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Winter College on Optics in Environmental Science

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LIDAR
- Parts I and II -

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LIDAR 1 & 2

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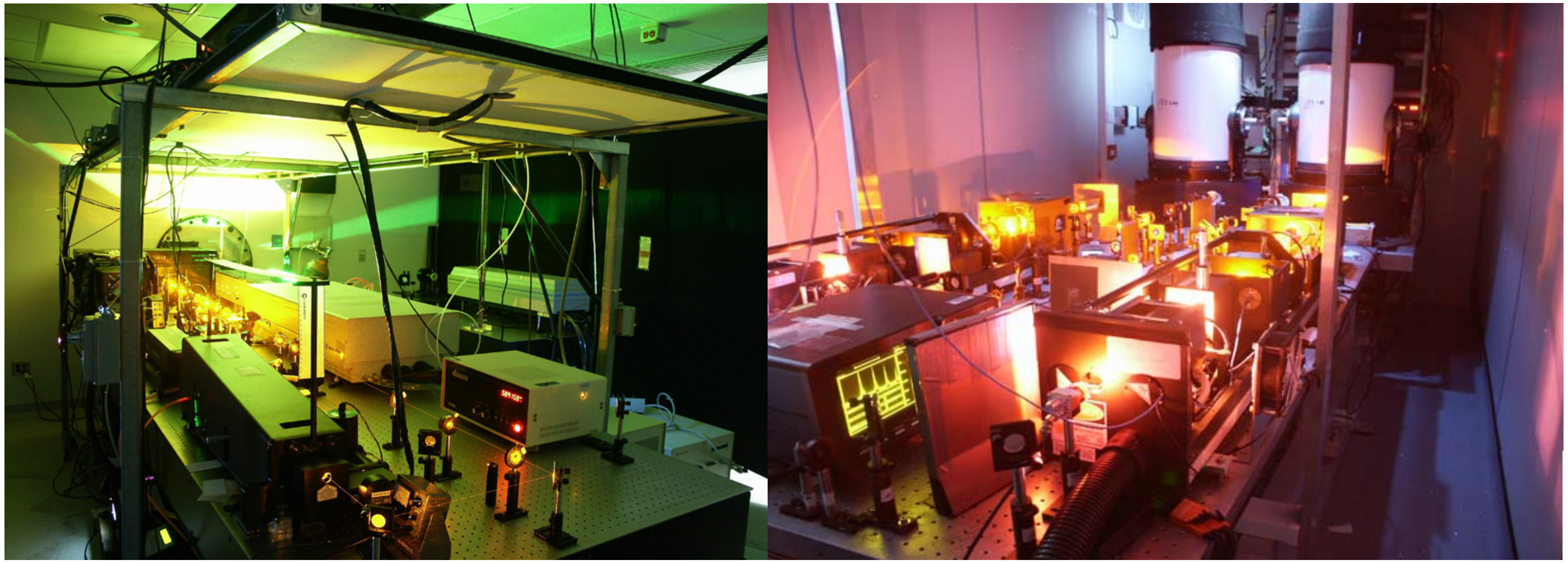


International Centre for Theoretical Physics (ICTP)

International College on Optics in Environmental Science

OUTLINE

Lidar 1: Fundamentals & Physical Processes in Lidars

Introduction

Fundamentals of the LIDAR as Remote Sensing Tool

Physical Picture of Lidar Equation
Fundamental Lidar Equation
Different Forms of Lidar Equation
Illustration of Lidar Equation

Brief Review of Physical Processes in Lidars

- **General Illustration of lidar equation**
- **Overview of physical processes in lidar**
- **Elastic and in-elastic scattering vs polarization**
- **Absorption and differential absorption**
- **Fluorescence and resonance fluorescence**
- **Comparison of backscatter cross section**
- **Doppler effect and Boltzmann distribution**

Solutions of Some Lidar Equations

- Solution for scattering form lidar equation
- Solution for fluorescence form lidar equation
- Solution for differential absorption lidar equation
- Solution for resonance fluorescence lidar

Outline Continued

Review of Lidar Architecture

- ☐ Configurations vs. Arrangements
- ☐ Lidar Classifications

Lidar 2: Classes of LIDARS

1. Temperature LIDAR
2. Wind LIDAR
3. Aerosol LIDAR
4. Constituent LIDAR
5. Target LIDAR

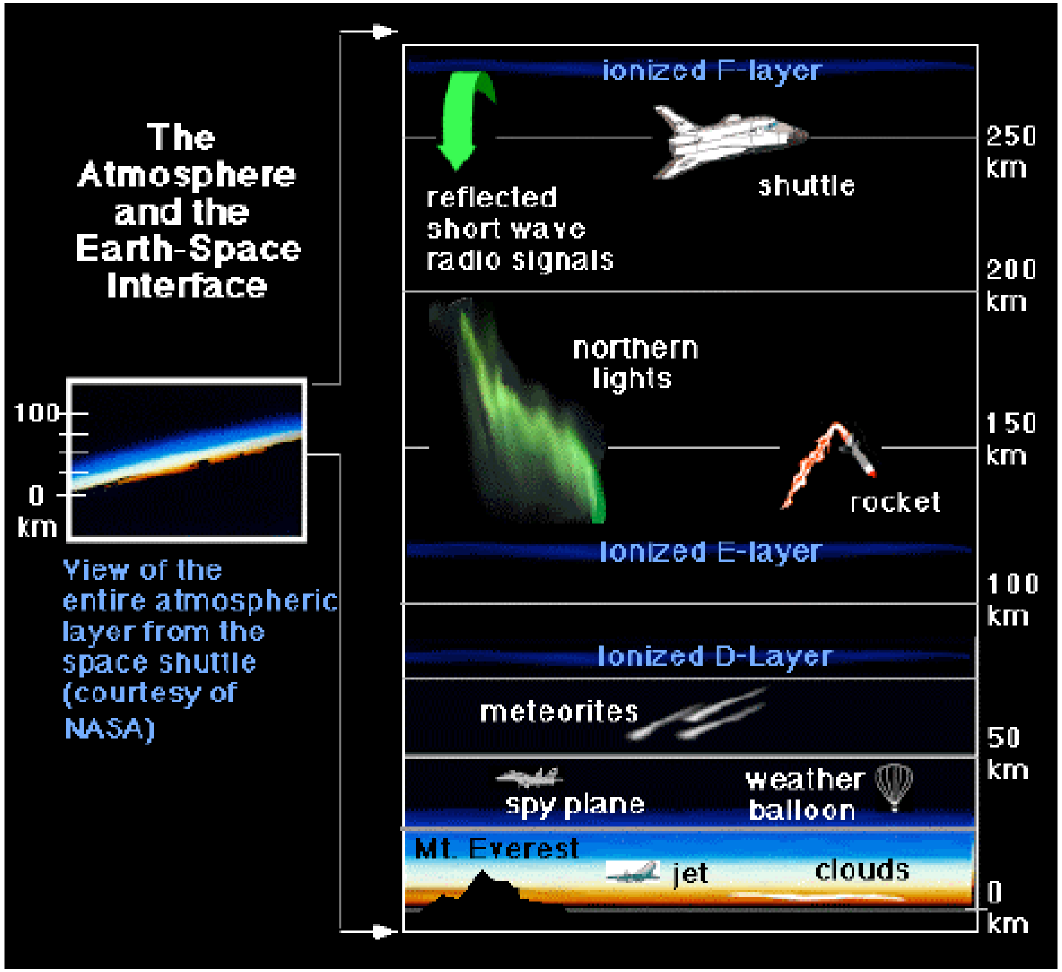
LIDAR: What and Why?

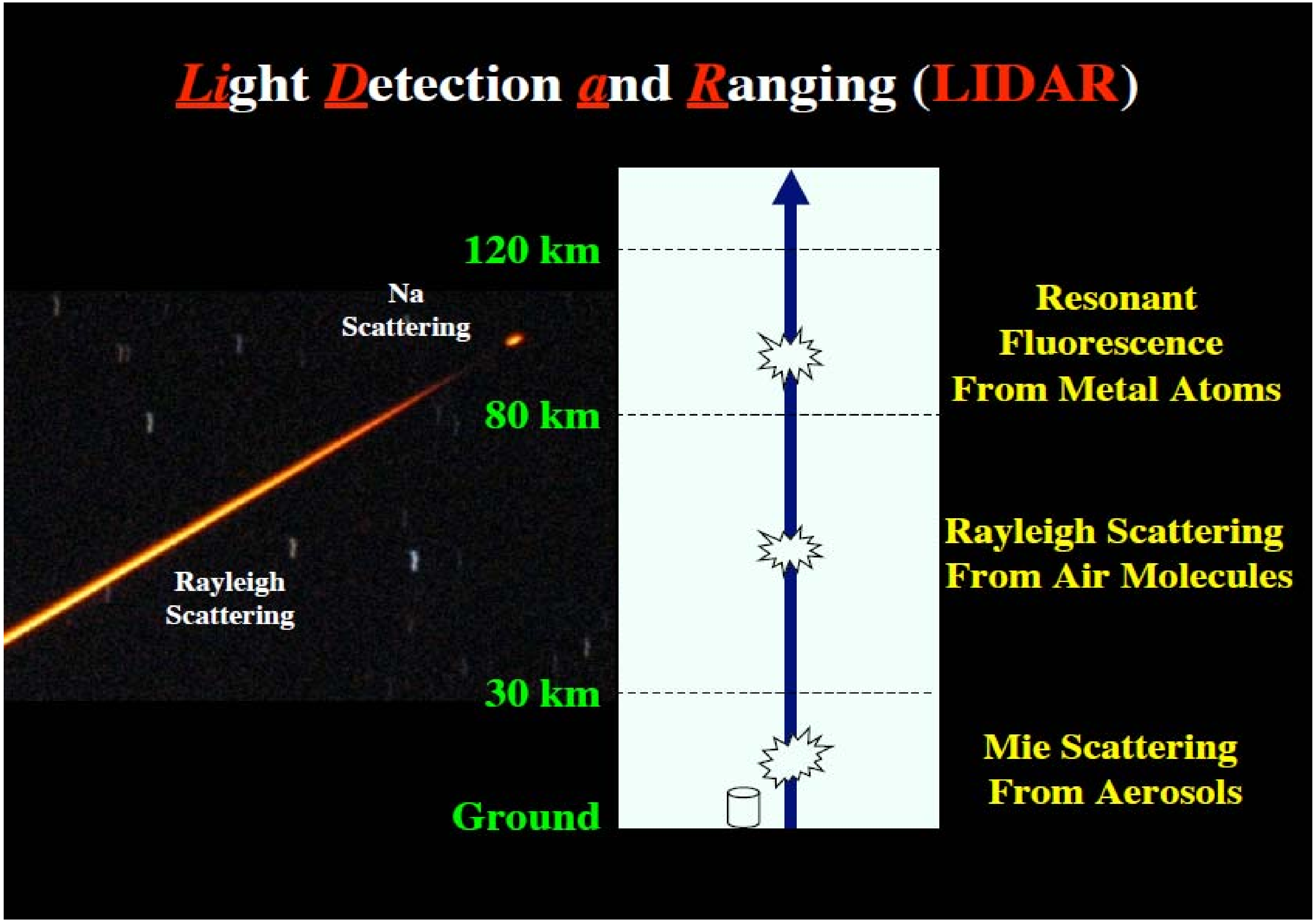
LIDAR stands for Light Detection and Ranging, commonly known as Laser Radar.

Lidar is not only replacing conventional sensors, but also creating new methods with unique properties that could not be achieved before.

Lidar is extremely useful in atmospheric and environmental research as well as space exploration. It also has wide applications in industry, defense, and military.

Earth Atmosphere and Space





***Li**ght **D**etection **a**nd **R**anging (LIDAR)*

Na
Scattering

Rayleigh
Scattering

120 km

80 km

30 km

Ground

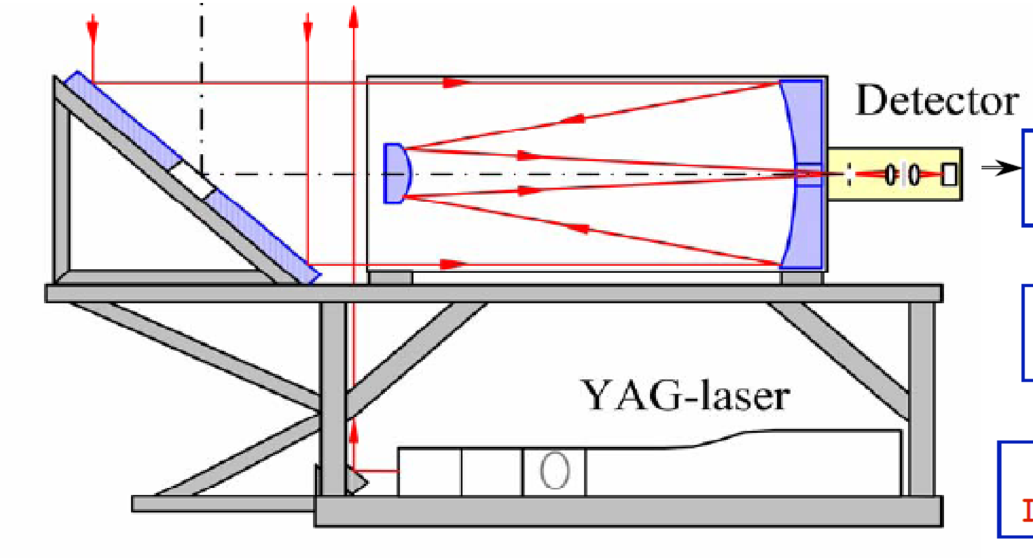
Resonant
Fluorescence
From Metal Atoms

Rayleigh Scattering
From Air Molecules

Mie Scattering
From Aerosols

Fundamentals of the LIDAR as Remote Sensing Tool

- ☐ Physical Picture of Lidar Equation
- ☐ Fundamental Lidar Equation
- ☐ Different Forms of Lidar Equation
- ☐ Illustration of Lidar Equation



