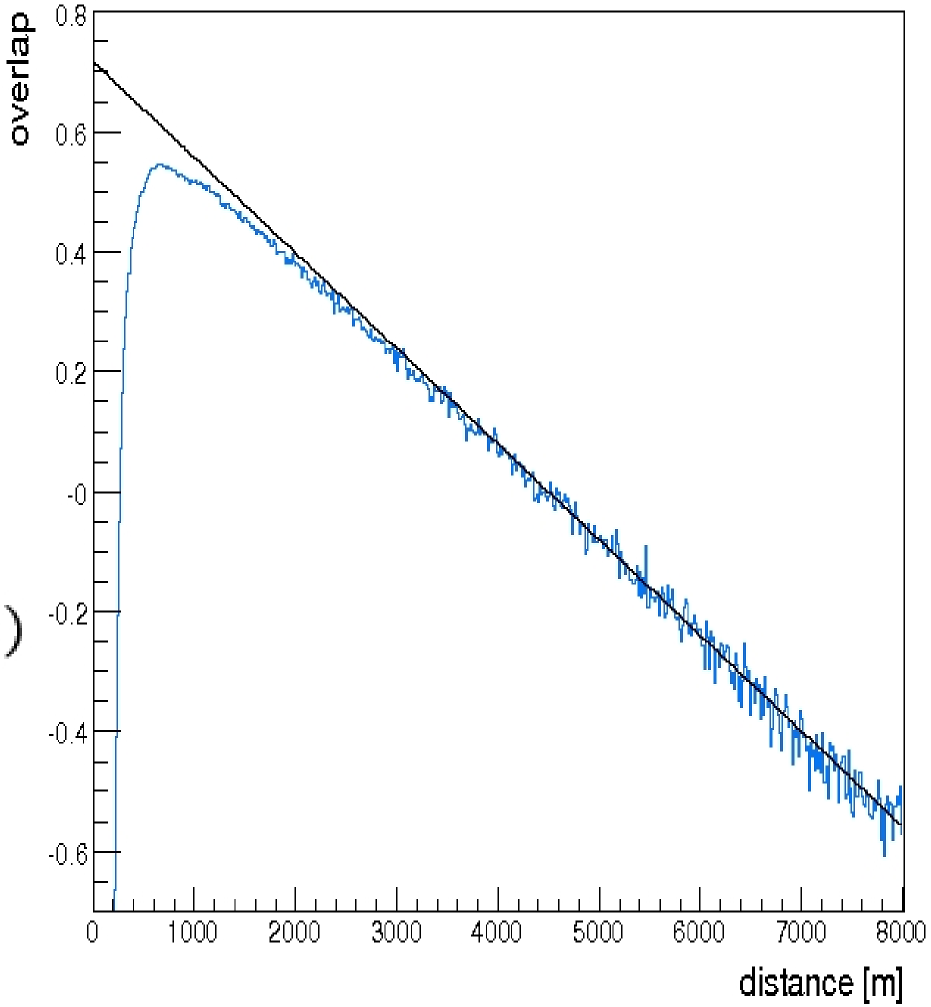
Horizontal shots are crucial to:

- check horizontal homogeneity
- measure aerosols at ground
- check laser-mirror alignment (overlap function)

$$S(r;r_n) = ln\left(\frac{\mathcal{O}(r)\beta(r)}{\mathcal{O}(r_n)\beta(r_n)}\right) - 2\tau(r_n, r)$$

simplifies to:

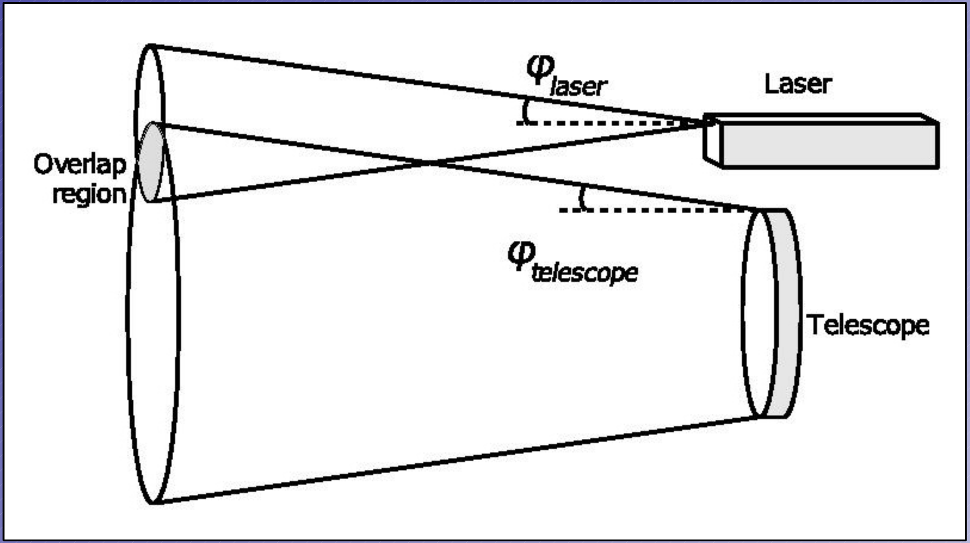
$$S(r;r_n) = ln\left(\frac{\mathcal{O}(r)}{\mathcal{O}(r_n)}\right) - 2\alpha_0(r - r_n)$$

