Backscatter and Raman LIDAR

(and UHECR fluorescence)

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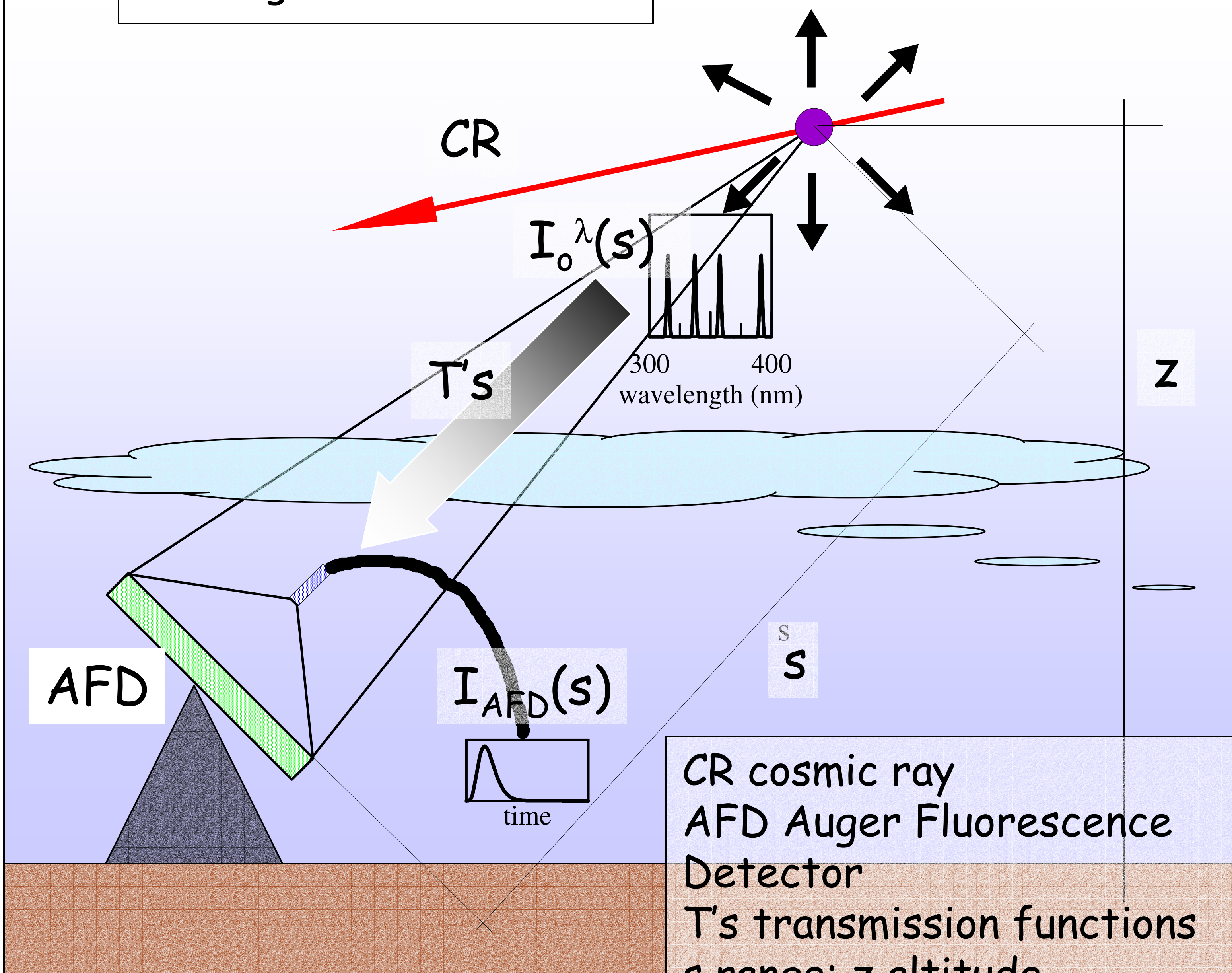
Summary

- **Atmospheric transmission of fluorescence light and determination of energy release by UHECR.**
- **Advantages of Raman lidar in measuring the aerosol transmission.**
- **Estimation of aerosol transmission (with real data).**

AFD light measurements



CR cosmic ray
AFD Auger Fluorescence Detector
T's transmission functions
s range; z altitude

AFD light measurements

In a single pixel:

$$I_{AFD}(s) = \int_{\Delta\lambda} I^{\lambda}(s) \cdot \eta(\lambda) \cdot QE(\lambda) d\lambda$$

s	range along the line of sight
$I_{AFD}(s)$	intensity measured by AFD single pixel
$\Delta\lambda$	Air fluorescence spectrum bandwidth
$I^{\lambda}(s)$	Spectral fluorescence intensity at AFD
$\eta(\lambda)$	AFD optical transmission efficiency
$QE(\lambda)$	PMT quantum efficiency

$$I^{\lambda}(s) = I_o^{\lambda}(s) \cdot T_{mol}^{\lambda}(s) \cdot T_{aer}^{\lambda}(s) \cdot T_{abs}^{\lambda}(s) \cdot (1 + f)\frac{d\Omega}{4\pi}$$

$I_o^{\lambda}(s)$ air fluorescence spectral intensity @ altitude z

($z = s \cdot \sin\theta$, θ is the elevation angle of AFD line of sight)

$T_{mol}^{\lambda}(s)$ molecular scattering transmission @ λ

$T_{aer}^{\lambda}(s)$ aerosol scattering transmission

$T_{abs}^{\lambda}(s)$ gas absorption transmission

f high order corrections (i.e., multiple scattering)

$d\Omega$ solid angle subtended by AFD

+air fluorescence yield → **Energy of CR**

$$\left.\frac{\Delta E}{E}\right)_{shower} \approx \left.\frac{\Delta T}{T}\right) \oplus \ldots$$

E: shower energy

T: atmospheric transmission

It can be easily estimated with sufficient precision ...!?

High variability ...

direct measurements with Raman lidar OR

strong assumption ...

Total atmospheric transmission

$$T^{\lambda}_{total}(s) = T^{\lambda}_{mol}(s) \cdot \underline{T^{\lambda}_{aer}(s)} \cdot T^{\lambda}_{abs}(s)$$

s range along the line of sight

The absorption can be neglected because of the FD optical transmission ...!?

$$T_{mol}^{\lambda}(s) = \exp\left(-\int_0^s \sigma_{mol}^{\lambda} n_{mol}(s) ds\right)$$

$$T_{aer}^{\lambda}(s) = \exp\left(-\int_0^s \left[\int_0^{\infty} dr \pi r^2 Q_{ext}(r,m,\lambda) n_{aer}(s,r)\right] ds\right)$$

Single scattering approx.!

$$T_{abs}^{\lambda}(s) = \exp\left(-\sum_i \int_0^s \sigma_{abs}^{i}(\lambda) n_{abs}^{i}(s) ds\right)$$

n_{mol} atmospheric molecular number density

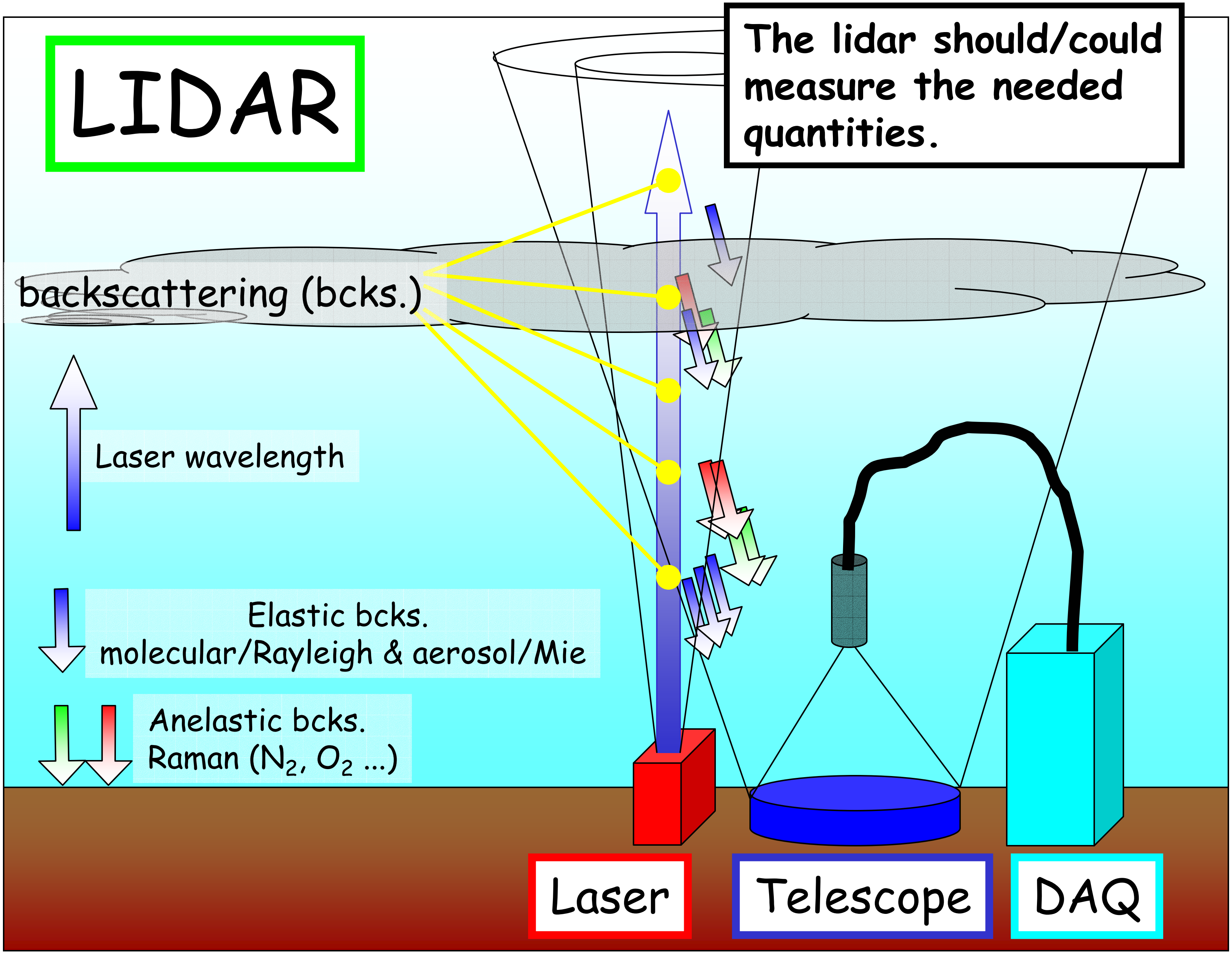
n_{aer} aerosol size distribution

n^{i}_{abs} i - th absorbing gas number density

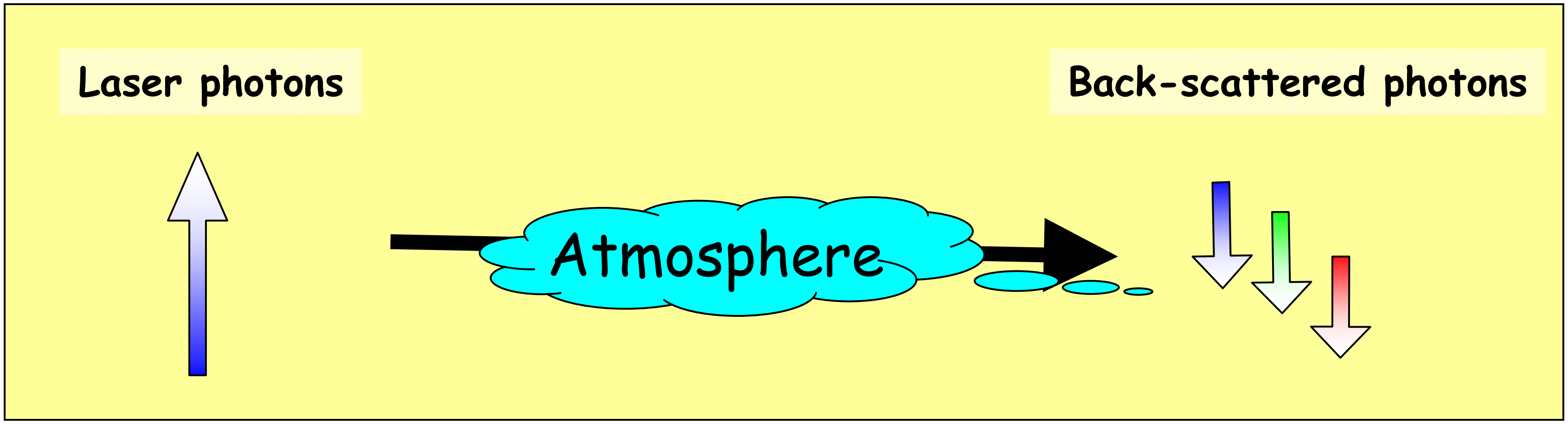
σ_{mol}^{λ} Rayleigh total cross section @ λ

$Q_{ext}(r,m,\lambda)$ Mie extinction efficiency of an aerosol particle of radius r, index of refraction m, @ λ wavelength

$\sigma^{i}_{abs}(\lambda)$ i - th absorbing gas cross section



LIDAR
The lidar should/could measure the needed quantities.
backscattering (bcks.)
Laser wavelength
Elastic bcks.
molecular/Rayleigh & aerosol/Mie
Anelastic bcks.
Raman (N_2, O_2 ...)
Laser
Telescope
DAQ



collected photons

laser photons

Atmospheric attenuation: scattering and absorption

$$N^{\lambda}(z) \propto N_{o}^{\lambda_o} \cdot T_{up}^{\lambda_o}(z) \cdot \left[backscattering \right] \cdot T_{down}^{\lambda}(z) \frac{d\Omega}{4\pi}$$

Scattering processes:

Rayleigh-Mie scattering

Raman scattering

Resonant scattering

solid angle subtended by the receiver $\propto 1/z^2$

z is the altitude/range

Aerosol backscatter calculation

- Following algorithms from Klett (1981) or Fernald (1972,1984)
- Lidar equation contains two unknown sets of parameters:
  - aerosol extinction
  - aerosol backscatter
- Equation can only be solved with prescribed lidar ratio LR (extinction to backscatter ratio)
- Additionally a calibration factor (usually in a height range with negligible aerosol backscatter) has to be applied

Elastic/Rayleigh Lidar signal

$$L^{\lambda_o}(s) = L_o^{\lambda_o} \cdot T_{mol}^{\lambda_o}(s) \cdot T_{aer}^{\lambda_o}(s) \cdot T_{abs}^{\lambda_o}(s) \cdot$$

upward travel

$$\cdot \left[\sigma_{\mathrm{mol}}^{\lambda_o}(\pi) \cdot n_{mol}(s) + \int_0^\infty dr \pi r^2 Q_{bck}(r,m,\lambda_o) n_{aer}(s,r) \right] \frac{d\Omega}{4\pi} \cdot$$

backscattering

$$\cdot T_{mol}^{\lambda_o}(s) \cdot T_{aer}^{\lambda_o}(s) \cdot T_{abs}^{\lambda_o}(s)$$

downward travel

$L_o^{\lambda_o}$ # of photons emitted by the laser

$\sigma_{mol}^{\lambda_o}(\pi)$ Rayleigh differential backscattering cross section :

$$\sigma_{mol}^{\lambda_o}(\pi) = 5.45 \left[\frac{550}{\lambda_o(nm)} \right]^4 \times 10^{-28} cm^2 sr^{-1} = \frac{3}{8\pi} \sigma_{mol}^{\lambda_o}$$

$Q_{bck}(r,m,\lambda_o)$ Mie backscattering efficiency of an aerosol particle

$d\Omega$ solid angle subtended by the telescope

Key features of Klett method.

Recasting the lidar equation

$$L^{\lambda_o}(s) = L_o^{\lambda_o} \cdot T_{tot}^{\lambda_o}(s) \cdot \beta^{\lambda_o}(s)\frac{d\Omega}{4\pi} \cdot T_{tot}^{\lambda_o}(s)$$

$$T_{tot}^{\lambda_o}(s) = \exp\left(-\int_o^s \alpha^{\lambda_o}(s)ds\right)$$

Mandatory assumption!

$$\beta^{\lambda_o}(s) = C \cdot \left[\alpha^{\lambda_o}(s)\right]^m$$

Unknown!