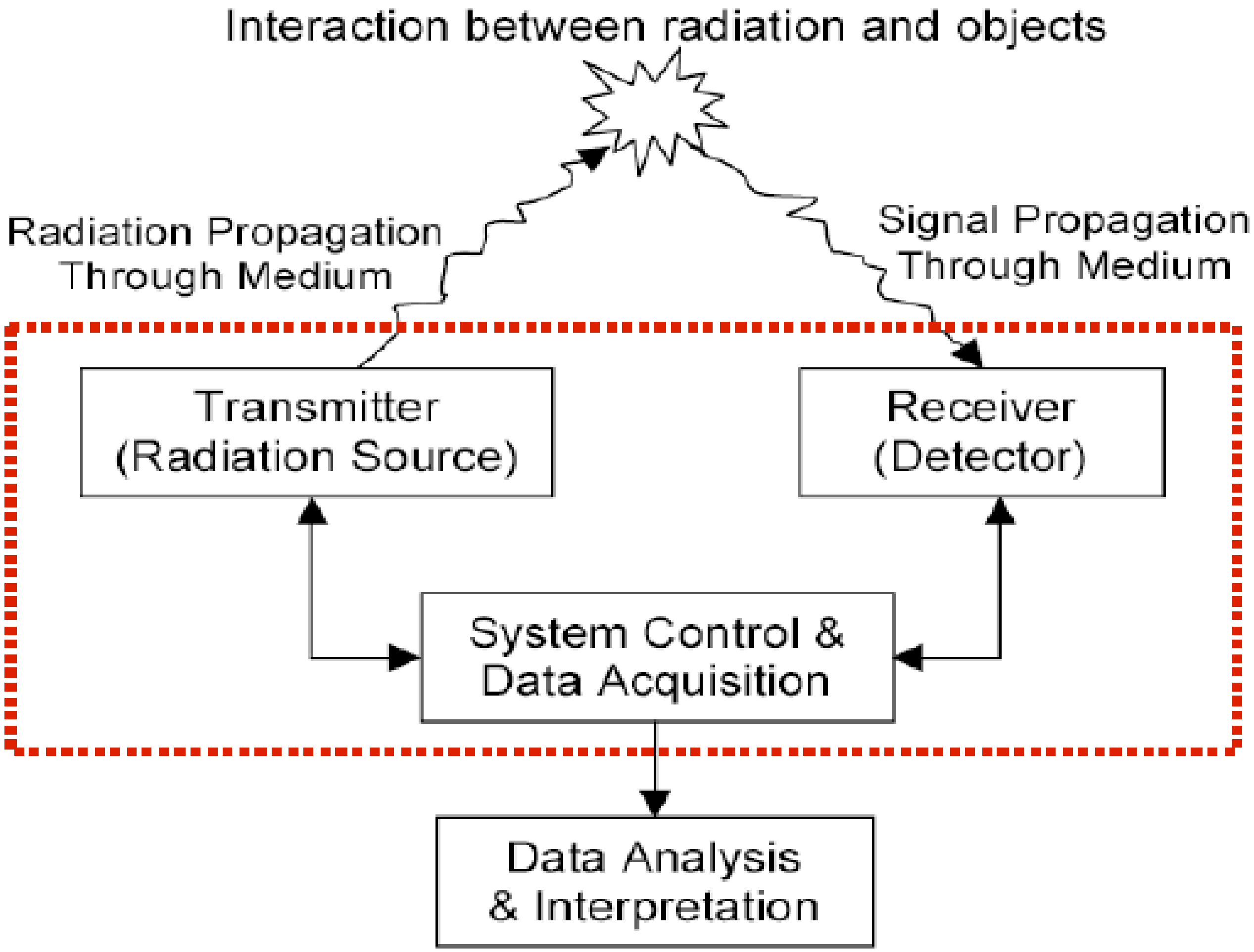
Data Acquisition

Data Processing

Data Interpretation

Information Product

Picture of LIDAR in its Environment



Interaction between radiation and objects

Radiation Propagation Through Medium

Signal Propagation Through Medium

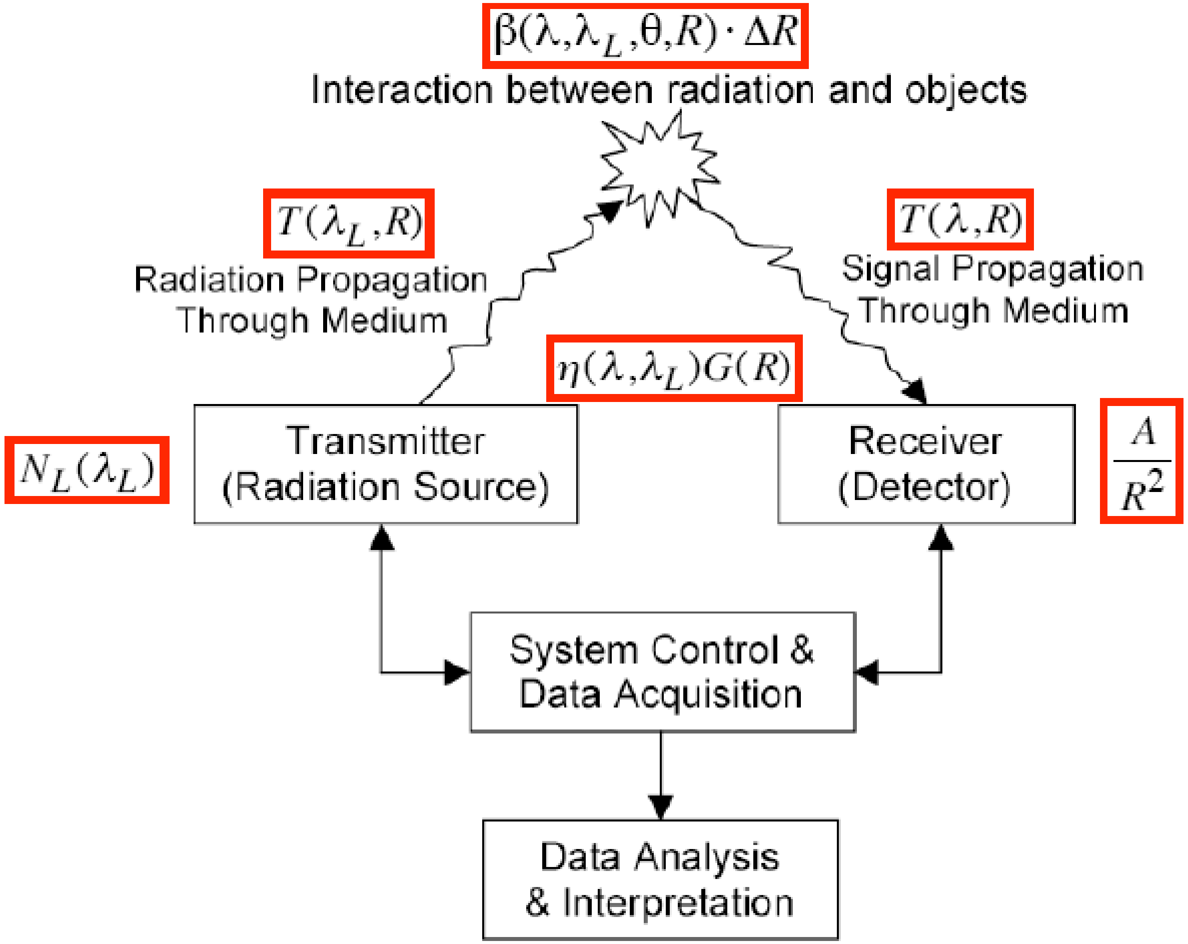
Transmitter (Radiation Source)

Receiver (Detector)

System Control & Data Acquisition

Data Analysis & Interpretation

Physical Picture of Lidar Equation



$\beta(\lambda,\lambda_L,\theta,R)\cdot\Delta R$

Interaction between radiation and objects

$T(\lambda_L,R)$

Radiation Propagation Through Medium

$T(\lambda,R)$

Signal Propagation Through Medium

$\eta(\lambda,\lambda_L)G(R)$

$N_L(\lambda_L)$

Transmitter (Radiation Source)

Receiver (Detector)

$\frac{A}{R^2}$

System Control & Data Acquisition

Data Analysis & Interpretation

Considerations for Lidar Equation

- ❑ In general, the interaction between the light photons and the particles is a scattering process.
- ❑ The expected photon counts are proportional to the product of the

(1) transmitted laser photon number,

(2) probability that a transmitted photon is scattered,

(3) probability that a scattered photon is collected,

(4) light transmission through medium, and

(5) overall system efficiency.

- ❑ Background photon counts and detector noise also contribute to the expected photon counts.

Basic Assumptions in Lidar Equation

- Independent scattering: particles are separated adequately and undergo random motion so that their contributions to the total scattered energy have no phase relation. Thus, the total intensity is simply a sum of the intensity scattered from each particle.
- Single scattering implies that a photon is scattered only once and multiple scattering is excluded.

Fundamental Lidar Equation

$$\boxed{N_S(\lambda,R) = N_L(\lambda_L)\cdot\left[\beta(\lambda,\lambda_L,\theta,R)\Delta R\right]\cdot\frac{A}{R^2}\cdot\left[T(\lambda_L,R)T(\lambda,R)\right]\cdot\left[\eta(\lambda,\lambda_L)G(R)\right]+N_B}$$

1st Term: Transmitted Photon Number

$$N_S(\lambda,R)=\boxed{N_L(\lambda_L)}\cdot\left[\beta(\lambda,\lambda_L,\theta,R)\Delta R\right]\cdot\frac{A}{R^2}\cdot\left[T(\lambda_L,R)T(\lambda,R)\right]\cdot\left[\eta(\lambda,\lambda_L)G(R)\right]+N_B$$

$$\boxed{N_L(\lambda_L)=\left(\frac{P_L(\lambda_L)\Delta t}{hc/\lambda_L}\right)}$$

$$\frac{\text{Laser Power x time bin length}}{\text{Planck constant x Laser frequency}}$$

$$=\frac{\text{Transmitted laser energy within time bin}}{\text{Single laser photon energy}}$$

$$=\text{Transmitted laser photon number within time bin length}$$

2nd Term: Probability to be Scattered

$$N_S(\lambda,R) = N_L(\lambda_L)\cdot\boxed{\left[\beta(\lambda,\lambda_L,\theta,R)\Delta R\right]}\cdot\frac{A}{R^2}\cdot\left[T(\lambda_L,R)T(\lambda,R)\right]\cdot\left[\eta(\lambda,\lambda_L)G(R)\right]+N_B$$

Angular scattering probability – the probability that a transmitted photon is scattered by scatters into a unit solid angle.

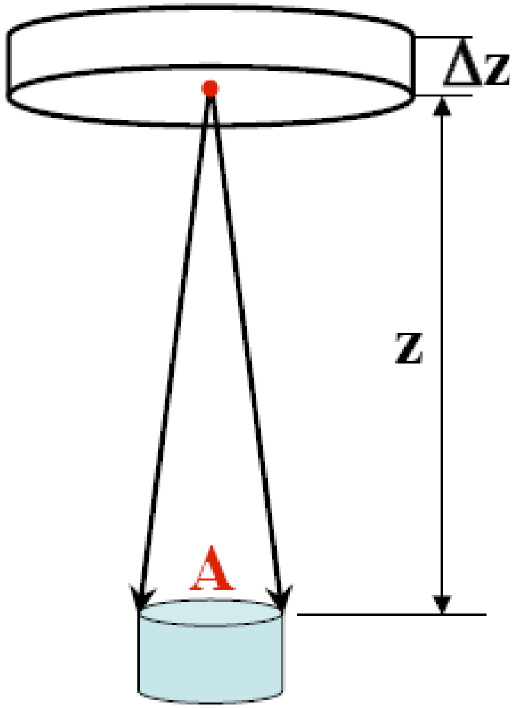
Angular scattering probability =
volume scatter coefficient β
x scattering layer thickness ΔR

$$\boxed{\beta(\lambda,\lambda_L,R) = \sum_i\left[\frac{d\sigma_i(\lambda_L,\theta)}{d\Omega}n_i(R)p_i(\lambda)\right]} \quad (\mathrm{m}^{-1}\mathrm{sr}^{-1})$$

3rd Term: Probability to be Collected

$$N_S(\lambda,R) = N_L(\lambda_L)\cdot\left[\beta(\lambda,\lambda_L,\theta,R)\Delta R\right]\cdot\boxed{\frac{A}{R^2}}\cdot\left[T(\lambda_L,R)T(\lambda,R)\right]\cdot\left[\eta(\lambda,\lambda_L)G(R)\right]+N_B$$

The probability that a scatter photon is collected by the receiving telescope,
i.e., the solid angle subtended by the receiver aperture to the scatterer.



4th Term: Light Transmission

$$N_S(\lambda,R) = N_L(\lambda_L)\cdot\left[\beta(\lambda,\lambda_L,\theta,R)\Delta R\right]\cdot\frac{A}{R^2}\cdot\boxed{\left[T(\lambda_L,R)T(\lambda,R)\right]}\cdot\left[\eta(\lambda,\lambda_L)G(R)\right]+N_B$$

The atmospheric transmission of laser light at outgoing wavelength λ_L and return signal at wavelength λ

Transmission for laser light →

$$T(\lambda_L,R) = \exp\left[-\int_0^R \alpha(\lambda_L,r)dr\right]$$

Transmission for return signal →

$$T(\lambda,R) = \exp\left[-\int_0^R \alpha(\lambda,r)dr\right]$$

Where $\alpha(\lambda_L, R)$ and $\alpha(\lambda, R)$ are extinction coefficients (m^{-1})

$$T(\lambda_L,R)T(\lambda,R) = \exp\left[-\left(\int_0^R \alpha(\lambda_L,r)dr + \int_0^R \alpha(\lambda,r)dr\right)\right]$$

when $\lambda = \lambda_L$ ↘

$$= \exp\left[-2\int_0^R \alpha(\lambda,r)dr\right]$$

Extinction Coefficient α

$$\alpha(\lambda,R) = \sum_i \left[\sigma_{i,ext}(\lambda) n_i(R)\right]$$

$\sigma_{i,ext}(\lambda)$ is the extinction cross-section of species i

$n_i(R)$ is the number density of species i

Extinction = Absorption + Scattering (Integrated)

$$\sigma_{i,ext}(\lambda) = \sigma_{i,abs}(\lambda) + \sigma_{i,sca}(\lambda)$$

Total Extinction = Aerosol Extinction + Molecule Extinction

$$\alpha(\lambda,R) = \alpha_{aer,abs}(\lambda,R) + \alpha_{aer,sca}(\lambda,R) + \alpha_{mol,abs}(\lambda,R) + \alpha_{mol,sca}(\lambda,R)$$

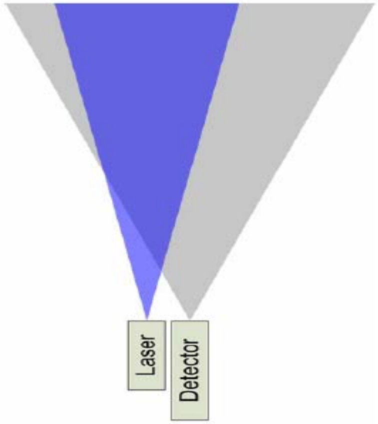
5th Term: Overall Efficiency

$$N_S(\lambda,R) = N_L(\lambda_L)\cdot\left[\beta(\lambda,\lambda_L,\theta,R)\Delta R\right]\cdot\frac{A}{R^2}\cdot\left[T(\lambda_L,R)T(\lambda,R)\right]\cdot\boxed{\left[\eta(\lambda,\lambda_L)G(R)\right]}+N_B$$

$\boxed{\eta(\lambda,\lambda_L) = \eta_T(\lambda_L)\cdot\eta_R(\lambda)}$ is the lidar hardware optical efficiency

e.g., mirrors, lens, filters, detectors, etc

$\boxed{G(R)}$ is the geometrical form factor, mainly concerning the overlap of the area of laser irradiation with the field of view of the receiver optics



6th Term: Background Noise

$$N_S(\lambda,R) = N_L(\lambda_L)\cdot\left[\beta(\lambda,\lambda_L,\theta,R)\Delta R\right]\cdot\frac{A}{R^2}\cdot\left[T(\lambda_L,R)T(\lambda,R)\right]\cdot\left[\eta(\lambda,\lambda_L)G(R)\right]\boxed{+N_B}$$