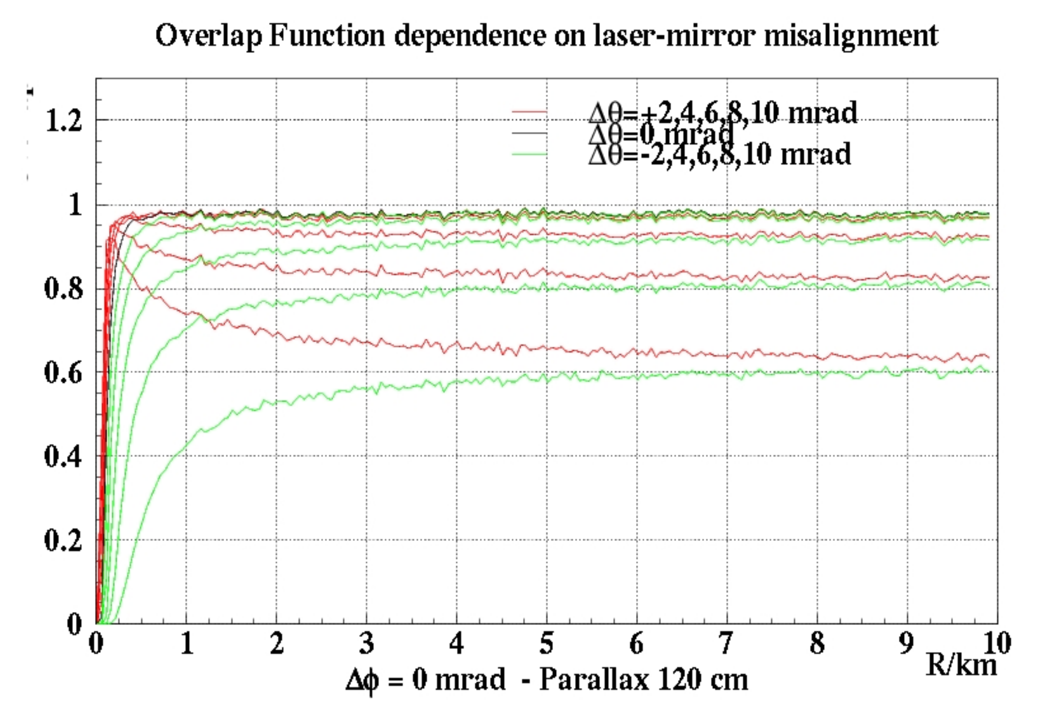


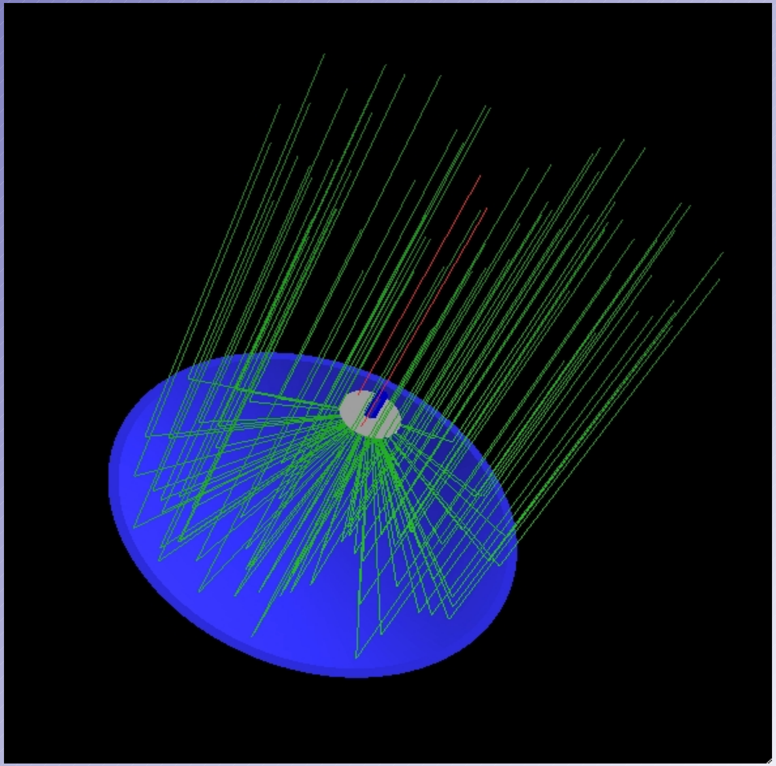
Lidar : overlap function

Depends on:
- laser-mirror alignment
- laser divergence
- PMT field of view

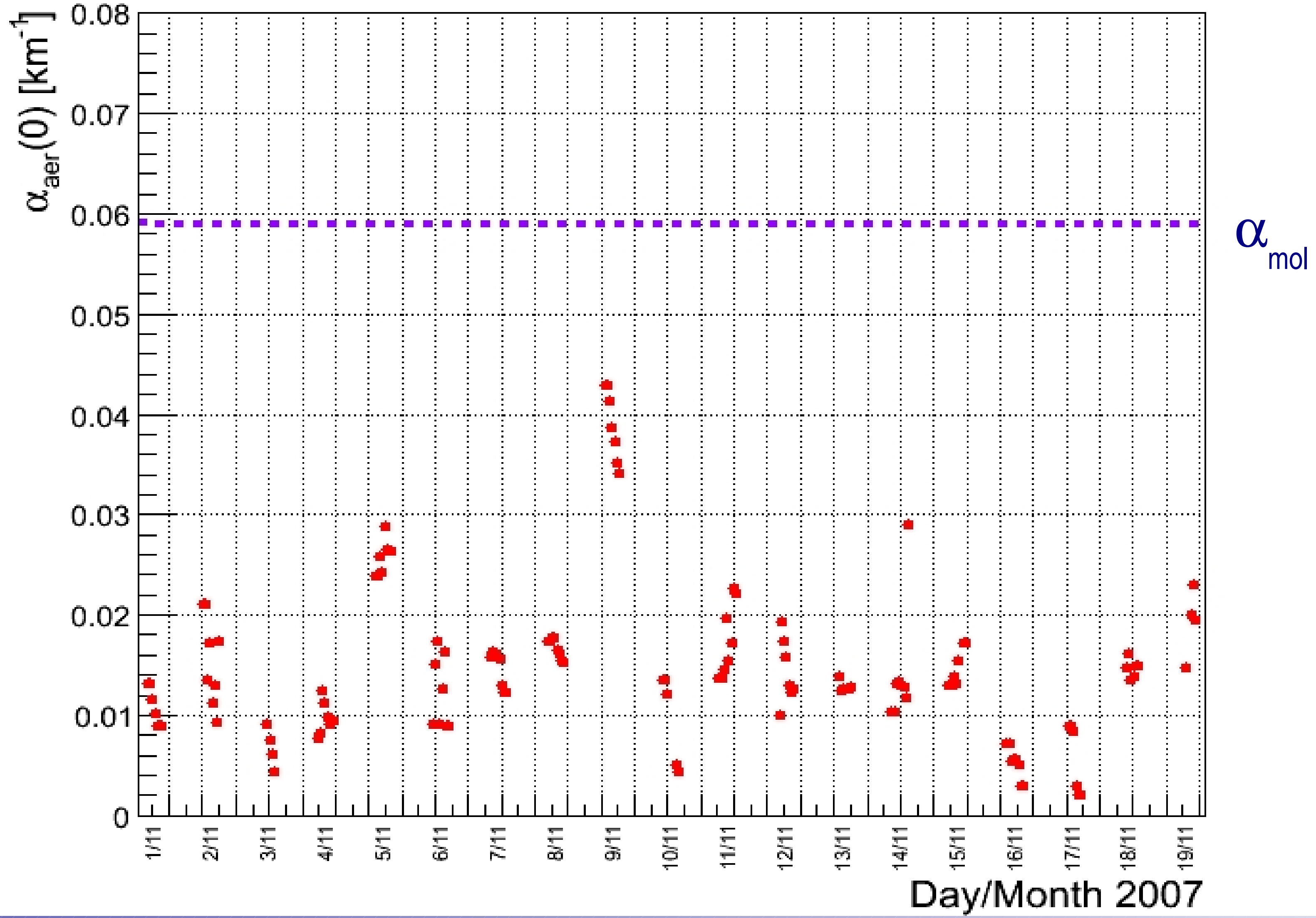
Ray tracing MonteCarlo used to account for shadowing effects from PMT support







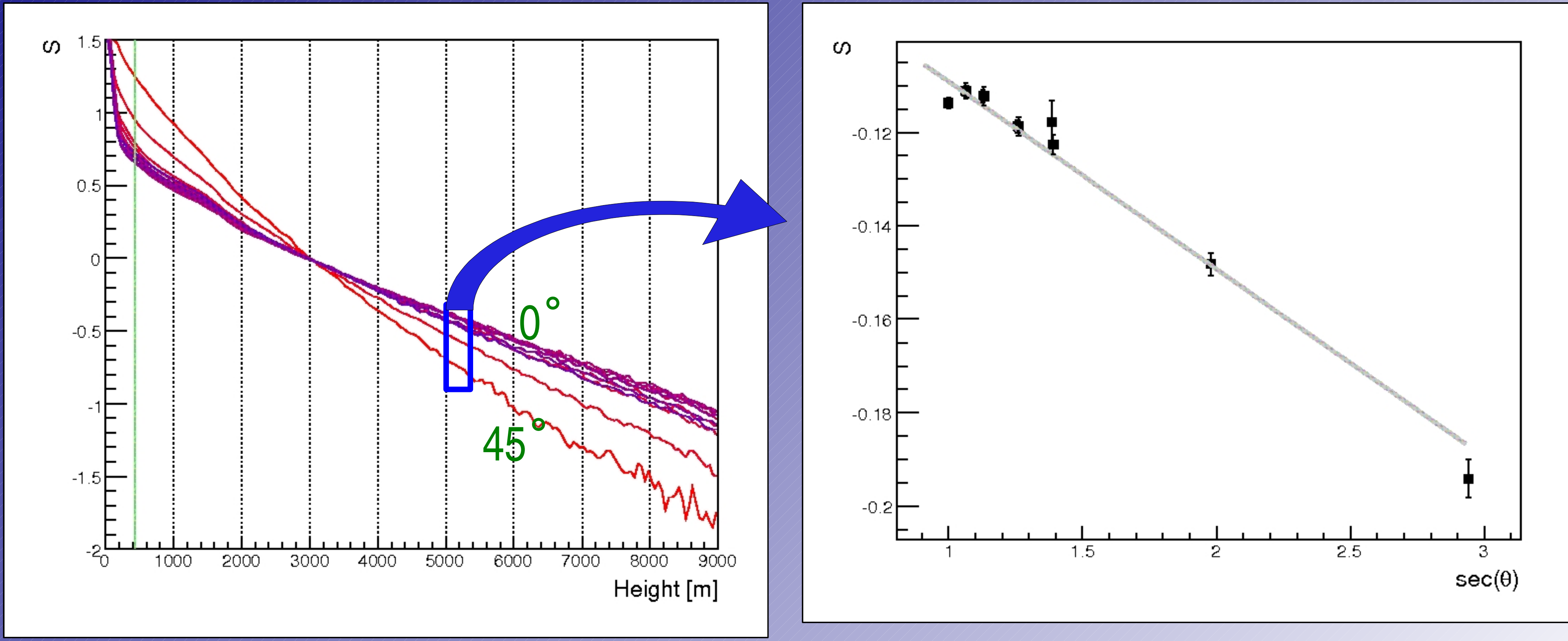
Lidar : aerosols at ground, daily variations