Solving for $T_{tot}^{\lambda_o}(s)$

$$\ln\left[T_{tot}^{\lambda_o}(s)\right] = -\int_0^s \left[\frac{\exp\left(\frac{L^{\lambda_o}(s) - L^{\lambda_o}(s_n)}{m}\right)}{\frac{1}{\alpha^{\lambda_o}(s_n)} + \frac{2}{m}\int_s^{s_n}\exp\left(\frac{L^{\lambda_o}(s') - L^{\lambda_o}(s_n)}{m}\right)ds'}\right]ds$$

Key features of Fernald method.

$$L^{\lambda_o}(s) = L_o^{\lambda_o} \cdot T_{mol}^{\lambda_o}(s) \cdot T_{aer}^{\lambda_o}(s) \cdot \left[\beta_{aer}^{\lambda_o}(s) + \beta_{mol}^{\lambda_o}(s)\right] \cdot \frac{d\Omega}{4\pi} \cdot T_{mol}^{\lambda_o}(s) \cdot T_{aer}^{\lambda_o}(s)$$

$$T_{aer}^{\lambda_o}(s) = \exp\left(-\int_o^s \alpha_{aer}^{\lambda_o}(s)\,ds\right)$$

$$LR \cdot \beta_{aer}^{\lambda_o}(s) = \alpha_{aer}^{\lambda_o}(s)$$

Mandatory assumption!

Unknown!

$$\beta_{mol}^{\lambda_o}(s) = \sigma_{mol}^{\lambda_o}(\pi)\, n_{mol}(s)$$

The Lidar Ratio (LR) is the inverse of the back scattering phase function.

$$\beta_{aer}^{\lambda_o}(s) = \int_0^\infty dr\, \pi r^2 Q_{bck}(r, m, \lambda_o)\, n_{aer}(s, r)$$

$$\alpha_{aer}^{\lambda_o}(s) = \int_0^\infty dr\, \pi r^2 Q_{ext}(r, m, \lambda_o)\, n_{aer}(s, r)$$

Solving for $T_{aer}^{\lambda_o}(s)$

$$\ln\left[T_{aer}^{\lambda_o}(s)\right]=$$

$$= -\int_0^s LR \cdot \left[\frac{s^2 L^{\lambda_o}(s) \cdot \exp\left[-2\left(LR - \frac{8\pi}{3}\right)\right] \cdot \int_{s_n}^{s} \beta_{mol}^{\lambda_o}(s')ds'}{\frac{s_n{}^2 L^{\lambda_o}(s_n)}{\beta_{mol}^{\lambda_o}(s_n) + \beta_{aer}^{\lambda_o}(s_n)} - 2 \cdot LR \cdot \int_{s_n}^{s} \left[s''^2 L^{\lambda_o}(s'') \cdot \exp\left[-2\left(LR - \frac{8\pi}{3}\right)\right] \cdot \int_{s_n}^{s''} \beta_{mol}^{\lambda_o}(s')ds' \right] ds''} \right] ds$$

See …: Scanning lidar based atmospheric monitoring for fluorescent detectors of cosmic showers, D. Veberič, A. Filipčič, M. Horvat, D. Zavrtanik, M. Zavrtanik, submitted, 2002.

KLETT INVERSION

In a more simple form

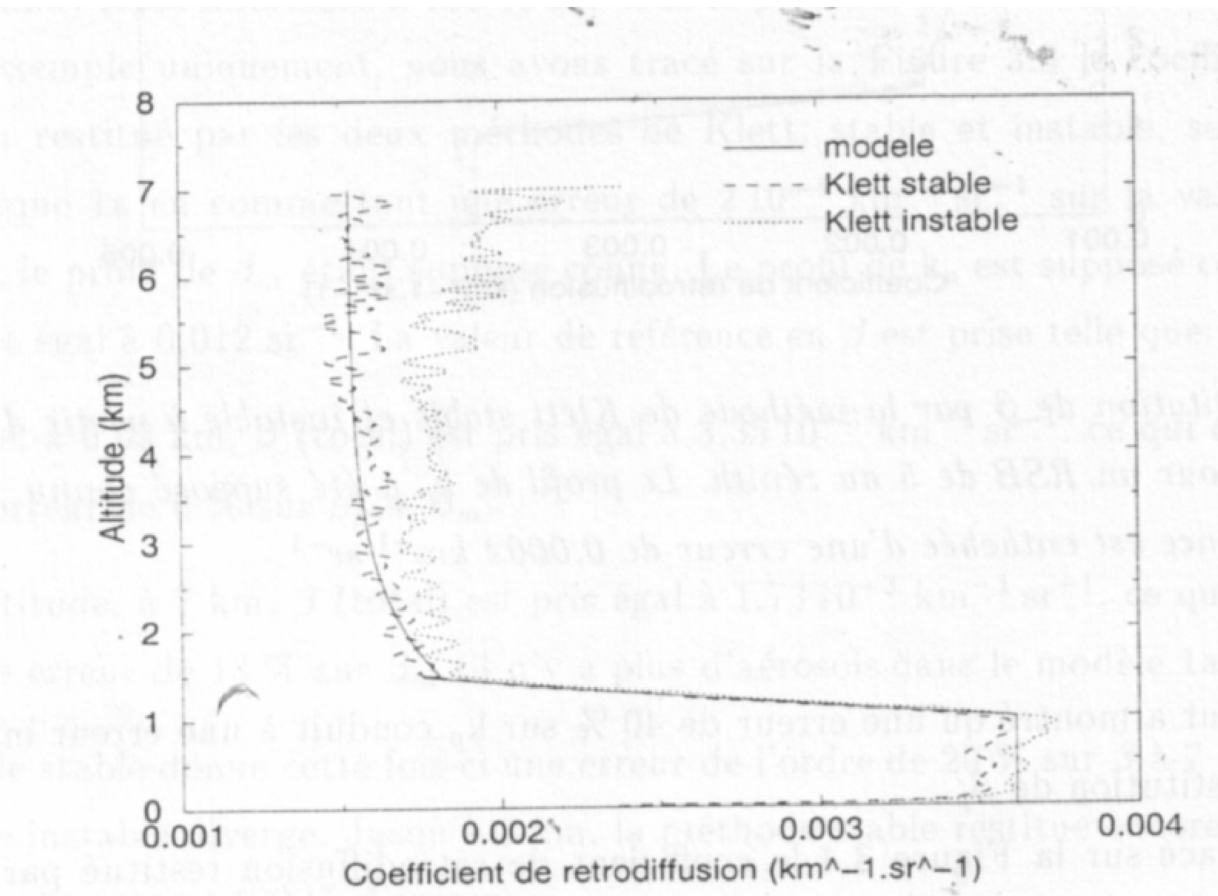
$$\beta(r) = \frac{\dfrac{S'(r)}{S(r_0)}}{1/\beta_0 \mu 2 \displaystyle\int_{r_0}^{r} \frac{1}{k_p(z)} \frac{S'(z)}{S(r_0)} dz}$$

S= range corrected signal

Assumptions :

β_m profile
LR profile
β_0 molecular reference value

KLETT INVERSION



Exemple of error due to a bad assumption on the lidar ratio (Error of 8%) Breference known

➡ **5% error on β**

➡ **Divergence of instable solution**

But instable solution works for cirrus clouds
(Iterative procedure to force the convegence by changing the LR value.)

LIDAR RATIO (1)

Lidar ratio can be retrieved from:

- **Models**

OPAC database

(Optical properties of aerosols and cloouds : The software package, M.Hess et al., BAMS, 79, pp831 – 855, 1998)
www.lrz-munchen.de/~uh234an/www/radaer/opac.html

- **Nephelometer**

- **Multi-angle LOS lidar**

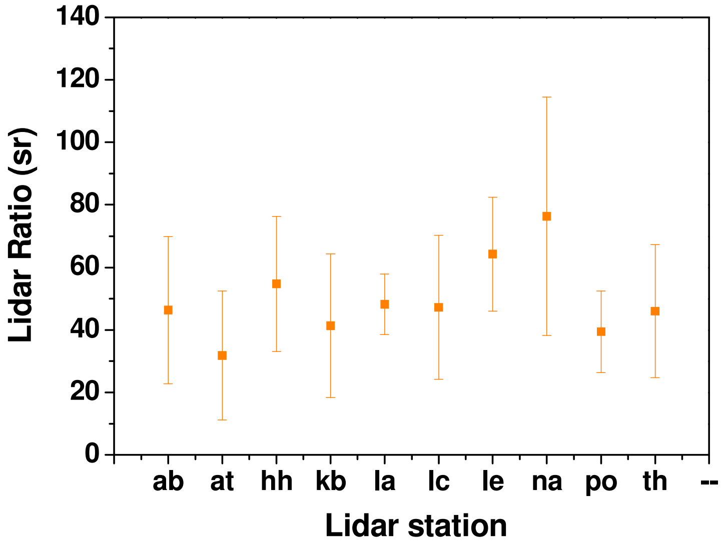
- **Raman lidar**

(EARLINET database www.lidarc.dkrz.de/earlinet
Schneider et al., Atm.Chem.Phys.Discus.,2, 2002.)

- **Double ended inversion of backscatter signal (for subvisible clouds)**

LIDAR RATIO (2)

- **Large variability of the lidar ratio**
- **Lidar ratio is an important parameter in estimating the climate impact of aerosols**
- **Importance of systematic lidar ratio measurements on continental scale**



LR from EARLINET database

Backscatter algorithm intercomparison

V.Matthias (MPI, Hamburg), C. Böckmann (Univ. Postdam), G. Pappalardo (CNR, Potenza), and V. Freudenthaler (Met Instit., Univ Munich)

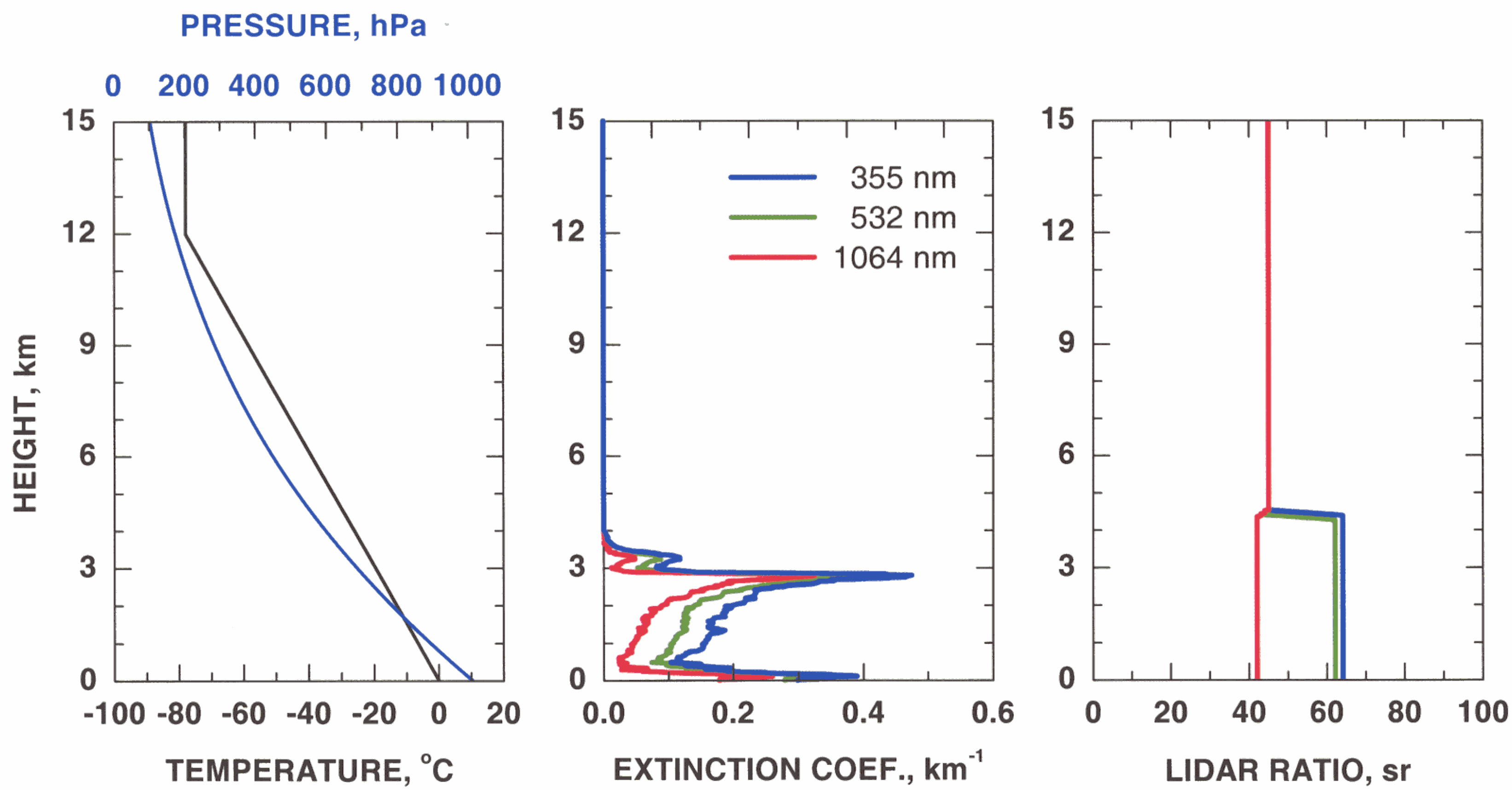
Simulated elastic lidar signals at 355 nm, 532 nm and 1064 nm

- 3 different cases with different degree of diffculty
  1. Stepwise profile with constant lidarratio and known solution
  2. Realistic profile with two steps of the lidar ratio
  3. Realistic profile with height dependent lidar ratio in the PBL

- 3 evaluation stages for each case
  1. No additional information except for the used standard atmosphere
  2. Lidar ratio profile was provided
  3. Calibration value was provided