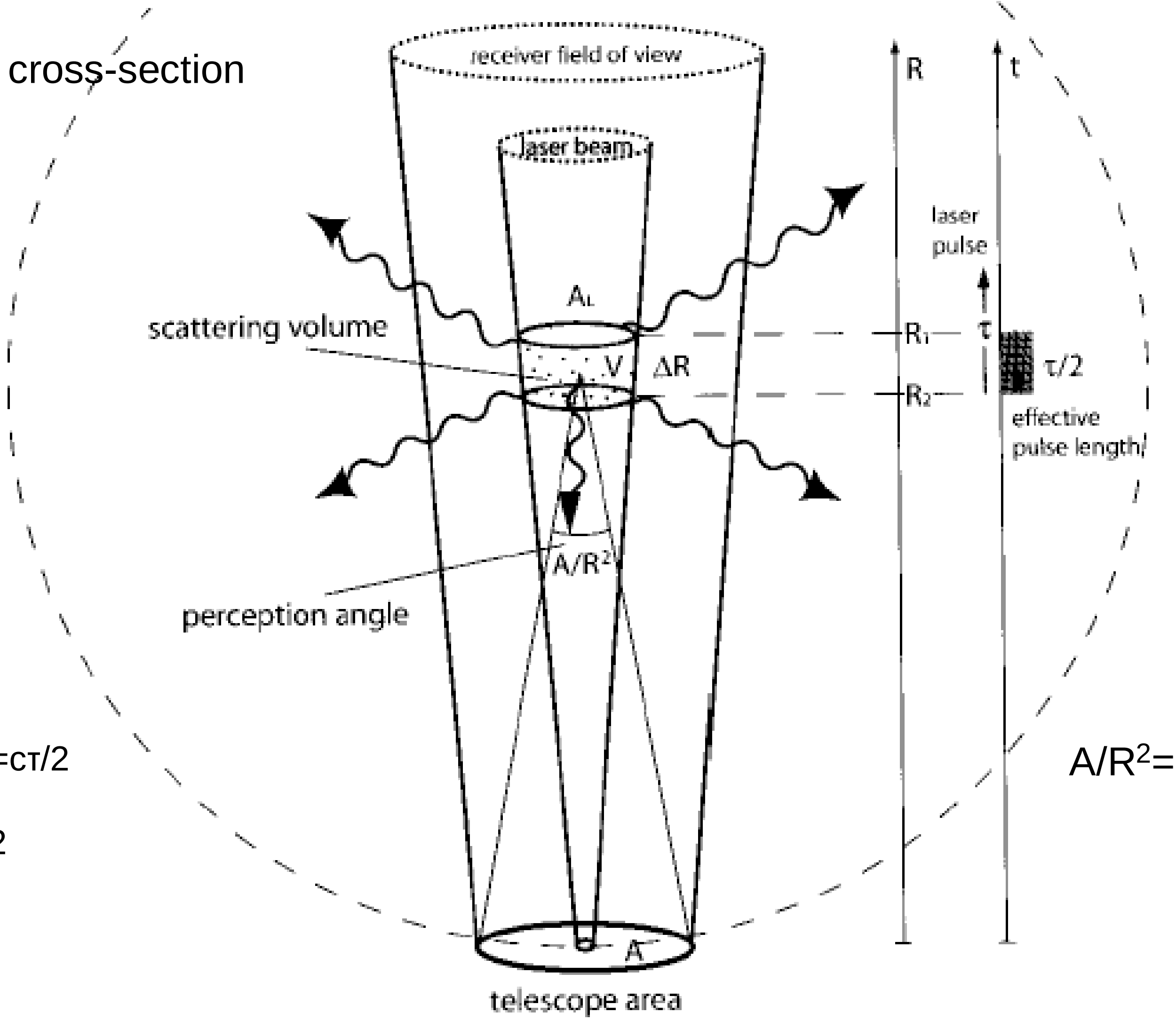
N_B: Background noise, detector and circuit shot noise.

Up-looking lidar: background noise comes from solar scattering, solar straight radiation, star/city light.

Down-looking lidar: besides above noise, it could have three extra backgrounds: (1) Specular reflection from water/ice surface; (2) Laser reflectance from ground;
(3) Solar reflectance from ground.

Illustration for LIDAR Equation

A_L= Laser cross-section



$\Delta R=R_1-R_2=c\tau/2$

$R_1=ct/2$

$R_2=c\,(t-\tau)/2$

A/R^2=solid angle

Brief Review of Physical Processes in Lidars

Physical Processes in LIDAR

- Interaction between light and objects

(1) Scattering (instantaneous elastic & inelastic):

Mie, Rayleigh, Raman, Brillouin scattering

(2) Absorption and differential absorption

(3) Laser induced fluorescence

(4) Resonance fluorescence

(5) Doppler shift and Doppler broadening

(6) Boltzmann distribution

(7) Reflection from target or surface

- Light propagation in atmosphere or medium: transmission vs extinction

Extinction = Scattering + Absorption

$$\boxed{T(\lambda,R) = \exp\left[-\int_0^R \alpha(\lambda,r)\,dr\right]} \qquad \boxed{\alpha(\lambda,R) = \sum_i \left[\sigma_{i,ext}(\lambda)\,n_i(R)\right]}$$

T(λ,R) represents the fraction of light lost on the way from the lidar to the scattering volume and back!

(1) Elastic and Inelastic Scattering

- ☐ Elastic scattering:

scattering with no apparent change of wavelength

Sum of elastic scattering from atmospheric molecules and elastic scattering from aerosol particles and cloud droplets

Rayleigh scattering and Mie scattering

- ☐ Inelastic scattering:

scattering with apparent change of wavelength

Raman scattering

Pure rotational Raman and vibration-rotational Raman

Elastic and Inelastic Scattering (cont'd)

Rayleigh scattering is referred to the elastic scattering from atmospheric molecules (particle size is much smallerthan the wavelength), i.e., scattering with no apparent change of wavelength

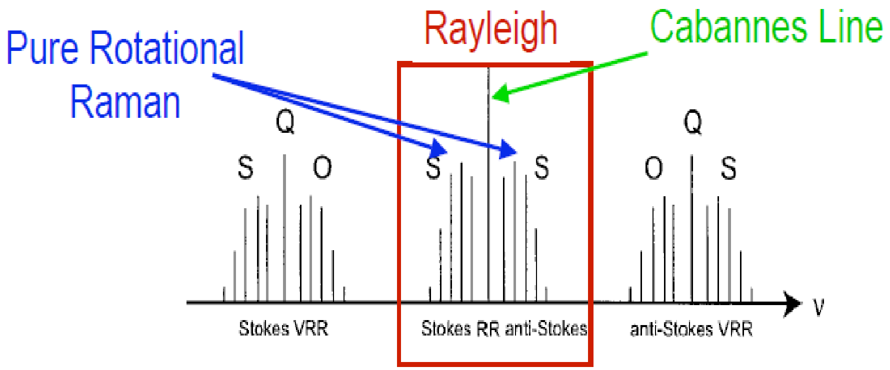
With lower detection resolution, Rayleigh scattering can consist of the Cabannes scattering (really elastic scattering from molecules) and pure rotational Raman scattering.

Scattering still undergoes Doppler broadening and Doppler shift.

Temp.; Press. and collective motion of molecules lead to spectral broadening.

Rayleigh scattering is therefore the sum of cabannes lines and the

rotational Raman bands



Rayleigh Backscatter Coefficient

- In lidar field, a common practice is to use the equation

$$\boxed{\beta_{Rayleigh}(\lambda, z, \theta = \pi) = 2.938 \times 10^{-32} \frac{P(z)}{T(z)} \cdot \frac{1}{\lambda^{4.0117}} \left(m^{-1} sr^{-1}\right)}$$

where P is the atmosphere pressure in mbar and T is the temperature in Kelvin at altitude z, λ is the wavelength in meter, and $\beta_{Rayleigh}$ is the backscatter coefficient (angular).

Rayleigh scattering is proportional to λ^{-4} and dominates elastic backscatter at short laser wavelength.

Rayleigh Backscatter Cross Section

- ☐ It is also common in lidar field to calculate the Rayleigh backscatter cross section using the following equation

$$\boxed{\frac{d\sigma_m(\lambda)}{d\Omega} = 5.45 \cdot \left(\frac{550}{\lambda}\right)^4 \times 10^{-32} \left(m^2 sr^{-1}\right)}$$

Elastic and Inelastic Scattering (cont'd)

Mie (Aerosol/Cloud) Scattering

In lidar field, Mie scattering is referred to the elastic scattering from spherical particles whose size is comparable to or larger than the wavelength of the laser.

Furthermore, Mie scattering is generalized to elastic scattering from overall aerosol particles and cloud droplets, i.e., including non-spherical particles.

Polarization in Scattering

Backscattering from spherical particles does not change the polarization state of the radiation (Mie). The backscattered light has polarization parallel to that of the transmitted beam (usually linearly polarized).

Large non-spherical particles lead to a depolarization of backscattered radiation, i.e., partial backscattered light has polarization perpendicular to that of the transmitted beam.

And hence the range-resolved linear depolarization ratio is:

$$\delta(R) = \left[\beta_{\perp}(R)/\beta_{\|}(R)\right]\exp\left(T_{\|} - T_{\perp}\right)$$

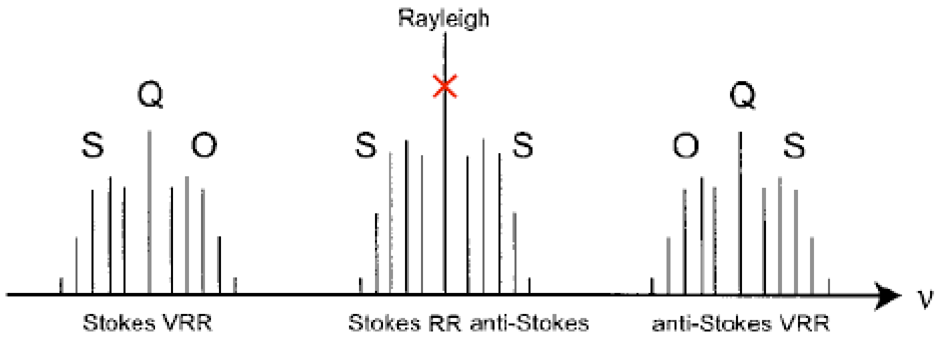
Elastic and Inelastic Scattering (cont'd)

Raman Scattering

Inelastic scaterring process involves the change of the vibrational-rotational energy level of the molecule.

Frequency shift corresponds to energy difference between initial and final molecular states and hence is specific for the interacting molecule.

Intensity distn. within the Raman bands contains information on temperature in scattering volume (energy levels population follows Boltzamann's distn. law)



Scattering Form of Lidar Equation

- Rayleigh, Mie, and Raman scattering processes are instantaneous scattering processes, so there are no finite relaxation effects involved, but infinitely short duration.

- For Rayleigh and Mie scattering, there is no frequency shift when the atmospheric particles are at rest. The lidar equation is written as

$$N_S(\lambda,R) = \left(\frac{P_L(\lambda)\Delta t}{hc/\lambda}\right)\left(\beta(\lambda,R)\Delta R\right)\left(\frac{A}{R^2}\right)T^2(\lambda,R)\left(\eta(\lambda)G(R)\right) + N_B$$

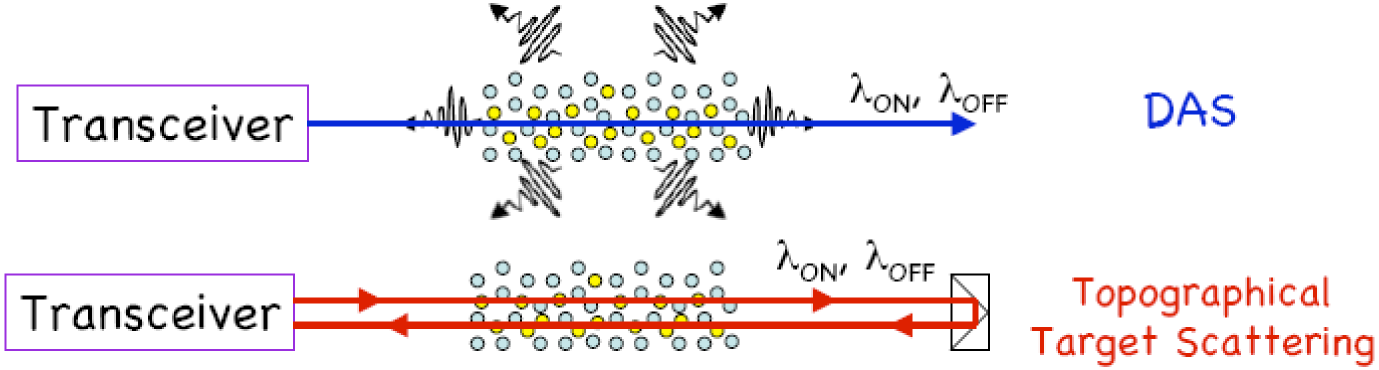
- For Raman scattering, there is a large frequency shift. Raman lidar equation may be written as

$$N_S(\lambda,R) = \left(\frac{P_L(\lambda_L)\Delta t}{hc/\lambda_L}\right)\left(\beta(\lambda,\lambda_L,R)\Delta R\right)\left(\frac{A}{R^2}\right)\left(T(\lambda_L,R)T(\lambda,R)\right)\left(\eta(\lambda,\lambda_L)G(R)\right) + N_B$$

(2) Differential Absorption

In the lidar equation for DIAL, the influence of molecular species is in the extinction (atmosphere transmission) part, not in the backscatter part of the lidar equation.

Scattering of laser light by air molecules and aerosols constitutes a distributed Reflector of the Laser beam.