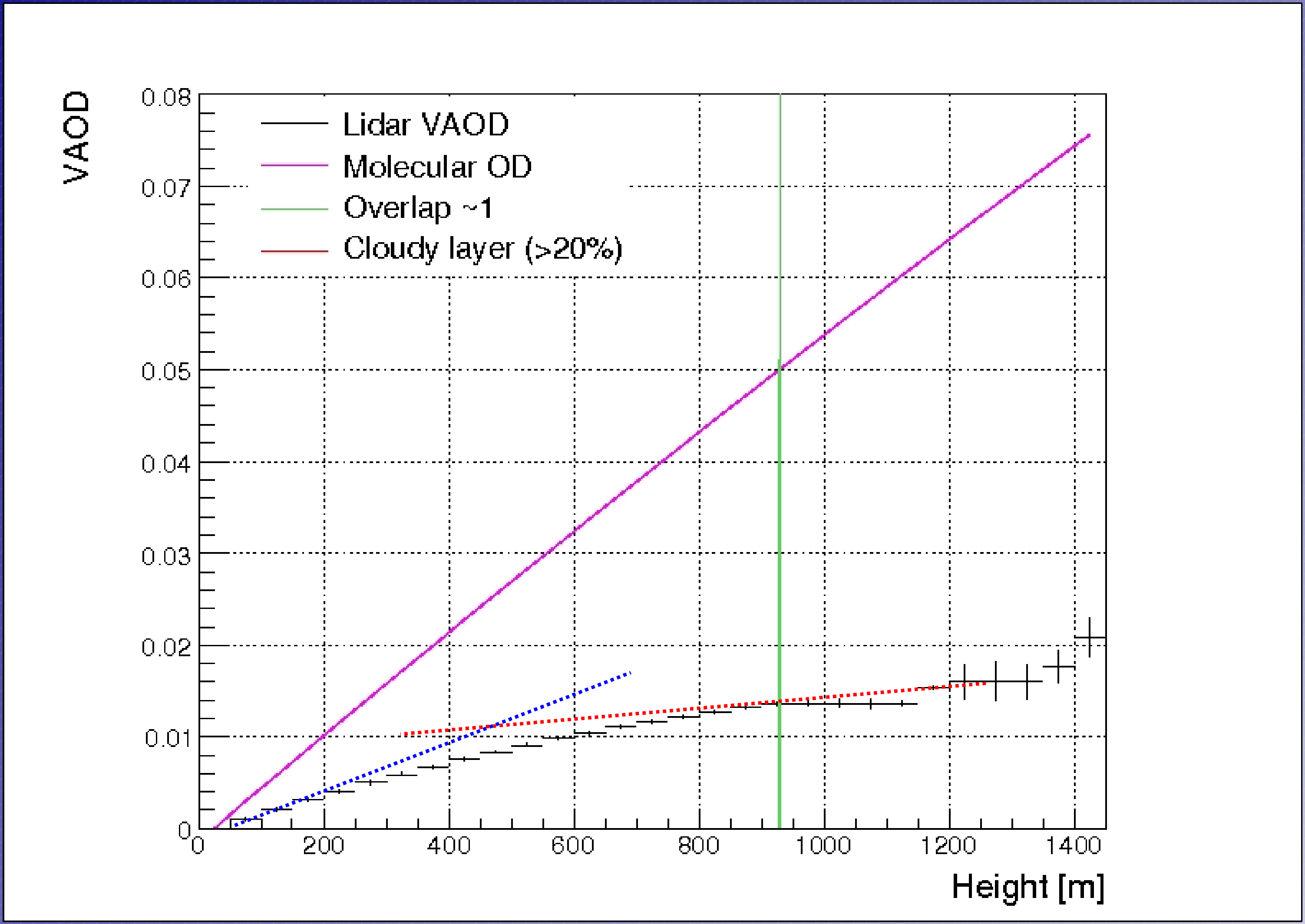
Lidar : VAOD with MultiAngle inversion

Main assumption:
Horizontal Homogeneity

$$S(h;h_n) = ln\frac{P(h)h^2}{P(h_n)h_n^2} = ln\frac{\beta(h)}{\beta(h_n)} - 2\tau(h_n,h)sec\theta$$

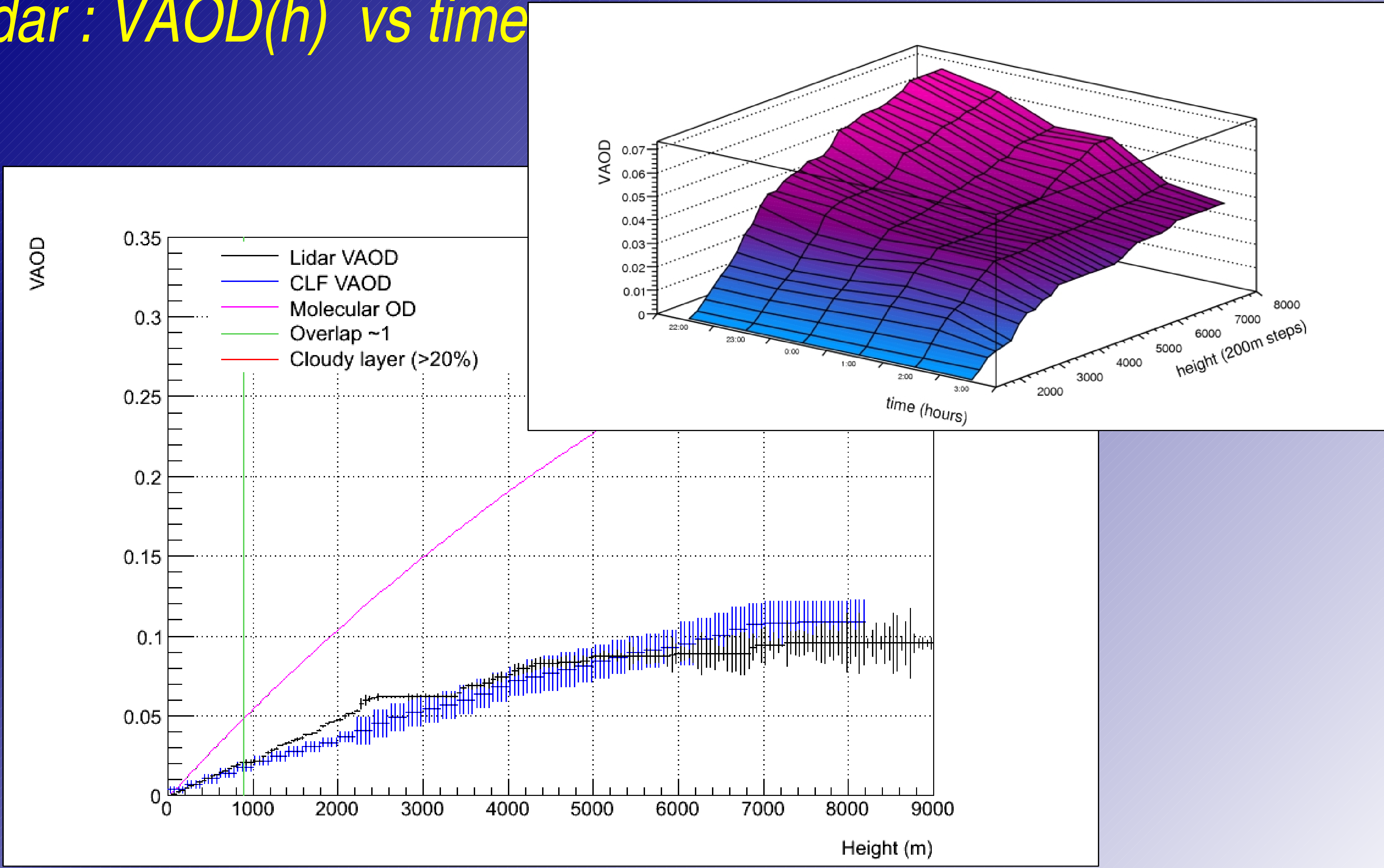


Lidar : VAOD in the short range



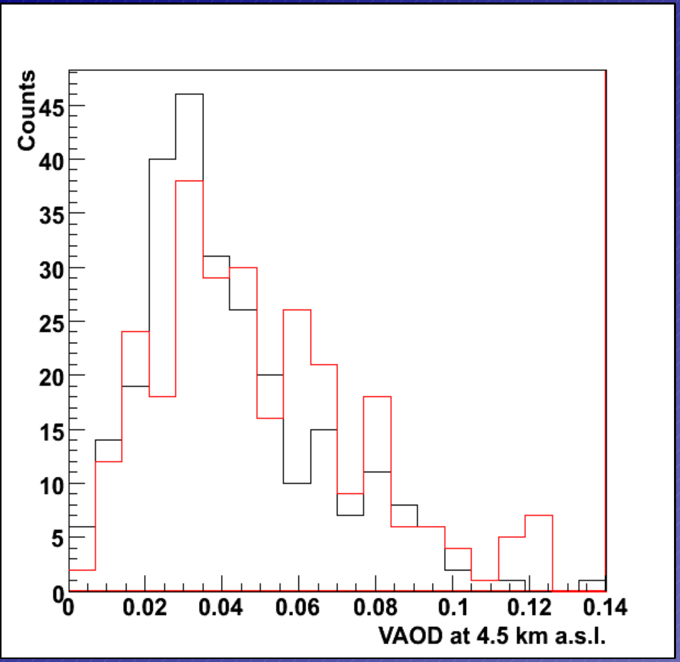
α at ground is used to interpolate the incomplete overlap region

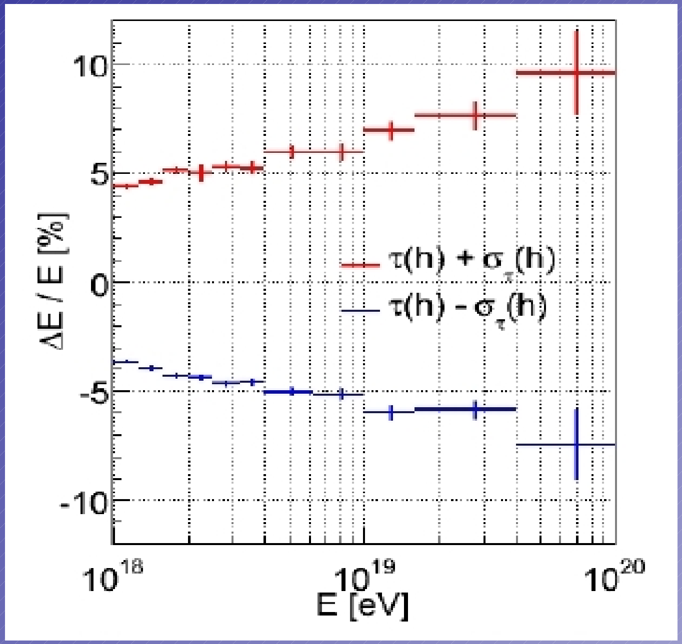
Lidar : VAOD(h) vs time

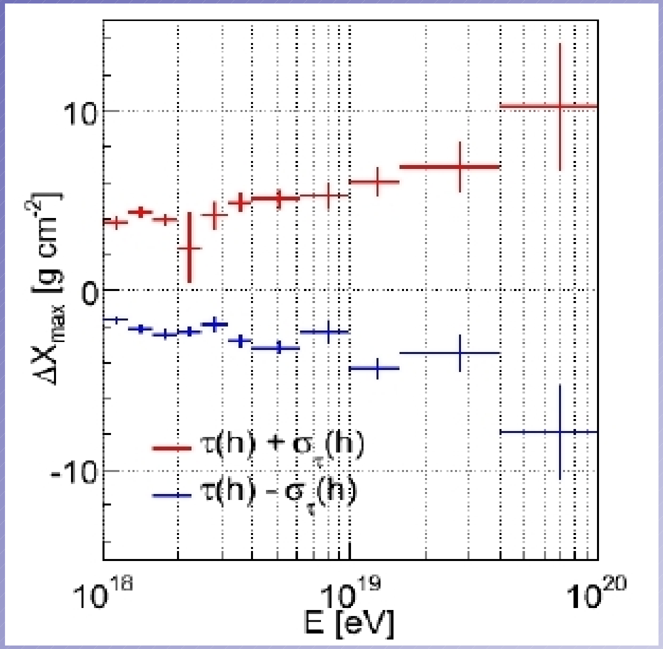


Lidar vs CLF

VAOD effects on shower Energy and X_{max}







Higher Energy → Larger Distance → Bigger Atmospheric effects :