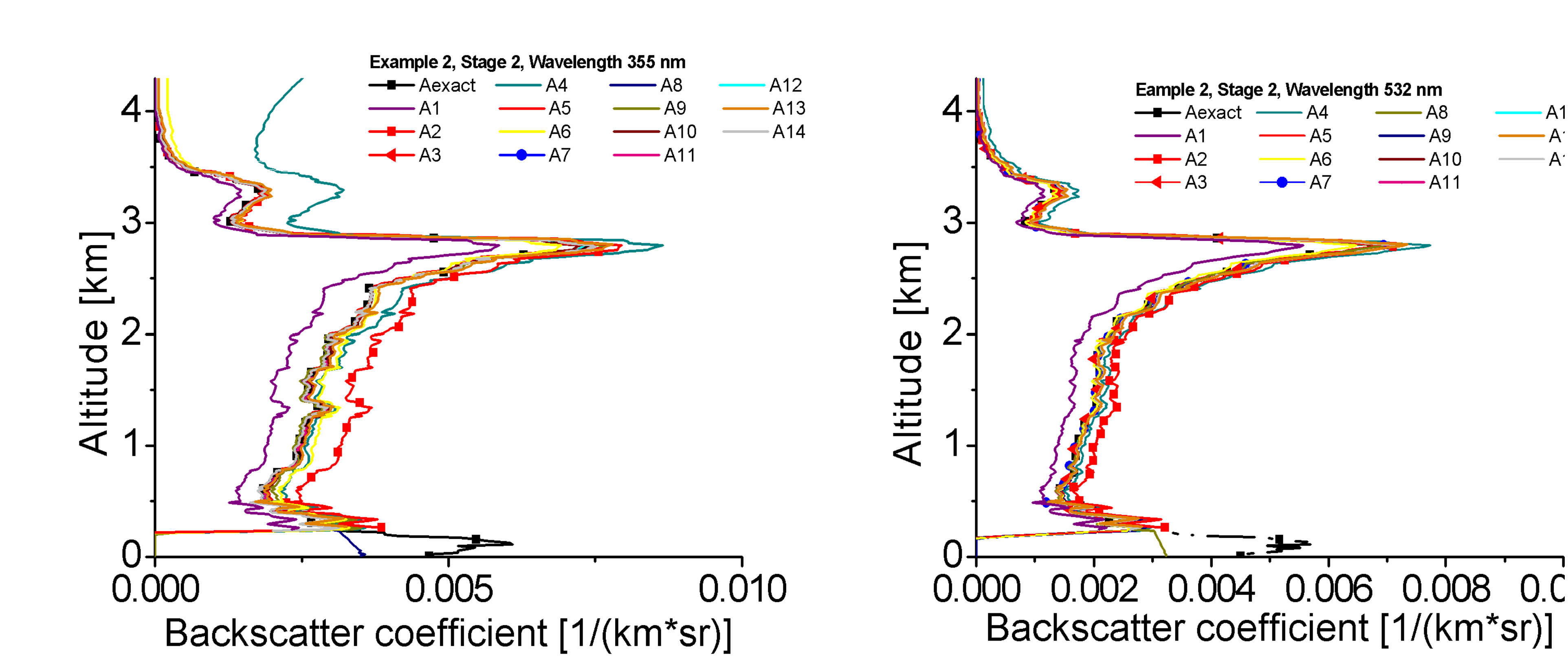
Case 2: prescribed profiles

Input profiles for simulation case 2



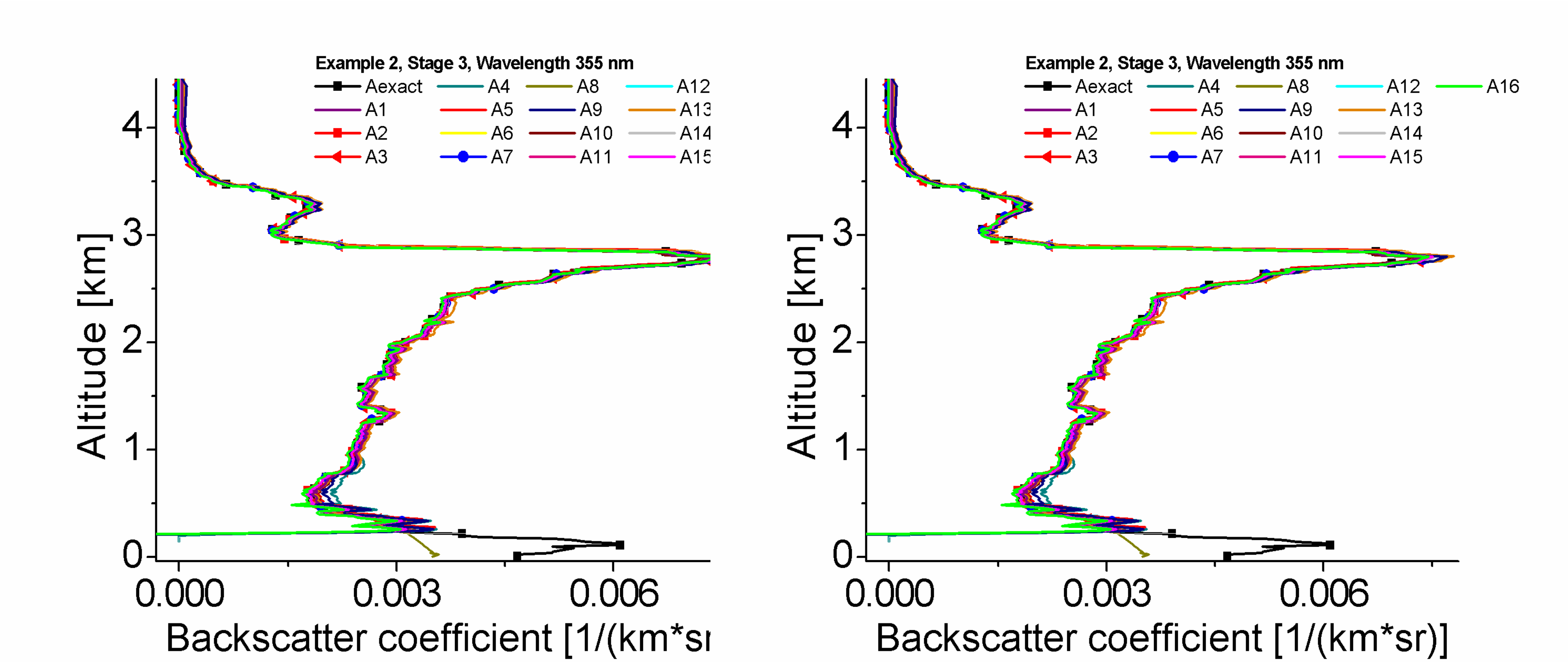
Backscatter algorithm intercomparison: Case 2, Stage 2

Unknown calibration value

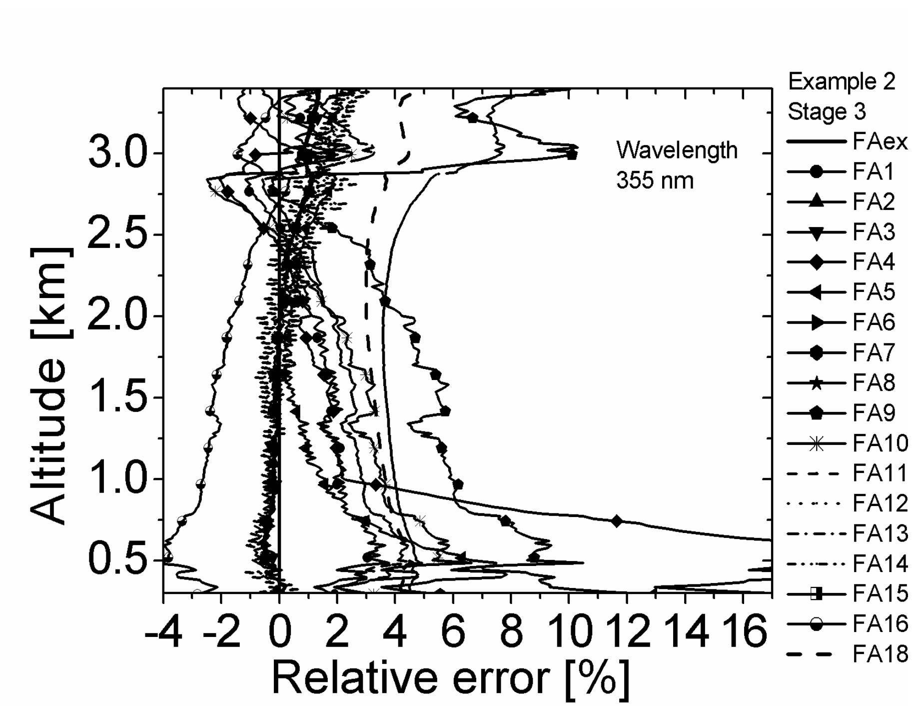


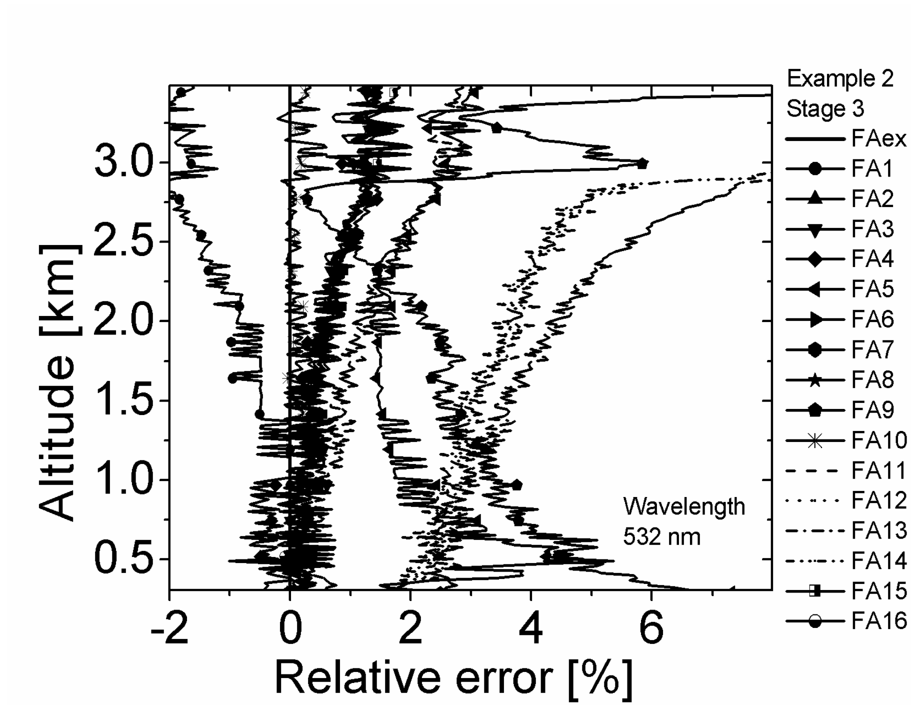
Backscatter algorithm intercomparison: Case 2, Stage 3

All parameters known



Backscatter algorithm intercomparison: Case 2, Stage 3, Rel. Errors





RAMAN SIGNAL

Anelastic/Raman Lidar signal

$$L^{\lambda_i=\lambda_o+\Delta\lambda_i}(s) = L_o^{\lambda_o} \cdot T_{mol}^{\lambda_o}(s)\cdot T_{aer}^{\lambda_o}(s)\cdot T_{abs}^{\lambda_o}(s)\cdot$$

upward travel

$$\cdot\left[\sigma_{\mathrm{Raman}}^{\lambda_i}(\pi)\cdot n_i(s)\right]\frac{d\Omega}{4\pi}\cdot$$

backscattering

$$\cdot T_{mol}^{\lambda_i}(s)\cdot T_{aer}^{\lambda_i}(s)\cdot T_{abs}^{\lambda_i}(s)$$

downward travel

$\Delta\lambda_i$ is the Raman shift of the i - th species

$(\mathrm{N}_2 :\approx 2331 cm^{-1}; \mathrm{O}_2 :\approx 1556 cm^{-1})$

$\sigma_{Raman}^{\lambda_i}(\pi)$ Raman differential backscattering cross section of the i - th species

$(\mathrm{N}_2 :\approx 3.5\times 10^{-30} cm^2 \mathrm{sr}^{-1}; \mathrm{O}_2 :\approx 4.6\times 10^{-30} cm^2 \mathrm{sr}^{-1}$ @ 337.1nm)

Key features of Raman method.

Unknown!

$$k = \frac{\log\left(\dfrac{\log(T_{aer}^{\lambda_o}(z))}{\log(T_{aer}^{\lambda_{N2i}}(z))}\right)}{\log\left(\dfrac{\lambda_o}{\lambda_{N_2}}\right)}$$

Assumption!

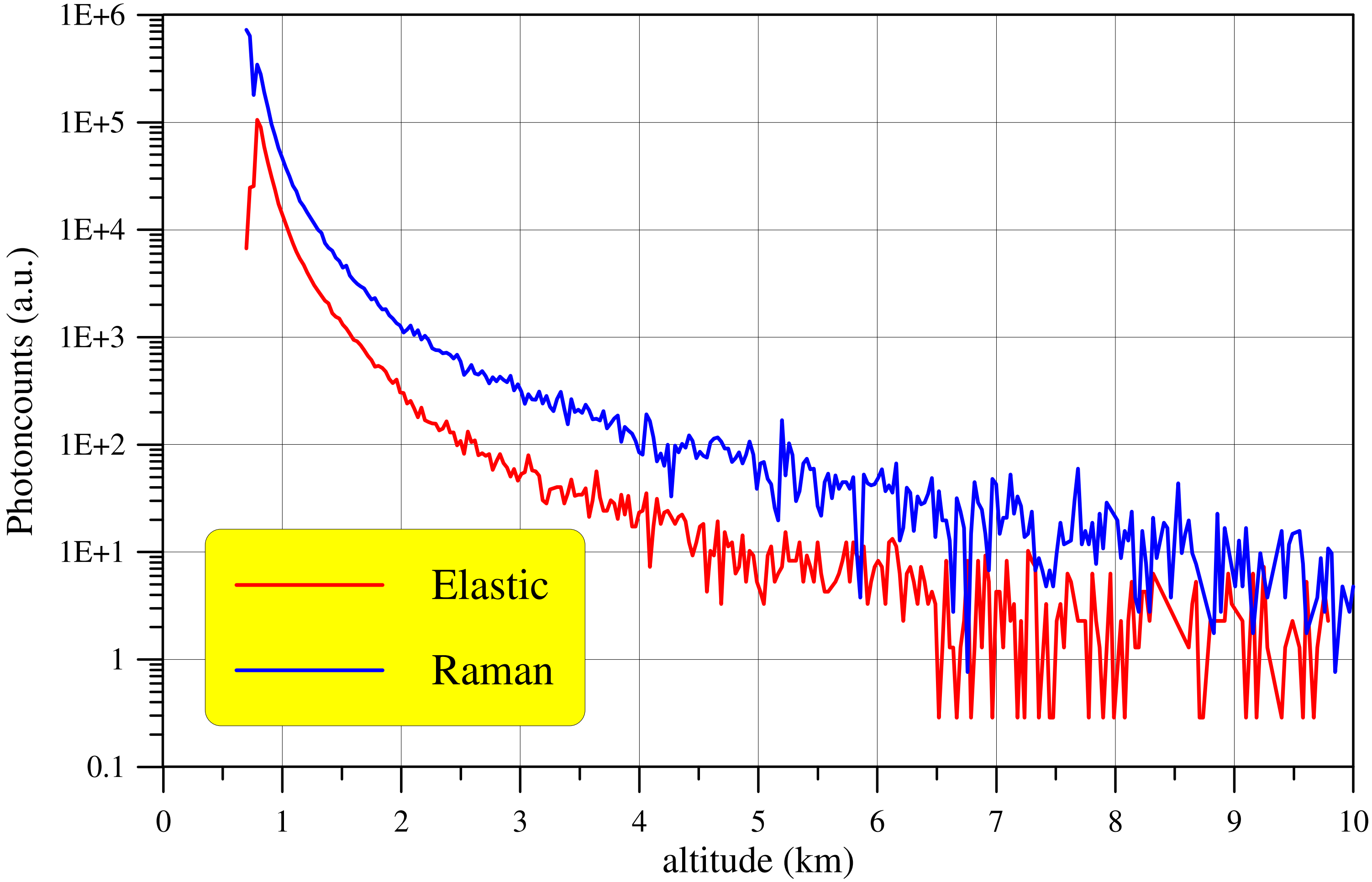
Unnecessary if Raman signals from O_2 and N_2 are measured!

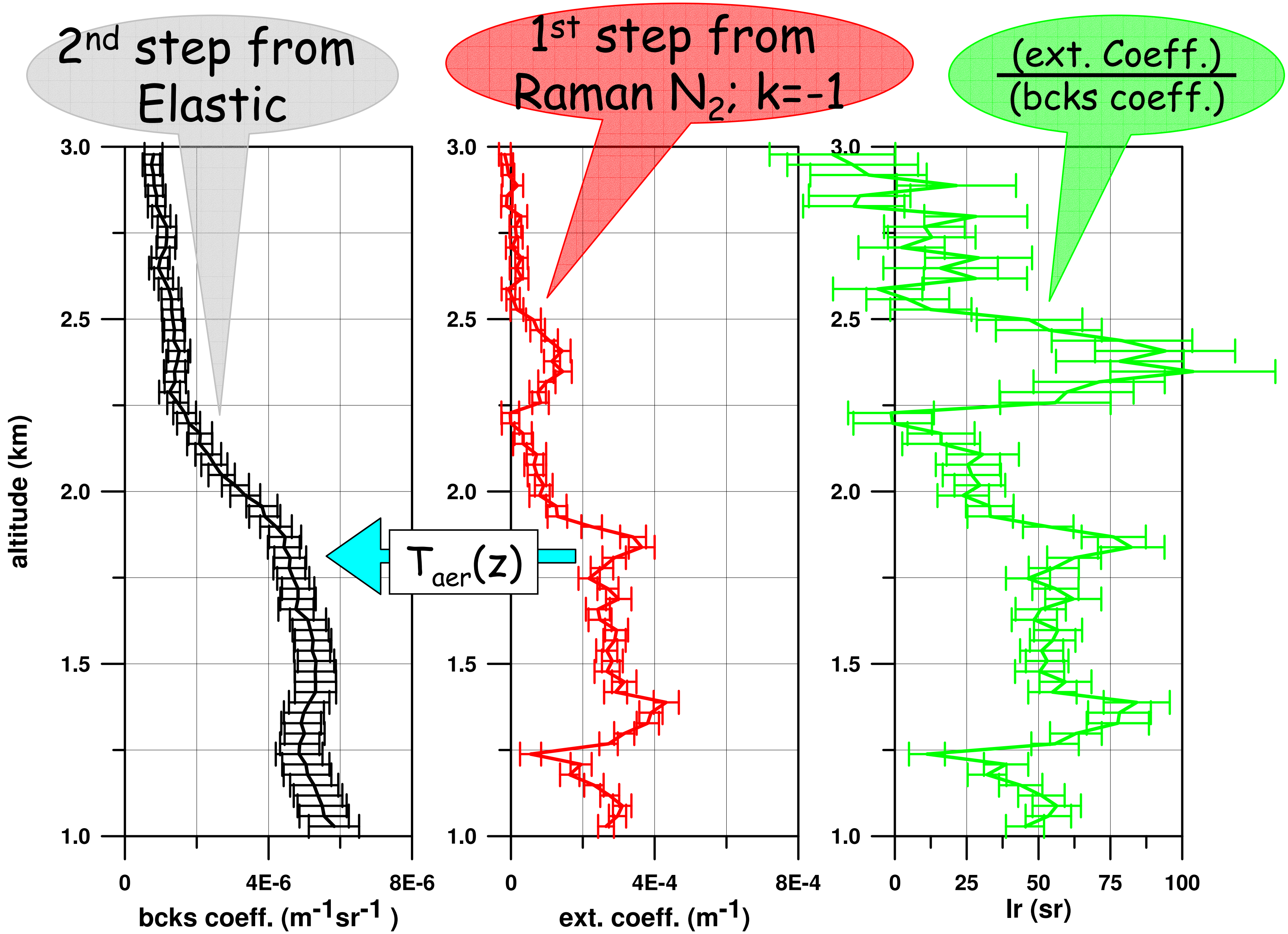
$$\log\left(T_{aer}^{\lambda_o}(s)\right) =$$

$$= \frac{1}{1+\left(\lambda_o / \lambda_{N_2}\right)^k} \log\left[\frac{L^{\lambda_{N2}}(s)}{L_o^{\lambda_o} \cdot \sigma_{\text{Raman}}^{\lambda_{N2}}(\pi) \cdot n_{N_2}(s) \cdot \dfrac{d\Omega}{4\pi}} \left[T_{mol}^{\lambda_o}(s)\right]^{\left[1+\left(\lambda_o/\lambda_{N_2}\right)^4\right]}\right]$$