Differential Absorption/Scattering Form of Lidar Equation

- For the laser with wavelength λ_{on} on the molecular absorption line

$$\boxed{\begin{aligned} N_S(\lambda_{on},R) &= N_L(\lambda_{on})\left[\beta_{sca}(\lambda_{on},R)\Delta R\right]\left(\frac{A}{R^2}\right)\exp\left[-2\int_0^z \overline{\alpha}(\lambda_{on},r')dr'\right] \\ &\quad \times \exp\left[-2\int_0^z \sigma_{abs}(\lambda_{on},r')n_c(r')dr'\right]\left[\eta(\lambda_{on})G(R)\right] + N_B \end{aligned}}$$

- For the laser with wavelength λ_{off} off the molecular absorption line

$$\boxed{\begin{aligned} N_S(\lambda_{off},R) &= N_L(\lambda_{off})\left[\beta_{sca}(\lambda_{off},R)\Delta R\right]\left(\frac{A}{R^2}\right)\exp\left[-2\int_0^z \overline{\alpha}(\lambda_{off},r')dr'\right] \\ &\quad \times \exp\left[-2\int_0^z \sigma_{abs}(\lambda_{off},r')n_c(r')dr'\right]\left[\eta(\lambda_{off})G(R)\right] + N_B \end{aligned}}$$

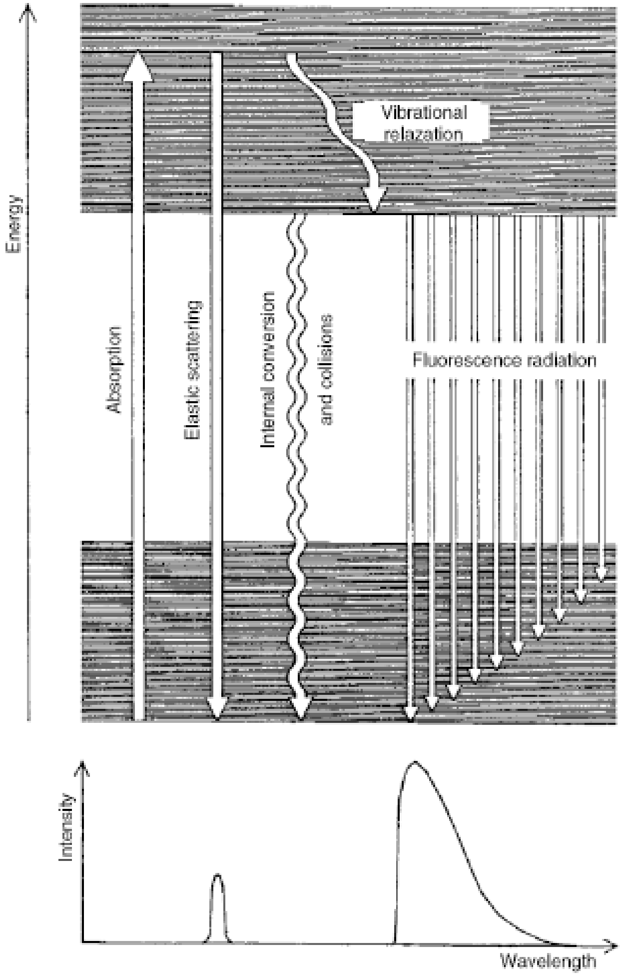
- Differential absorption cross-section

$$\boxed{\Delta\sigma_{abs}(R) = \sigma_{abs}(\lambda_{ON},R) - \sigma_{abs}(\lambda_{OFF},R)}$$

(3) Laser Induced Fluorescence

- Strong intermolecular interactions in solids and liquids cause broad absorption and emission spectra.
- A fixed frequency laser can be used for the excitation due to the broad absorption.
- Following the excitation, a very fast (ps) radiationless relaxation down to the lowest sub-level of the excited state, where the molecules remain for a typical excited state (fluorescence lifetime).
- A decay to different sublevels of the ground state gives rise to a distribution of fluorescence light, which reflect the lower-state level distribution.

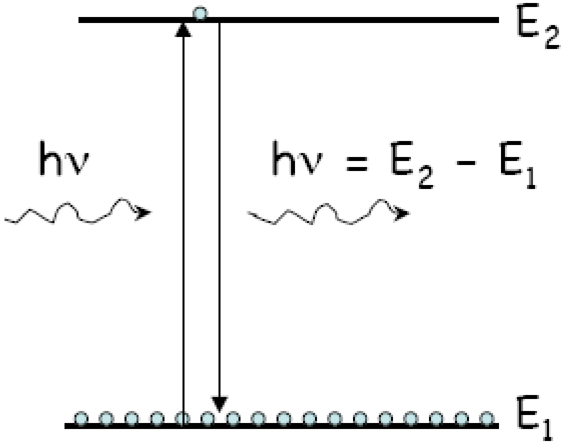
1- Fixing the excitation wavelength, we can obtain fluorescence spectra. 2- While fixing the detection channel and varying the excit. wavelength, an excitation spectrum can be recorded.



(4) Resonance Fluorescence

Resonance fluorescence is obtained if energy of incoming photon coincides with energy of a transition in an atom, ion, or molecule from one level into another energy level.

In the middle and upper atmosphere, there exist some metal atoms (Na) and atomic ions with large absorption cross section. Quenching is not a problem in that region.
Therefore, laser tuned to the resonance frequency of the absorption lines can excite resonance fluorescence from these atoms and ions.



Fluorescence Form of Lidar Equation

- The lidar equation in fluorescence form is given by

$$N_S(\lambda,R)=\left(\frac{P_L(\lambda)\Delta t}{hc/\lambda}\right)\left(\sigma_{eff}(\lambda,R)n_c(z)R_B(\lambda)\Delta R\right)\left(\frac{A}{4\pi R^2}\right)\left(T_a^2(\lambda,R)T_c^2(\lambda,R)\right)\left(\eta(\lambda)G(R)\right)+N_B$$

- Here, $T_c(R)$ is the transmission caused by the constituent absorption.

$$T_c(R)=\exp\left(-\int_{R_{bottom}}^{R}\sigma_{eff}(\lambda,r')n_c(r')\mathrm{d}r'\right)=\exp\left(-\int_{R_{bottom}}^{R}\alpha_c(\lambda,r')\mathrm{d}r'\right)$$

- Here, $\alpha(\lambda,R)$ is the extinction coefficient caused by the absorption.

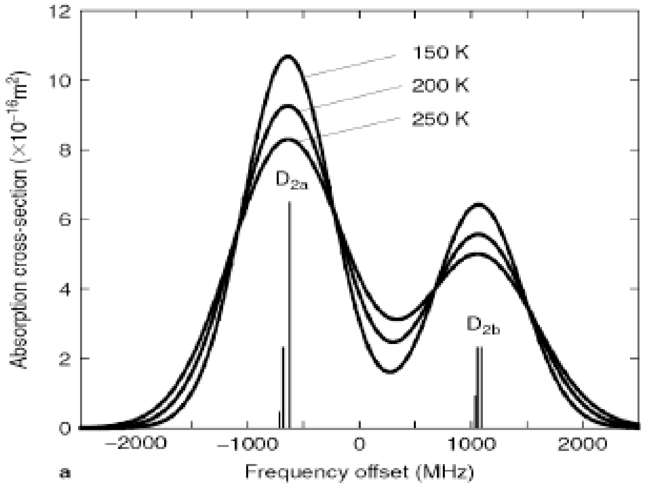
$$\alpha_c(\lambda,R)=\sigma_{eff}(\lambda,R)n_c(R)$$

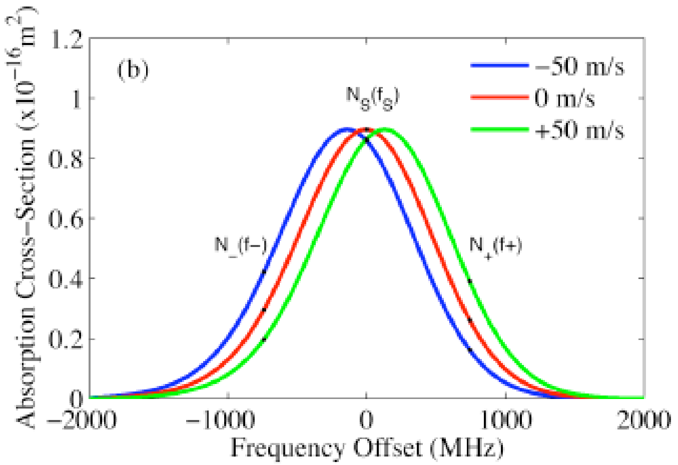
Backscatter Cross-Section Comparison

Physical Process	**Backscatter Cross-Section**	**Mechanism**
Mie (Aerosol) Scattering	10^{-8} - 10^{-10} cm^2sr^{-1}	Two-photon process Elastic scattering, instantaneous
Resonance Fluorescence	10^{-13} cm^2sr^{-1}	Two single-photon process (absorption and spontaneous emission) Delayed (radiative lifetime)
Molecular Absorption	10^{-19} cm^2sr^{-1}	Single-photon process
Fluorescence from molecule, liquid, solid	10^{-19} cm^2sr^{-1}	Two single-photon process Inelastic scattering, delayed (lifetime)
Rayleigh Scattering	10^{-27} cm^2sr^{-1}	Two-photon process Elastic scattering, instantaneous
Raman Scattering	10^{-30} cm^2sr^{-1}	Two-photon process Inelastic scattering, instantaneous

(5) Doppler Shift and Broadening

❑ **Doppler Technique** - Doppler linewidth broadening and Doppler frequency shift are temperature-dependent and wind-dependent, respectively (applying to both Na, K, Fe resonance fluorescence and molecular scattering)



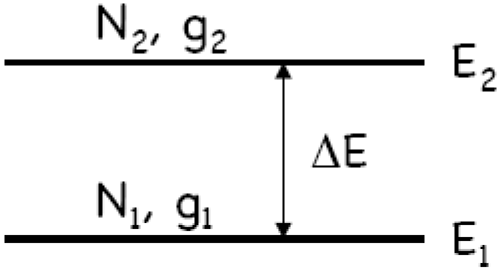


$$\boxed{\sigma_{rms} = \frac{\omega_0}{c}\sqrt{\frac{k_B T}{M}} = \frac{1}{\lambda_0}\sqrt{\frac{k_B T}{M}}}$$

$$\boxed{\Delta\omega = \omega - \omega_0 = -\vec{k}\cdot\vec{v} = -\omega_0 \frac{v\cos\theta}{c}}$$

(6) Boltzmann Distribution

- Boltzmann distribution is the law of particle population distribution according to energy levels



$$\boxed{\frac{N_2}{N_1} = \frac{g_2}{g_1}\exp\{-(E_2 - E_1)/k_B T\}}$$

$$\Downarrow$$

$$\boxed{T = \frac{\Delta E / k_B}{\ln\left(\frac{g_2}{g_1}\cdot\frac{N_1}{N_2}\right)}}$$

$$\boxed{\frac{N_k}{N} = \frac{g_k \exp(-E_k / k_B T)}{\sum_i g_i \exp(-E_i / k_B T)}}$$

N_1 and N_2 – particle populations on energy levels E_1 and E_2
g_1 and g_2 – degeneracy for energy levels E_1 and E_2, $\Delta E = E_2 - E_1$
k_B – Boltzmann constant, T – Temperature, N – total population

Population Ratio ⇨ Temperature

Fe Boltzmann temperature lidar

By measuring the Fe signal level at the two wavelengths, one can derive the temperature provided that the ratios of the extinction and the effective backscatter cross sections are known.

$$T(z) = \frac{\Delta E/k_B}{\ln\left[\frac{g_2}{g_1}\frac{R_{B374}}{R_{B372}}\left(\frac{\lambda_{374}}{\lambda_{372}}\right)^{4.0117}\frac{R_E^{\,2}(z)R_\sigma}{R_T(z)}\right]}$$

$$= \frac{598.44}{\ln\left[\frac{0.7221 R_E^{\,2}(z)R_\sigma}{R_T(z)}\right]}\ (\mathrm{K}).$$

Where

$$R_E(z) = \frac{E(\lambda_{374},\ z)}{E(\lambda_{372},\ z)},$$

$$R_\sigma = \frac{\sigma_{\mathrm{eff}}(\lambda_{374},\ T,\ \sigma_{L374})}{\sigma_{\mathrm{eff}}(\lambda_{372},\ T,\ \sigma_{L372})}.$$

Solutions of Some Lidar Equations

- Solution for scattering form lidar equation
- Solution for fluorescence form lidar equation
- Solution for differential absorption lidar equation
- Solution for resonance fluorescence lidar

Solution for
Scattering Form Lidar Equation

- Scattering form lidar equation

$$N_S(\lambda,R)=\left[\frac{P_L(\lambda_L)\Delta t}{hc/\lambda_L}\right]\cdot\left[\beta(\lambda,\lambda_L,R)\Delta R\right]\cdot\left[\frac{A}{R^2}\right]\cdot\left[T(\lambda_L,R)T(\lambda,R)\right]\cdot\left[\eta(\lambda,\lambda_L)G(R)\right]+N_B$$

- Solution for scattering form lidar equation

$$\beta(\lambda,\lambda_L,R)=\frac{N_S(\lambda,R)-N_B}{\left[\frac{P_L(\lambda_L)\Delta t}{hc/\lambda_L}\right]\Delta R\left(\frac{A}{R^2}\right)\left[T(\lambda_L,R)T(\lambda,R)\right]\left[\eta(\lambda,\lambda_L)G(R)\right]}$$

Solution for
Fluorescence Form Lidar Equation

- Fluorescence form lidar equation

$$N_S(\lambda,R)=\left(\frac{P_L(\lambda)\Delta t}{hc/\lambda}\right)\left(\sigma_{eff}(\lambda,R)n_c(R)R_B(\lambda)\Delta R\right)\left(\frac{A}{4\pi R^2}\right)\left(T_a^2(\lambda,R)T_c^2(\lambda,R)\right)\left(\eta(\lambda)G(R)\right)+N_B$$

- Solution for fluorescence form lidar equation

$$n_c(R)=\frac{N_S(\lambda,R)-N_B}{\left(\frac{P_L(\lambda)\Delta t}{hc/\lambda}\right)\left(\sigma_{eff}(\lambda)R_B(\lambda)\Delta R\right)\left(\frac{A}{4\pi R^2}\right)\left(\eta(\lambda)T_a{}^2(\lambda,R)T_c^2(\lambda,R)G(R)\right)}$$

Differential Absorption/Scattering Form

- For the laser with wavelength λ_{on} on the molecular absorption line

$$N_S(\lambda_{on},R) = N_L(\lambda_{on})[\beta_{sca}(\lambda_{on},R)\Delta R]\left(\frac{A}{R^2}\right)\exp\left[-2\int_0^R \overline{\alpha}(\lambda_{on},r')dr'\right] \times \exp\left[-2\int_0^R \sigma_{abs}(\lambda_{on},r')n_c(r')dr'\right][\eta(\lambda_{on})G(R)] + N_B$$

- For the laser with wavelength λ_{off} off the molecular absorption line

$$N_S(\lambda_{off},R) = N_L(\lambda_{off})[\beta_{sca}(\lambda_{off},R)\Delta R]\left(\frac{A}{R^2}\right)\exp\left[-2\int_0^R \overline{\alpha}(\lambda_{off},r')dr'\right] \times \exp\left[-2\int_0^R \sigma_{abs}(\lambda_{off},r')n_c(r')dr'\right][\eta(\lambda_{off})G(R)] + N_B$$

Differential Absorption/Scattering Form

- The ratio of photon counts from these two channels is a function of the differential absorption and scattering:

$$\boxed{\begin{aligned}\frac{N_S(\lambda_{on},R)-N_B}{N_S(\lambda_{off},R)-N_B} &= \frac{N_L(\lambda_{on})\beta_{sca}(\lambda_{on},R)}{N_L(\lambda_{off})\beta_{sca}(\lambda_{off},R)}\frac{\eta(\lambda_{on})}{\eta(\lambda_{off})}\\ &\times\exp\left\{-2\int_0^R\left[\overline{\alpha}(\lambda_{on},r')-\overline{\alpha}(\lambda_{off},r')\right]dr'\right\}\\ &\times\exp\left\{-2\int_0^R\left[\sigma_{abs}(\lambda_{on},r')-\sigma_{abs}(\lambda_{off},r')\right]n_c(r')dr'\right\}\end{aligned}}$$

$$\boxed{\Delta\sigma=\sigma_{abs}(\lambda_{on})-\sigma_{abs}(\lambda_{off})}$$

Solution for
Differential Absorption Lidar Equation

- Solution for differential absorption lidar equation

$$\boxed{n_c(R) = \frac{1}{2\Delta\sigma}\frac{d}{dR}\left\{ \begin{aligned} &\ln\left[\frac{N_L(\lambda_{on})\beta_{sca}(\lambda_{on},R)}{N_L(\lambda_{off})\beta_{sca}(\lambda_{off},R)}\,\frac{\eta(\lambda_{on})}{\eta(\lambda_{off})}\right] \\ &\qquad -\ln\left[\frac{N_S(\lambda_{on},R)-N_B}{N_S(\lambda_{off},R)-N_B}\right] \\ &\qquad -2\int_0^R\left[\overline{\alpha}(\lambda_{on},r')-\overline{\alpha}(\lambda_{off},r')\right]dr' \end{aligned} \right\}}$$

$$\boxed{\Delta\sigma = \sigma_{abs}(\lambda_{on}) - \sigma_{abs}(\lambda_{off})}$$