@ 1 EeV : $\Delta E/E \sim 4\%$, $\Delta X_{max} \sim 3\ \mathrm{g/cm^2}$

>40 EeV : $\Delta E/E \sim 8\%$, $\Delta X_{max} \sim 9\ \mathrm{g/cm^2}$

Lidar : VAOD with Fernald inversion/1

If we have only molecules, $\beta=(3/8\pi)\alpha$; differentiating :

$$S = ln(\alpha(r)/\alpha(r_0)) - 2\int_{r_0}^{r} \alpha(r')dr'$$

we get

$$\frac{dS}{dr} = \frac{1}{\alpha}\frac{d\alpha}{dr} - 2\alpha$$

that we can multiply by e^S/α to obtain:

$$\frac{d(e^S/\alpha)}{dr} = -2e^S$$

IF we know α at some (large) distance r_∞, we can integrate

it to get :

$$\frac{e^{S(r)}}{\alpha(r)} = \frac{e^{S(r_\infty)}}{\alpha(r_\infty)} + 2\int_{r}^{r_\infty} e^{S(r')}dr'$$

Lidar : VAOD with Fernald inversion/2

IF the aerosol phase function is known and does not change with altitude then we can write $F = P_m/P_a$ and write S as:

$$S = ln\left(\frac{F\alpha_m(r)+\alpha_a(r)}{F\alpha_m(r_0)+\alpha_a(r_0)}\right)-2\int_{r_0}^{r}(\alpha_m(r')+\alpha_a(r'))dr'$$

IF we then can assume that we know α_a at some large distance, we can define the auxiliary function :

$$S' = S + 2(1-F)\int \alpha_m(r')dr'$$

and invert the previous equation in

$$\alpha' = F\alpha_m + \alpha_a$$

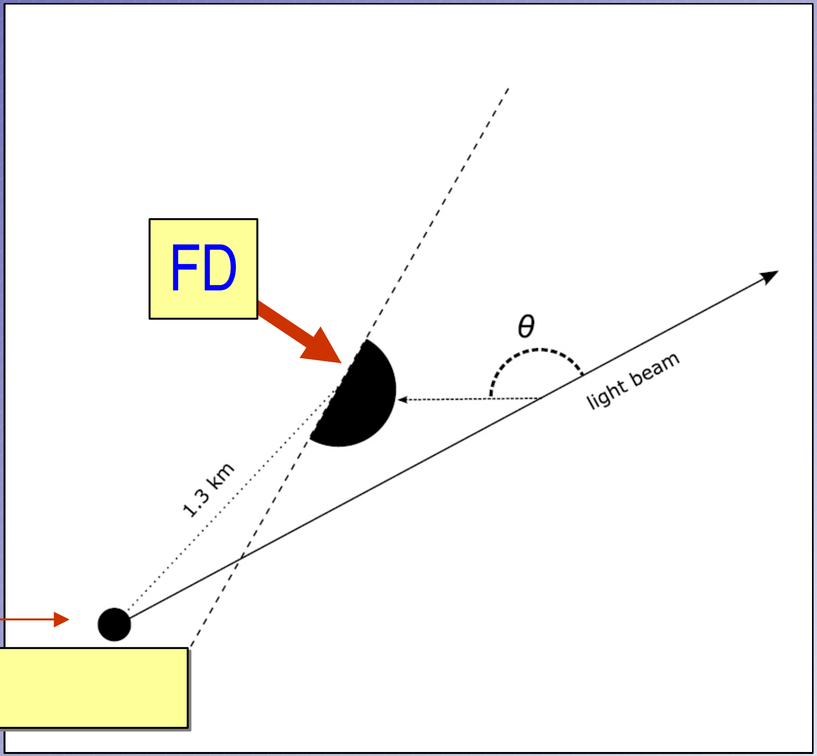
Problem: large systematics from the value we assume for F.

Aerosol angular distribution

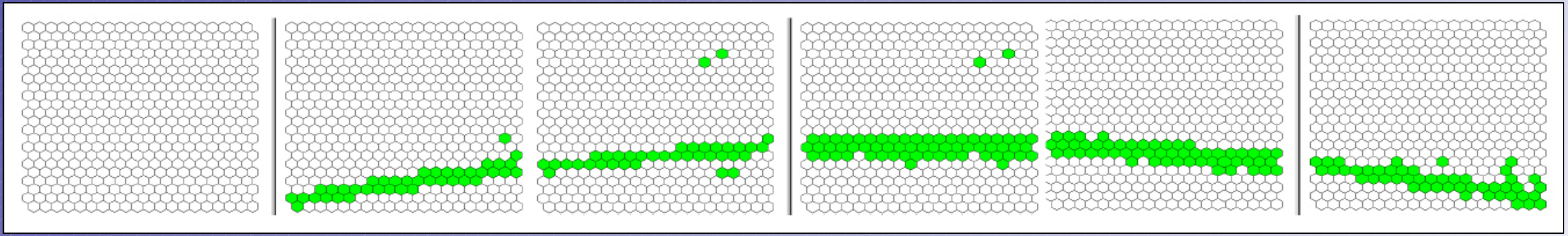
APF: Aerosol Phase Function

$$\mathcal{P}(\Omega) = \frac{1}{\sigma}\left(\frac{d\sigma}{d\Omega}\right)$$

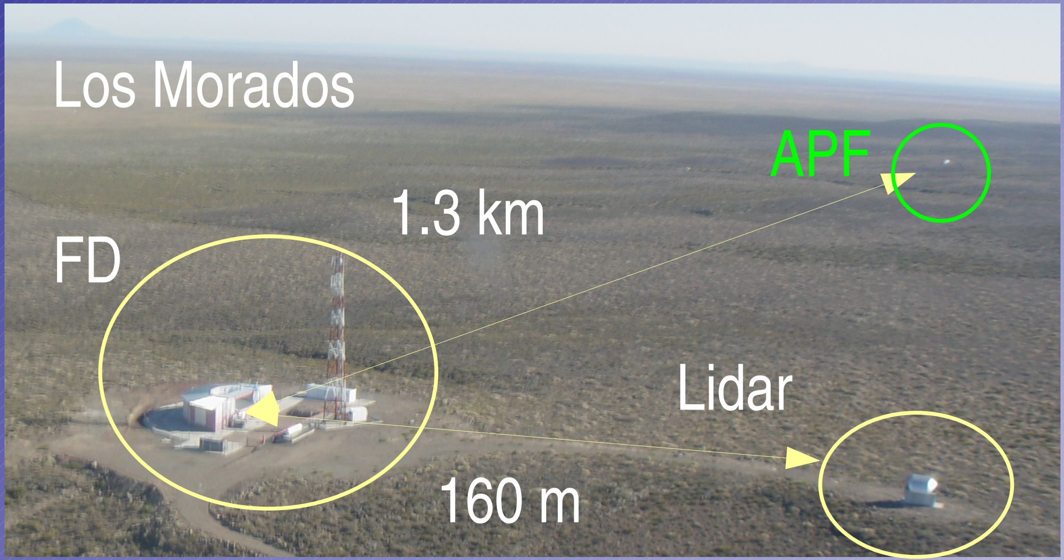
Measurement of the aerosol differential cross section directly in the proximity of the FD sites.

