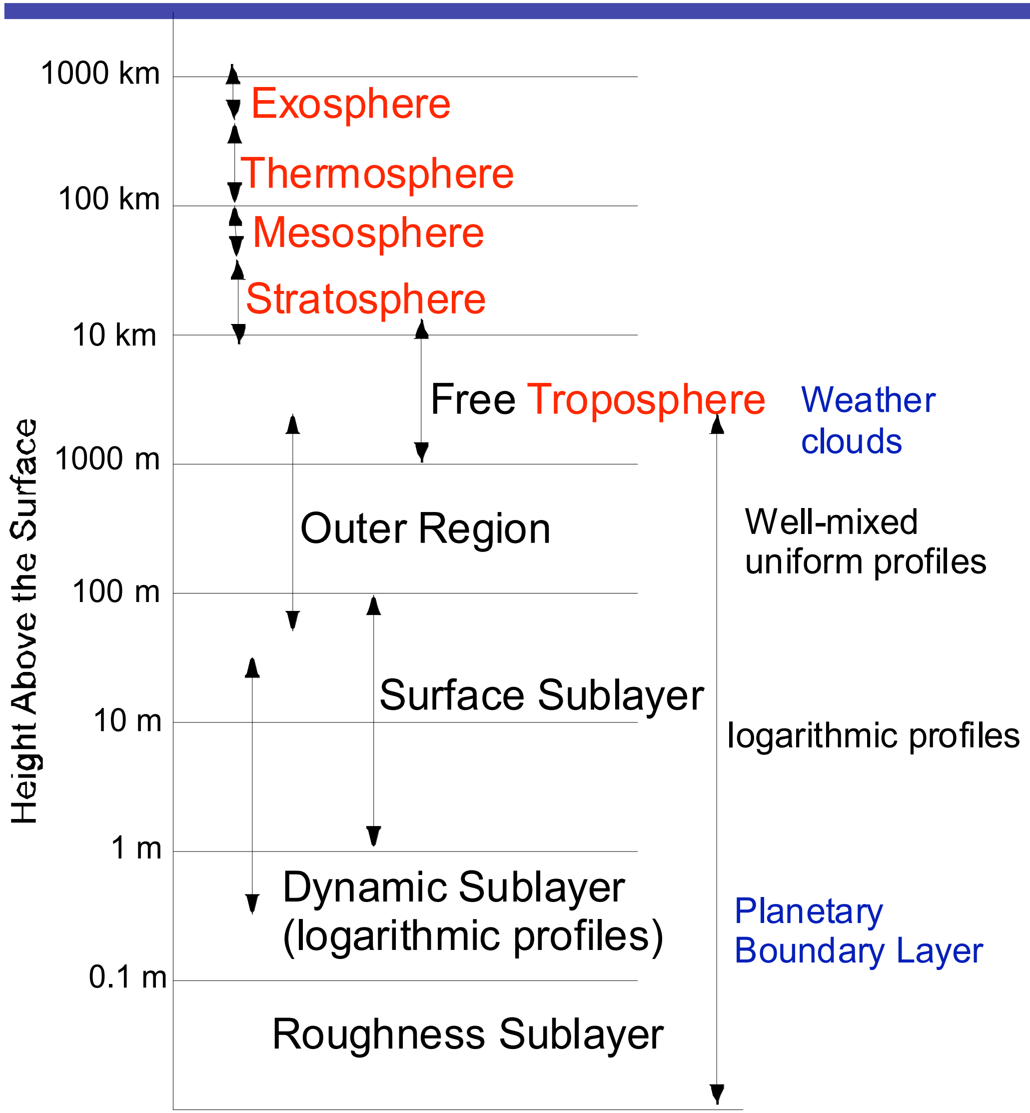
Study of Aerosols in Troposphere

Fei Gao

Center for Atmospheric Research
University of Nova Gorica

Atmospheric structure



Atmospheric layers

Troposphere: all weather takes place

Pressure and density rapidly decrease with height, and temperature generally decrease with height at a constant rate about 6.5℃/km (Boundary Layer)

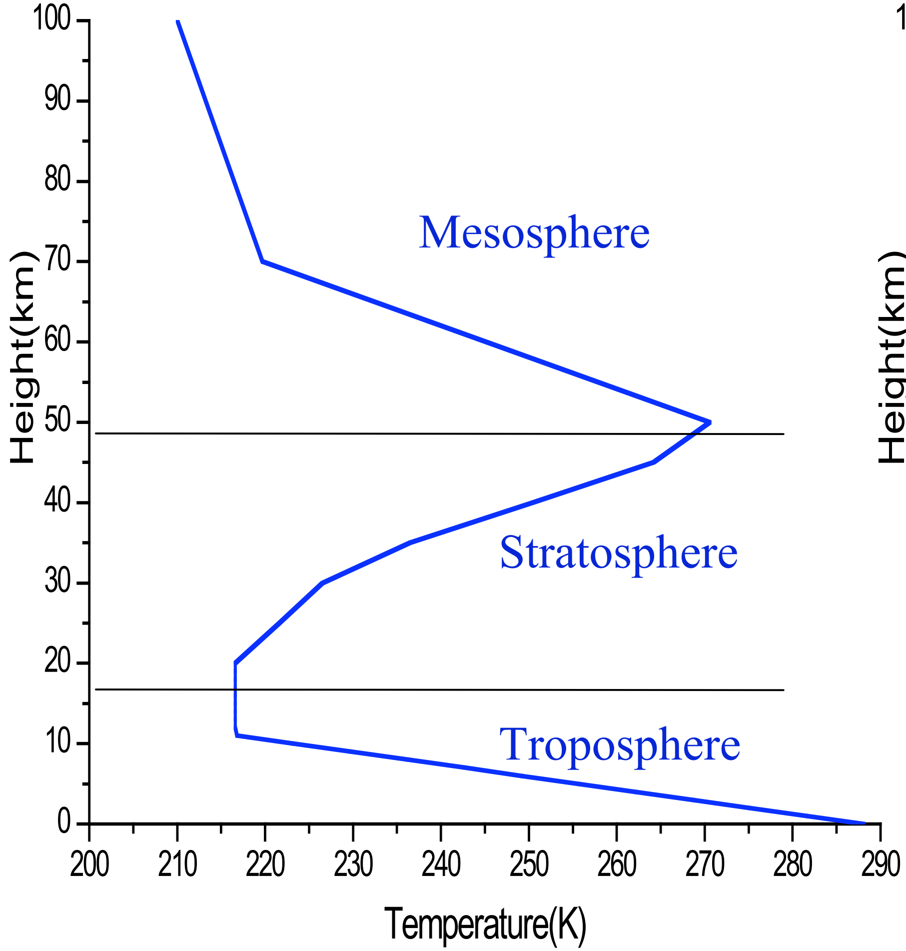
Stratosphere: stable stratified layer

Large temperature inversion throughout its depth because the absorption of UV light warms the atmosphere (Ozone Layer)

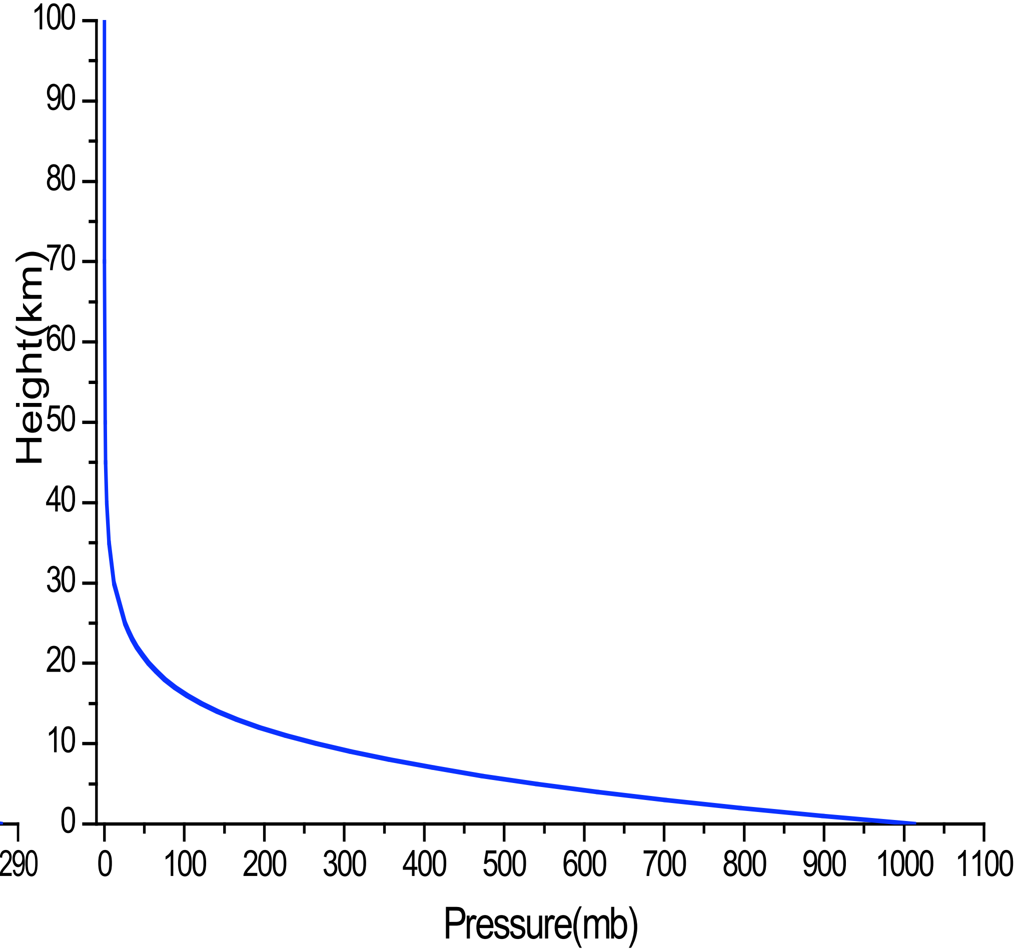
Mesosphere: middle layer

Temperature decreases with altitude, air is extremely thin with 99.9% of the atmospheric mass lying below this layer (between 75 and 110 km, there exists a layer containing high concentrations of sodium, potassium, and iron)

Atmospheric properties



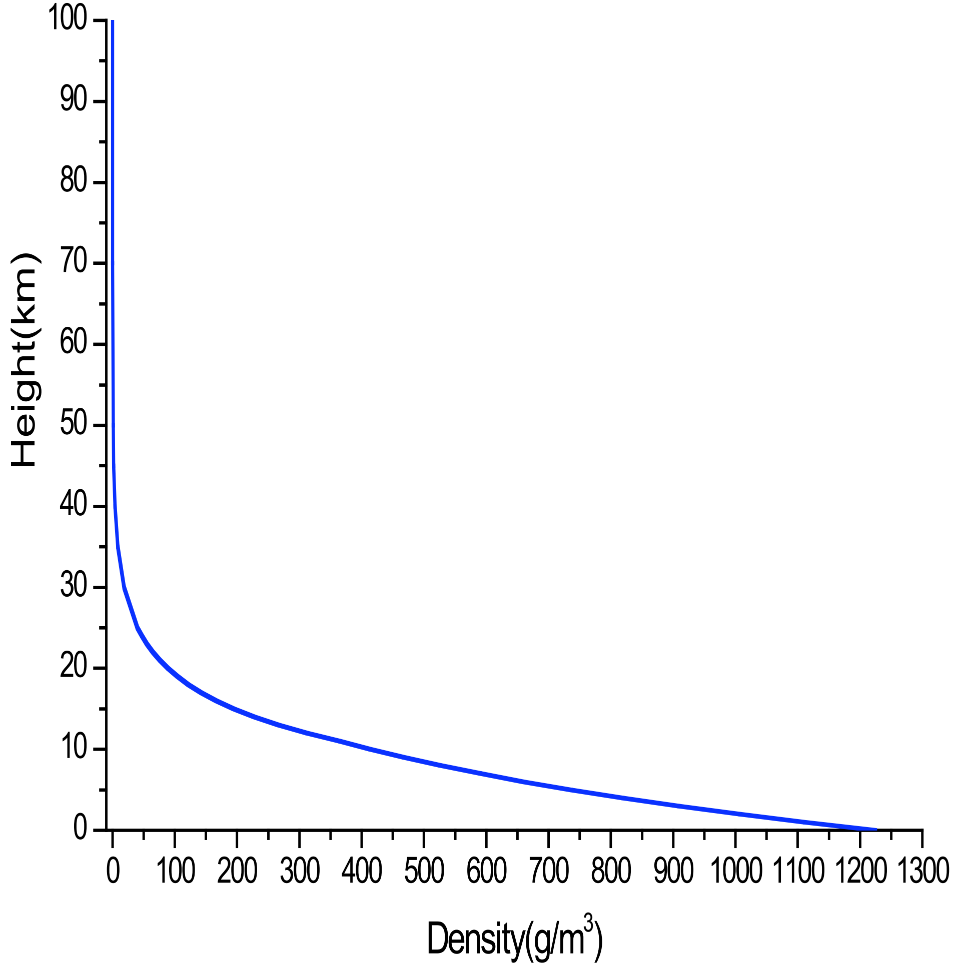
Vertical profile of temperature



Vertical profile of pressure

From the U.S. Standard Atmosphere(1976)

Atmospheric properties



Vertical profile of Number Density of molecules

Vertical profile of aerosols

From the U.S. Standard Atmosphere(1976)

What are aerosols

1. Definition of aerosols:

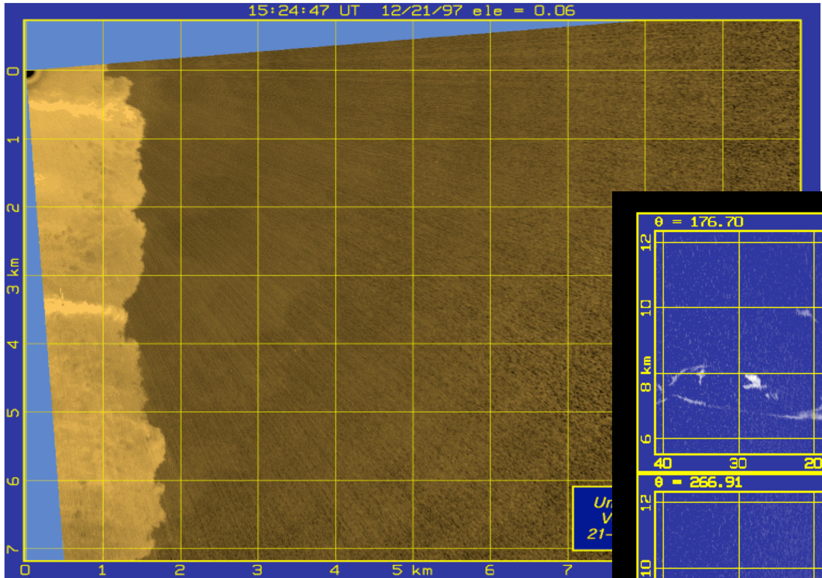
   A gaseous suspension of fine solid or liquid particles which diameter is between 0.001 and 100 μm. Examples are smoke, oceanic haze, air pollution, smog …