Solution for
Resonance Fluorescence Lidar Equation

- ☐ Resonance fluorescence and Rayleigh lidar equations

$$N_S(\lambda,z)=\left(\frac{P_L(\lambda)\Delta t}{hc/\lambda}\right)\left(\sigma_{eff}(\lambda,z)n_c(z)R_B(\lambda)\Delta z\right)\left(\frac{A}{4\pi z^2}\right)\left(T_a^{\,2}(\lambda)T_c^2(\lambda,z)\right)\left(\eta(\lambda)G(z)\right)+N_B$$

$$N_R(\lambda,z_R)=\left(\frac{P_L(\lambda)\Delta t}{hc/\lambda}\right)\left(\sigma_R(\pi,\lambda)n_R(z_R)\Delta z\right)\left(\frac{A}{z_R^{\,2}}\right)T_a^{\,2}(\lambda,z_R)\left(\eta(\lambda)G(z_R)\right)+N_B$$

- ☐ Rayleigh normalization

$$\frac{n_c(z)}{n_R(z_R)}=\frac{N_S(\lambda,z)-N_B}{N_R(\lambda,z_R)-N_B}\cdot\frac{z^2}{z_R^{\,2}}\cdot\frac{4\pi\sigma_R(\pi,\lambda)}{\sigma_{eff}(\lambda,z)R_B(\lambda)}\cdot\frac{\cancel{T_a^{\,2}(\lambda,z_R)}\cancel{G(z_R)}}{\cancel{T_a^{\,2}(\lambda,z)}T_c^2(\lambda,z)\cancel{G(z)}}$$

- ☐ Solution for resonance fluorescence

$$\boxed{n_c(z)=n_R(z_R)\frac{N_S(\lambda,z)-N_B}{N_R(\lambda,z_R)-N_B}\cdot\frac{z^2}{z_R^{\,2}}\cdot\frac{4\pi\sigma_R(\pi,\lambda)}{\sigma_{eff}(\lambda,z)R_B(\lambda)}\cdot\frac{1}{T_c^2(\lambda,z)}}$$

Solution for
Rayleigh and Mie Lidars

- Rayleigh and Mie (middle atmos) lidar equations

$$N_S(\lambda,z)=\left(\frac{P_L(\lambda)\Delta t}{hc/\lambda}\right)\left(\beta_R(z)+\beta_{aerosol}(z)\right)\Delta z\left(\frac{A}{z^2}\right)T_a^{\,2}(\lambda,z)\left(\eta(\lambda)G(z)\right)+N_B$$

$$N_R(\lambda,z_R)=\left(\frac{P_L(\lambda)\Delta t}{hc/\lambda}\right)\left(\beta_R(z_R)\Delta z\right)\left(\frac{A}{z_R^{\,2}}\right)T_a^{\,2}(\lambda,z_R)\left(\eta(\lambda)G(z_R)\right)+N_B$$

- Rayleigh normalization

$$\frac{\beta_R(z)+\beta_{aerosol}(z)}{\beta_R(z_R)}=\frac{N_S(\lambda,z)-N_B}{N_R(\lambda,z_R)-N_B}\cdot\frac{z^2}{z_R^{\,2}}\cdot\frac{\cancel{T_a^{\,2}(\lambda,z_R)}\cancel{G(z_R)}}{\cancel{T_a^{\,2}(\lambda,z)}\cancel{G(z)}}$$

- For Rayleigh scattering at z and z_R

$$\boxed{\frac{\beta_R(z)}{\beta_R(z_R)}=\frac{\sigma_R(z)n_{atm}(z)}{\sigma_R(z_R)n_{atm}(z_R)}=\frac{n_{atm}(z)}{n_{atm}(z_R)}}$$

Solution (Continued)

- Solution for Mie scattering in middle atmosphere

$$\boxed{\beta_{aerosol}(z) = \beta_R(z_R)\left[\frac{N_S(\lambda,z)-N_B}{N_R(\lambda,z_R)-N_B}\cdot\frac{z^2}{z_R{}^2}-\frac{n_{atm}(z)}{n_{atm}(z_R)}\right]}$$

$$\boxed{\beta_R(\lambda,z_R,\pi) = 2.938\times10^{-32}\frac{P(z_R)}{T(z_R)}\cdot\frac{1}{\lambda^{4.0117}}\left(m^{-1}sr^{-1}\right)}$$

- Rayleigh normalization when aerosols not present

$$\frac{\beta_R(z)}{\beta_R(z_R)} = \frac{N_S(\lambda,z)-N_B}{N_R(\lambda,z_R)-N_B}\cdot\frac{z^2}{z_R{}^2}\cdot\frac{\cancel{T_a^2(\lambda,z_R)}\cancel{G(z_R)}}{\cancel{T_a^2(\lambda,z)}\cancel{G(z)}}$$

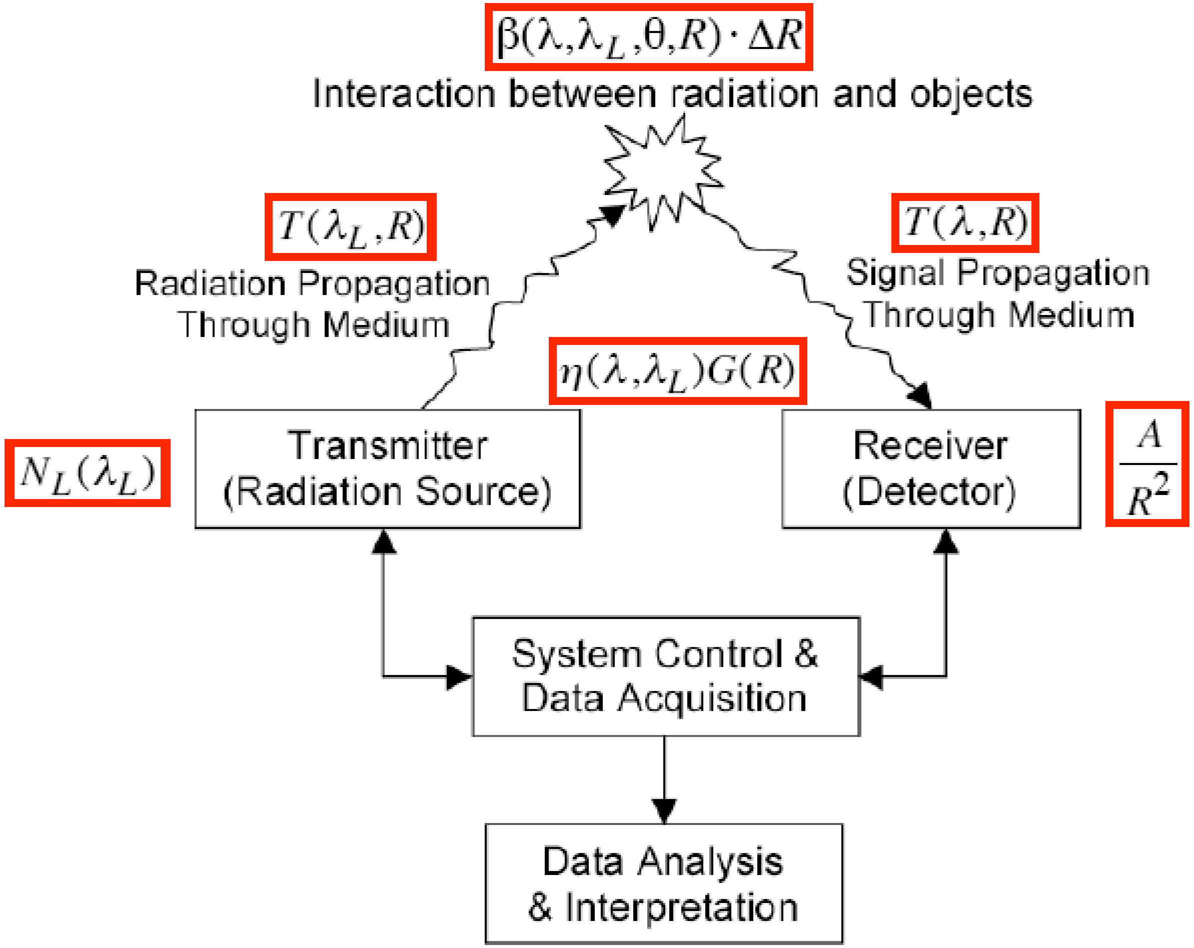
- Solution for relative number density in Rayleigh lidar

$$\boxed{RND(z) = \frac{n_{atm}(z)}{n_{atm}(z_R)} = \frac{\beta_R(z)}{\beta_R(z_R)} = \frac{N_S(\lambda,z)-N_B}{N_R(\lambda,z_R)-N_B}\cdot\frac{z^2}{z_R{}^2}}$$

Review of Lidar Architecture

- Basic Lidar Architecture
- Configurations vs. Arrangements
- Lidar Classifications

Physical Picture in Lidar Equation



$\boxed{\beta(\lambda,\lambda_L,\theta,R)\cdot\Delta R}$

Interaction between radiation and objects

$\boxed{T(\lambda_L,R)}$

Radiation Propagation Through Medium

$\boxed{T(\lambda,R)}$

Signal Propagation Through Medium

$\boxed{\eta(\lambda,\lambda_L)G(R)}$

$\boxed{N_L(\lambda_L)}$

Transmitter (Radiation Source)

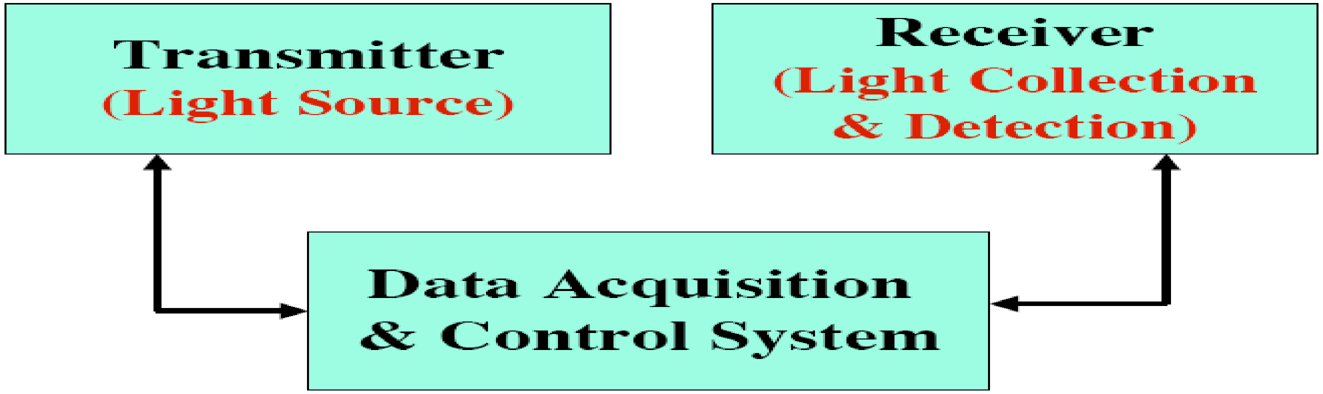
Receiver (Detector)

$\boxed{\frac{A}{R^2}}$

System Control & Data Acquisition

Data Analysis & Interpretation

Basic Architecture of LIDAR



Transmitter
(Light Source)

Receiver
(Light Collection
& Detection)

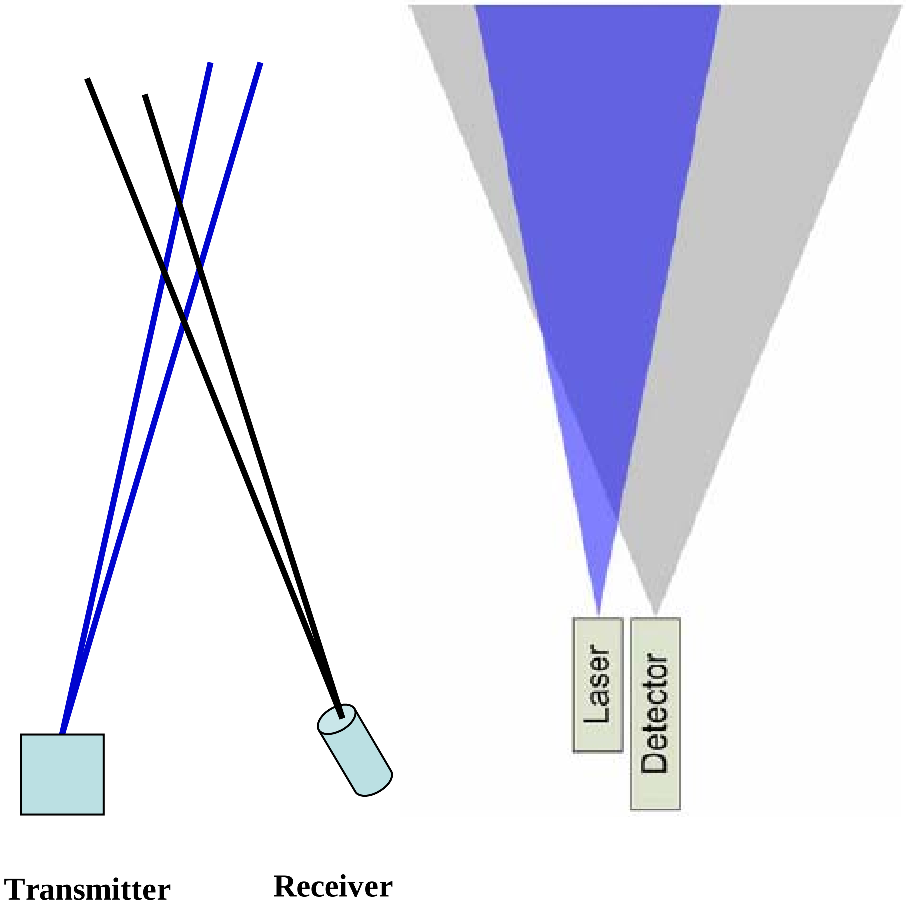
Data Acquisition
& Control System

Transmitter (laser pulses that meet some requirements): wavelength, frequency accuracy, bandwidth, pulse duration time, pulse energy, repetition

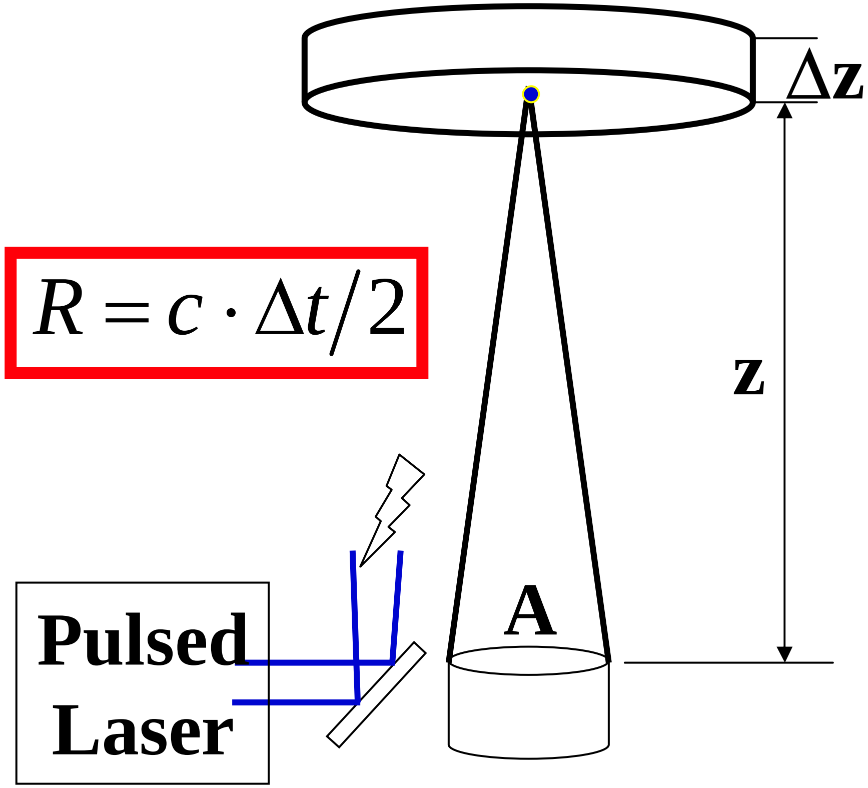
rate, divergence angle, etc
Receiver (receiver is to collect and detect returned photon signals while compressing background noise): it consists of telescopes, filters, collimating optics, photon detectors, discriminators, etc.