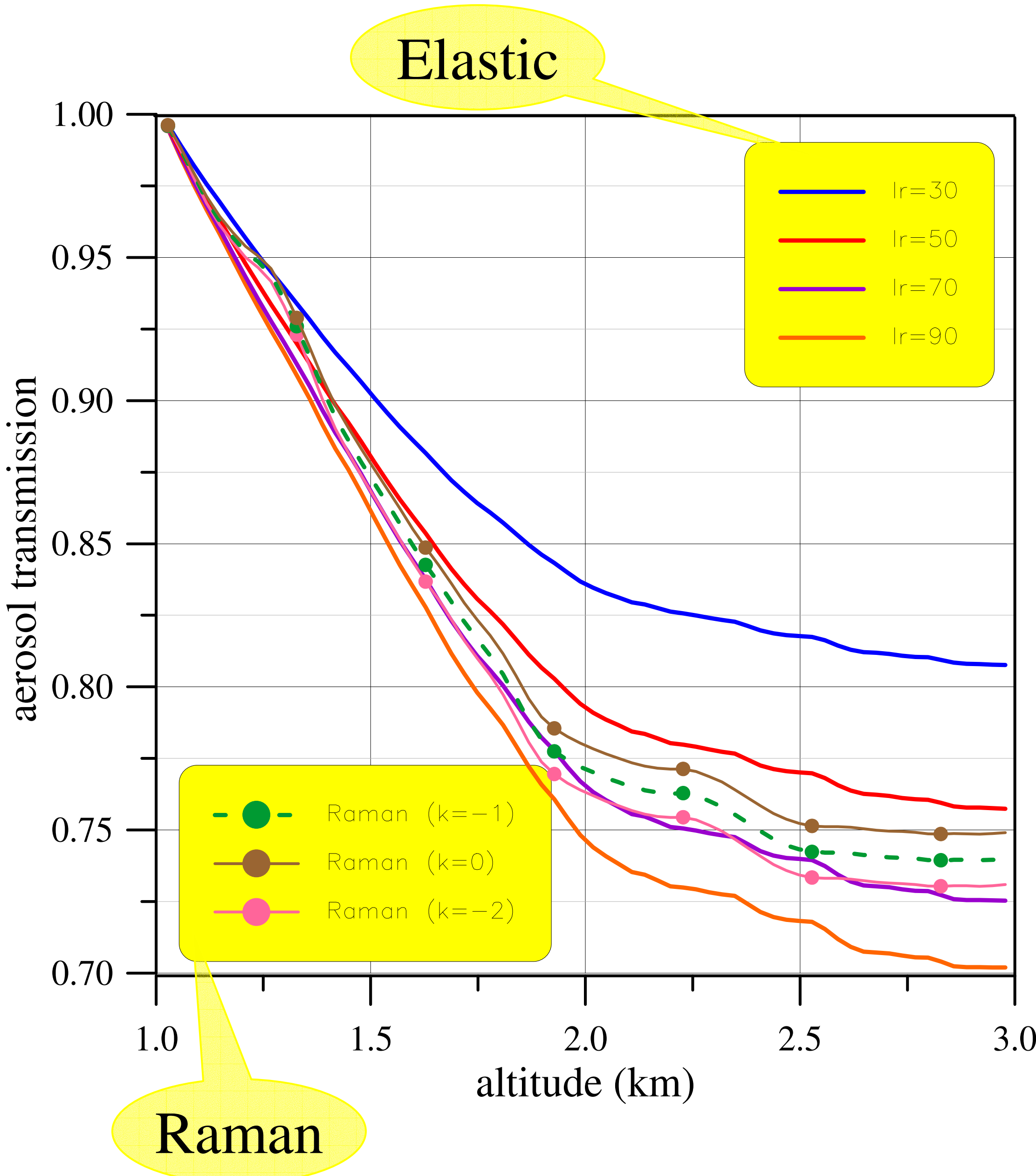
Estimation of aerosol transmission with real data.

UV Raman Vertical lidar - Dipartimento di Fisica -
Università Degli Studi - L'Aquila
λ_o=351nm; λ_{Raman}=382nm (N_2); September 2001
L'Aquila 42°N (rural site) 1/2 hour measurements





2nd step from Elastic
1st step from Raman N2; k=-1
(ext. Coeff.)
(bcks coeff.)
T aer(z)
altitude (km)
3.0
2.5
2.0
1.5
1.0
0
4E-6
8E-6
bcks coeff. (m-1sr-1)
0
4E-4
8E-4
ext. coeff. (m-1)
0
25
50
75
100
lr (sr)



The aerosol transmission function retrieved from real lidar signals (at Univ. AQ)
The continuous lines refer to the case in which only the elastic signal is used (the lidar ratio is assumed), the dashed lines with symbols show the transmission calculated using the Raman signal.

Outlines

• elastic lidar

More infos on backscattering than extinction.

For simple non-scanning lidar system
the aerosol extinction profiles (i.e., transmission function)
derived by inverting the elastic signal, and assuming
the lidar ratio, might have large systematic errors.

• anelastic lidar

reliable aerosol transmission with *no assumptions.*

A combined Raman/Rayleigh-Mie lidar
measures aerosol extinction and backscattering
independently.

• best configuration

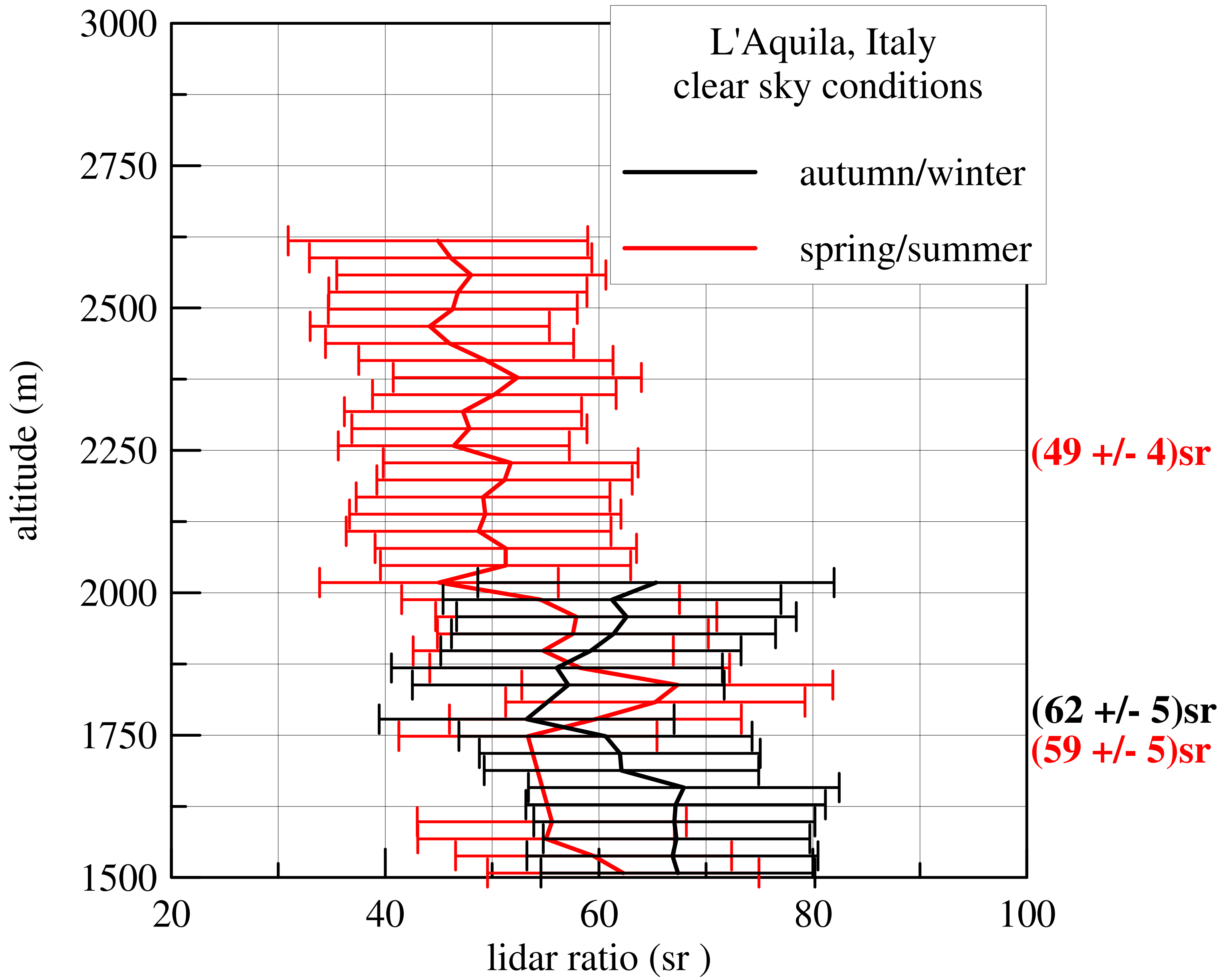
Scanning Raman/Rayleigh-Mie lidar

Aerosol variability

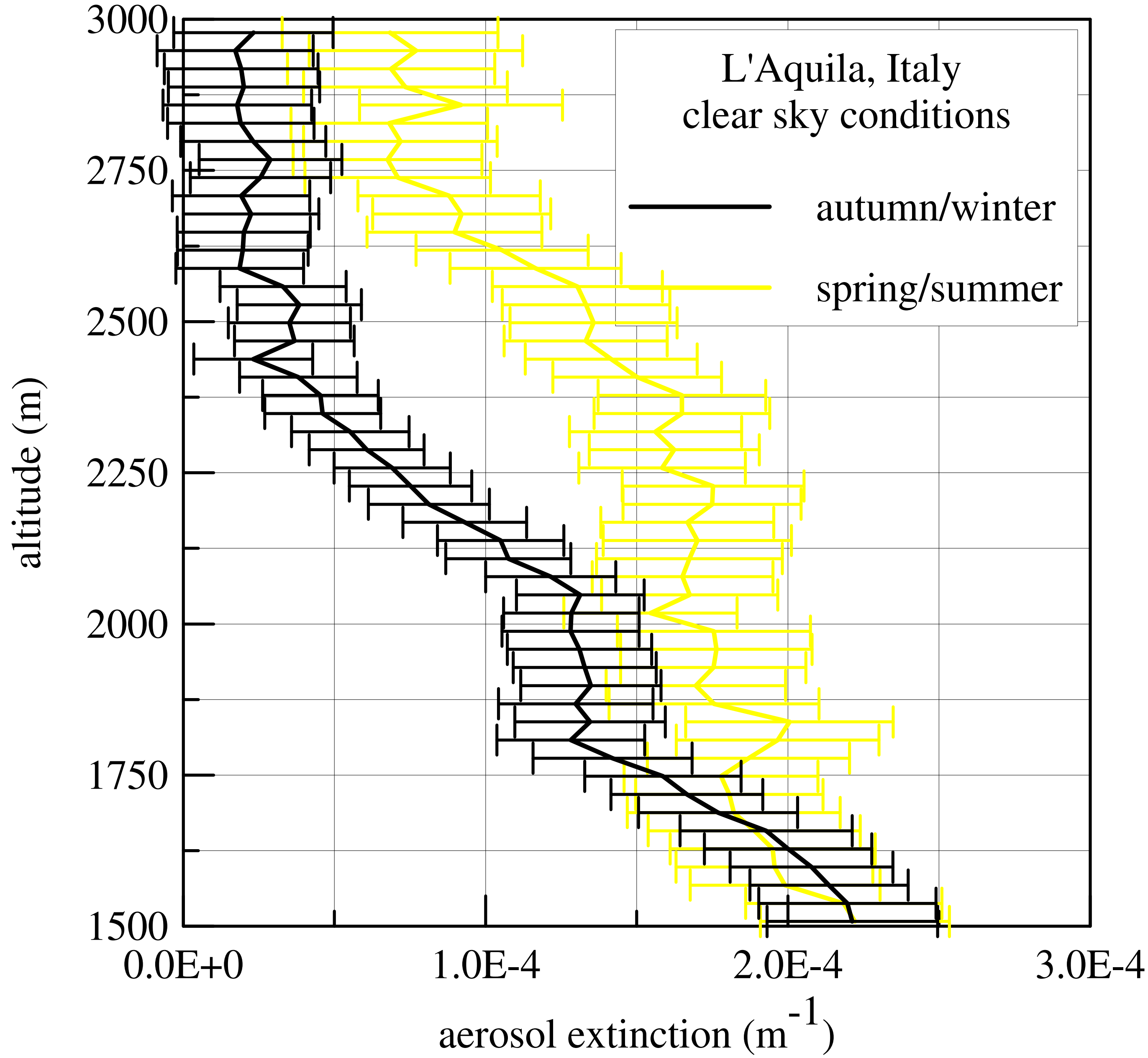
data from RAMAN LIDAR
L'Aquila - Italy (~42°N)

clear sky
above 1500m (virtual Auger FD site)

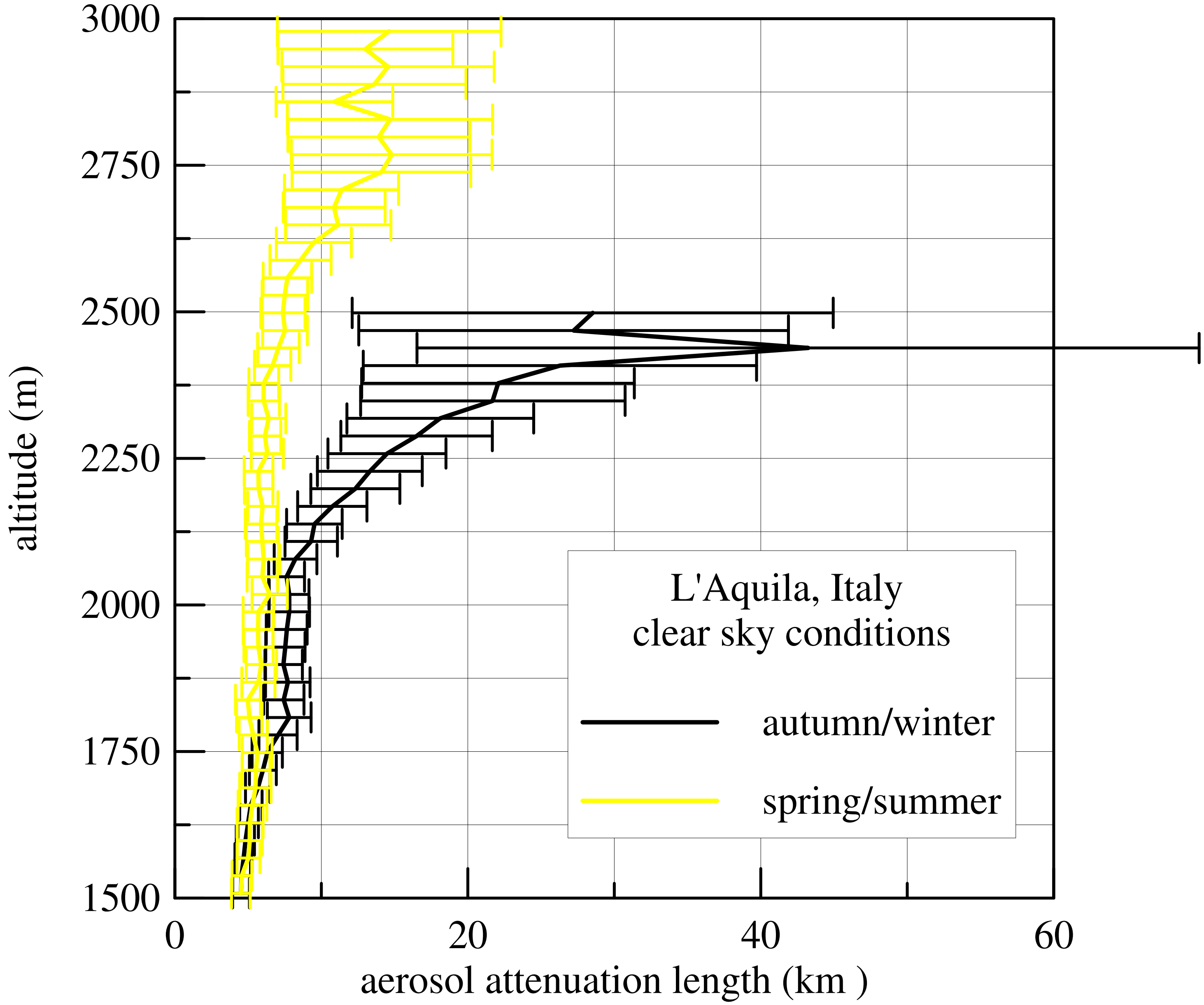
Lidar ratio (LR) seasonal & altitude variation.