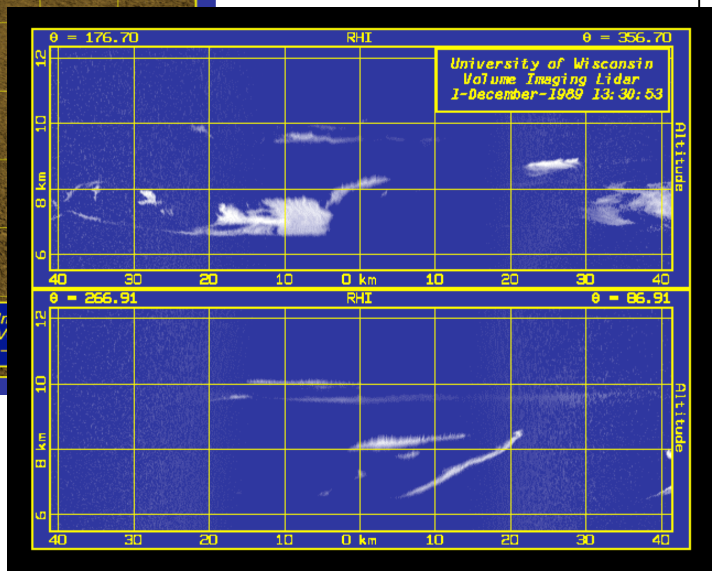
2. The importance of aerosol measurements:

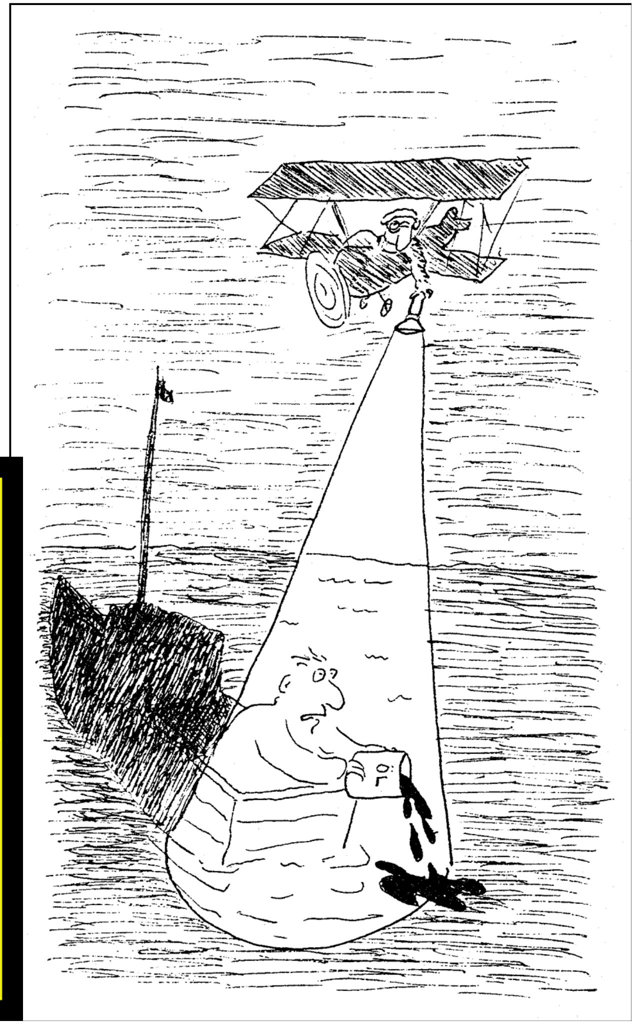
   1) forecast the air quality

   2) research the mechanism of air pollution

   3) find the source of air pollution







Aerosol detection

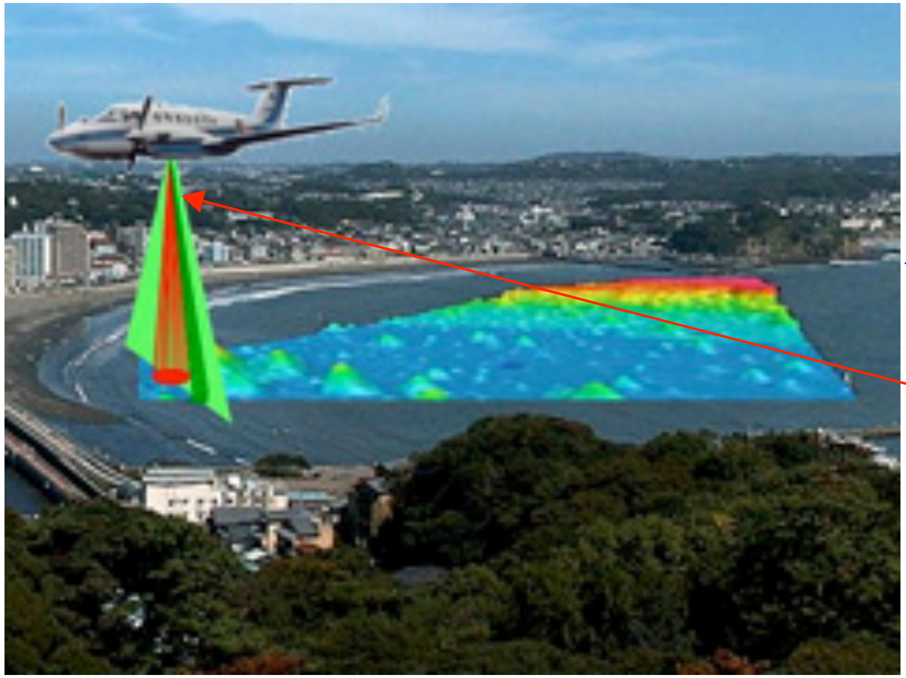
1. In situ measurement

- Mini-Vol portable aerosol samplers
- Aethalometer

Properties:

chemical analysis of aerosols: size, shape can be determined

point measurement, not in real time



2. Remote sensing

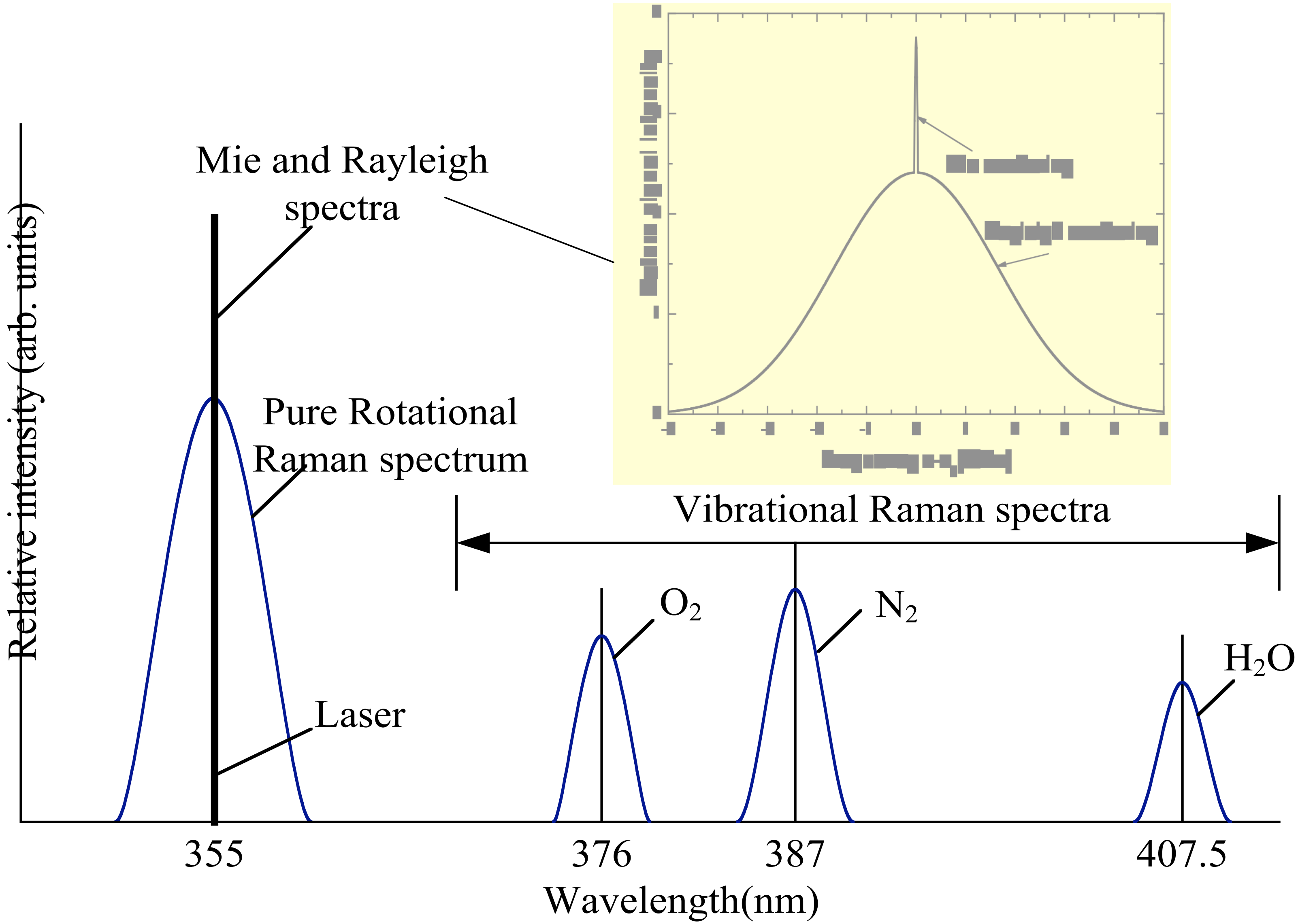
- Radar: long wavelength → cm, m
- Lidar : short wavelength → μ m, nm

Properties:

optical analysis of aerosols in the atmosphere

line and profile measurement, spatial and temporal measurement.

Scattering spectrum of light in the atmosphere

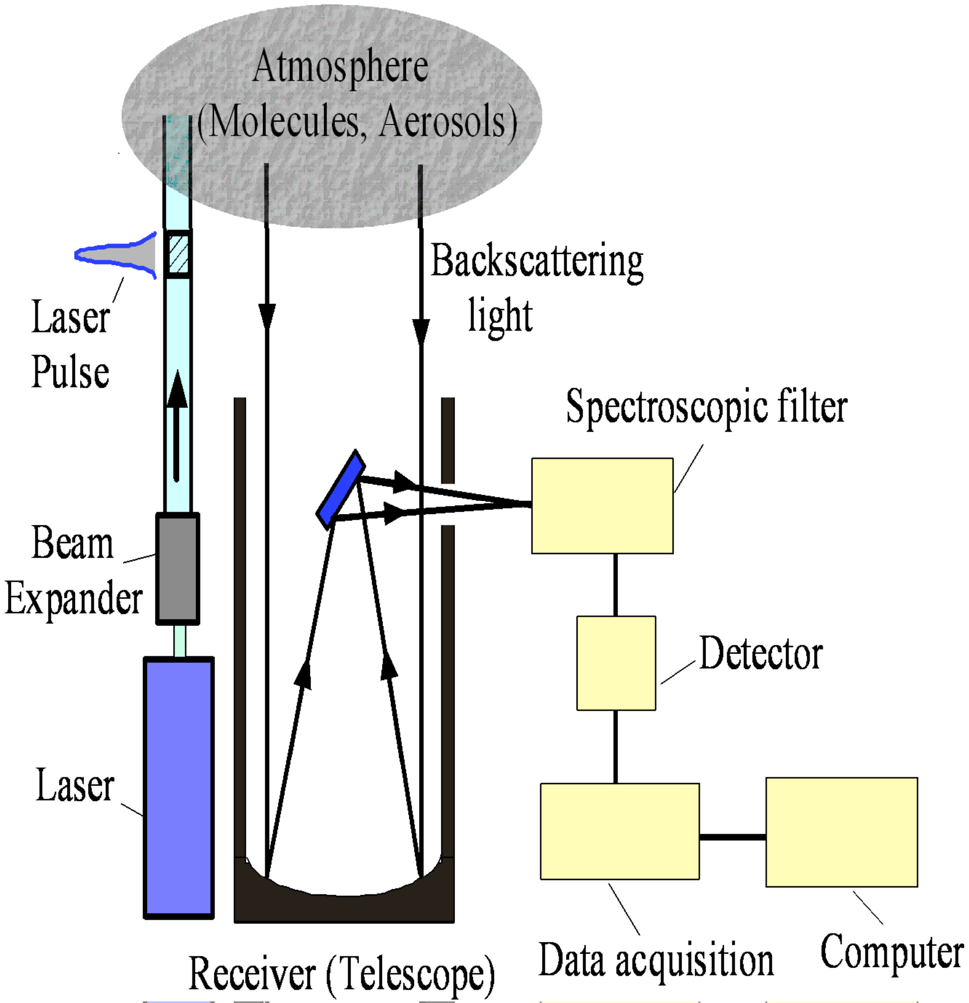


Overview of lidar spectrum for excitation wavelength of 355nm

Types of aerosol lidar

	Advantage	Disadvantage
Mie Lidar	compactness relatively low cost easy operation	need some assumption about atmospheric conditions, which limit the measurement accuracy
HSRL	No need assumption about atmospheric conditions, high accuracy measurement	Need additional spectroscopic filter, and it is complex and difficult to adjust lidar return light
Raman Lidar	The concentration of nitrogen in the atmosphere is relatively stable, and no need assumption about atmospheric conditions	High power laser Large diameter telescope Photon counting DAQ system