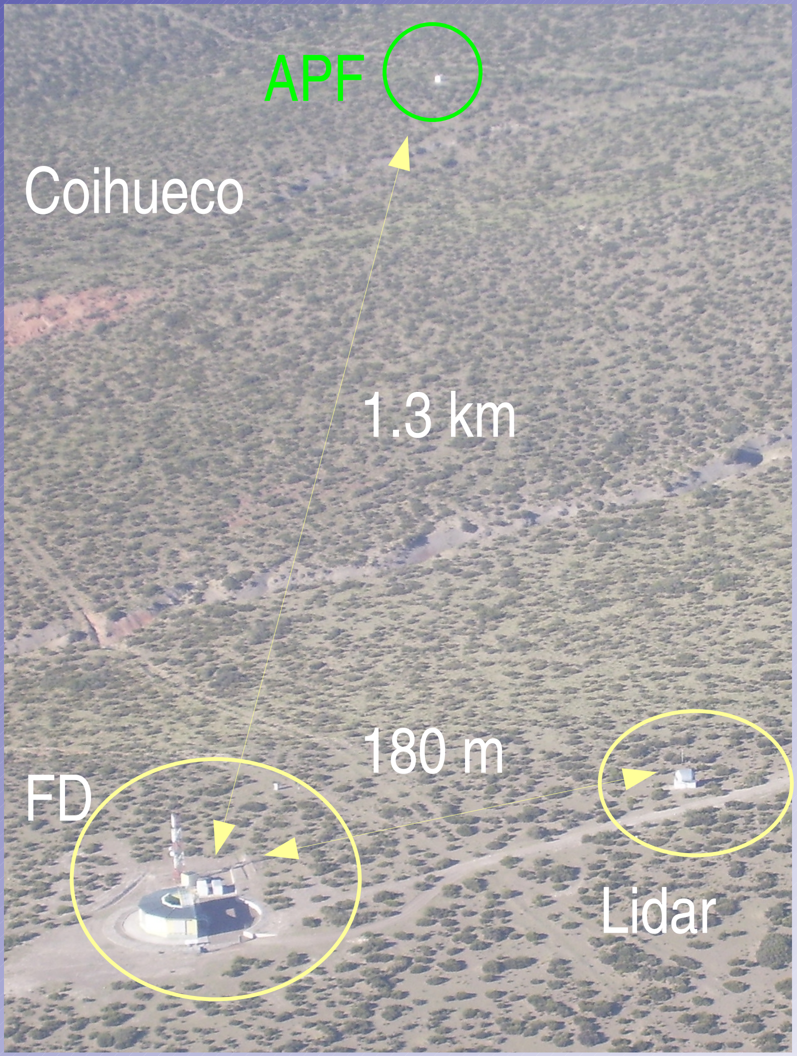


APF: Xenon flash lamp source



APF locations





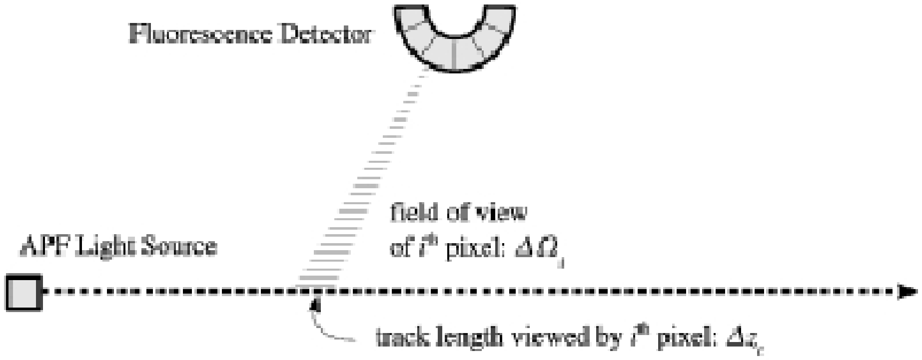
Aerosol angular distribution

- **Signal from the APF light source in each pixel of the FD is given by**

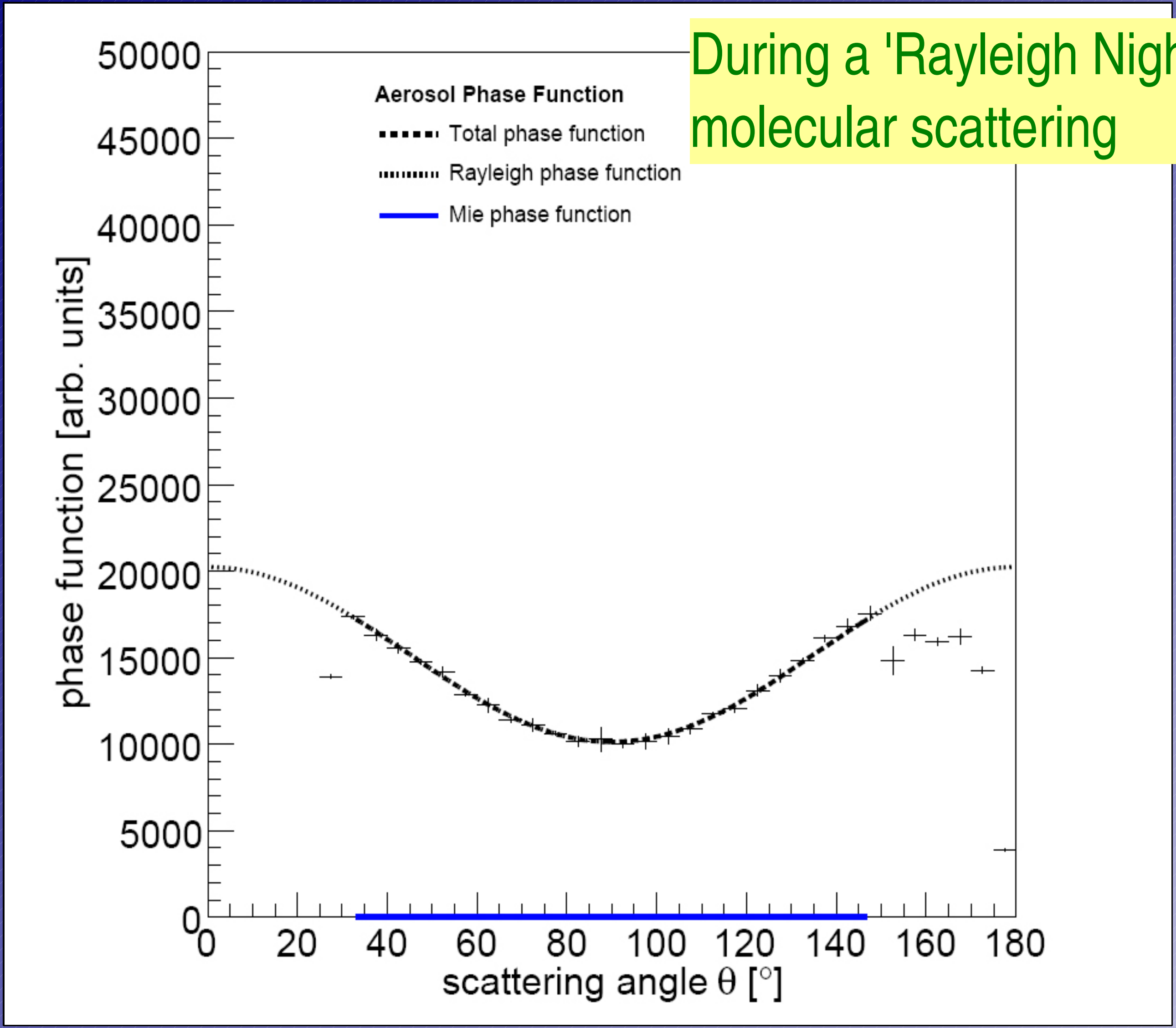
$$S_i = I_0 \cdot \frac{T}{r_i^2}\left[\frac{1}{\Lambda^m}\left(\frac{1}{\sigma^m}\left(\frac{d\sigma^m}{d\Omega}\right)\right) + \frac{1}{\Lambda^a}\left(\frac{1}{\sigma^a}\left(\frac{d\sigma^a}{d\Omega}\right)\right)\right]_i \cdot \Delta z_i \cdot \Delta\Omega_i \cdot \varepsilon_i$$

Rayleigh Aerosol

- I_0 light source intensity
- r_i distance beam to detector
- T transmission factor (set to 1 in this analysis)
- Λ^m / Λ^a total molecular/aerosol extinction length
- Δz_i track length
- $\Delta\Omega_i$ pixel solid angle
- ε efficiency