Data acquisition and control system (record returned data and corresponding time-offlight, provide system control and coordination to transmitter and receiver.): it usually consists of multi-channel scaler which has very precise clock so can record time precisely, discriminator, computer and software.

Basic Configurations of LIDAR
Bistatic and Monostatic



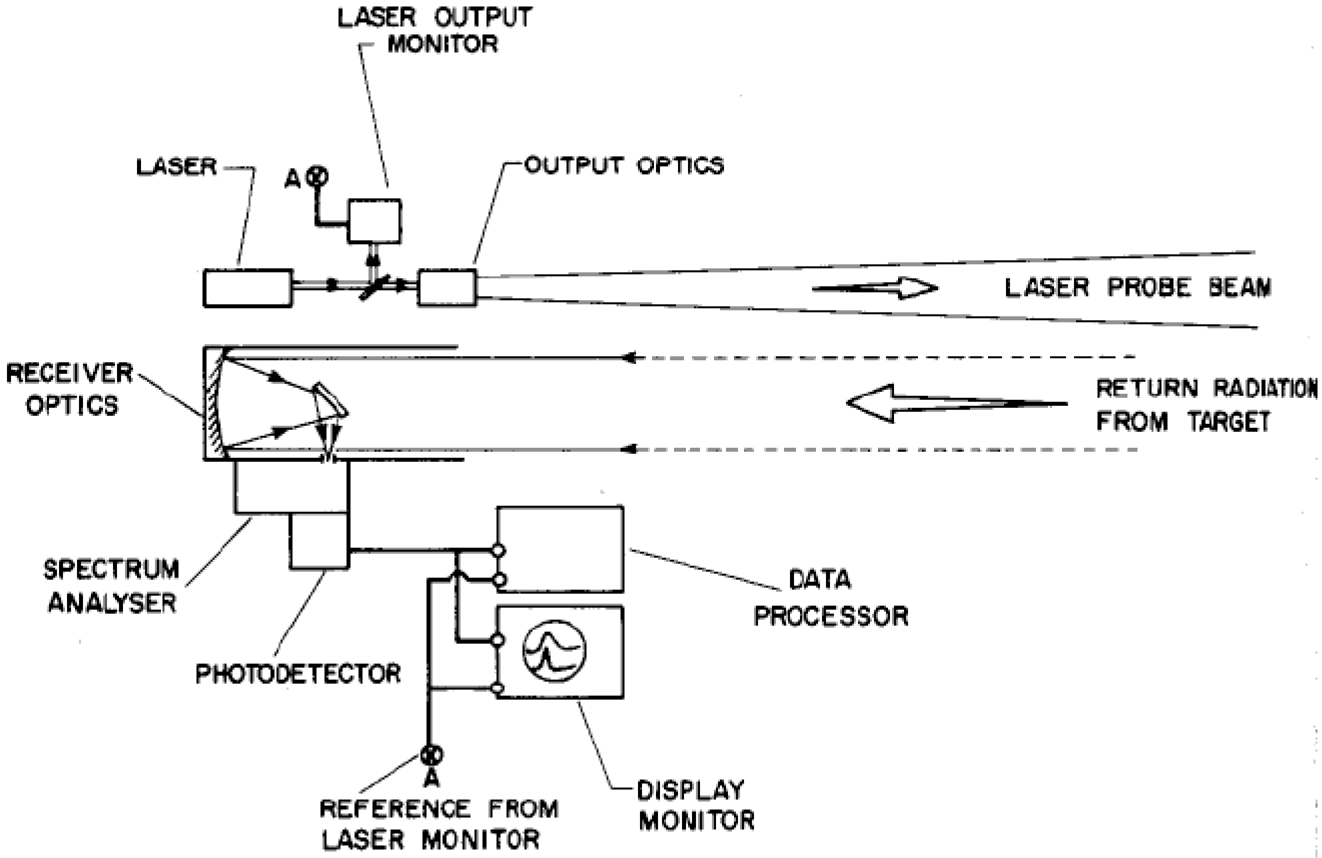
Bistatic Configuration



$$R = c \cdot \Delta t / 2$$

Monostatic Configuration

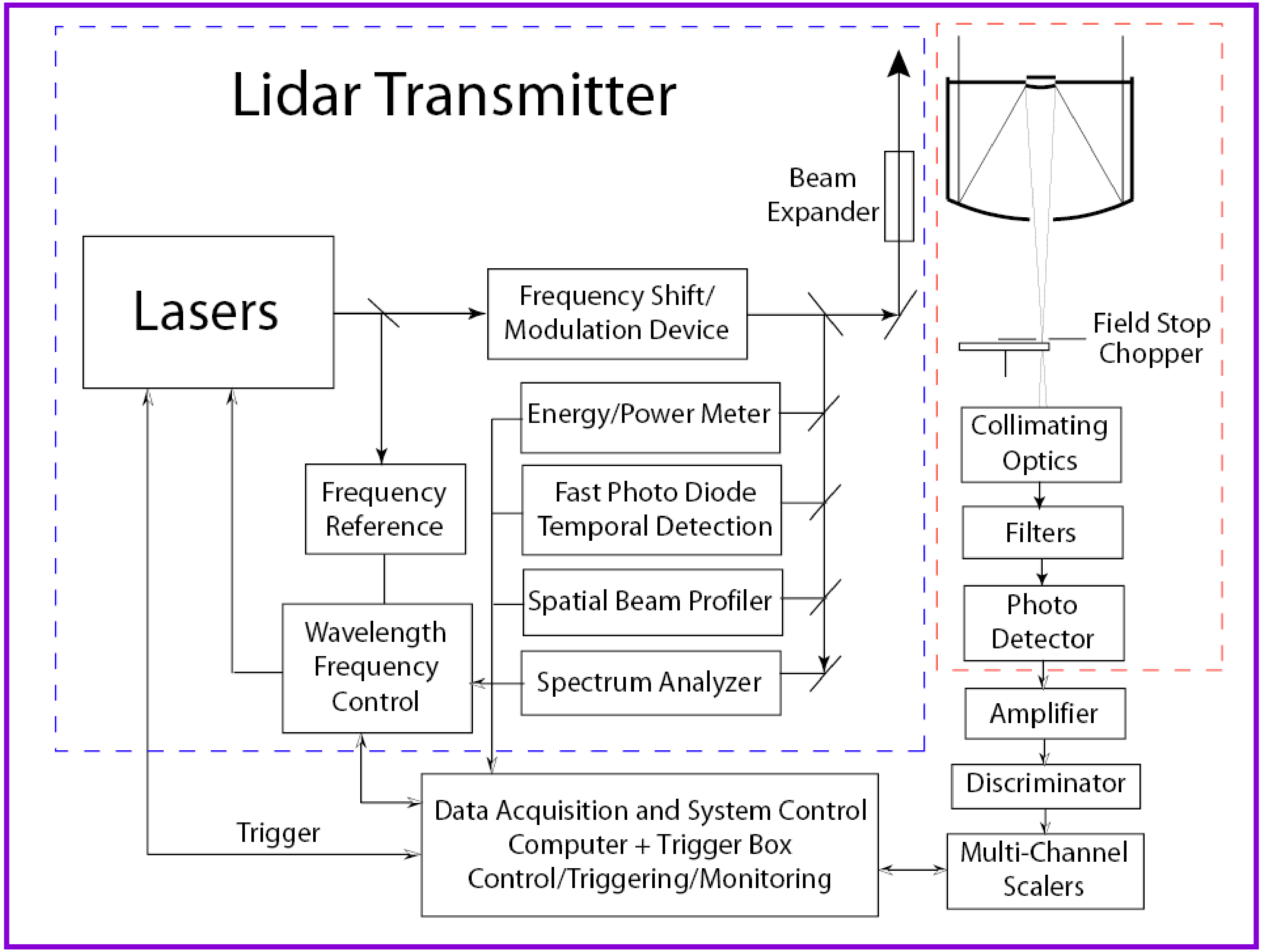
Monostatic Configuration Example



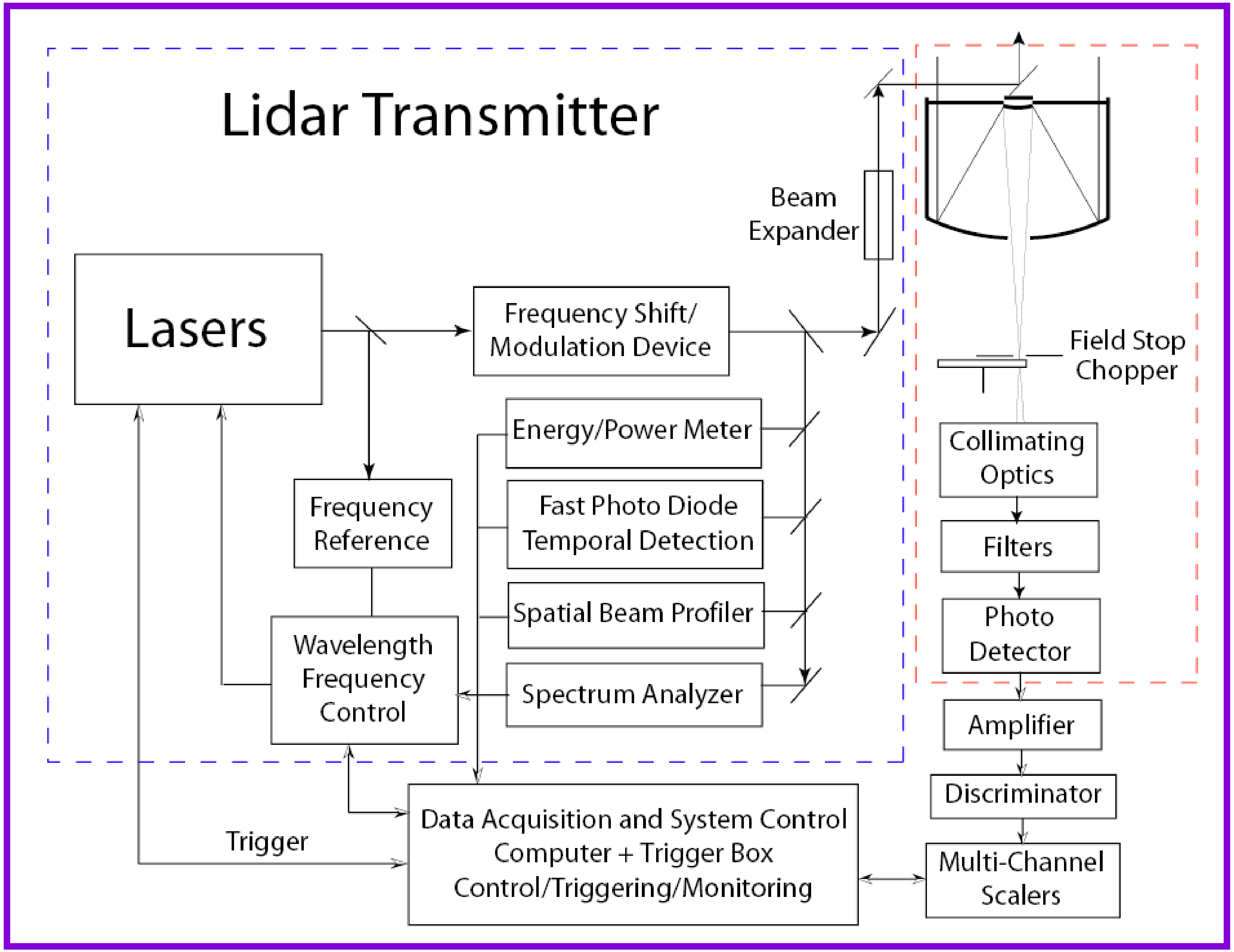
Coaxial vs. Biaxial Arrangements

- In a coaxial system, the axis of the laser beam is coincident with the axis of the receiver optics.
- In the biaxial arrangement, the laser beam only enters the field of view of the receiver optics beyond some predetermined range.
- Biaxial arrangement helps avoiding near-field backscattered radiation saturating photo-detector.
- The near-field backscattering problem in a coaxial system can be overcome by either gating of the photo-detector or use of a fast shutter or chopper.