Typical setup of a lidar



Transmitter: transmit an intense pulse of optical energy to atmosphere

Receiver: gather the backscattering signal, which comprises several components: Mie scattering due to particles, Rayleigh scattering from molecules, Raman scattering caused by the rotation and vibration of molecules and sent them into spectroscopic filter

* Spectroscopic filter and detector: optical analysis of the backscattered signal from spectrum and energy, polarizer, grating spectrometer, interferometers, and atomic -vapor filter are employed. Detector (PMT or photodiodes) realizes the conversion from light signal to electrical signal

DAQ system and computer: analog-digital conversion and numerical analysis

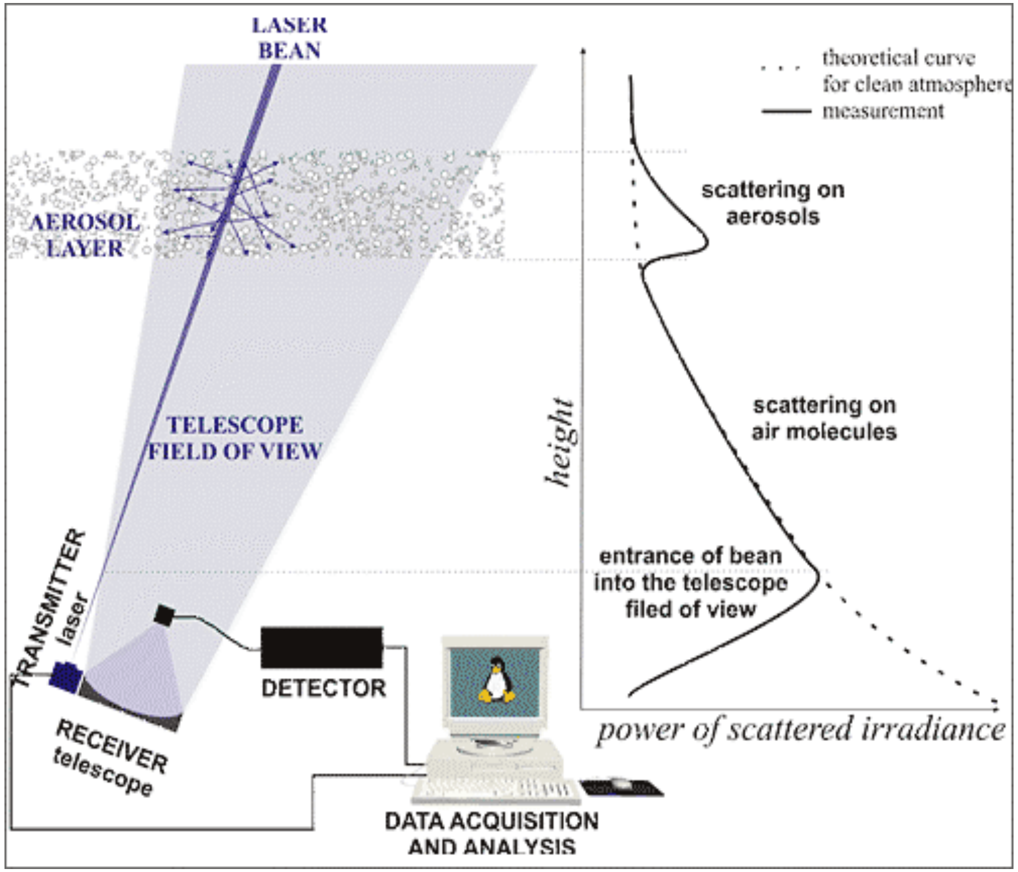
Mie scattering lidar

For a monostatic single-wavelength pulsed lidar, the lidar equation is

$$P(z) = CP_0 \frac{c\tau}{2} A_{tel} Y(z) \frac{\beta(z)}{z^2} \exp\left[-2\int_0^z \alpha(z^*)dz^*\right] \qquad (1)$$

P(z) –lidar received power
C –the lidar system constant
c– light speed
τ—pulse duration
P_0 –the transmitted power
A_{tel} –the effective system receiver area
Y(z) –the geometrical form factor.

★β(z) –the volume backscatter coefficient, related to atmospheric optical thickness and visibility
★α(z) – the volume extinction coefficient, related to density of aerosols and molecules



Klett method for Mie lidar

★James D. Klett, "Stable analytical inversion solution for processing lidar returns," Appl. Opt. 20, 211-220 (1981)

$\beta(z)$ and $\alpha(z)$ can be related approximately according to a power law

→ $$\beta = const * \alpha^k \qquad (2)$$

Where k depends on the lidar wavelength and various properties of the obscuring aerosol

Solution:

$$\alpha(z) = \frac{\exp[(S - S_m)/k]}{\left\{\alpha_m^{-1} + \frac{2}{k}\int_z^{z_m} \exp[(S - S_m)/k]dz'\right\}} \qquad (3)$$

Where $S(z)=\ln[z^2P(z)]$, α_m and S_m are, respectively, the attenuation coefficient and S value of the reference point.

Fernald method for Mie lidar

★Frederick G. Fernald, "Analysis of atmospheric lidar observations: some comments," Appl. Opt. 23, 652-653 (1984)

The contribution of aerosol and molecular are considered, respectively

$$P(z) = CP_0 z^{-2}(\beta_a(z) + \beta_m(z)) \exp\left[-2\int_0^z \alpha_a(z^*)dz^*\right] \exp\left[-2\int_0^z \alpha_m(z^*)dz^*\right] \quad (4)$$

Assumption: aerosol ⟶ $s_1 = \alpha_a / \beta_a = 50$ molecular ⟶ $s_2 = \alpha_m / \beta_m = 8\pi/3$

Aerosol extinction coefficient under z_c

$$\alpha_a(z) = -\frac{s_1}{s_2} \cdot \alpha_m(z) \quad (5)$$

Aerosol extinction coefficient above z_c

$$\alpha_a(z) = -\frac{s_1}{s_2} \cdot \alpha_m(z) + \frac{X(z) \cdot \exp\left[-2\left(\frac{s_1}{s_2} - 1\right)\int_{z_c}^{z} \alpha_m(z')dz'\right]}{\frac{X(z_c)}{\alpha_a(z_c) + \frac{s_1}{s_2}\alpha_m(z_c)} - 2\int_{z_c}^{z} X(z') \exp\left[-2\left(\frac{s_1}{s_2} - 1\right)\int_{z_c}^{z'} \alpha_m(z'')dz''\right]dz'} \quad (6)$$

Principle of HSRL

Fabry-Perot interference filter

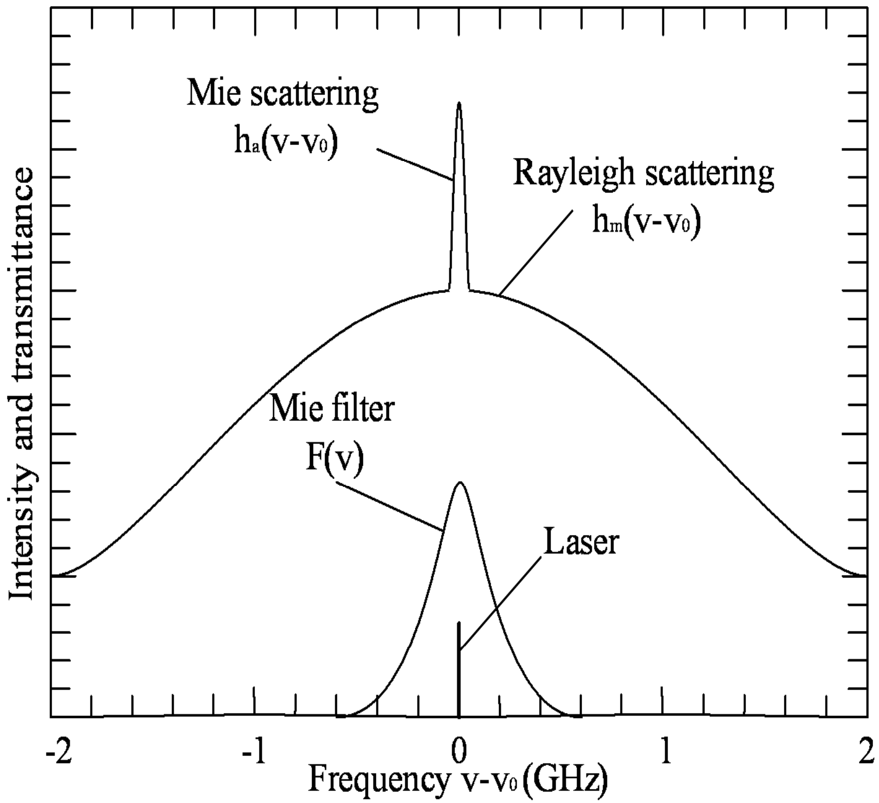


Fig14. Fabry-Perot etalon as the filter

Molecular absorption filter of iodine (only for 532nm)

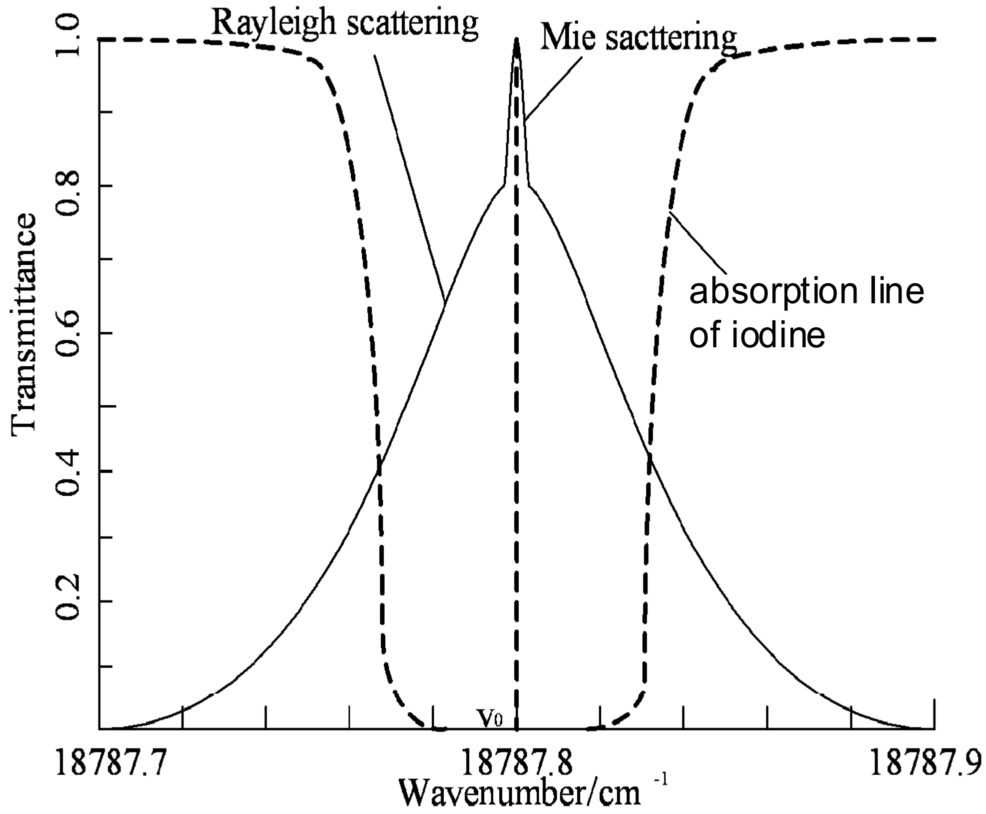
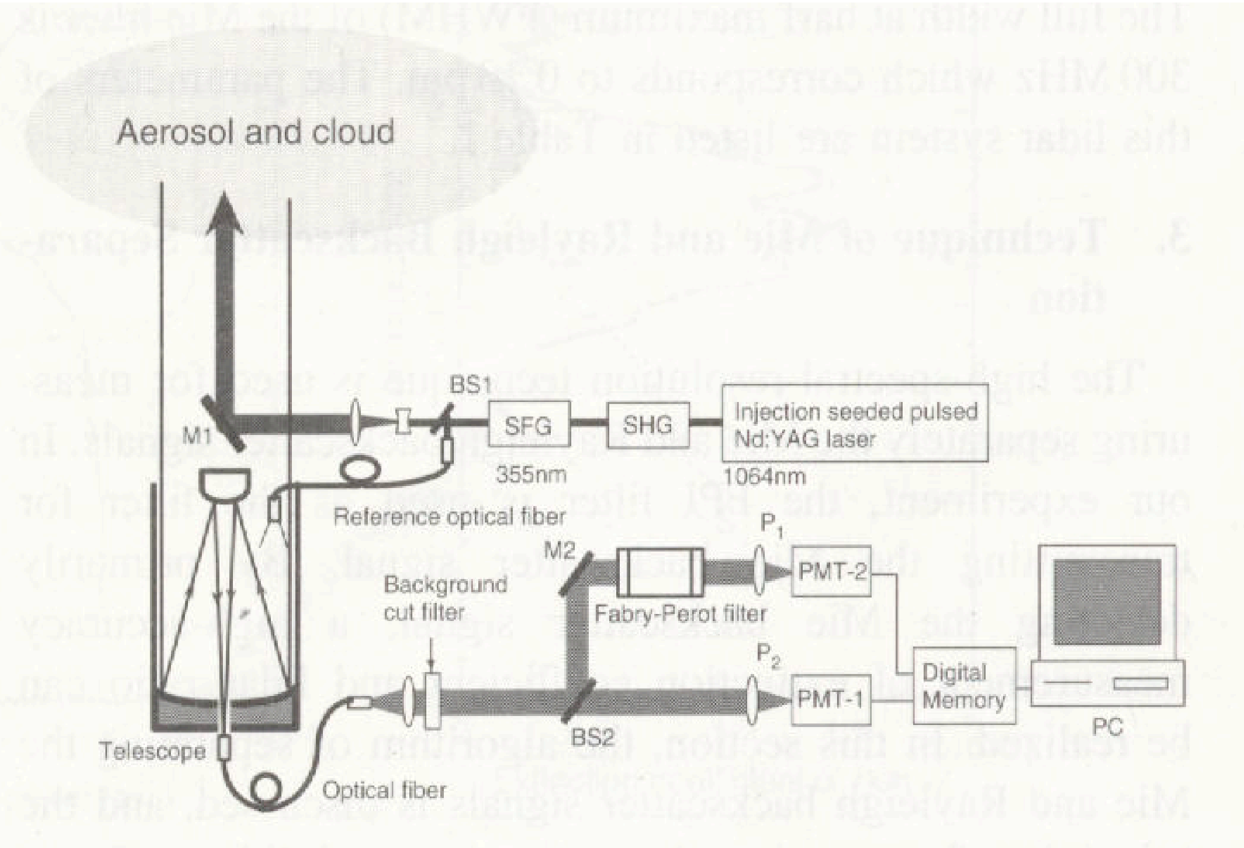


Fig15. Iodine absorption cell as the filter

Example of HSRL



Schematic of ultraviolet high-spectral-resolution lidar system

System parameter

Laser: Nd:YAG third harmonics

wavelength	355nm
Energy per pulse	150mJ
Repetition frequency	20Hz
Pulse width	10ns
Spectral width	150MHz

Optics:

Telescope diameter	250mm
Field of view	0.1mrad
Fiber core diameter	100 μ m
Band width of background cut filter	1nm

Filter: Fabry-Perot etalon filter

Spectral width	300MHz
Peak transmittance	0.4

Detector: PMT

Quantum efficiency	23%

Masaharu Imaki etc, University of Fukui.