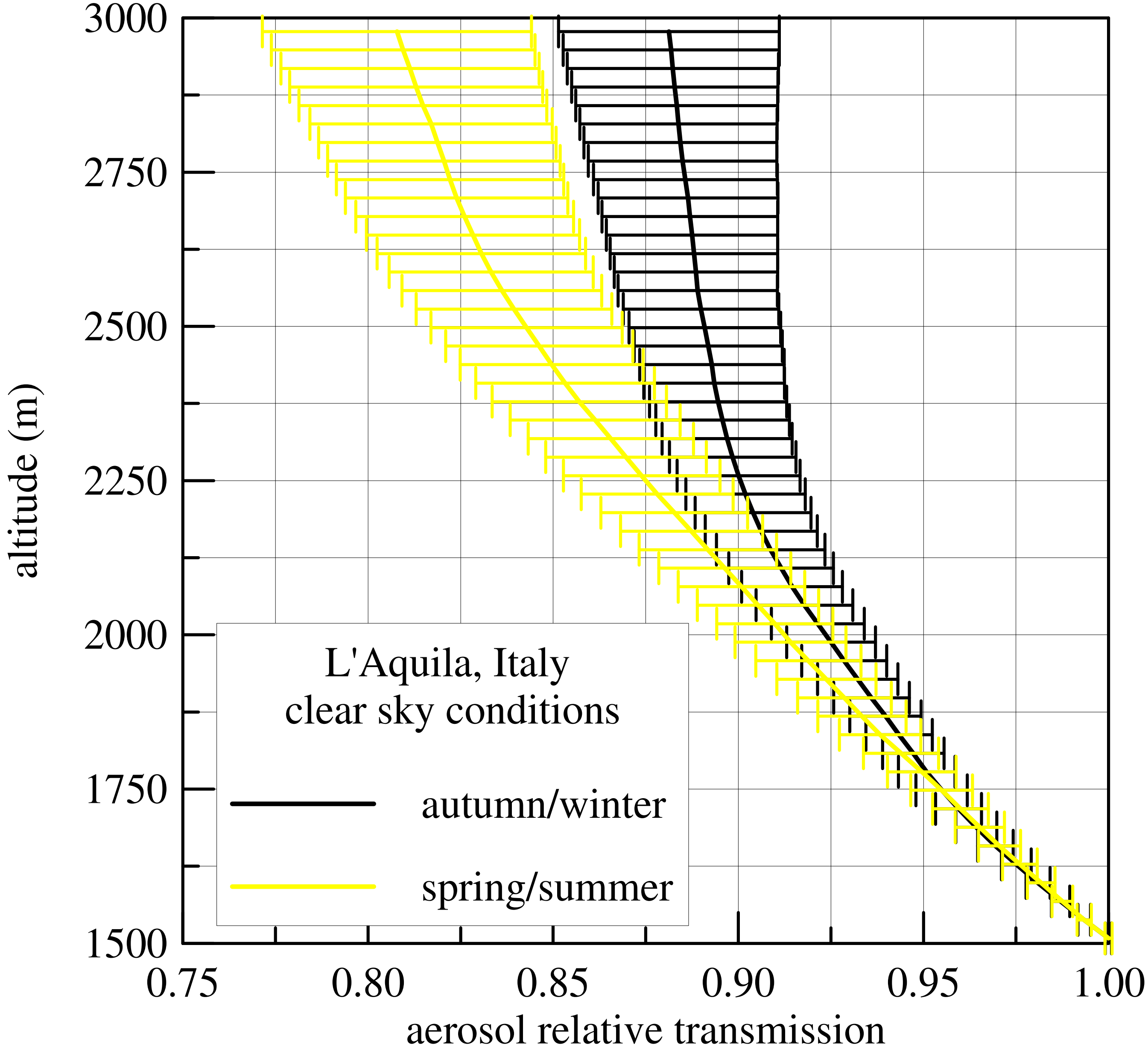
Aerosol extinction seasonal variation.



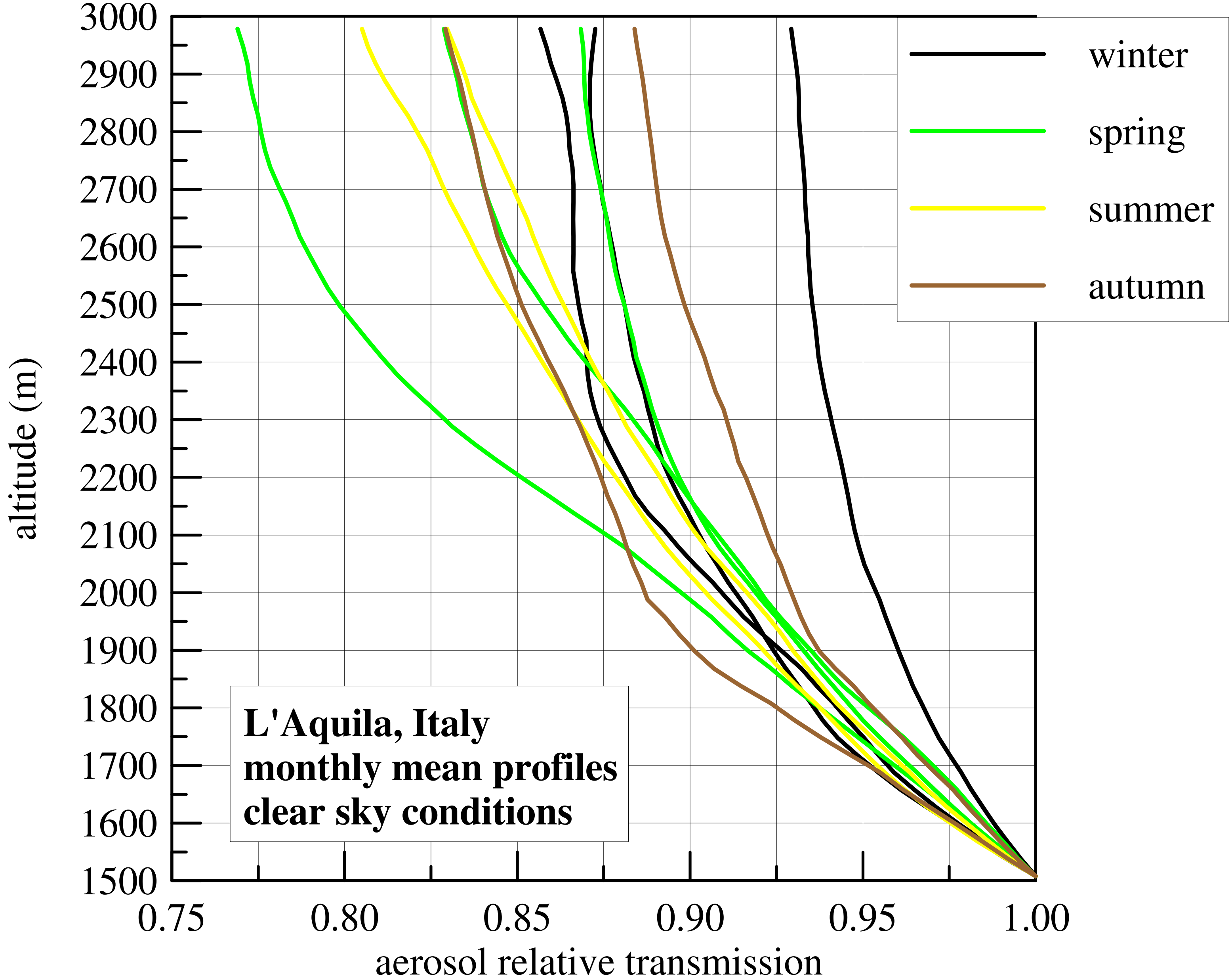
Aerosol attenuation length seasonal variation.



Aerosol transmission seasonal variation.

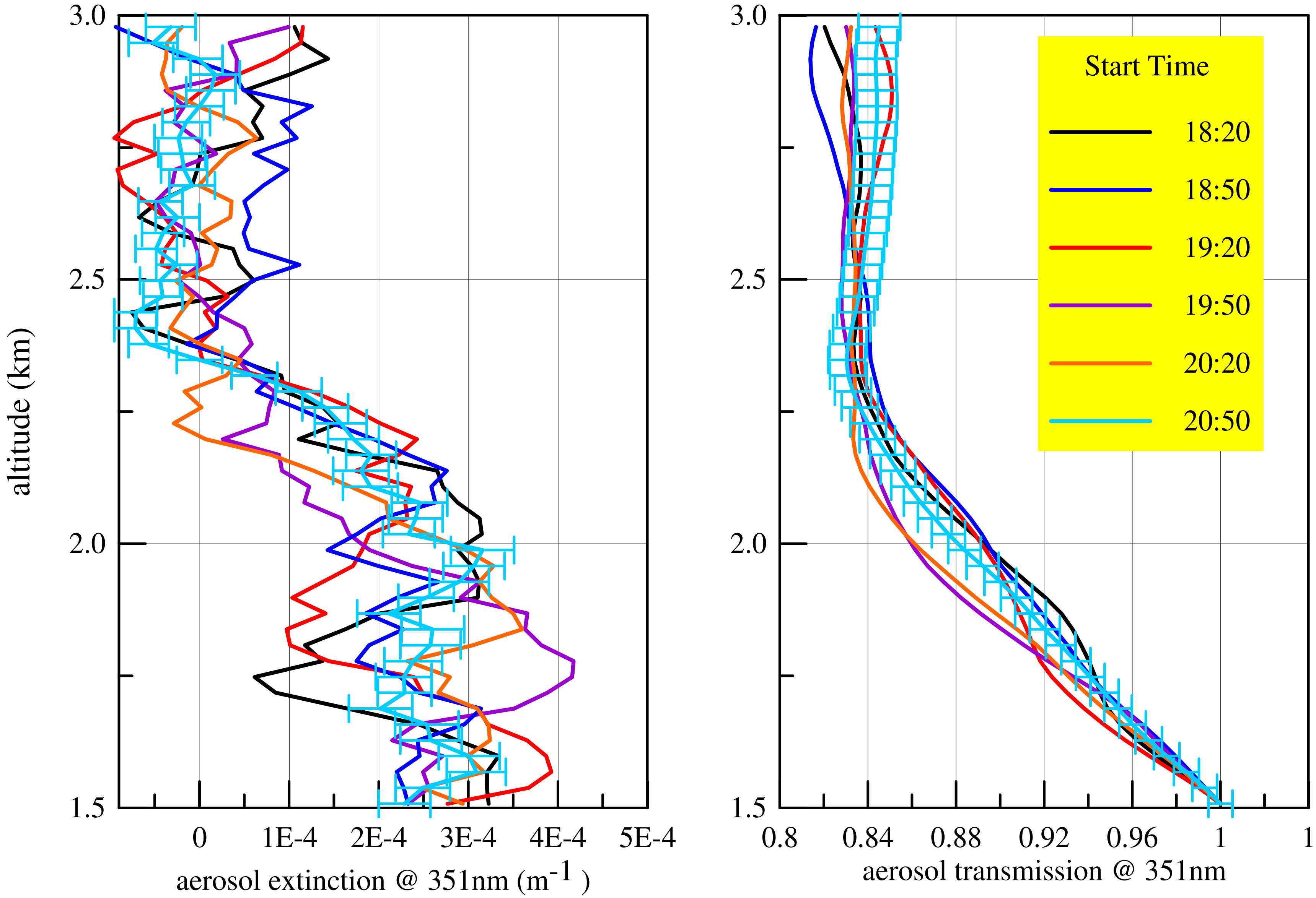


Aerosol transmission seasonal variation.



Aerosol extinction and transmission “day” variation.

L'Aquila, Italy, aerosol-water Raman lidar February 4, 2002 - six profiles from 18:20 to 21:20LT



Outlines - aerosol contribution to light transmission

Most of the aerosol in the planetary boundary layer (<3km a.s.l.)

clear sky

from ~ 1500m a.s.l.

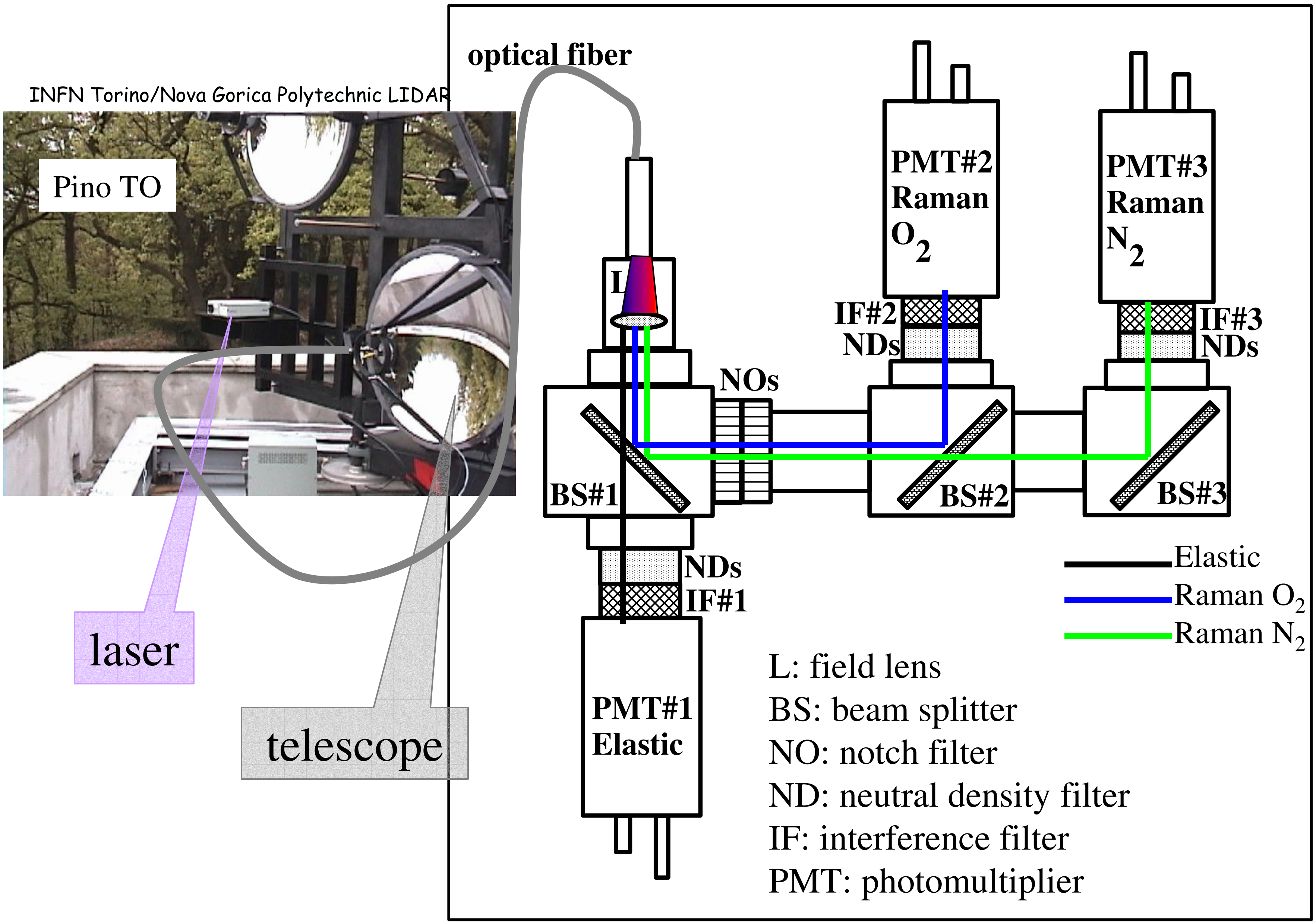
relative transmission mean value ~0.85

seasonal variability up to 15% (3σ)