Example of Biaxial Arrangement



Example of Coaxial Arrangement

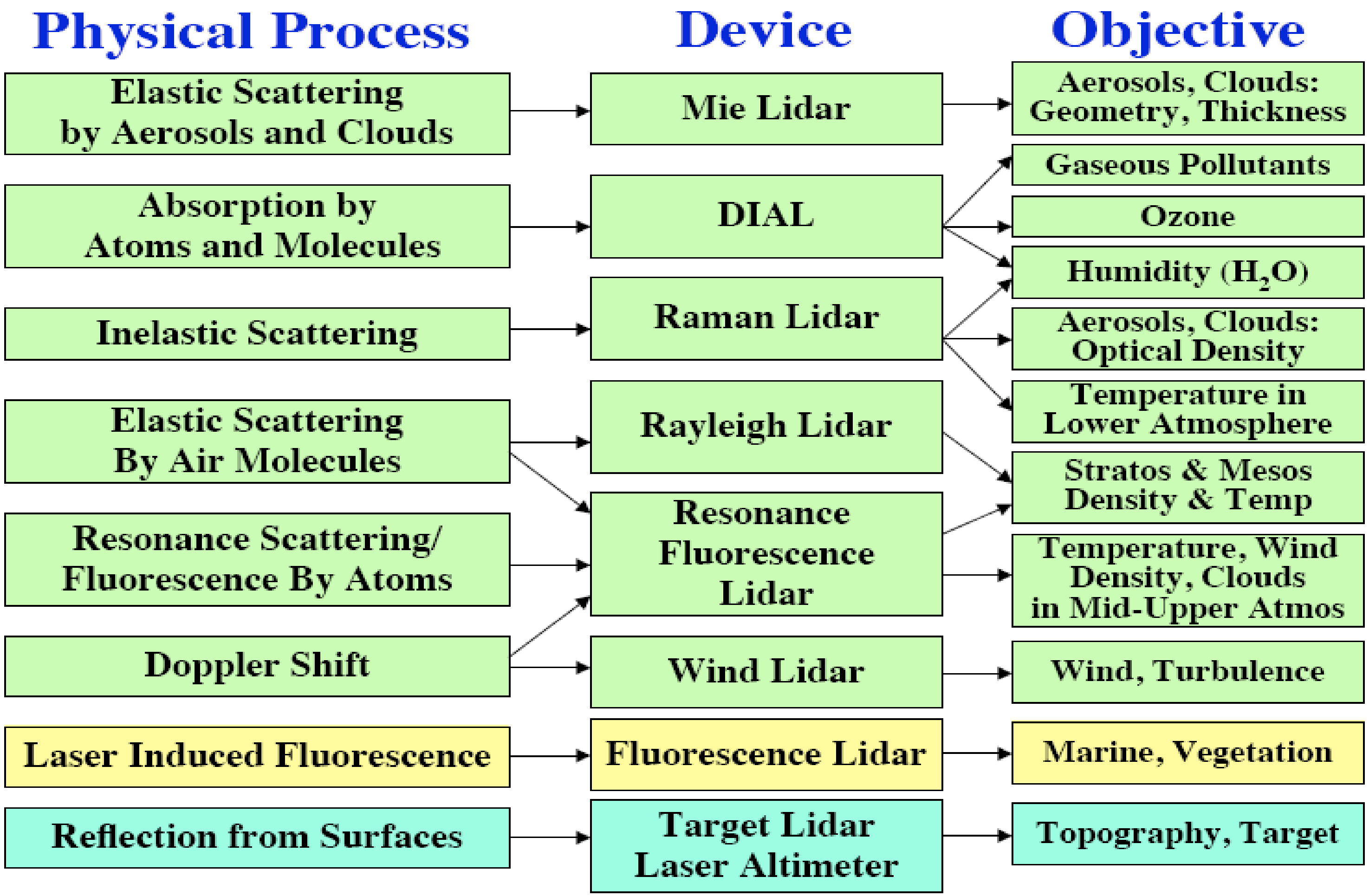


Classifications of Lidar

There are several different classifications on lidars
e.g., based on the physical process;
(Mie, Rayleigh, Raman, Res. Fluorescence, ...)
based on the platform;
(Groundbased, Airborne, Spaceborne, ...)
based on the detection region;
(Atmosphere, Ocean, Solid Earth, Space, ...)
based on the emphasis of signal type;
(Ranging, Scattering, ...)
based on the topics to detect;
(Aerosol, Constituent, Temp, Wind, Target, ...)

... ...

Classification on Physical Process



Physical Process

Elastic Scattering by Aerosols and Clouds

Absorption by Atoms and Molecules

Inelastic Scattering

Elastic Scattering By Air Molecules

Resonance Scattering/ Fluorescence By Atoms

Doppler Shift

Laser Induced Fluorescence

Reflection from Surfaces

Device

Mie Lidar

DIAL

Raman Lidar

Rayleigh Lidar

Resonance Fluorescence Lidar

Wind Lidar

Fluorescence Lidar

Target Lidar Laser Altimeter

Objective

Aerosols, Clouds: Geometry, Thickness

Gaseous Pollutants

Ozone

Humidity (H_2O)

Aerosols, Clouds: Optical Density

Temperature in Lower Atmosphere

Stratos & Mesos Density & Temp

Temperature, Wind Density, Clouds in Mid-Upper Atmos

Wind, Turbulence

Marine, Vegetation

Topography, Target

Classification on Platform

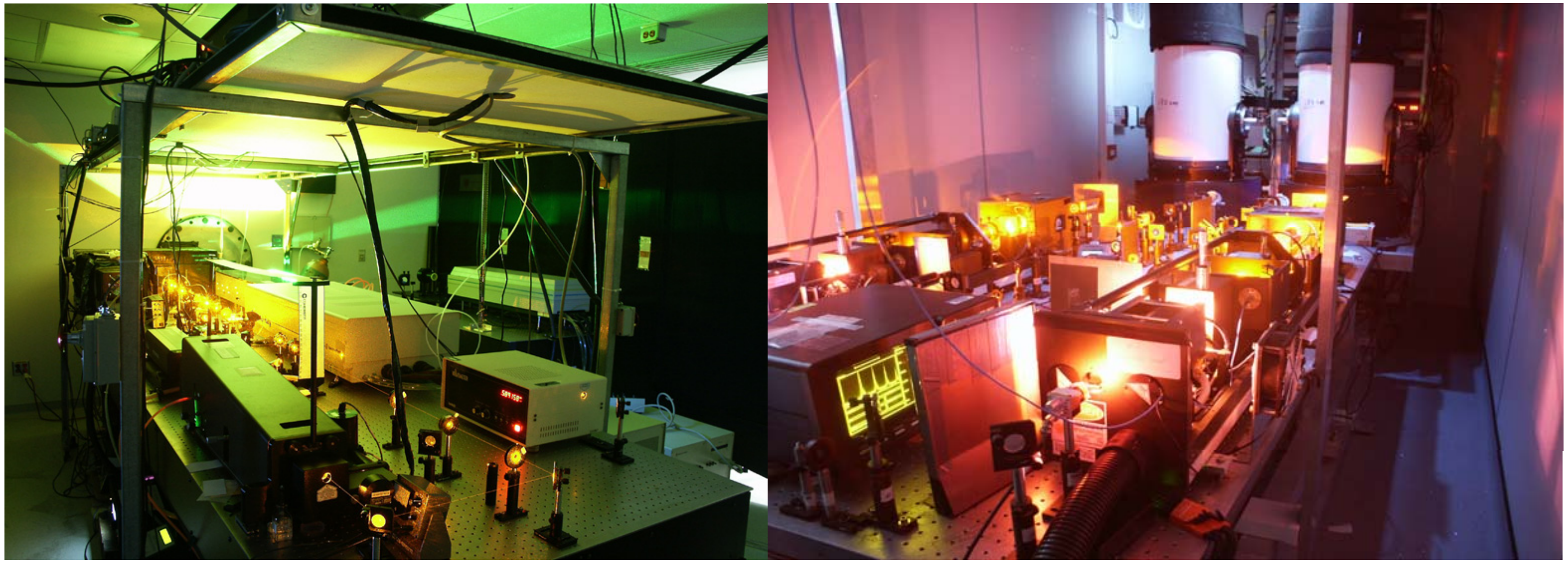
Spaceborne lidar	Satellite, Space Shuttle. Space Station
Airborne lidar	Jet, Propeller Airplanes Unmanned Aerial Vehicle (UAV) Kite
Groundbased lidar	Stationary Contanerized moved with truck
Shipborne lidar	Icebreaker, Ships
Submarine lidar	Submarine

Classification on Detection Regions

Atmosphere lidar	Various types From various platforms
Hydrosphere lidar	Various types From various platforms
Solid Earth lidar	Airborne or Spaceborne Laser altimeter
Target lidar	Various type With or without Imaging function

LIDAR 1 & 2

Taieb Gasmi
College of Science & Engineering
Saint Louis University in Spain



International Centre for Theoretical Physics (ICTP)

International College on Optics in Environmental Science

LIDAR 2: Classes of LIDARS

1. Temperature LIDAR
2. Wind LIDAR (review)
3. Aerosol LIDAR
4. Constituent LIDAR

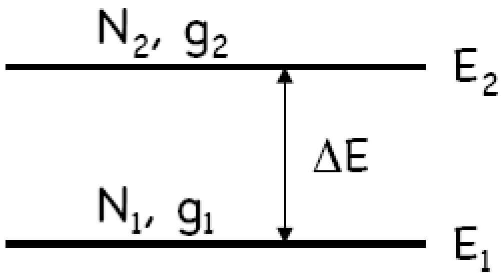
Temperature Measurement LIDAR

Use temperature-dependent effects or phenomena

- ☐ Doppler Technique – Doppler broadening (not only for Na, K, and Fe, but also for Rayleigh scattering, as long as Doppler broadening dominate and can be detected)
- ☐ Boltzmann Technique – Boltzmann distribution of atomic populations on different energy levels (not only for Fe, but also for molecular spectroscopy in optical remote sensing)
- ☐ Integration Technique (Rayleigh or Raman) – integration lidar technique using ideal gas law and assuming hydrostatic equilibrium (not only for modern lidar, but also for cw searchlight and rocket falling sphere – some way to measure atmosphere number density)
- ☐ Rotational Raman Technique – temperature dependence of population ratio, similar to Boltzmann technique

Boltzmann Distribution

- Boltzmann distribution is the law of particle population distribution according to energy levels



$$\boxed{\frac{N_k}{N} = \frac{g_k \exp(-E_k / k_B T)}{\sum_i g_i \exp(-E_i / k_B T)}}$$

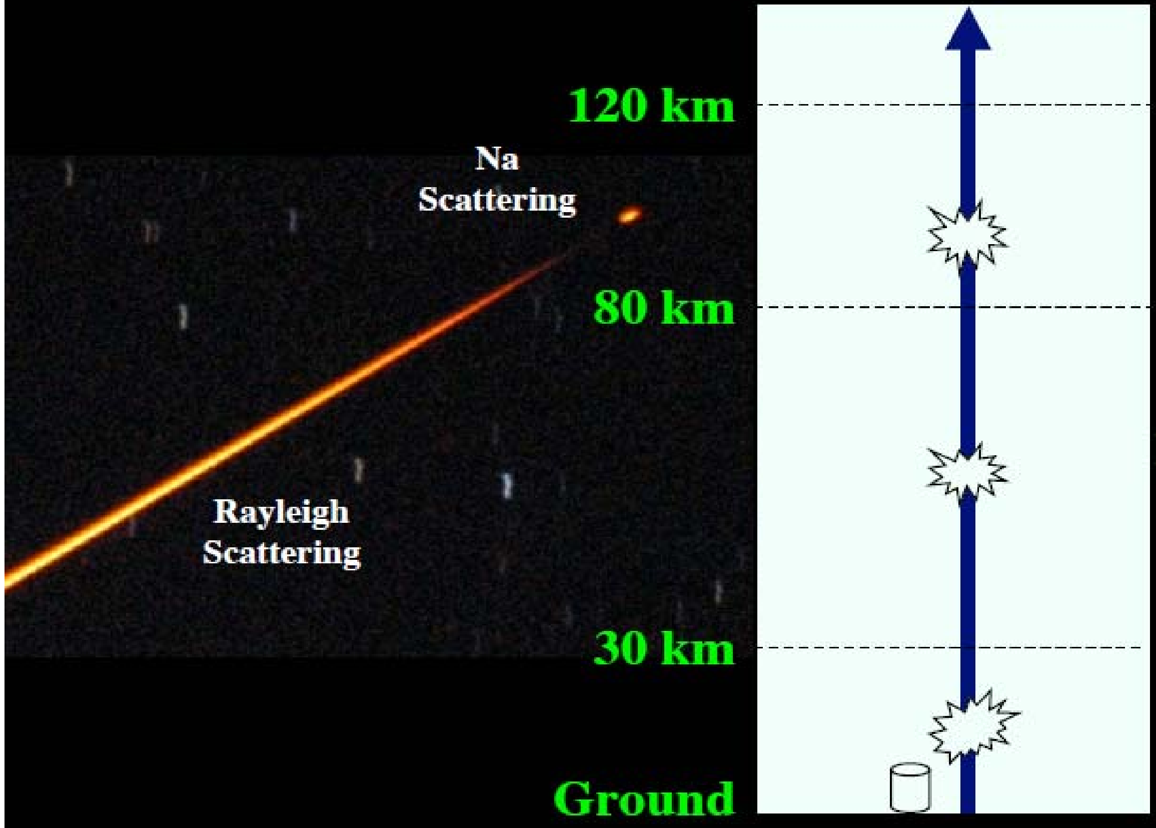
$$\boxed{\frac{N_2}{N_1} = \frac{g_2}{g_1} \exp\{-(E_2 - E_1)/k_B T\}}$$

$$\boxed{T = \frac{\Delta E / k_B}{\ln\left(\frac{g_2}{g_1} \cdot \frac{N_1}{N_2}\right)}}$$

N_1 and N_2 – particle populations on energy levels E_1 and E_2
g_1 and g_2 – degeneracy for energy levels E_1 and E_2, $\Delta E = E_2 - E_1$
k_B – Boltzmann constant, T – Temperature, N – total population

Population Ratio ⇨ Temperature

Light Detection and Ranging (LIDAR)



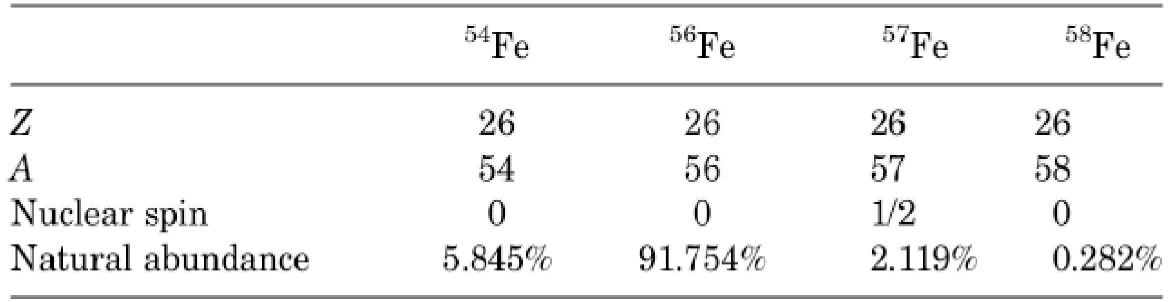
Resonant
Fluorescence
From Metal Atoms

Rayleigh Scattering
From Air Molecules

Mie Scattering
From Aerosols

Temperature Measurement Principle of the Fe Boltzmann Lidar Technique

There are four natural isotopes of Fe atoms: ^{54}Fe, ^{56}Fe, ^{57}Fe and ^{58}Fe. Among them ^{56}Fe is the most abundant isotope with natural abundance of 91.754%. The isotopic data of Fe atoms are summarized in the following table.