Data processing of HSRL

Molecular Rayleigh backscatter power:

Aerosol Mie backscatter power:

(7)

(8)

Where $P_1(z)$is total detector power by PMT1 $P_2(z)$ is Mie detector power by PMT2

Extinction coefficient of aerosol

(9)

Volume backscatter coefficient of aerosol

(10)

Lidar ratio

$$S_1(z) = \alpha_a(z) / \beta_a(z) \quad (11)$$

Principle of Raman lidar

1. Raman scattering is a weak molecular-scattering process that is characterized by a Shift in wavelength of the scattered beam of light relative to the incident one.

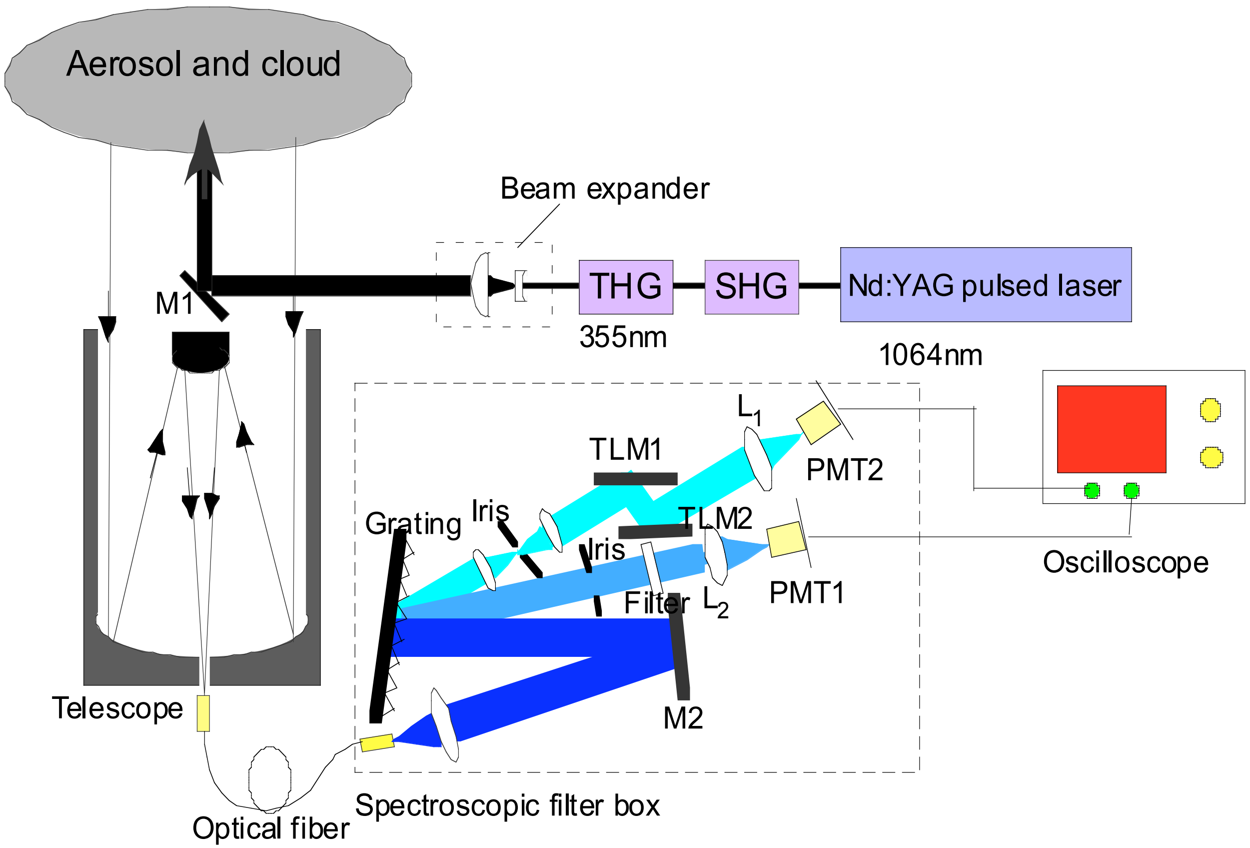
2. In Raman lidar, the inelastic (Raman) backscattering signal is affected by aerosol extinction but not by aerosol backscatter.

3. The fixed frequency shift of Raman effect:

Molecular		Air	O_2	N_2	H_2O
Frequency shift (Δcm^{-1})		0	1556	2331	3654
Raman Spectrum (nm)	354.7	354.7	375.4	386.7	407.5
	532.1	532.1	580.1	607.4	660.6

4. Because the distribution of the concentration of N_2 versus height is relatively stable in the atmosphere, select the intensity of the vibrational Raman scattering of N_2 as the object.

Example of Raman lidar



Schematic of ultraviolet Raman lidar system

System parameter

Transmitter: Nd:YAG laser

wavelength	354.7nm
Energy per pulse	250mJ
Repetition frequency	20Hz
Pulse width	10ns
Beam divergence	0.1mrad

Receiver optics:

Telescope diameter	250mm
Fiber core diameter	200 μ m
Field of view	0.2mrad

Spectroscopic optics:

Grating	2400gr/mm
Bandwidth of filter	31nm

Detector: PMT

Quantum efficiency	23%

Oscilloscope:

Tektronix TDS5104B

Fei Gao, Dengxin Hua etc, Xi'an University of Technology

Data processing of Raman lidar

Single-scattering Raman lidar equation as a function of range is:

(12)

P – the received power
λ_0 – the transmitted wavelength
λ_N – the nitrogen Raman wavelength
K – the system constant

$\sigma_N(\pi)$ – the differential backscatter cross section,
$n_N(z)$ – the number density of nitrogen,
$\alpha(z)$ – the volume extinction coefficient including $\alpha_a(z)$ and $\alpha_m(z)$.

Assuming a wavelength dependence of aerosol extinction such as:

$$\alpha_a(\lambda_0)/\alpha_a(\lambda_N) = \lambda_N/\lambda_0 \qquad (13)$$

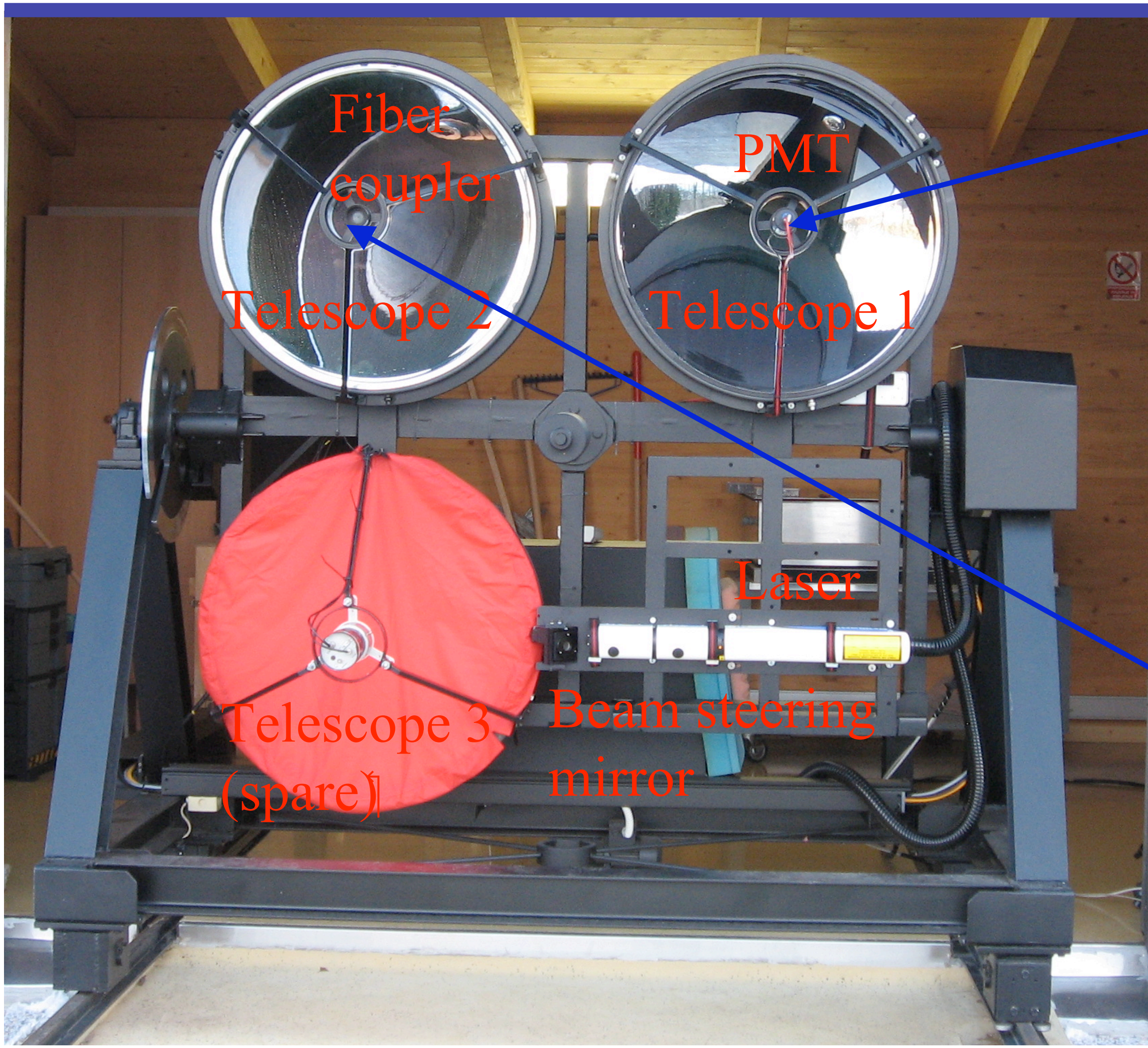
Solution of the Raman method

(14)

Albert Ansmann etc, "Measurement of atmospheric aerosol extinction profiles with a Raman lidar" Optics Letters, Vol. 15(13), 1990

An example of a lidar observatory
---Otlica Observatory

Otlica lidar system



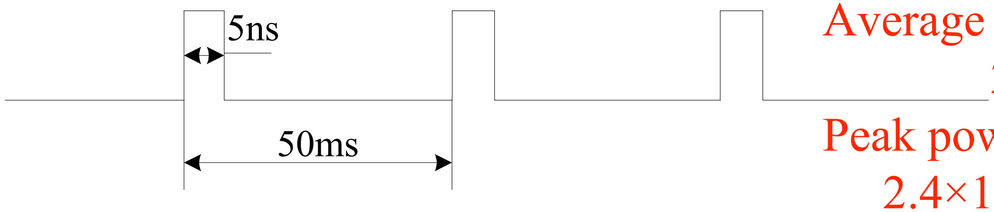
Mie lidar system (for measurement of aerosols)
- routine atmospheric measurements are being performed

Raman lidar system (aerosol and water vapor measurements)
- under construction

Components of Mie lidar system

1. Transmitter: Quantel Brilliant B
Nd:YAG pulsed laser

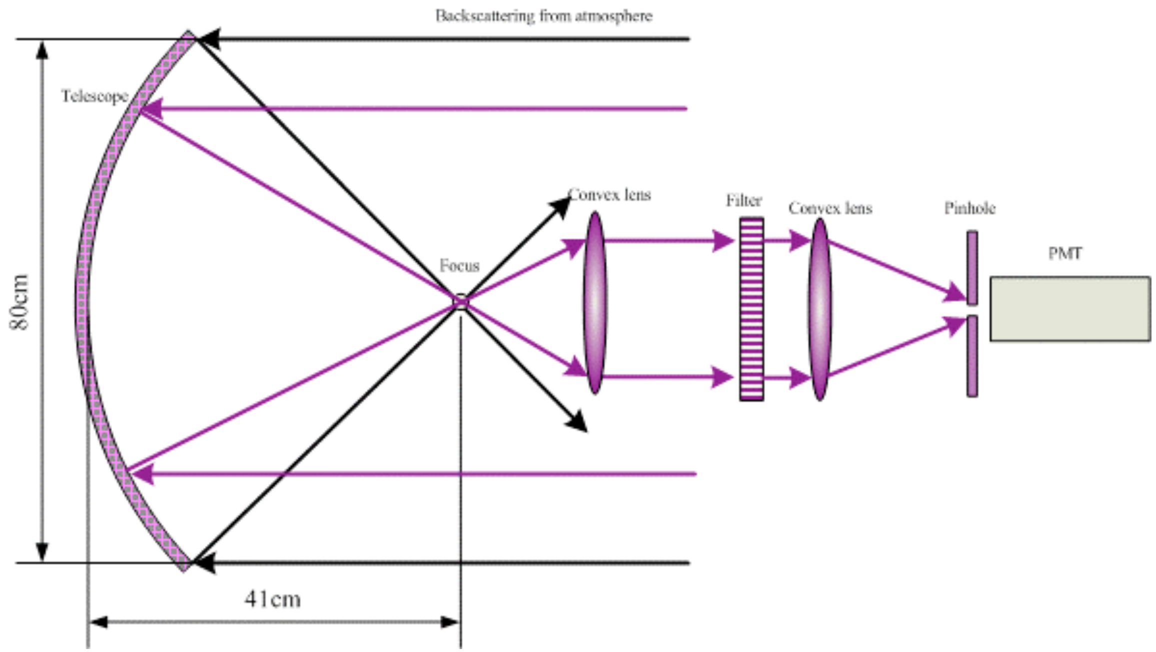
beam diameter	9mm
wavelength	355nm
repetition rate	20Hz
energy per pulse	120mJ
pulse duration	5ns