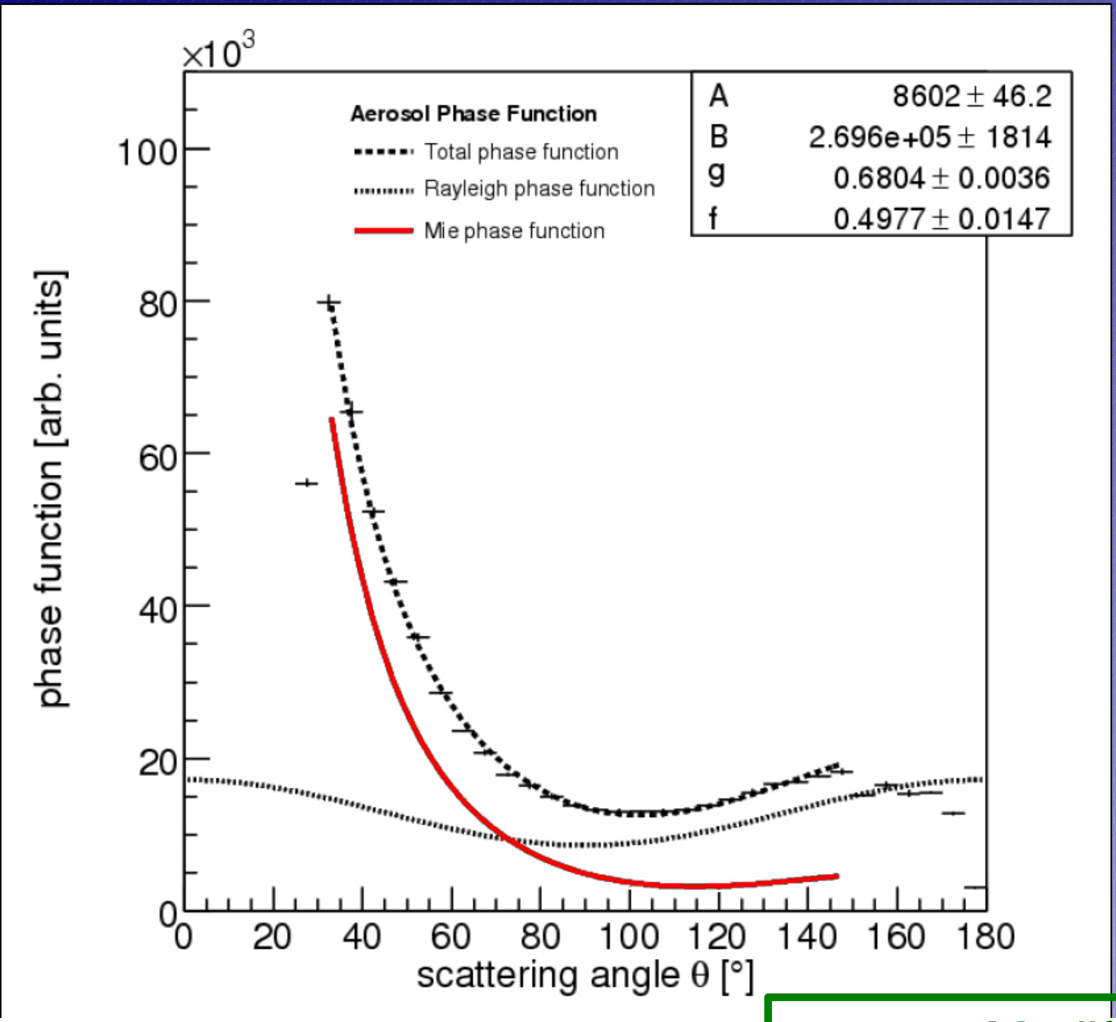


Aerosol angular distributions



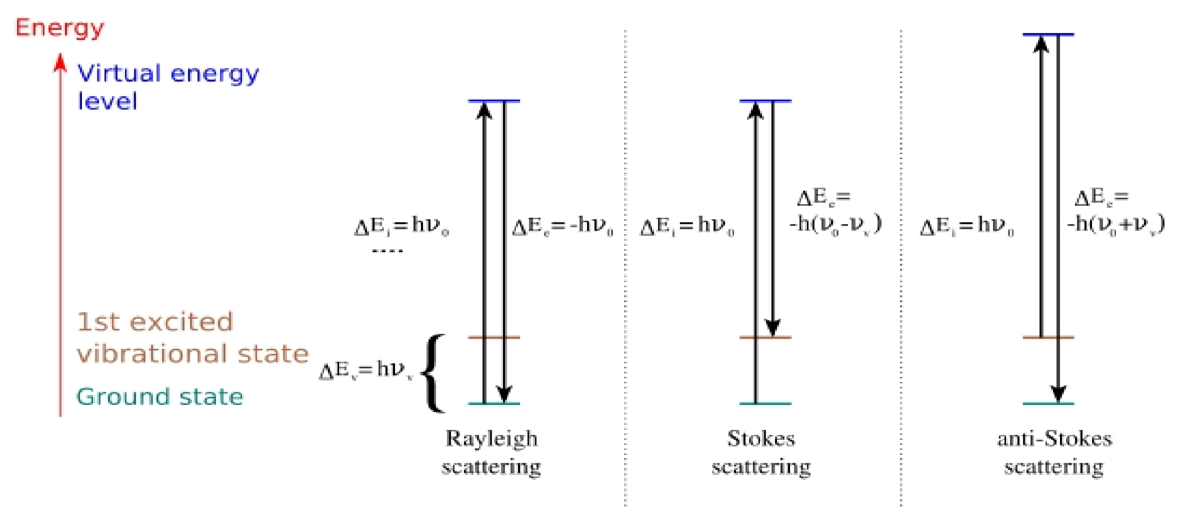
During a 'Rayleigh Night': pure molecular scattering

Aerosol angular distributions



$$F(\vartheta) = A \times \underbrace{\left(1+\cos^2\vartheta\right)}_{\text{Rayleigh}} + \overbrace{B \times \left(1-g^2\right) \times \left(\frac{1}{\left(1+g^2-2g\cos\vartheta\right)^{3/2}} + f \cdot \frac{3\cos^2\vartheta - 1}{2\left(1+g^2\right)^{3/2}} \right)}^{\text{Modified Henyey-Greenstein function}}$$