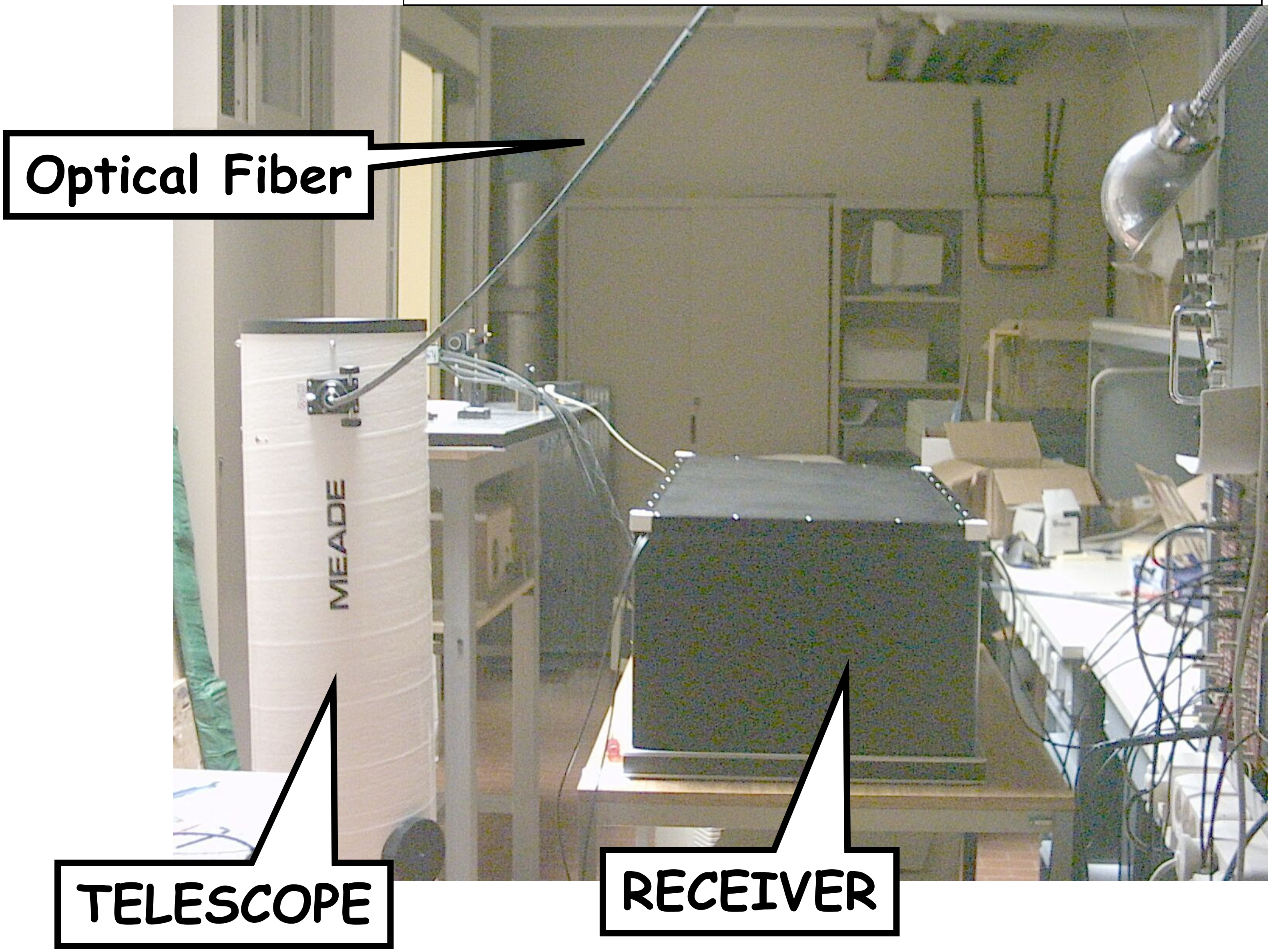
"day" variability (over 3hours - night) ~6%

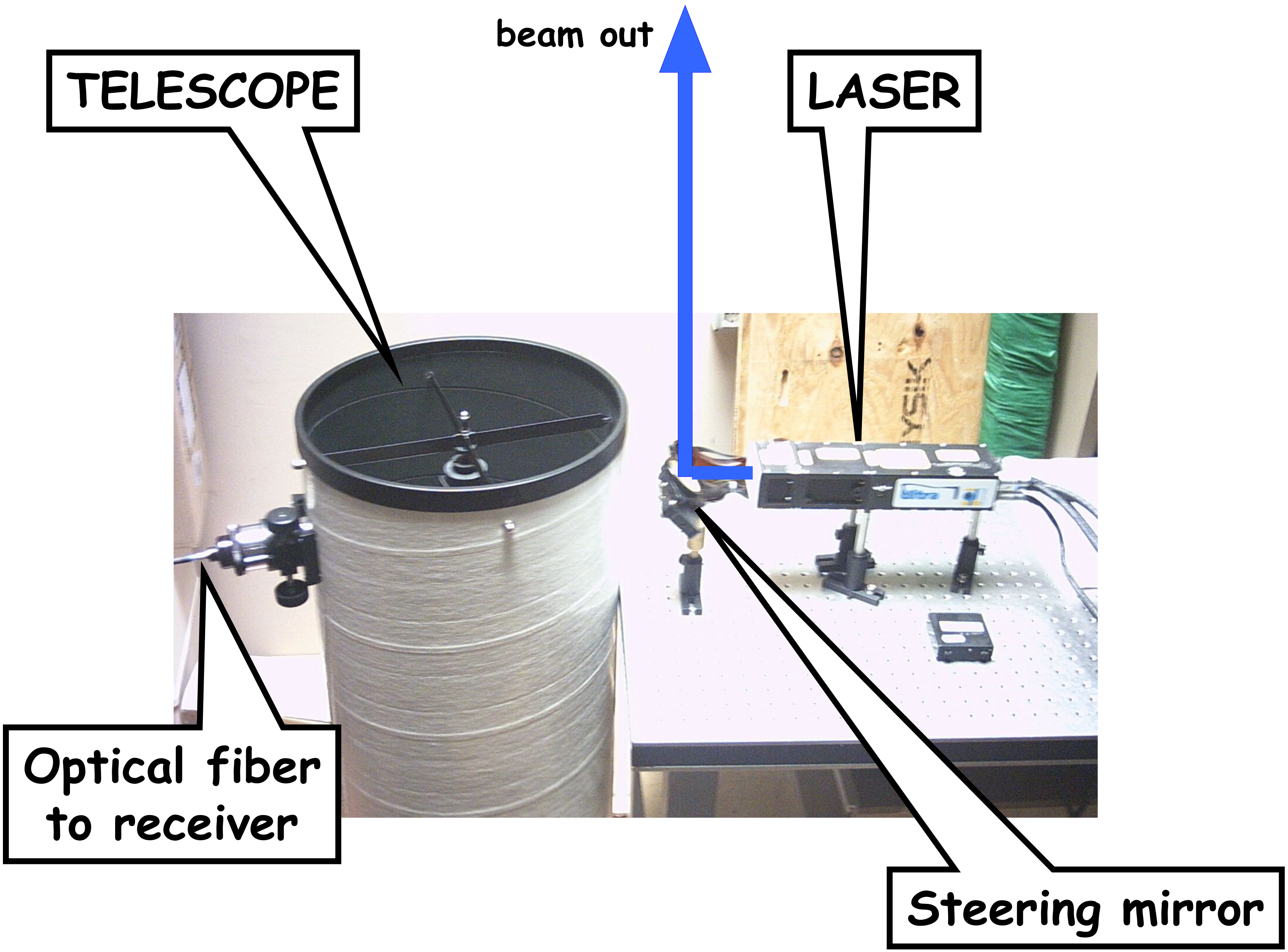
Status of Raman channel integration in Auger lidar.

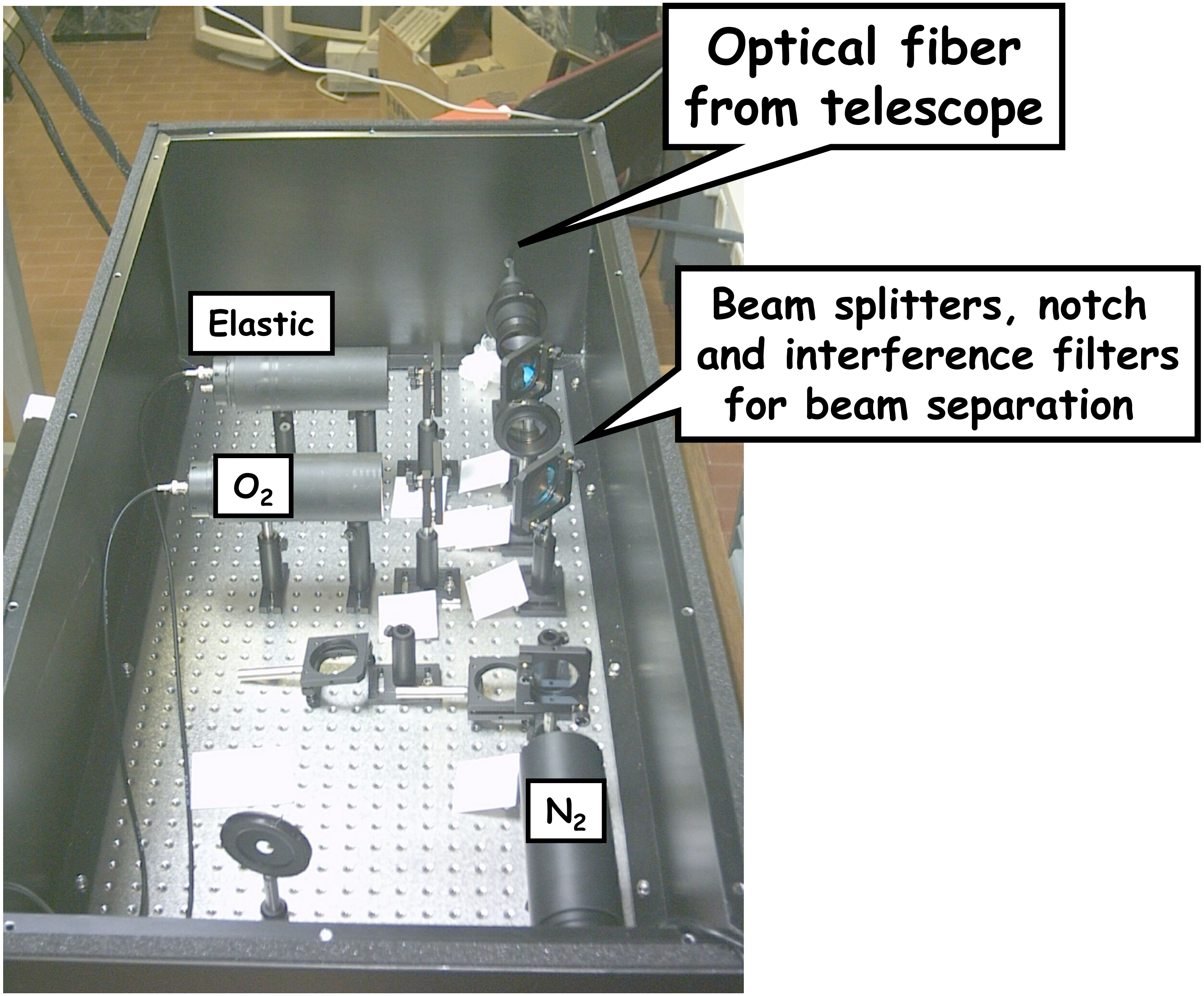
Technical details of Raman lidar

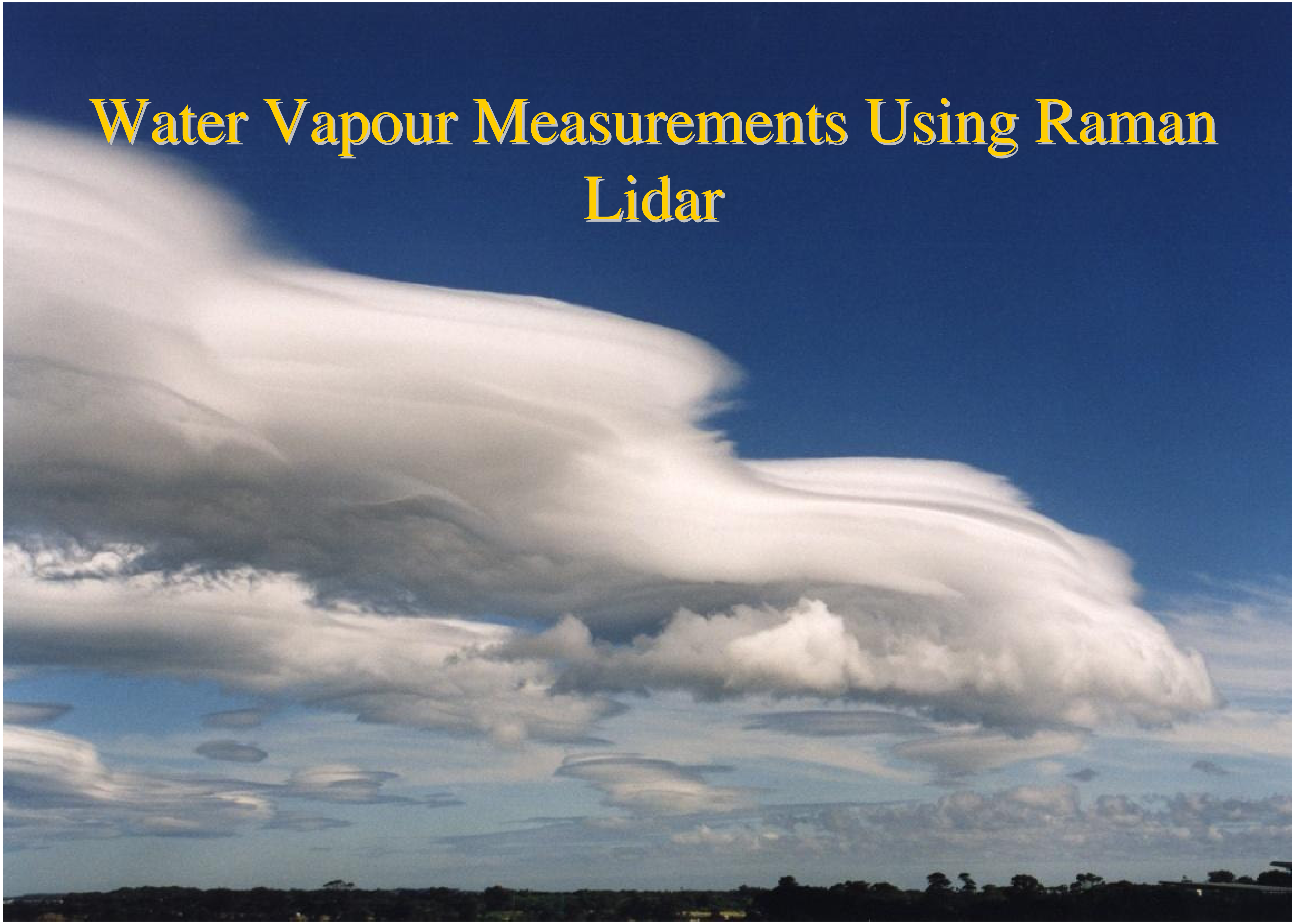


Lab tests of the Raman receiver




beam out
TELESCOPE
LASER
Optical fiber to receiver
Steering mirror


Optical fiber from telescope
Beam splitters, notch and interference filters for beam separation
Elastic
O_2
N_2


Water Vapour Measurements Using Raman
Lidar

Water Vapour Measurements Using Raman Lidar

Water vapor is estimated by the ratio between the Raman WV signal and the Raman N2 Signal (proportional to atm. Density)

The advantage is to have a straightforward estimate with a relatively simple instrumental set-up