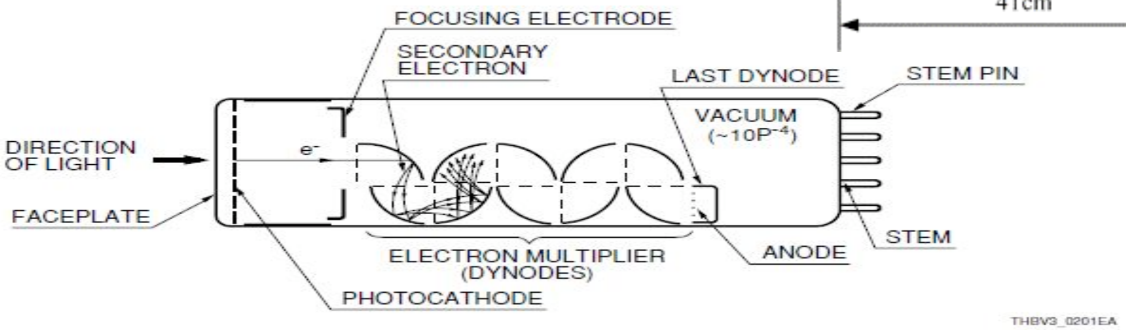
Average power
2.4W
Peak power
2.4×10^{7}W

2. Receiver: A parabolic mirror

diameter	800mm
focal length	410mm

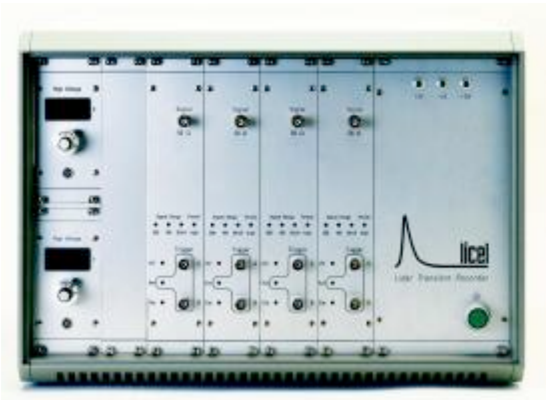


3. Detector:
Hamamatsu PMT R7400U-06

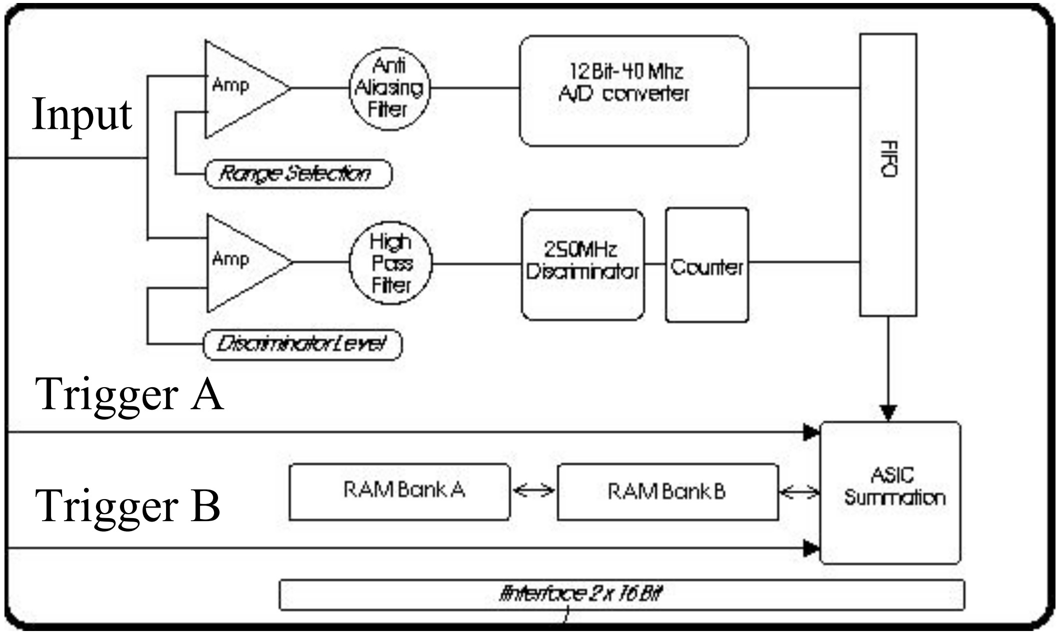


Components of Mie lidar system

4. DAQ--LICEL TR40—160



Picture of Transient Recorder



★Two channel: analog channel
photon counting channel

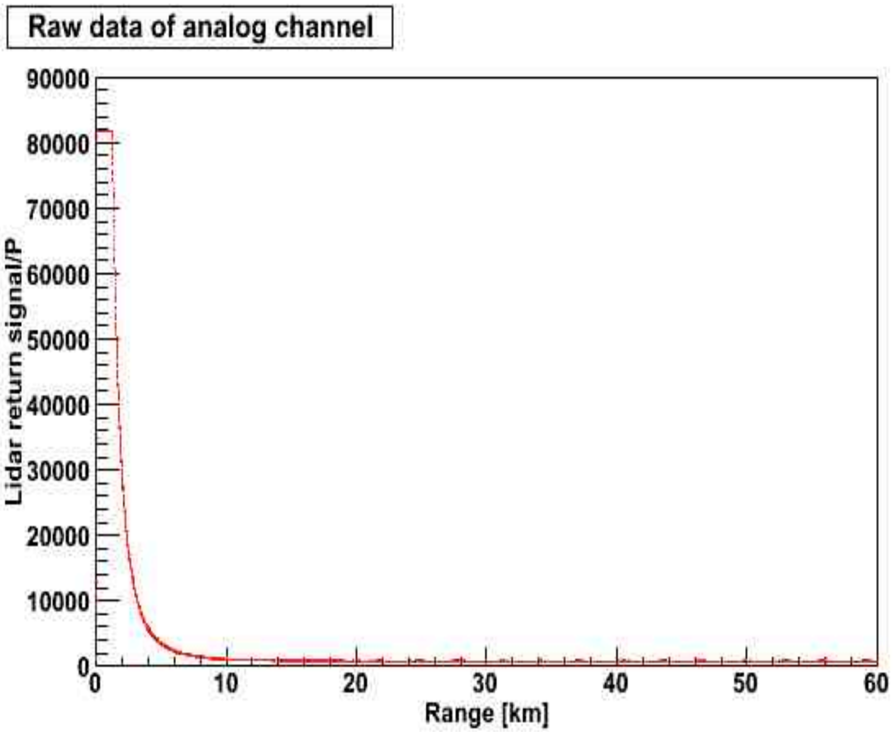
Computer

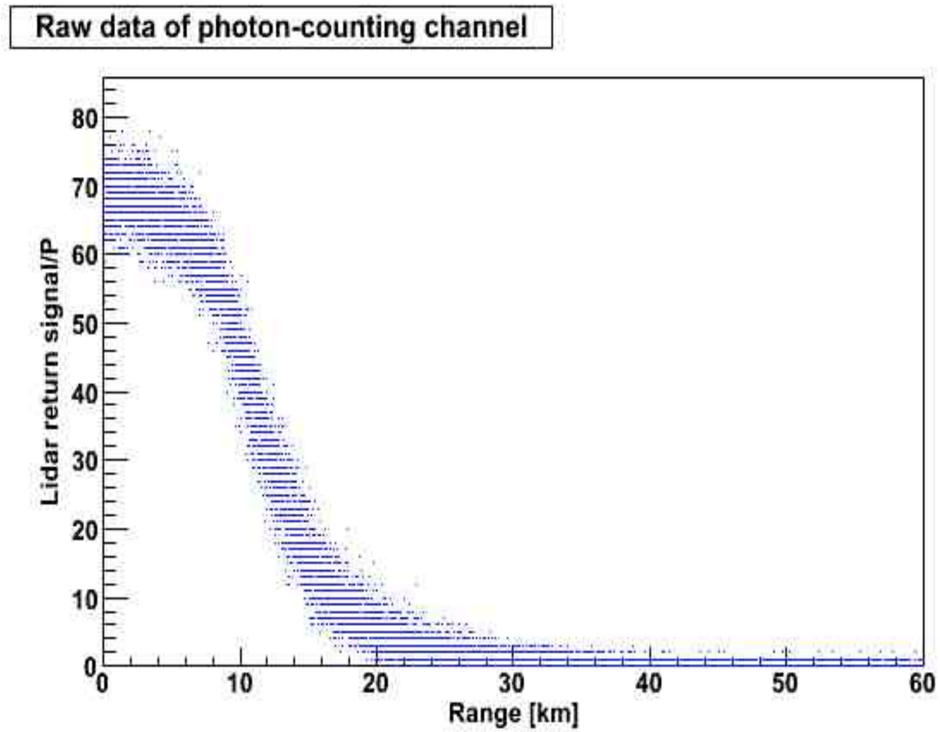
Principle of transient recorder

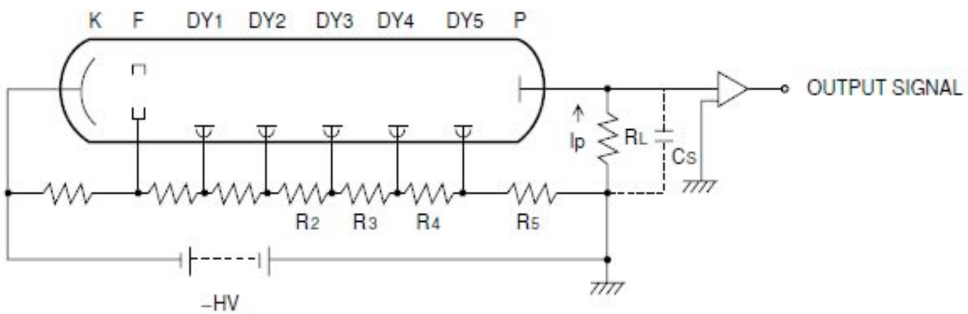
5. Lidar data

Collected data is stored in root binary files. (C++, ROOT)