Raman LIDAR: principles

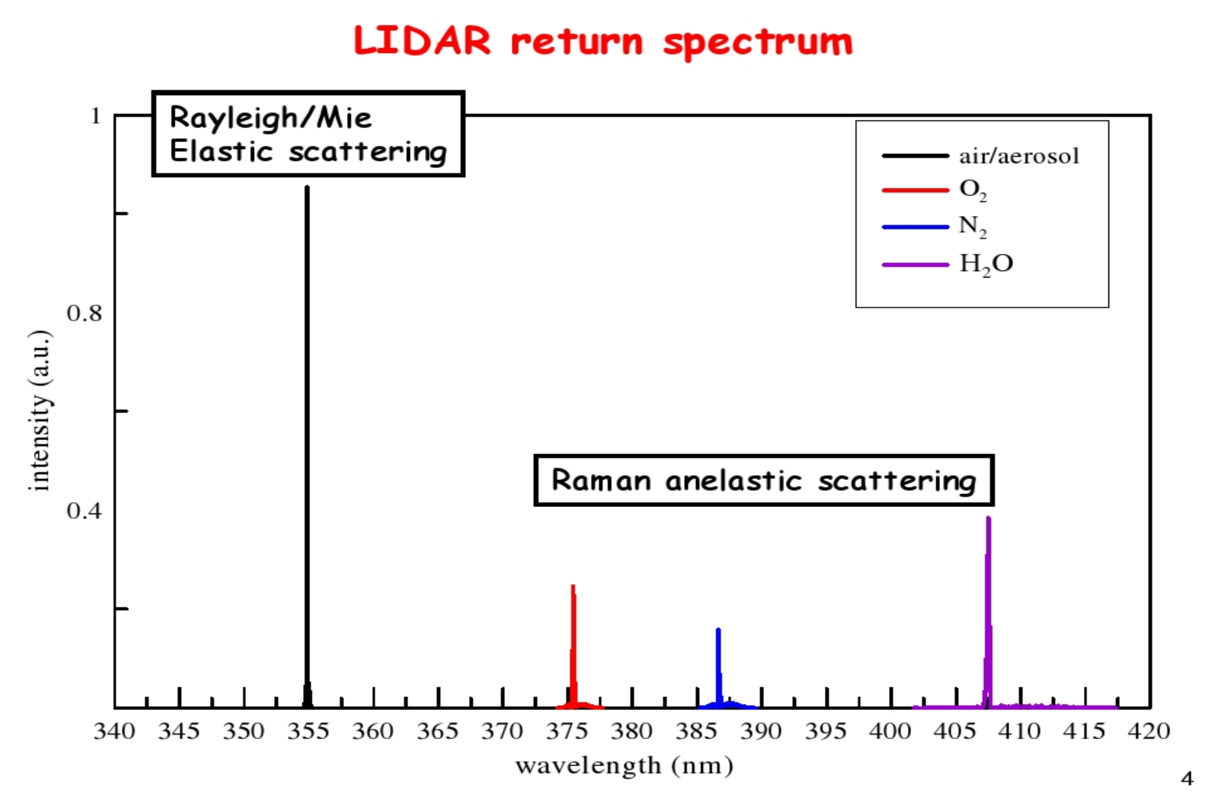


Pro: allows to recognize on what molecule the back scattering happened

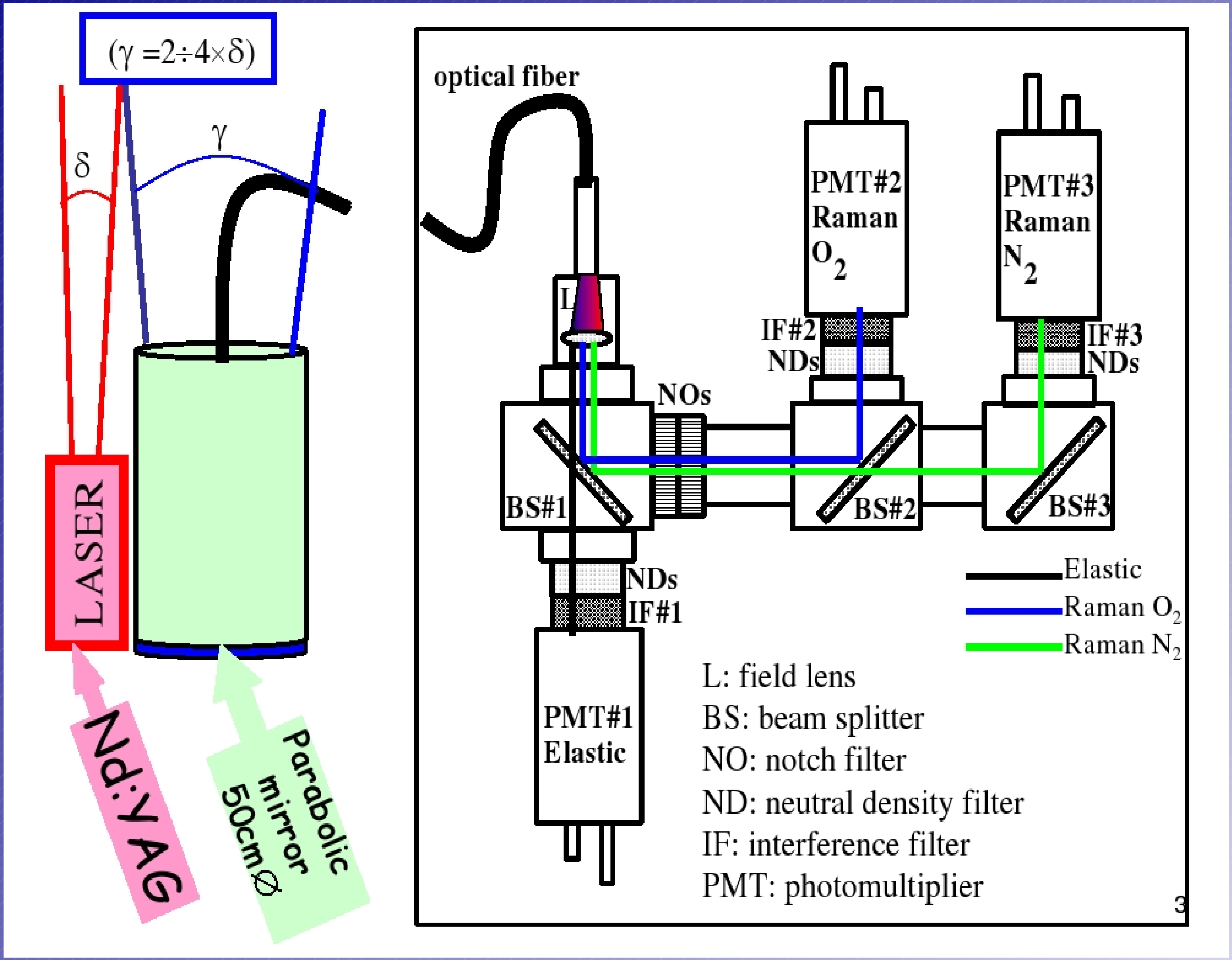
Contra: $\sigma_{\text{Raman}} \sim 10^{-3}\ \sigma_{\text{Rayleigh}}$

Requires MANY shots and HIGH power laser.

Operating Mode:
40 min before FD starts
20 min after FD ends

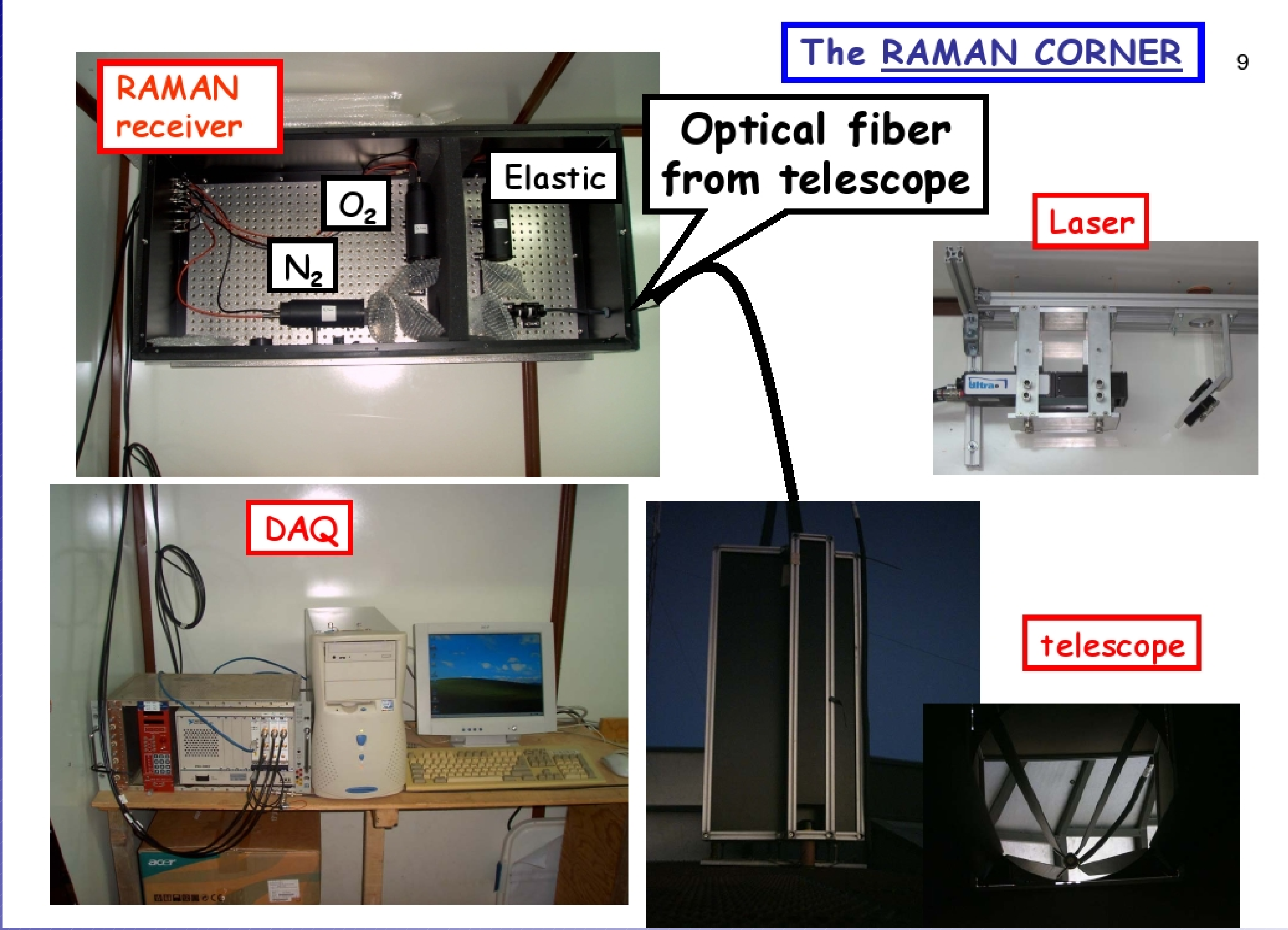


Raman LIDAR: layout



L: field lens
BS: beam splitter
NO: notch filter
ND: neutral density filter
IF: interference filter
PMT: photomultiplier