The disadvantage is the weakness of S/N ratio in daytime, leading this technique well adapted for night-time measurements

The measurement needs an external calibration provided by radiosoundings (GPS…)

The technique is becoming widely used (up to 11 lidars working in EU, 3 in Italy, Several proposals for Raman networks)

ROMA Raman lidar

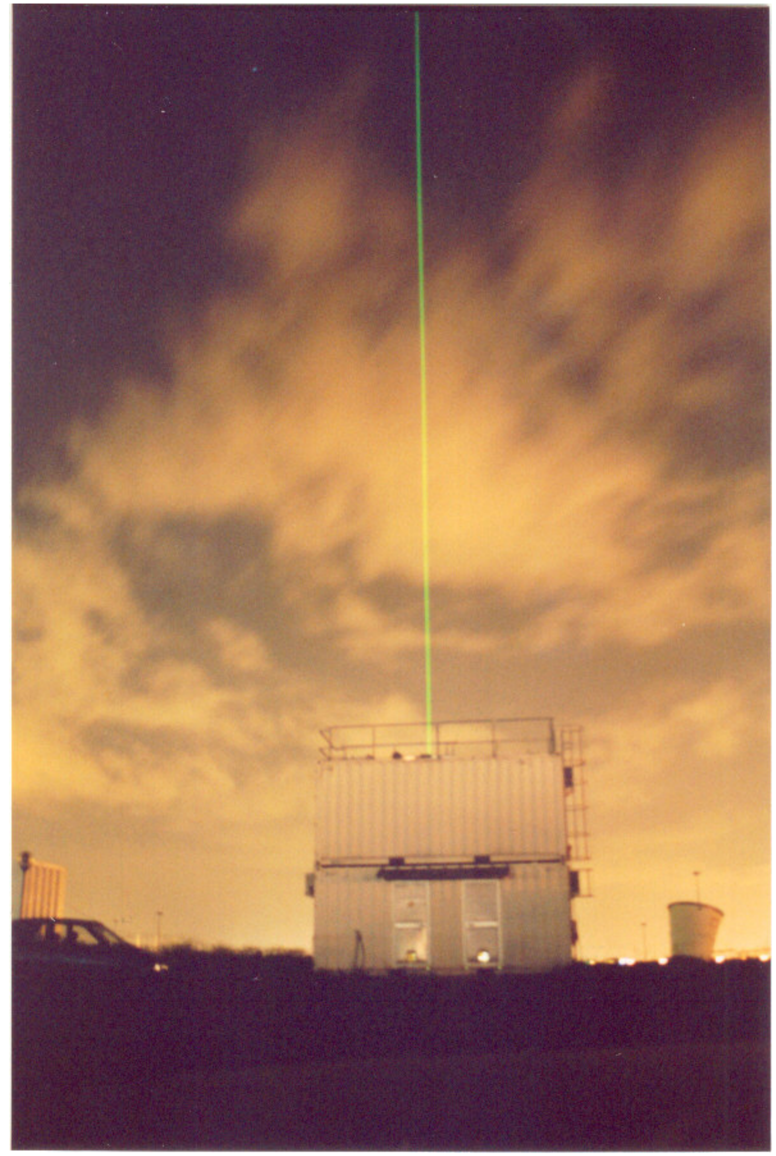
Data shown as example are taken with the Raman Lidar developed in CNR-Rome

3 wavelengths from Nd-Yag laser

9 telescopes array to acquire signal from different atmospheric layer (wide vertical range, high S/N)

407 nm (Raman UV beam from the water vapor molecules)
387 nm (Raman backscattering of the UV beam from the nitrogen molecules) used to estimate the WV content

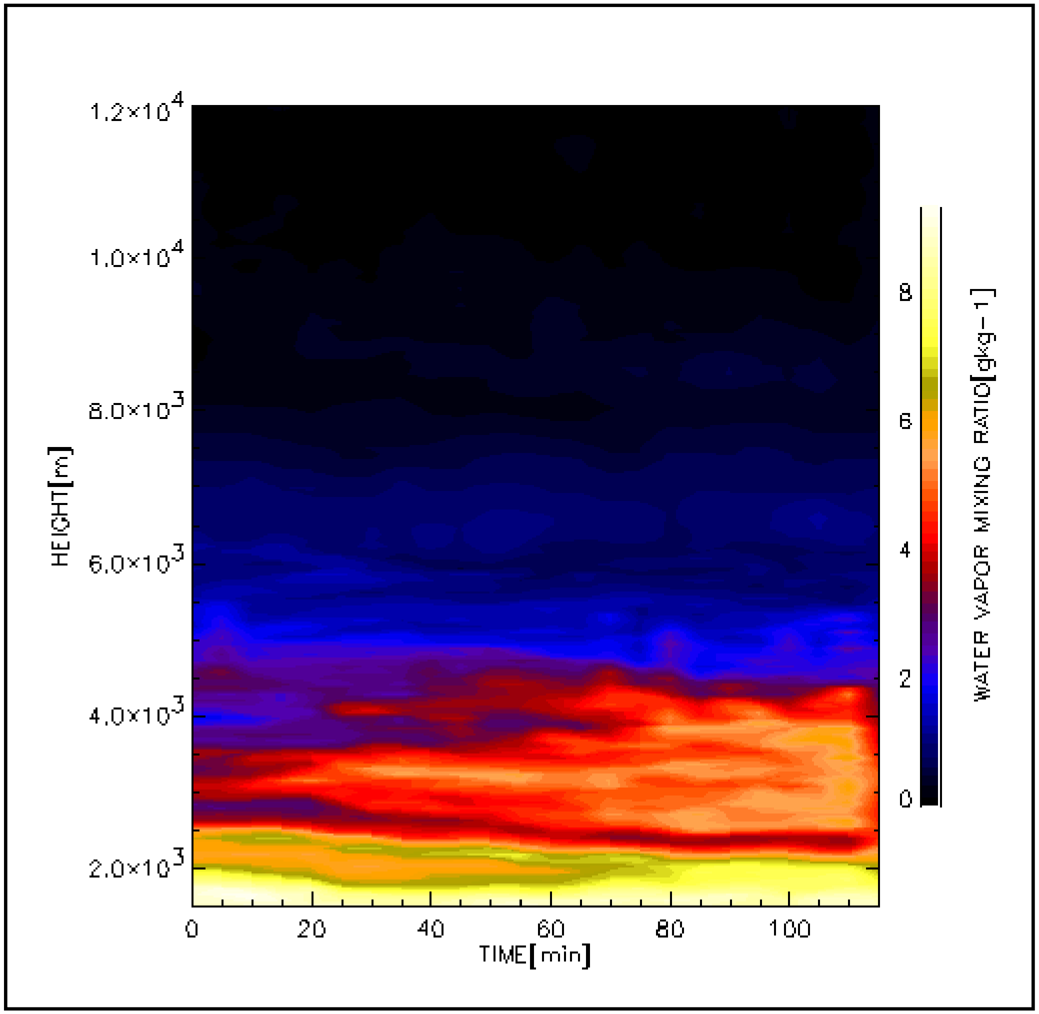
Calibration using Rome radiosounding (25 km far)



September 5, 2002
Rome Tor Vergata
(43°N, 11°E)

It is possible to estimate the variability over one night
(15 min time resolution, 75 m height resolution)

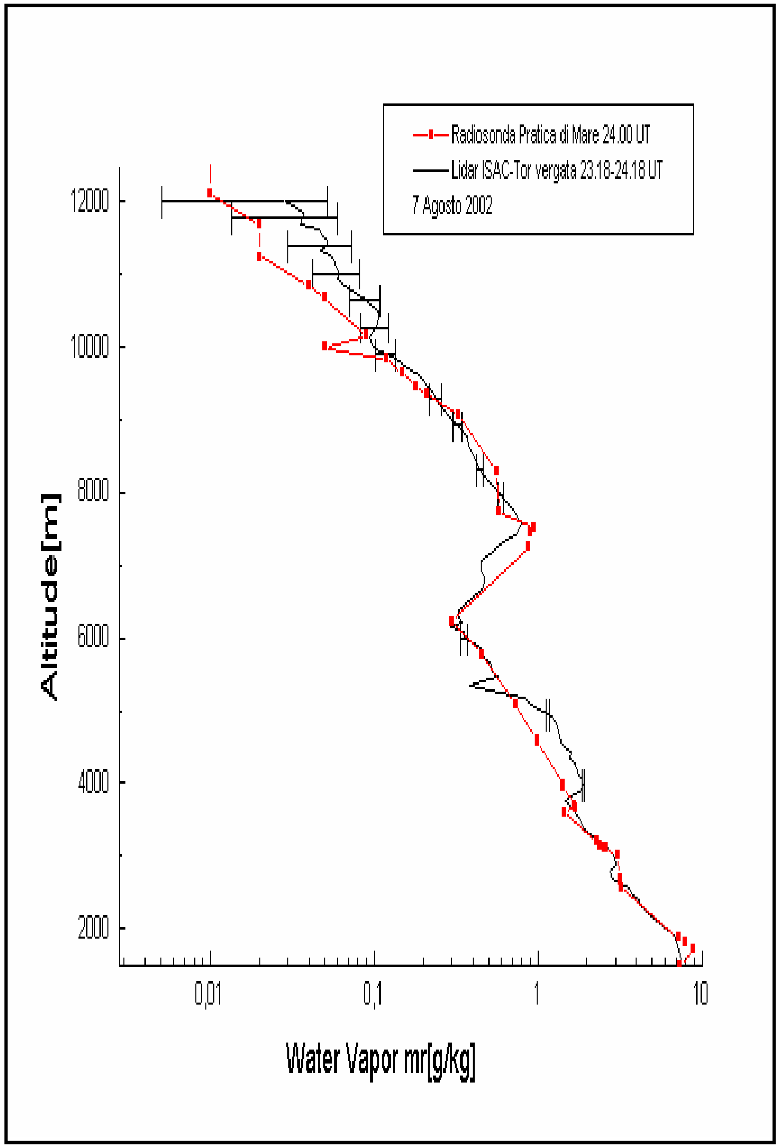
Lidar measurements often reveal the presence of layers characterised by different WV concentrations



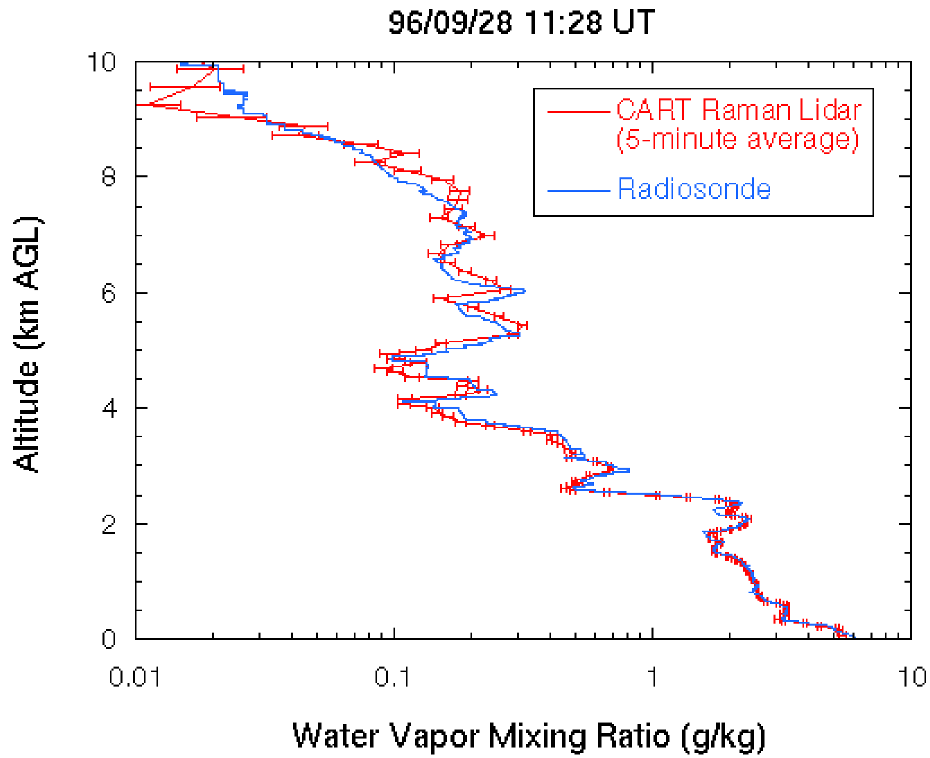
September 5, 2002
Rome Tor Vergata
(43°N, 11°E)