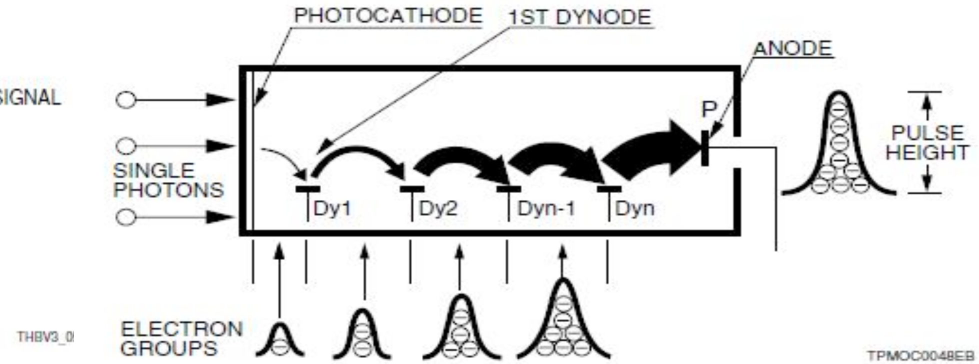
Raw data taken by Mie lidar







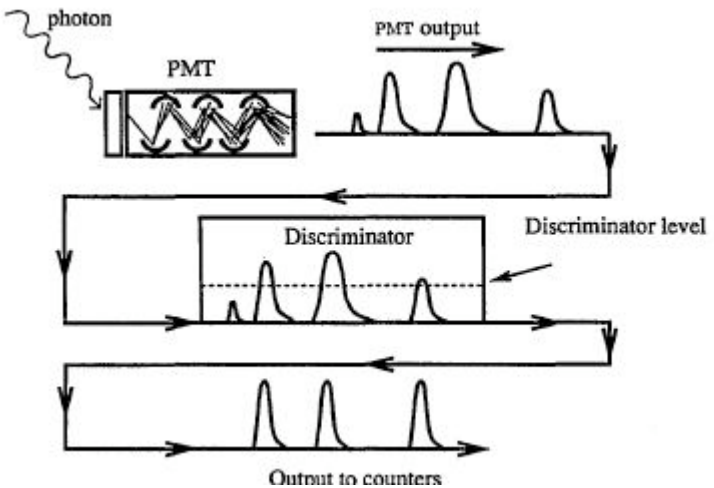
Analog mode



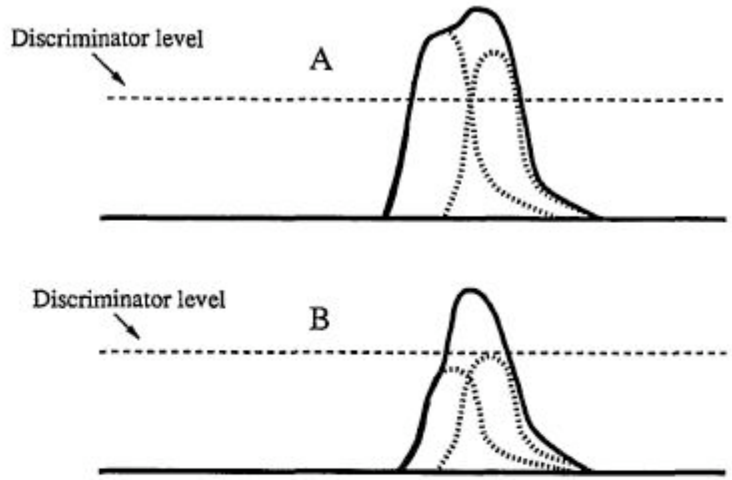
Photon counting mode

Processing of lidar data

1. Dead time correction of photon counting data



Schematic representation of a pc system



Pulse pileup effects: A, count loss B, count gain

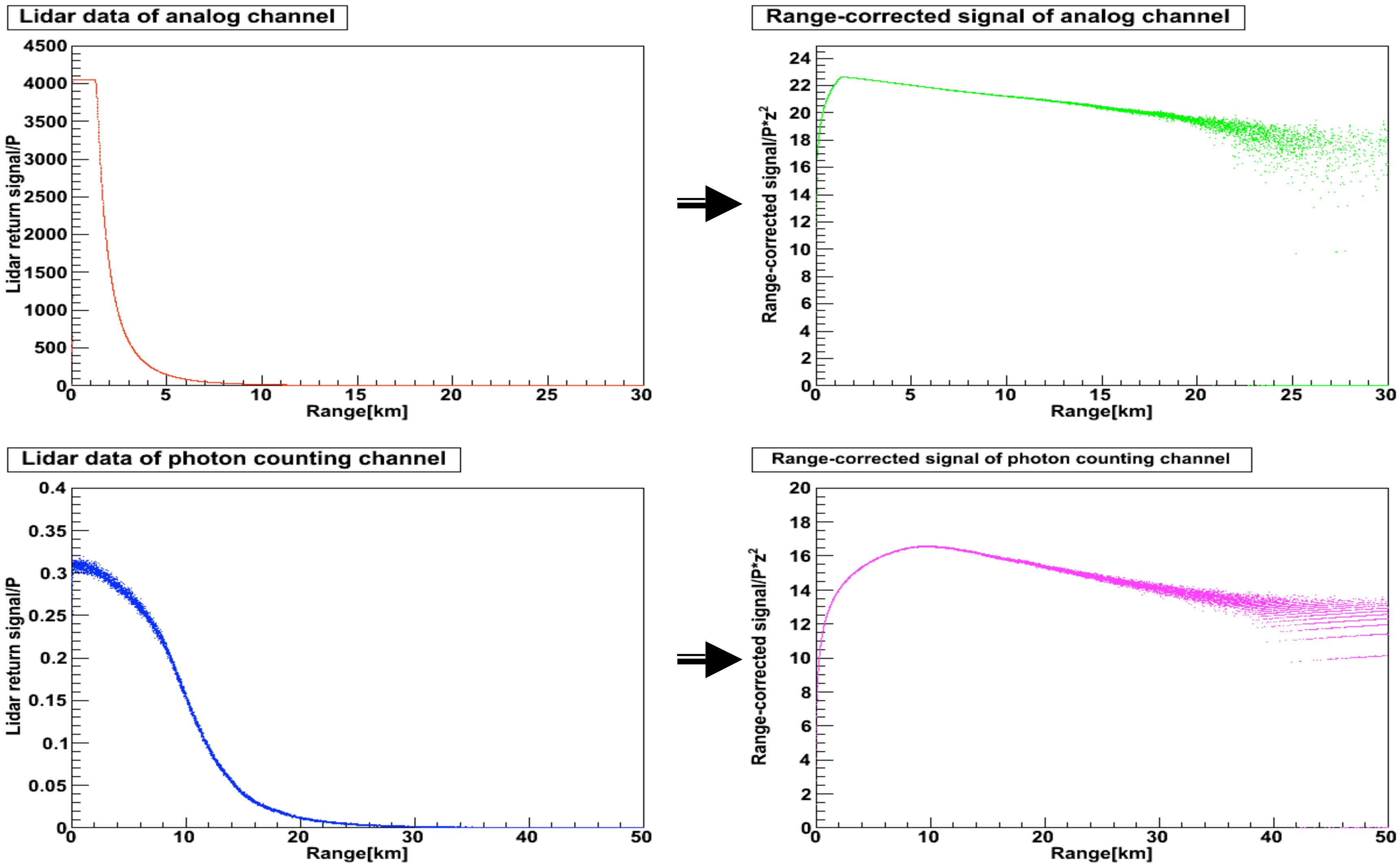
In order to overcome the influence of pulse pileup effect, dead time correction is necessary in photon counting channel

2. Event averaging
3. Rebin
4. Subtraction of the background

→ increase the signal to noise ratio

---because the range covered by the lidar is so far(61.4km), all measurements recorded at the far end of the trace are assumed to come from background.

Lidar range-normalized signal

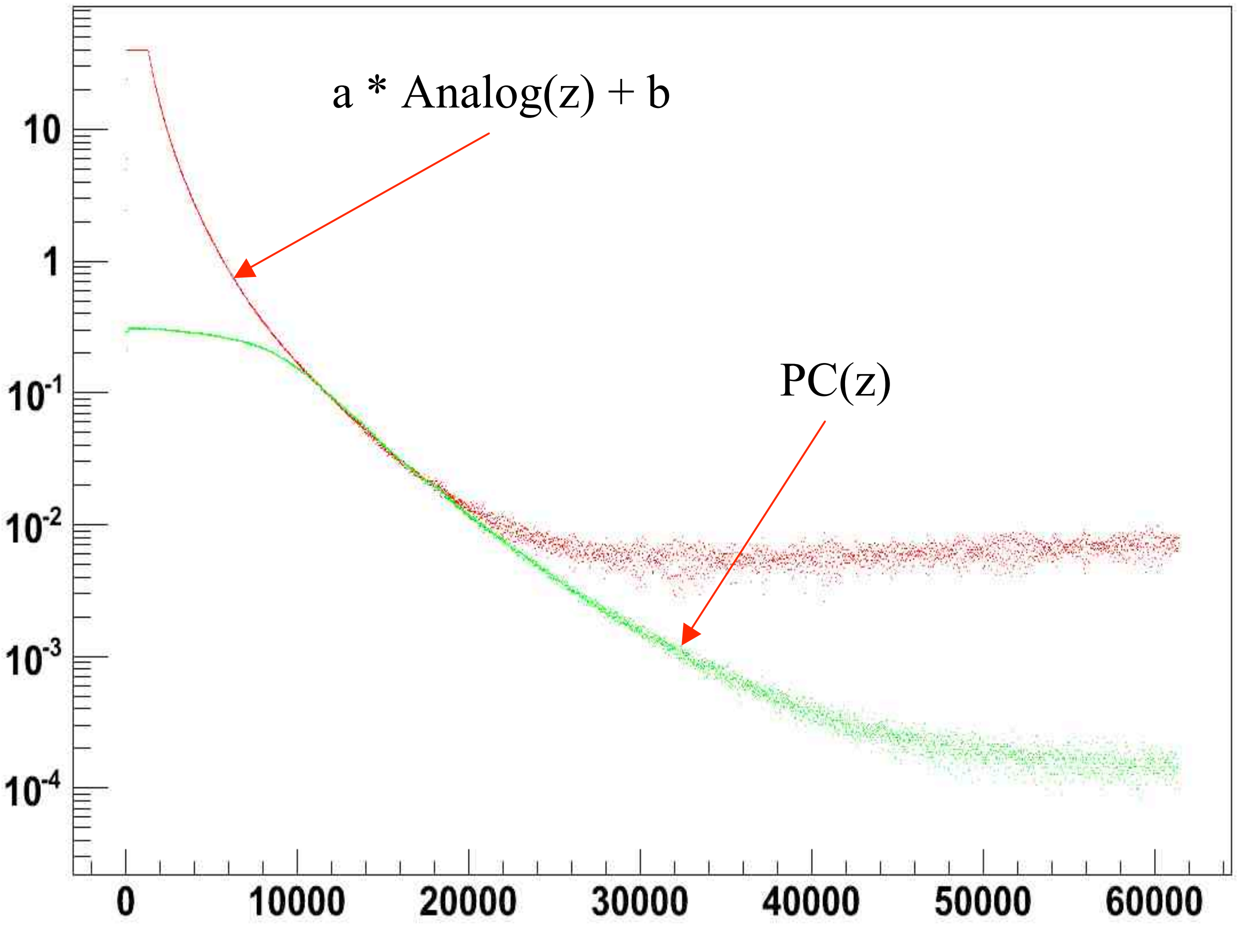


Range normalized signal $S=\ln(P(z)*z^2)$, express all information about atmospheric condition such as aerosol, cloud, cirrus…

Combination of analog and photon counting

$$\sum_{i=1}^{n} \frac{\left(PC(z_i) - \left(a * Analog(z_i) + b\right)\right)^2}{PC(z_i)} = \mathbf{min} \qquad (15)$$

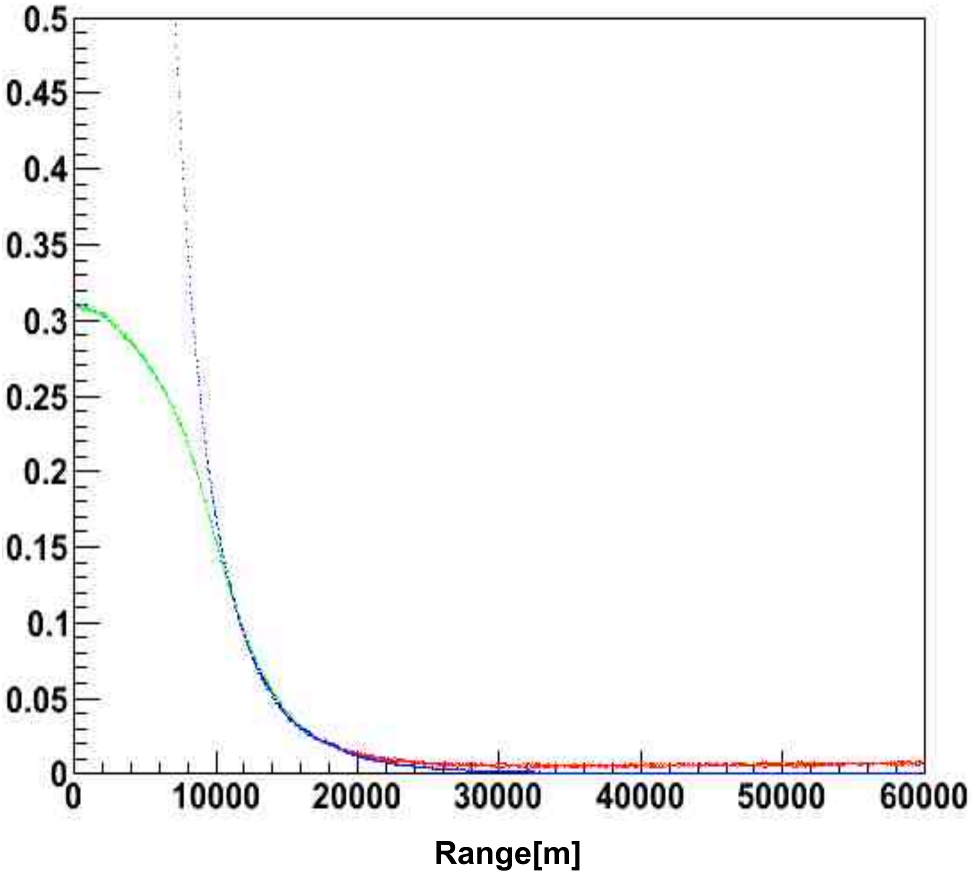
Gluing data



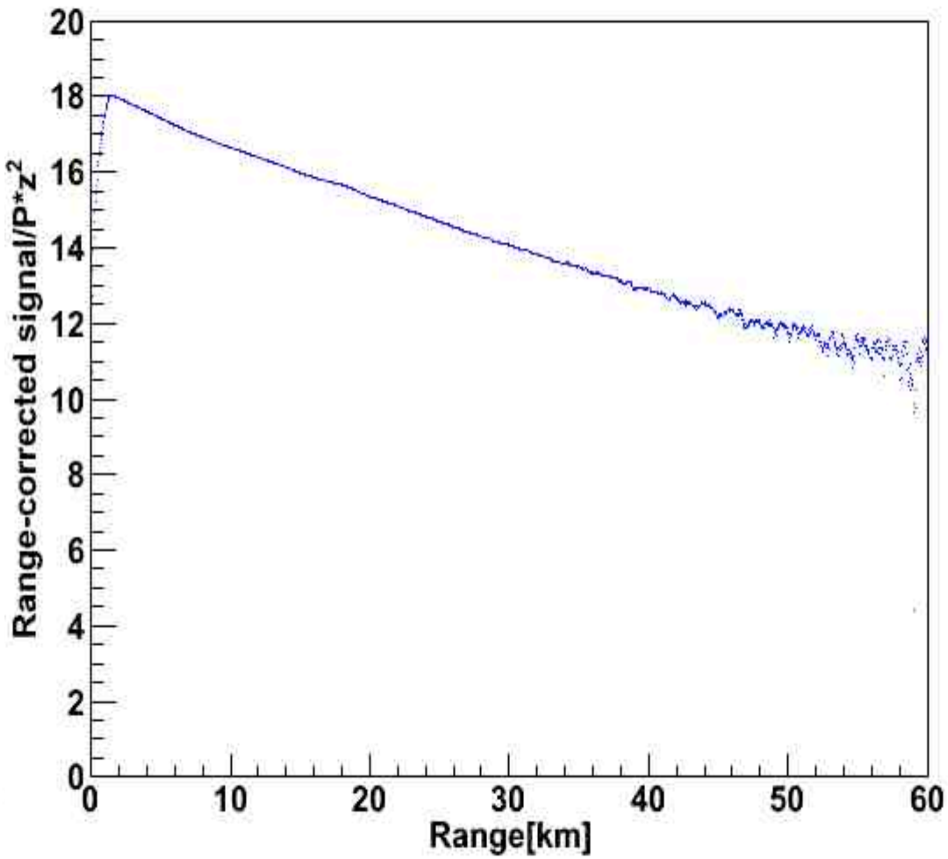
In the valid region of both signals between the lower toggle rate (typical 0.5MHz) and the upper toggle rate (typical 10MHz), one seeks the linear regression coefficients to transfer the analog data into photon counting data

ROOT: --"TMinuit.h"

Example of gluing data



Gluing data (blue line)