Raman LIDAR @ LL



The RAMAN CORNER

9

RAMAN receiver

O_2

N_2

Elastic

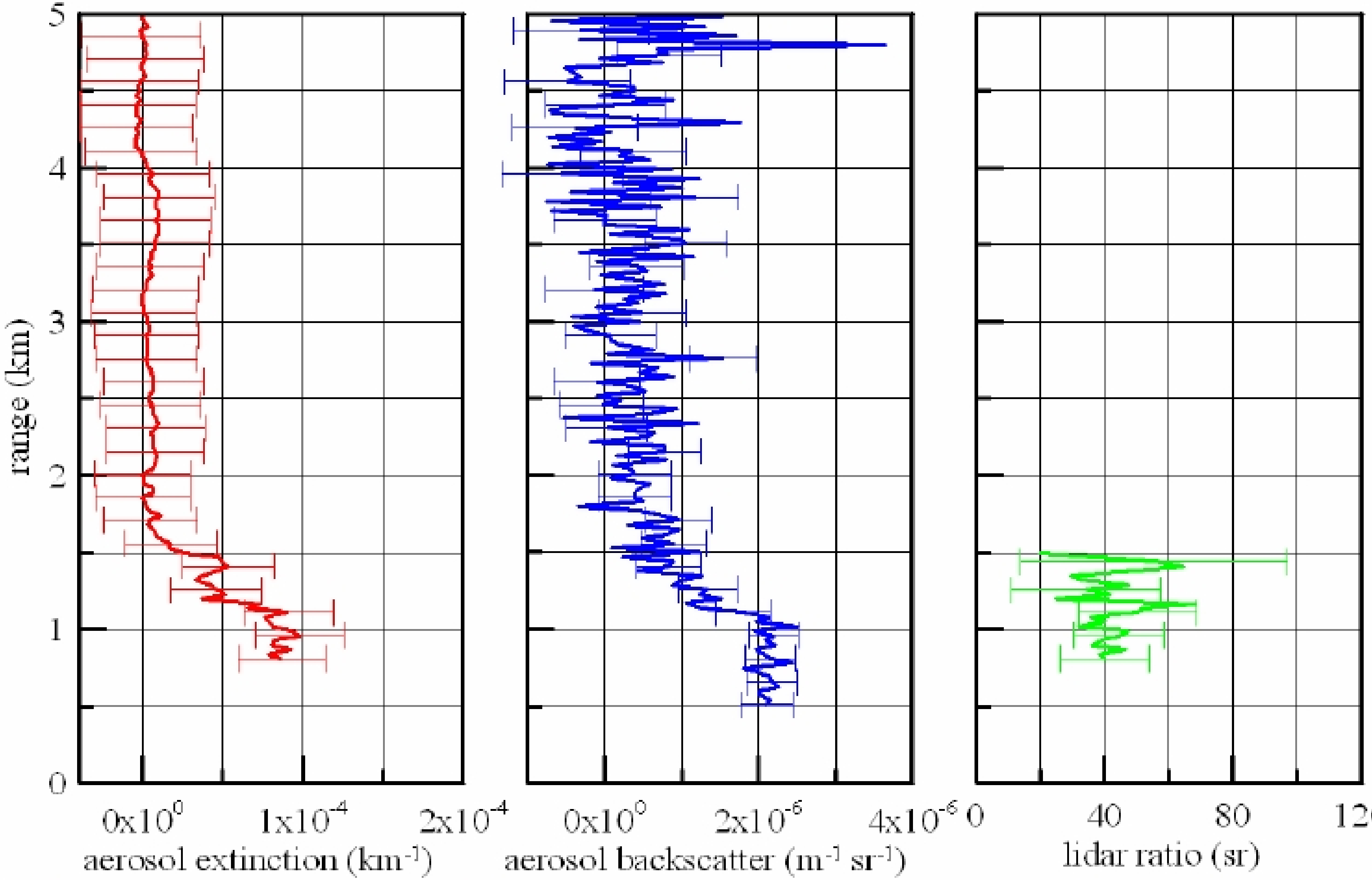
Optical fiber from telescope

Laser

DAQ

telescope

Raman LIDAR: data

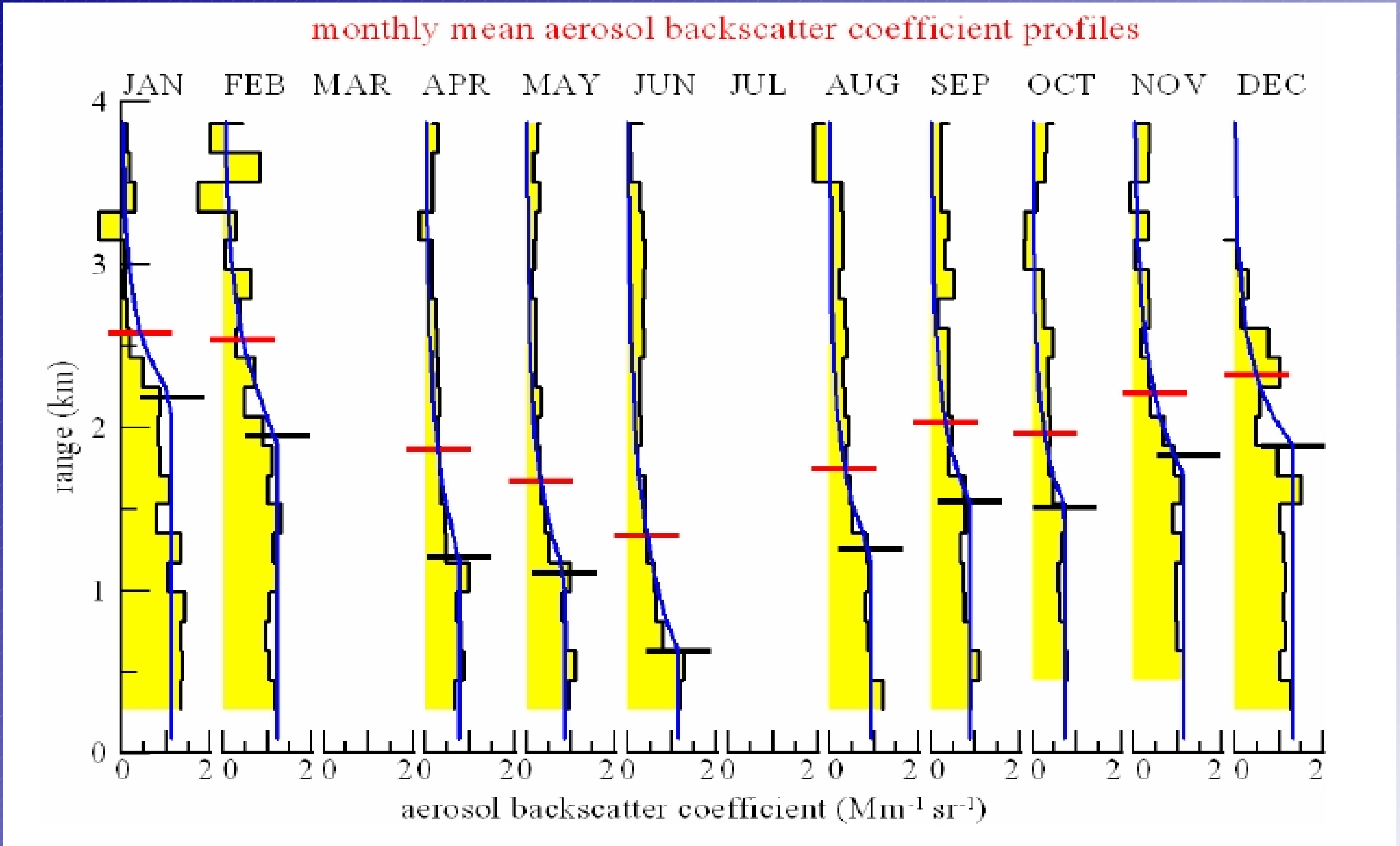


α(s) aerosol volume extinction coefficient

β(s) aerosol volume backscatter coefficient

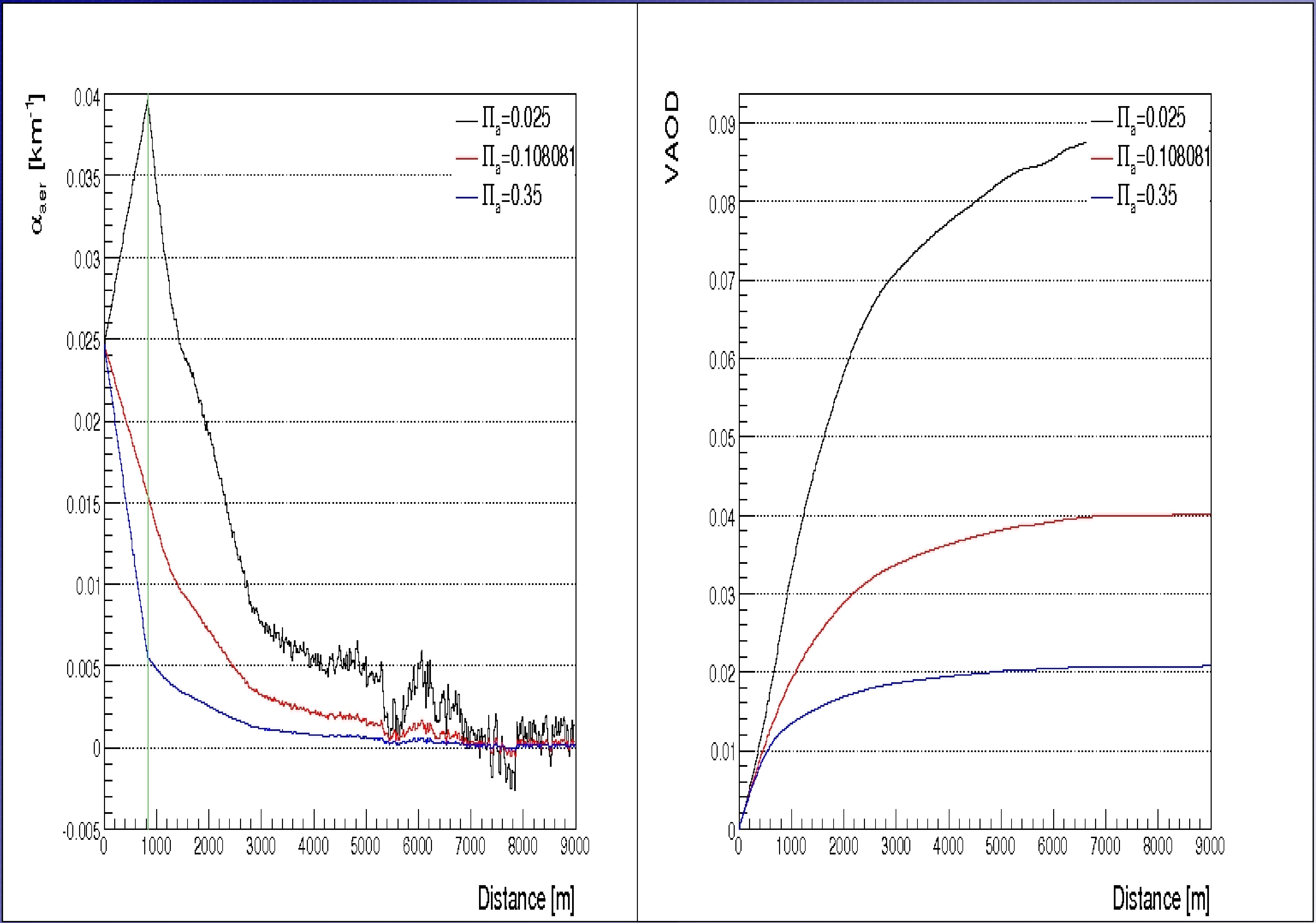
Lidar ratio

Raman LIDAR data vs month



Thanks Jose ,
Thanks Johana,

Thanks to all of you !!!



α_aer [km^-1]
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
-0.005
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
Distance [m]
Π_a=0.025
Π_a=0.108081
Π_a=0.35
VAOD
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
Distance [m]
Π_a=0.025
Π_a=0.108081
Π_a=0.35