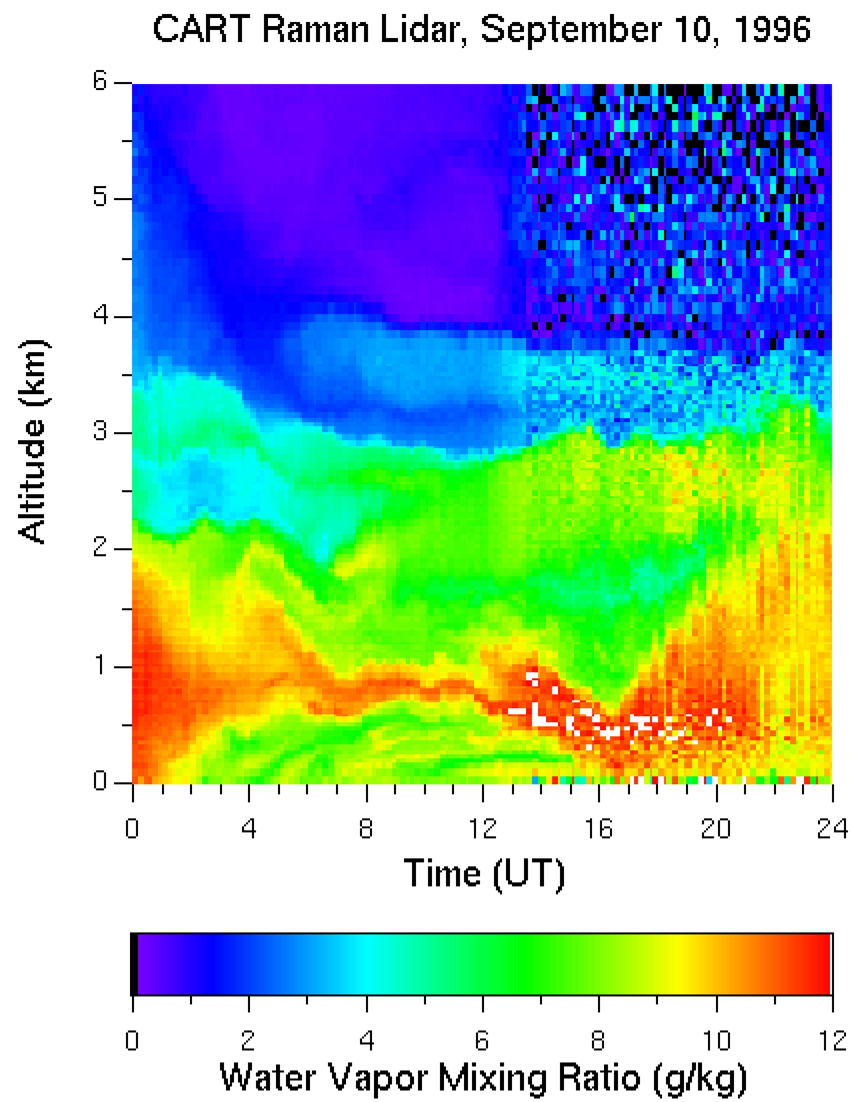
60 minutes time integration

The uncertainty in WV estimate is 6-7% at 7000 m and 20% at 9000 m



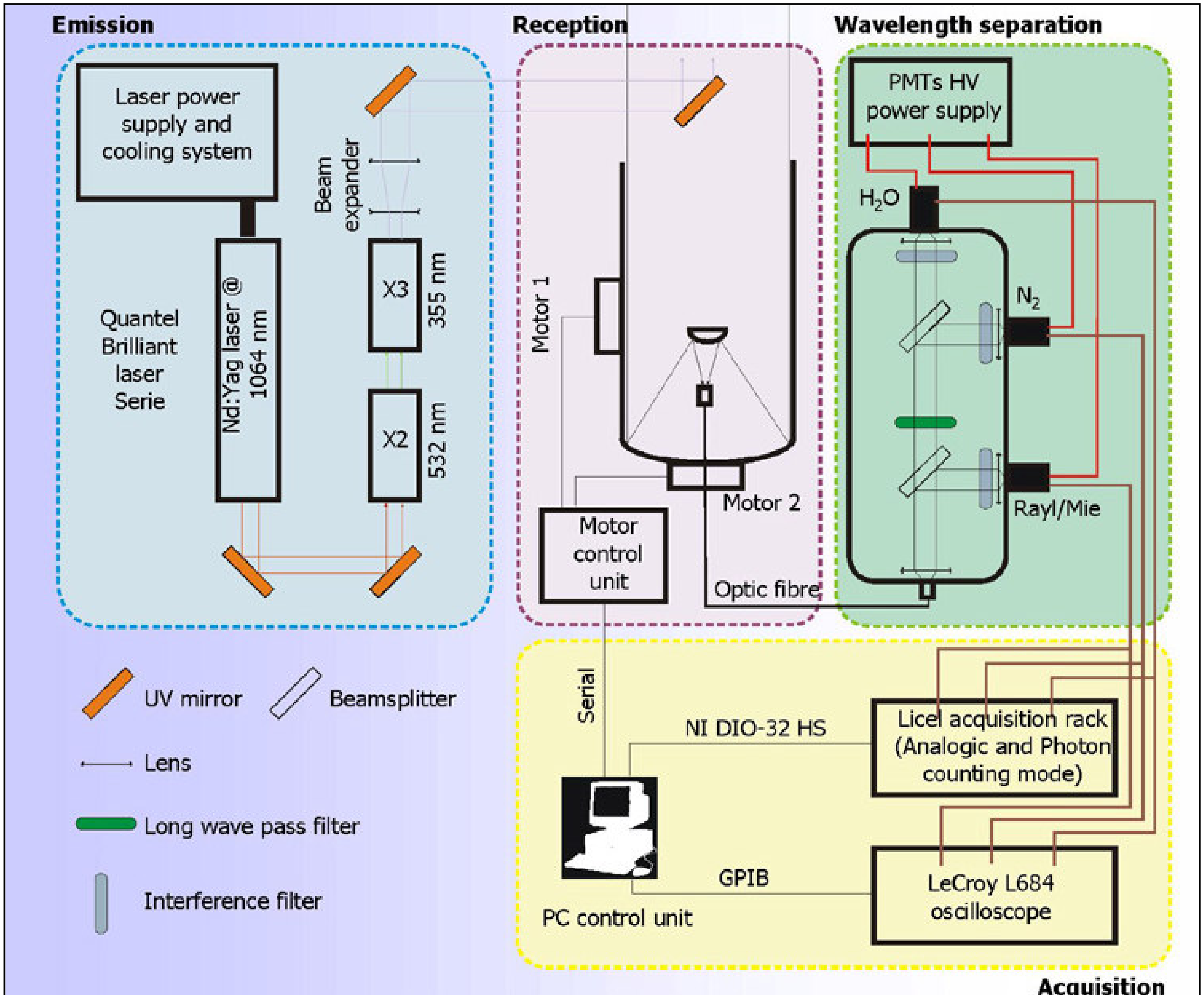
CART site raman lidar (Oklahoma)



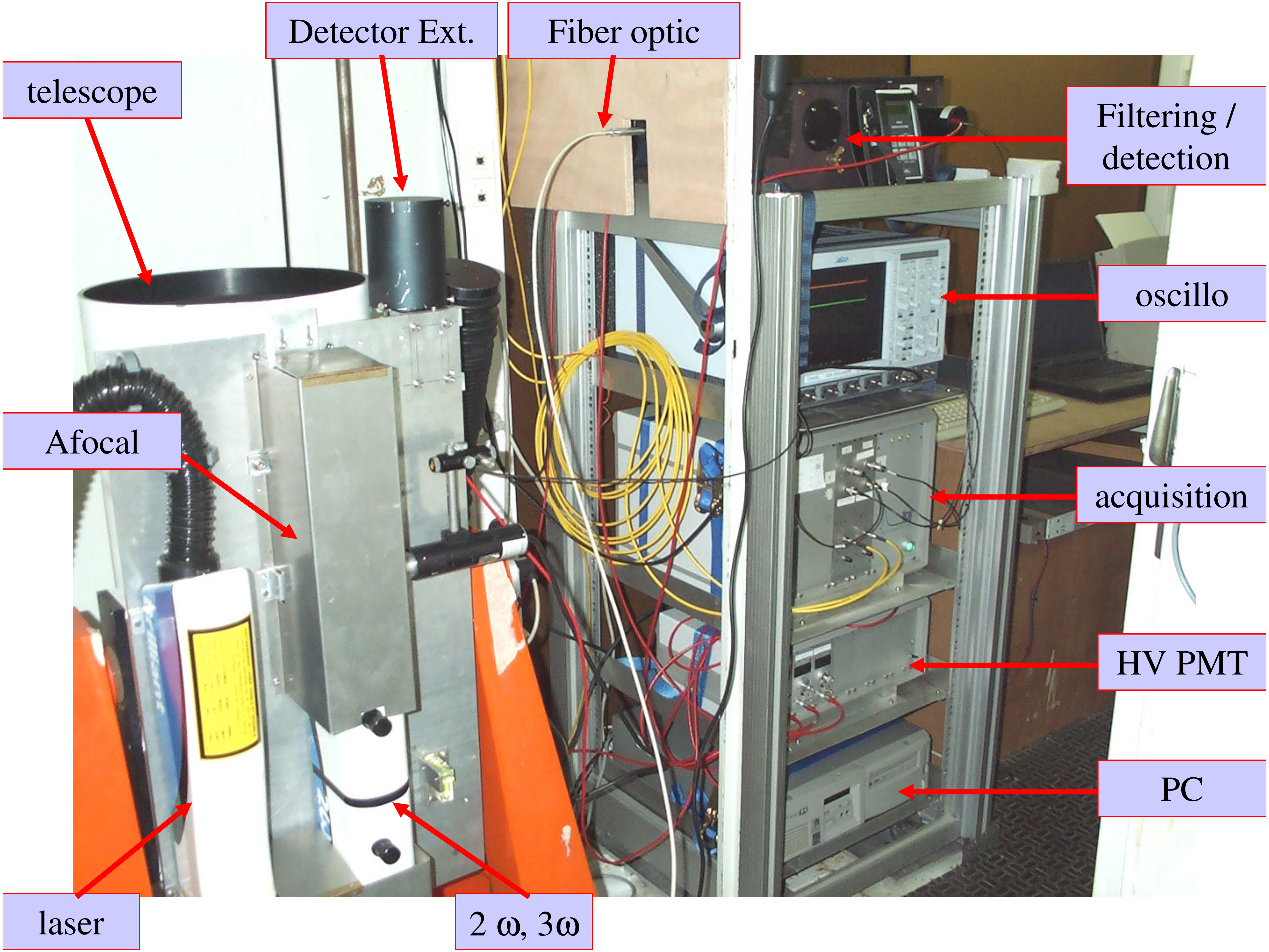


Discrepancies between the two profiles may be due to measurement errors, but are more likely due to the fact that the radiosonde blows downwind as it rises, and thus the vertical-pointing lidar and the radiosonde do not measure the same air parcels

Raman IGN-SA raman lidar (O.Bock, J. Pelon)



Schematic bloc diagram of the Raman lidar system


Detector Ext.
Fiber optic
telescope
Filtering / detection
oscillo
Afocal
acquisition
HV PMT
PC
laser
2 ω, 3ω

Characteristics of Raman lidar IGN-SA

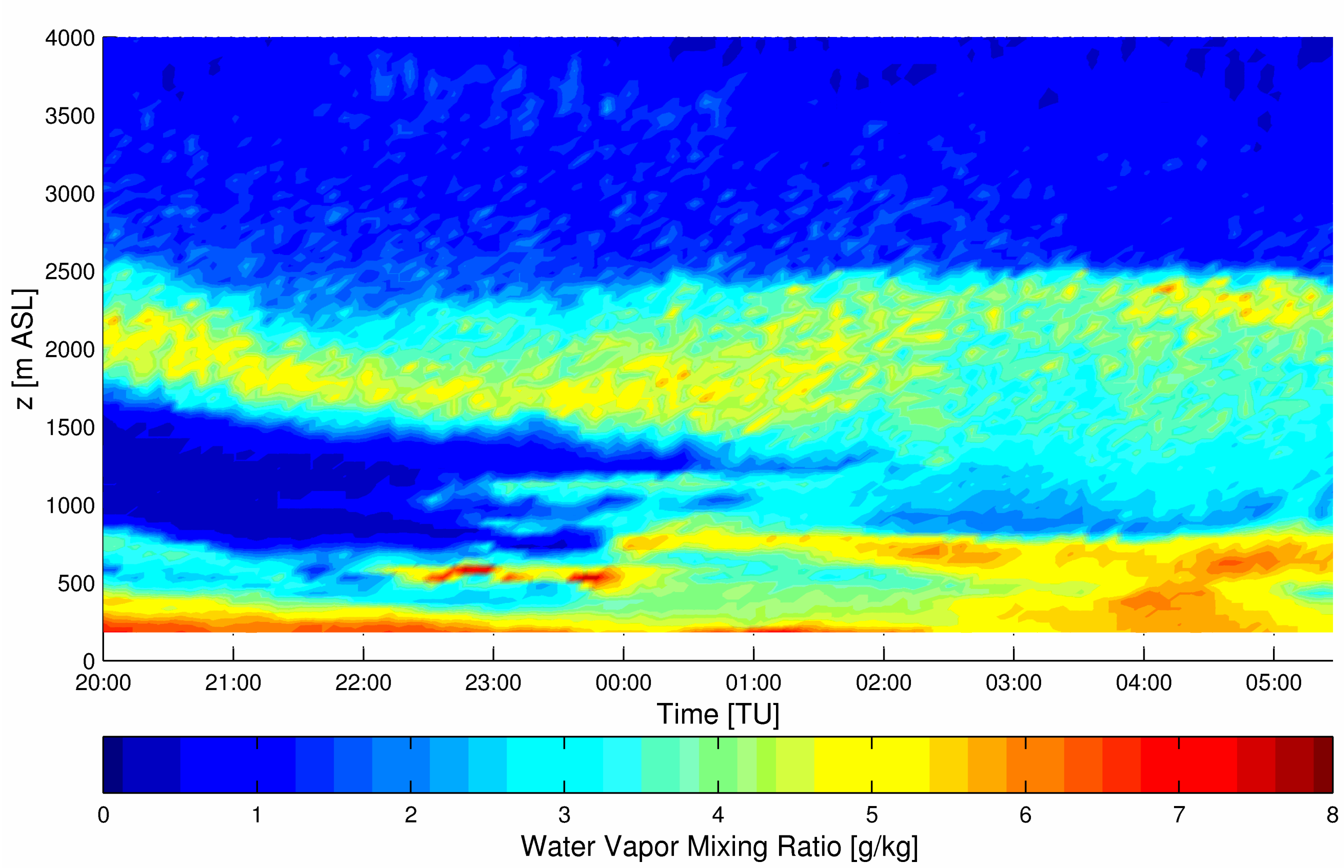
Emission Laser Quantel Brillant (Nd:YAG triplé)	 Fréquence de répétition Energie par pulse Divergence (après afocal) Diamètre faisceau (après afocal)	 10 Hz 30 mJ @ 355nm ≈0.1 mrad 27 mm
Réception Télescope type Cassegrain Fibre optique quartz	 Diamètre / focale Diamètre / champ en réception	 30 cm / 1 m 0,8 mm / 0,8 mrad
Filtrage Filtres interférentiels : Passe-bande Omega	 Rayleigh/Mie Azote Vapeur d'eau	λ / FHWM / transmission / blocage 355 nm / 4,7 nm / 35 % / OD5 387 nm / 7 nm / 40 % / OD5 408 nm / 6 nm / 40 % / OD5
Détection Photomultiplicateurs : Hamamatsu Série 7400	 RQ @ 355 / 387 / 408 nm	 ~ 20 %
Acquisition Rack Licel mode AD / PC Δt=50 ns (Δz=7,5 m) Fichiers de 200 tirs (20 s)	 Signal / mode	 355 nm / AD (analogique - digital) 387 nm / PC (comptage de photons) 408 nm / PC

Observations:

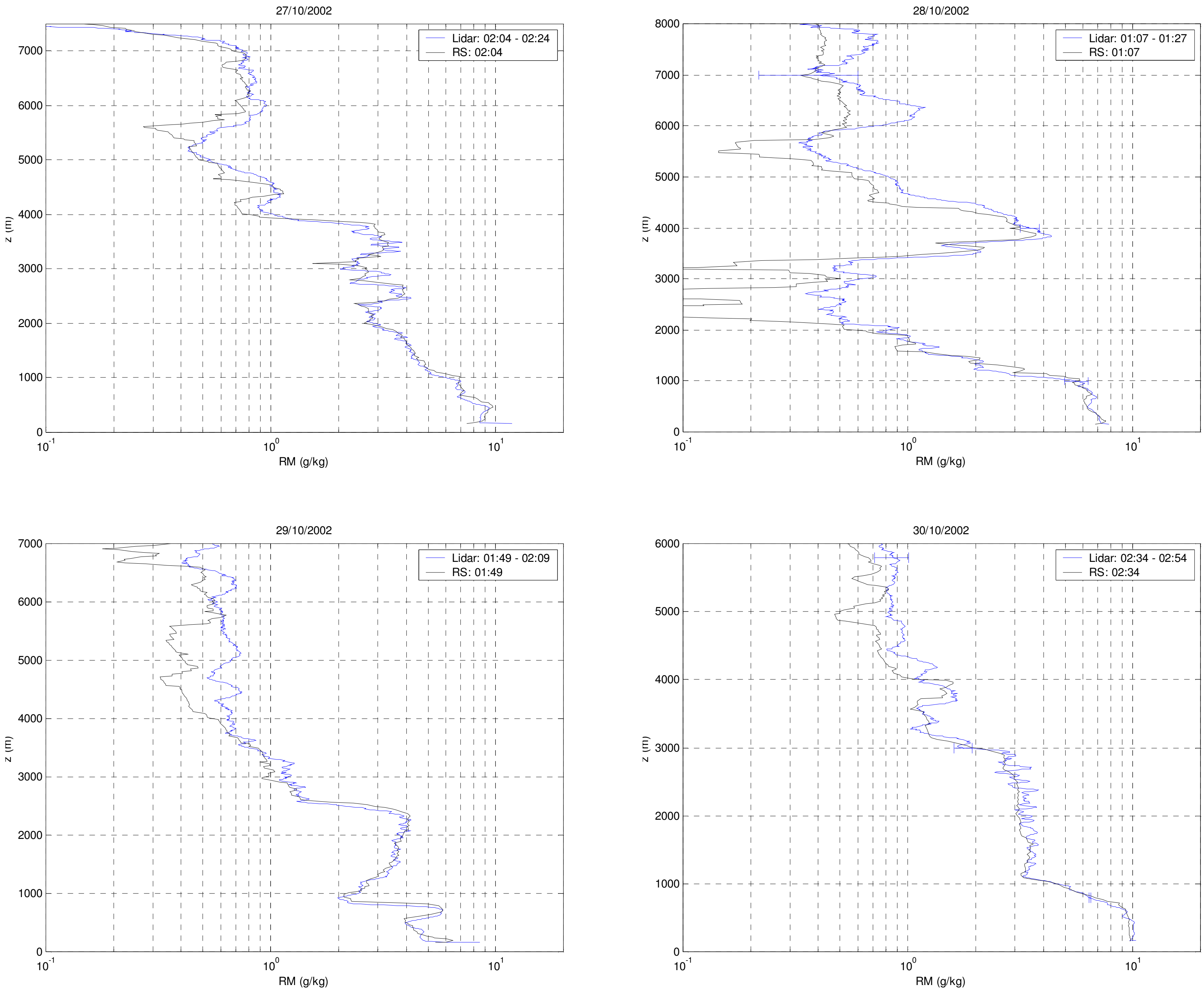
-2 Rayleigh/Mie signals (355 nm)

- 2 Raman signals H_2O (408 nm) and N_2 (387 nm)

RM2D : 29 Octobre 2002, 20:00 UTC – 05:30 UTC



5 minutes average


27/10/2002
Lidar: 02:04 - 02:24
RS: 02:04
z (m)
RM (g/kg)
28/10/2002
Lidar: 01:07 - 01:27
RS: 01:07
z (m)
RM (g/kg)
29/10/2002
Lidar: 01:49 - 02:09
RS: 01:49
z (m)
RM (g/kg)
30/10/2002
Lidar: 02:34 - 02:54
RS: 02:34
z (m)
RM (g/kg)

CONCLUSION

Lidars can give a good retrieval of the variability of various atmospheric conponents on the vertical and on a continuous manner and with a very good accuracy.