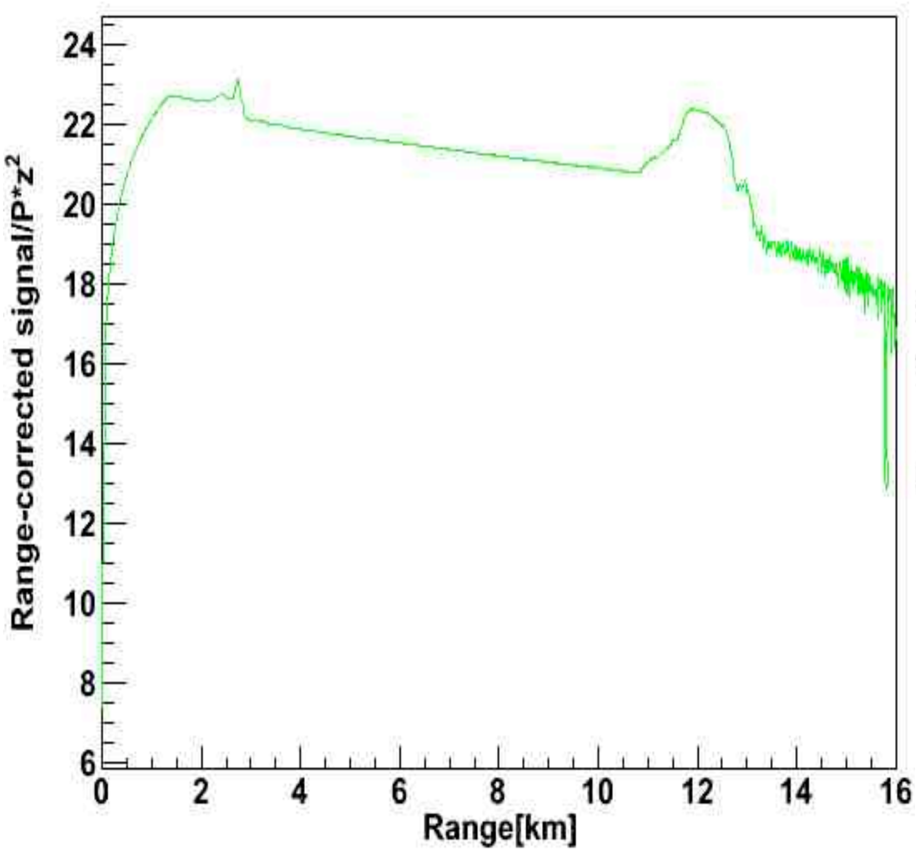


Range-corrected signal (after gluing)

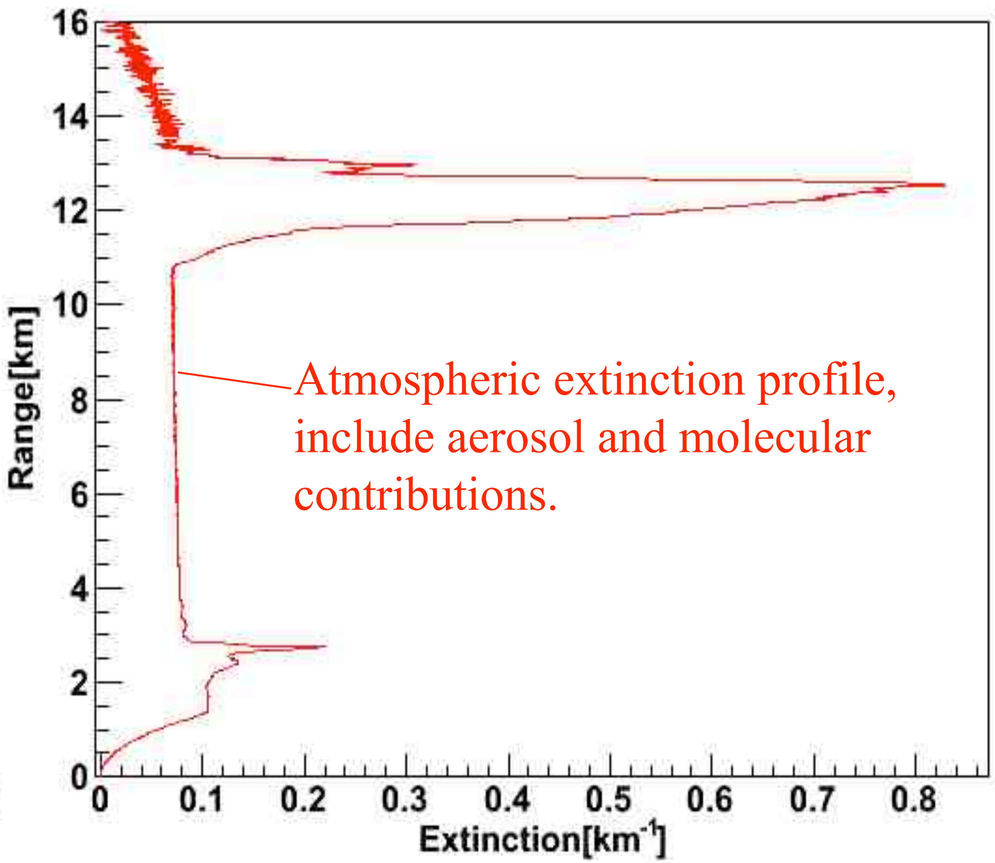
Lidar raw data is from file "*lidar-ot-20081127-174730-R486.root*"

Extinction coefficient calculation (Klett)

Definition: Extinction Coefficient is the fraction of light lost to scattering and absorption per unit distance in a participating medium.



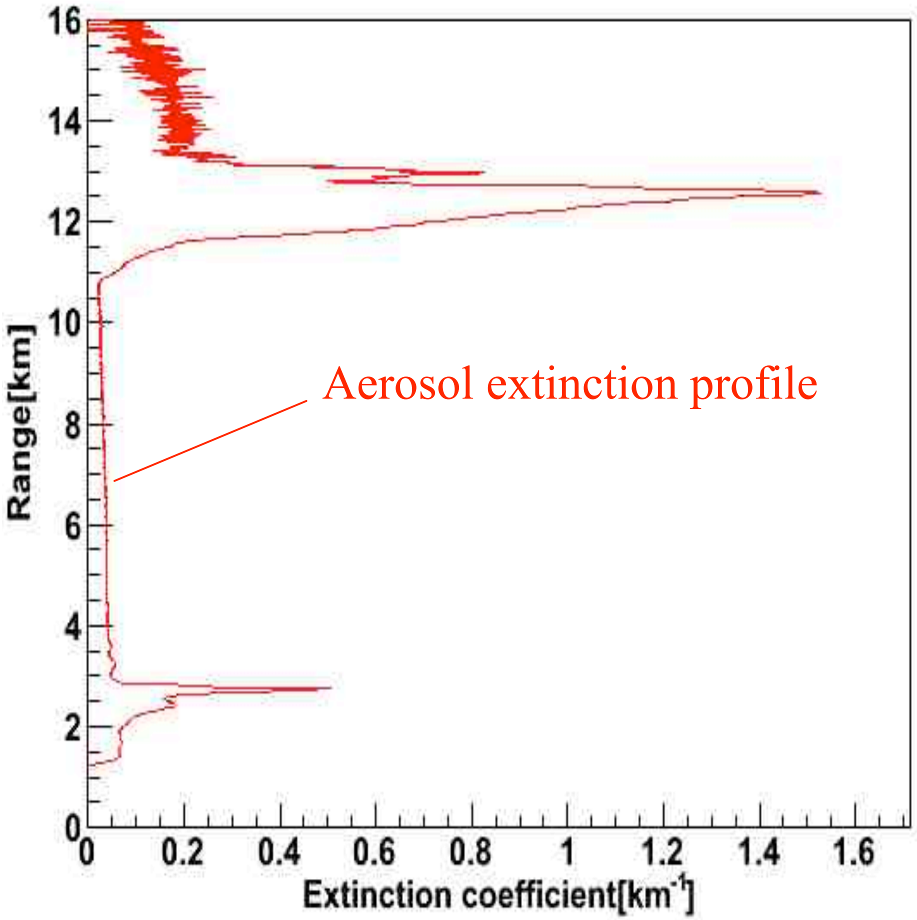
Range-corrected signal

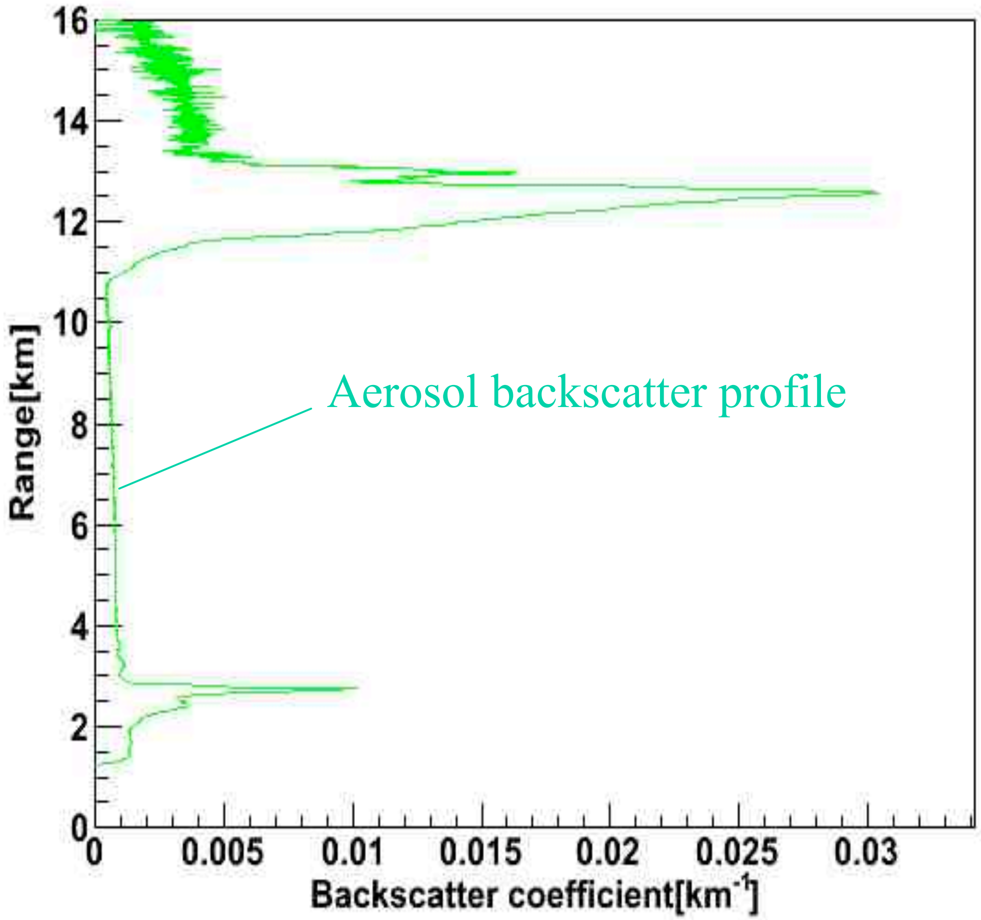


Atmospheric extinction profile

Lidar raw data is from file "*lidar-ot-20081105-182241-R438.root*"

Extinction and backscatter coefficient calculation (Fernald)



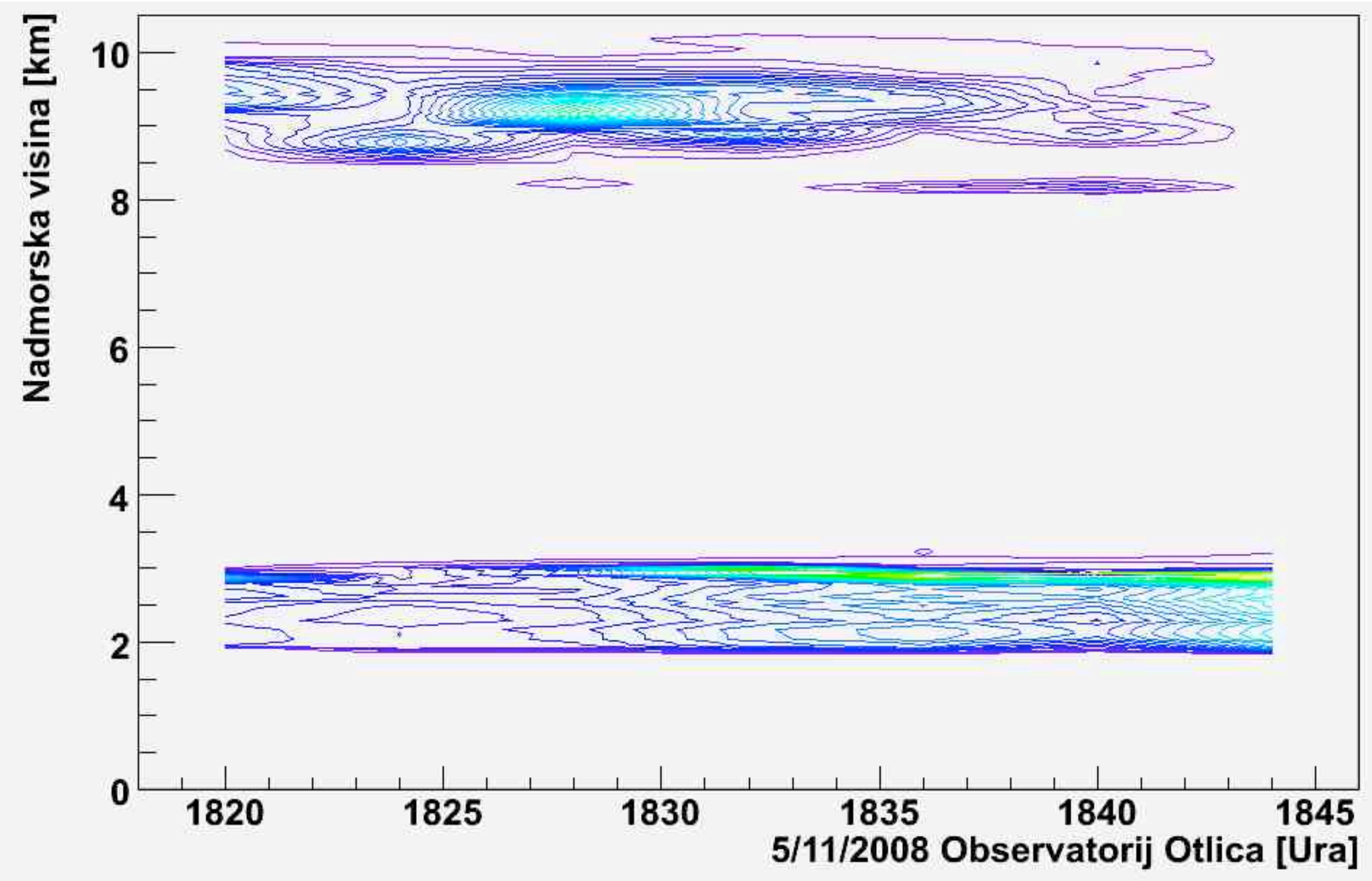


Aerosol extinction profile

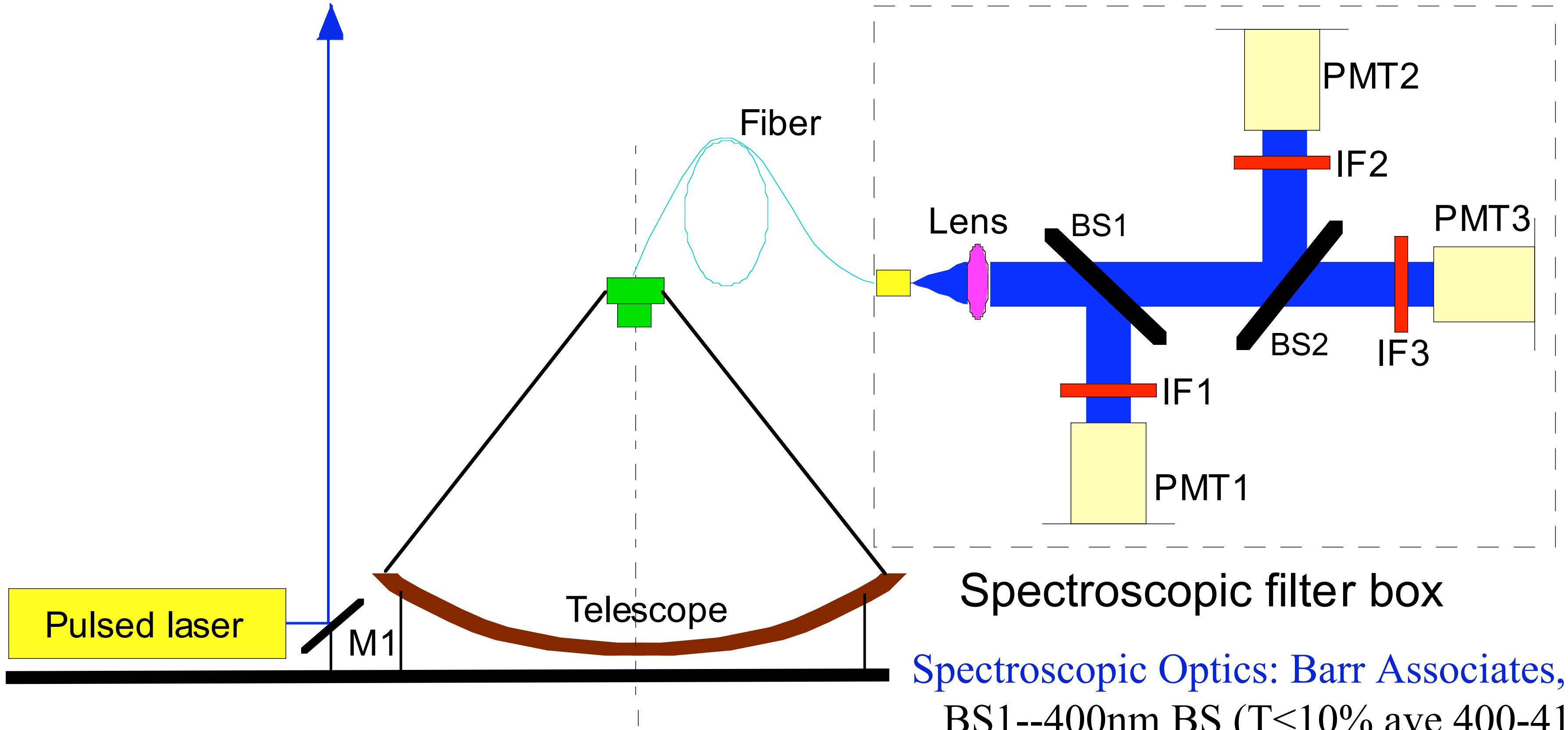
Aerosol backscatter profile

Lidar raw data is from file "*lidar-ot-20081105-182241-R438.root*"

Consecutive observation



Raman lidar design scheme



Schematic of Raman lidar system

Channel 1: water vapor Raman scattering
Channel 2: nitrogen Raman scattering
Channel 3: Mie scattering

Spectroscopic Optics: Barr Associates, Inc.

BS1--400nm BS (T<10% ave 400-415nm
T>85% ave 345-395nm)

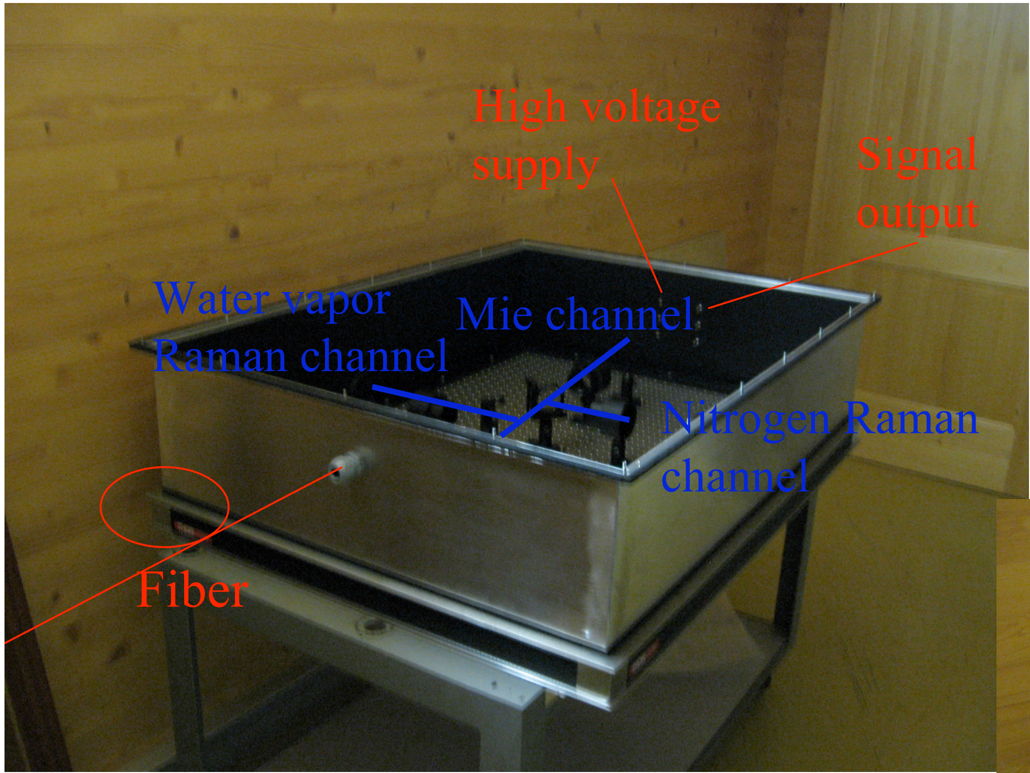
BS2--380nm BS (T<10% ave 385-395nm,
T>85% ave 345-365nm)

IF1--407.4nm (4.8nm)

IF2--386.5nm (5.2nm)

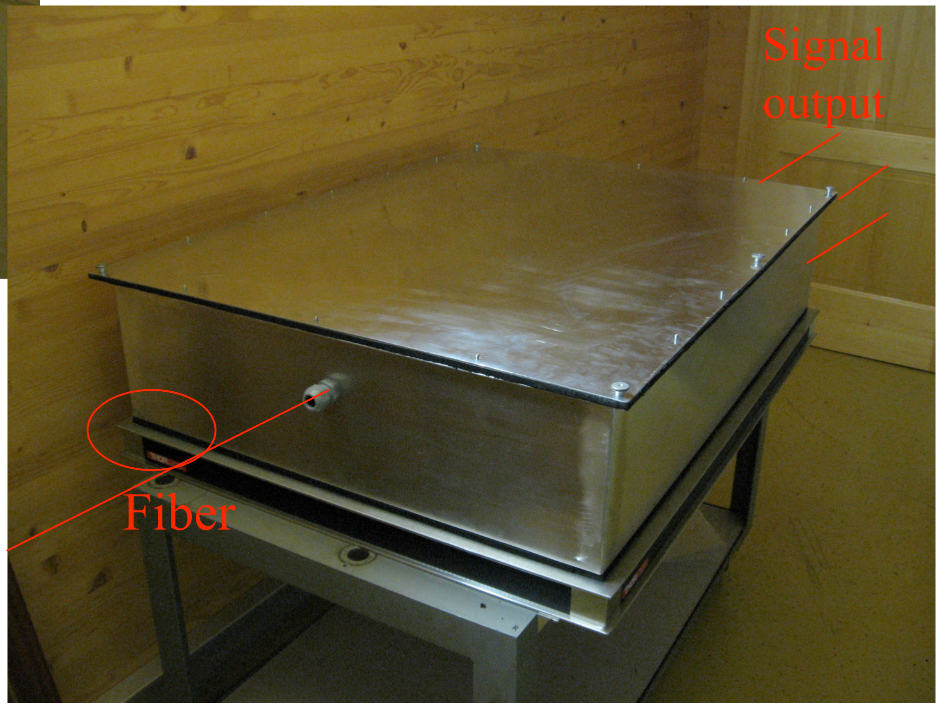
IF3—FL355nm

Scene of Raman spectroscopic box



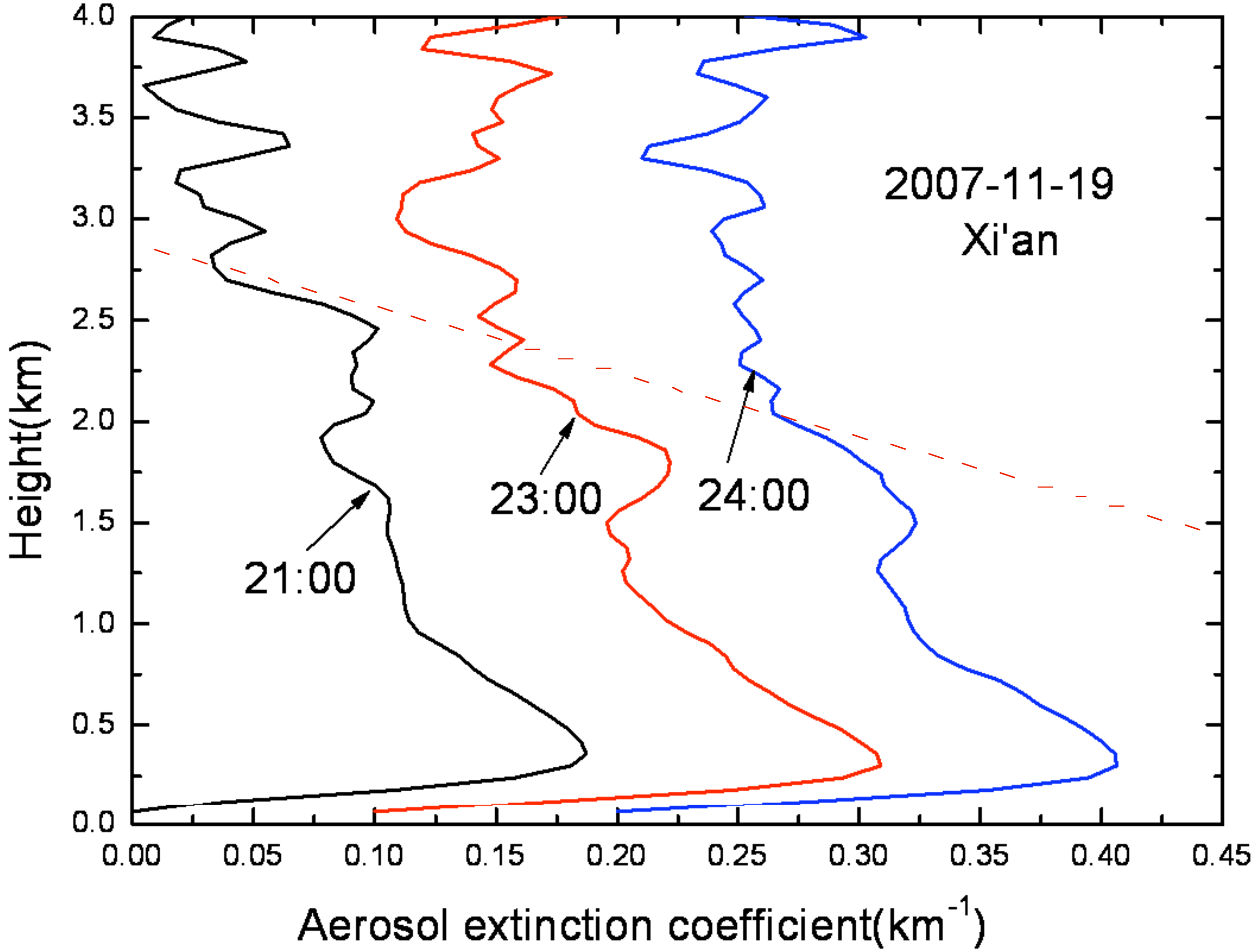
Layout of the Raman spectroscopic filter, components are ready:

- PMT tubes w. machined supports
- Filters and other beam components
- Optic fiber
- HV cables (HV supply needed)
- Fiber/telescope coupler



Picture of the Raman spectroscopic box

Example of Raman lidar results



(With $0.1km^{-1}$ offset between consecutive profiles)

Consecutive aerosol extinction profiles measured with Raman lidar system which taken at 21:00-24:00 CST on 19 November 2007 in Xi'an

Summary

1. Study of aerosols in the troposphere is important for forecasting air quality and finding the source of air pollution
2. Remote sensing, especially using lidar techniques, is the best way for measuring aerosol properties in the atmosphere
3. Due to no assumptions about atmospheric conditions, Raman lidar and high-spectral-resolution lidar over Mie lidar have many advantages for accurate measurement of aerosol properties in the atmosphere, and are the tendency in future lidar research
4. Routine measurements by Mie lidar at Otlica and data processing are performed
5. Lidar system in Otlica Observatory is being upgraded to Raman lidar system with the ability to measure the aerosol and water vapor without any assumptions

Thanks for your attention!