	^{54}Fe	^{56}Fe	^{57}Fe	^{58}Fe
Z	26	26	26	26
A	54	56	57	58
Nuclear spin	0	0	1/2	0
Natural abundance	5.845%	91.754%	2.119%	0.282%

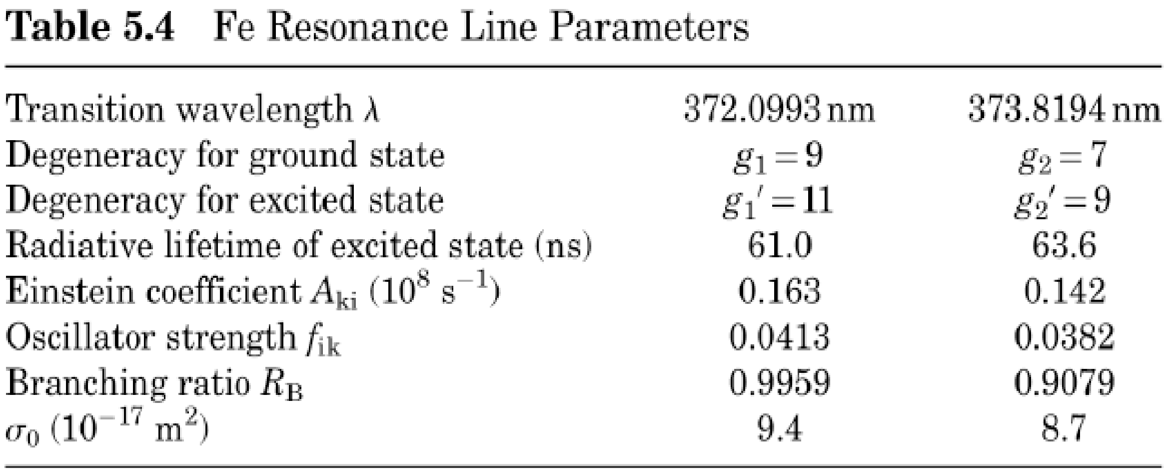
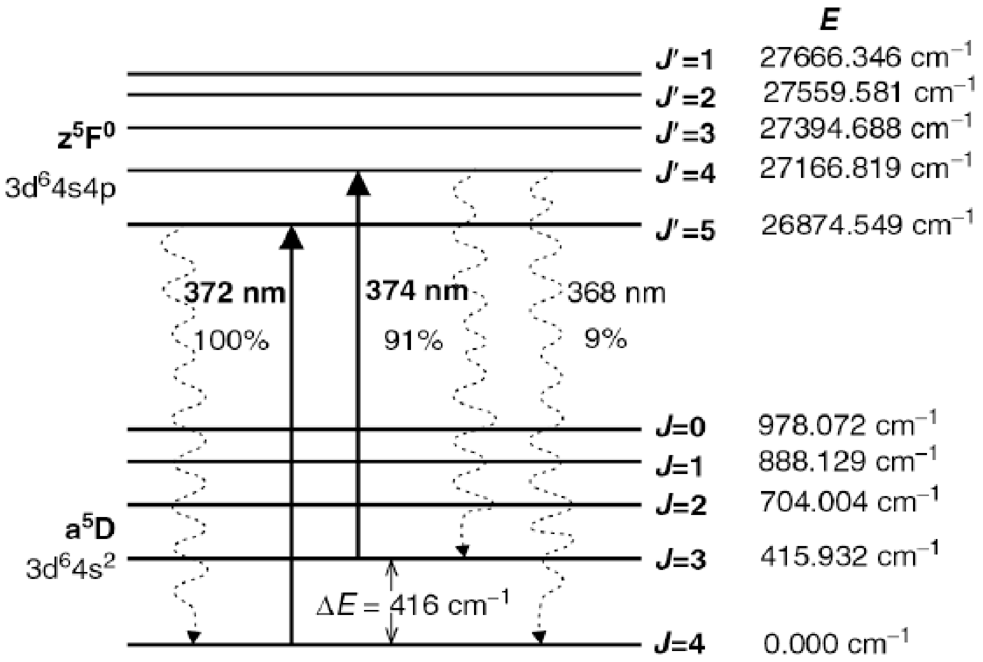


Table 5.4 Fe Resonance Line Parameters

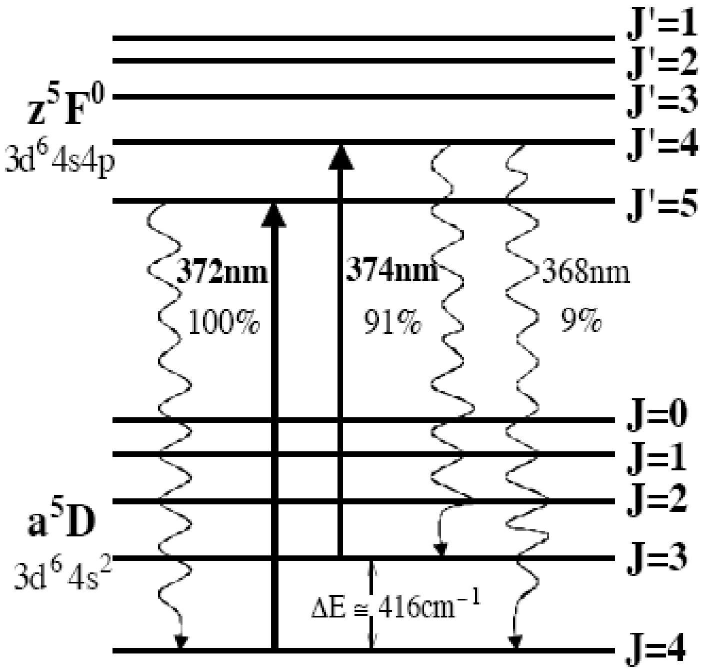
Transition wavelength λ	372.0993 nm	373.8194 nm
Degeneracy for ground state	$g_1 = 9$	$g_2 = 7$
Degeneracy for excited state	$g_1' = 11$	$g_2' = 9$
Radiative lifetime of excited state (ns)	61.0	63.6
Einstein coefficient A_{ki} (10^8 s^{-1})	0.163	0.142
Oscillator strength f_{ik}	0.0413	0.0382
Branching ratio R_B	0.9959	0.9079
σ_0 (10^{-17} m^2)	9.4	8.7



-The isotope shifts of ^{54}Fe, ^{57}Fe and ^{58}Fe with respect to ^{56}FE are ~ 1 Ghz for the two resonance lines 372 nm and 374 nm.

- Energy difference between the lowest ground states is about 416 cm^{-1} which is almost 1,25 x10^{4} GHz, which means that the contribution of these isotope shifts (^{54}Fe, ^{57}Fe and ^{58}Fe) to the Boltzmann factor (exp(-ΔE/K_BT) is negligible (less than 1x10^{-4}).
- The Fe Boltzmann temperature Lidar relies on the unique energy level distribution diagram of the ground state manifold of Fe atom. In thermodynamic equilibrium, the ratio of the populations in the J=3 and J=4 sublevels in the ground state manifold is given by Maxwell-Boltzamnn distribution law.

Boltzmann Technique



Atomic Fe Energy Level

[Gelbwachs, 1994; Chu et al., 2002]

Maxwell-Boltzmann Distribution in Thermal-dynamic Equilibrium

$$\frac{P_2(J=3)}{P_1(J=4)} = \frac{\rho_{Fe(374)}}{\rho_{Fe(372)}} = \frac{g_2}{g_1}\exp(-\Delta E/k_B T)$$

⇩

$$T = \frac{\Delta E / k_B}{\ln\left(\frac{g_2}{g_1}\cdot\frac{P_1}{P_2}\right)}$$

P_1, P_2 -- Fe populations
g_1, g_2 -- Degeneracy
k_B -- Boltzmann constant
T -- Temperature

ρ(372) and ρ(374) are the associated number desities. ΔE is the energy difference between the two level= 416 cm^{-1}. Subscripts 372 and 374 refers to the excitation wavelengths of the two transitions.

The Fe densities at those two states can be measured using resonance fluorescence lidar technique.

The Fe photon count is therefore given by the lidar equation:

$$N_{\mathrm{Fe}}(\lambda, z) = \left(\frac{P_{\mathrm{L}} \Delta t T_{\mathrm{a}}}{hc/\lambda} E(\lambda, z)\right) \sigma_{\mathrm{eff}}(\lambda, T, \sigma_{\mathrm{L}}) R_{\mathrm{B}\lambda} \rho_{\mathrm{Fe}}(\lambda, z) \times \Delta z \left(E(\lambda, z) T_{\mathrm{a}} \frac{A_{\mathrm{R}}}{4\pi z^2} \eta\right) \qquad (5.92)$$

RFLE

- Z is the altitude; P_L laser power; ΔT temporal resolution; ΔZ is the vertical resolution; T_a is the lower transmitance of the atmosphere; E(λ.**z**) is the extinction coefficient of the signal associated with the Fe absorption; $\sigma_{eff}(\lambda, T, \sigma_L)$ is the effective scattering cross-section; R_B is the branching ratio.

- The system uses two separate lasers because of the two Fe lines which are far apart in λ to be tuned easily with a single laser.
- To compensate for the signal variations in each of these systems, number densities of Fe layers at each wavelength are normalized by the Rayleigh count (N_R) over an altitude range of 50 Km.

$$N_R(\lambda, z_R) = \left(\frac{P_L(\lambda)\Delta t}{hc/\lambda}\right)\left(\sigma_R(\pi,\lambda) n_R(z_R) \Delta z\right)\left(\frac{A}{z_R^{\ 2}}\right) T_a^{\ 2}(\lambda, z_R)\left(\eta(\lambda) G(z_R)\right)$$

The Rayleigh-normalized background-corrected Fe signal count is hence defined:

$$N_{\mathrm{norm}}(\lambda, z) = \frac{N_{\mathrm{Fe}}(\lambda, z) + N_{\mathrm{B}}(\lambda, z) - \hat{N}_{\mathrm{B}}(\lambda)}{N_{\mathrm{R}}(\lambda, z_{\mathrm{R}}) + N_{\mathrm{B}}(\lambda, z_{\mathrm{R}}) - \hat{N}_{\mathrm{B}}(\lambda)}$$

$$= \frac{z_{\mathrm{R}}^2 E^2(\lambda, z) R_{\mathrm{B}\lambda} \sigma_{\mathrm{eff}}(\lambda, T, \sigma_{\mathrm{L}}) \rho_{\mathrm{Fe}}(\lambda, z)}{z^2 \sigma_{\mathrm{R}}(\lambda) \rho_{\mathrm{atmos}}(z_{\mathrm{R}})}$$

N^B(λ) is the estimated background noise count.

The Fe densities ρ(372) and ρ(374) at each wavelength can be derived from the last equation.

The ratio of the normalised signal counts at two wavelengths (R_T) can be related to the temperature as follows:

$$T(z) = \frac{\Delta E/k_{\mathrm{B}}}{\ln\left[\frac{g_2}{g_1}\frac{R_{\mathrm{B374}}}{R_{\mathrm{B372}}}\left(\frac{\lambda_{374}}{\lambda_{372}}\right)^{4.0117}\frac{R_E^2(z)R_\sigma}{R_{\mathrm{T}}(z)}\right]}$$

$$\begin{aligned}R_{\mathrm{T}}(z) &= \frac{N_{\mathrm{norm}}(\lambda_{374},z)}{N_{\mathrm{norm}}(\lambda_{372},z)}\\ &= \frac{g_2}{g_1}\frac{R_{\mathrm{B374}}}{R_{\mathrm{B372}}}\left(\frac{\lambda_{374}}{\lambda_{372}}\right)^{4.0117}\frac{E^2(\lambda_{374},z)}{E^2(\lambda_{372},z)}\\ &\quad\times\frac{\sigma_{\mathrm{eff}}(\lambda_{374},T,\sigma_{\mathrm{L374}})}{\sigma_{\mathrm{eff}}(\lambda_{372},T,\sigma_{\mathrm{L372}})}\exp(-\Delta E/k_{\mathrm{B}}T)\end{aligned}$$

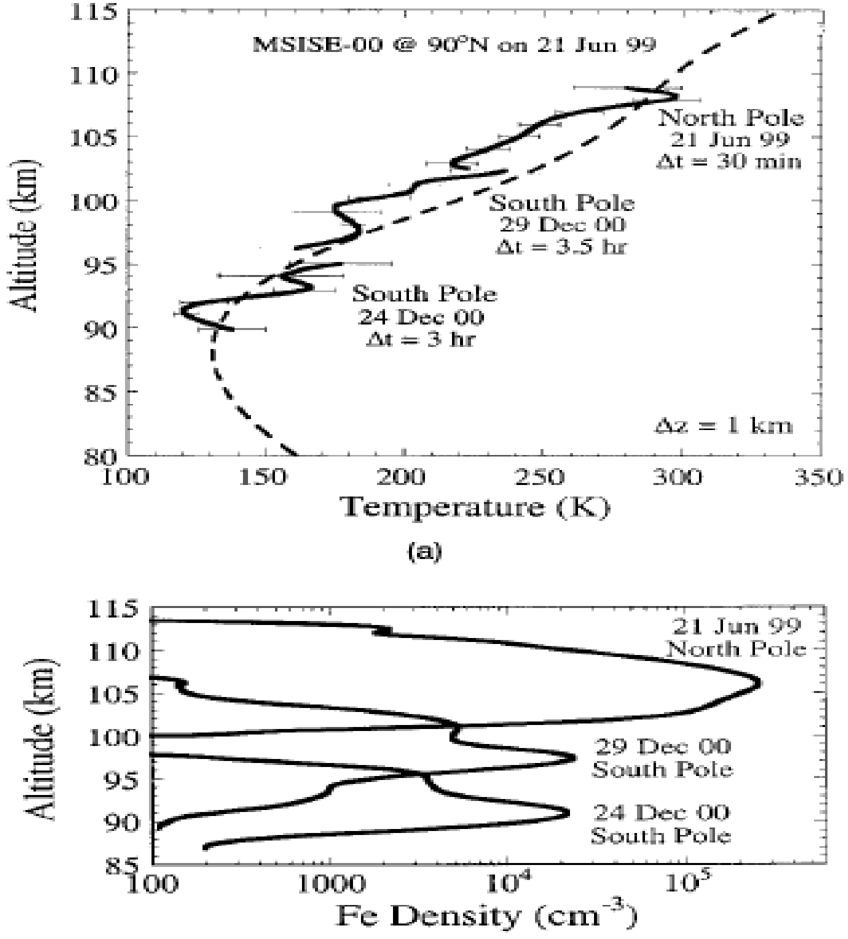
$$R_\sigma = \frac{\sigma_{\mathrm{eff}}(\lambda_{374},T,\sigma_{\mathrm{L374}})}{\sigma_{\mathrm{eff}}(\lambda_{372},T,\sigma_{\mathrm{L372}})}$$

$$R_E(z) = \frac{E(\lambda_{374},z)}{E(\lambda_{372},z)}$$

At 200 K, (372nm) Fe signal is ~ 30 times stronger than (374nm) Fe signal so R_T ~ 1/30. So the final result is:

$$= \frac{598.44K}{\ln\left[\frac{0.7221R_E^2(z)R_\sigma}{R_{\mathrm{T}}(z)}\right]}$$

Thus, by measuring the Fe signal level at the two wavelengths and computing *RT(z)*, one can derive the temperature, provided that the ratios of the extinction and the effective backscatter cross sections are known.



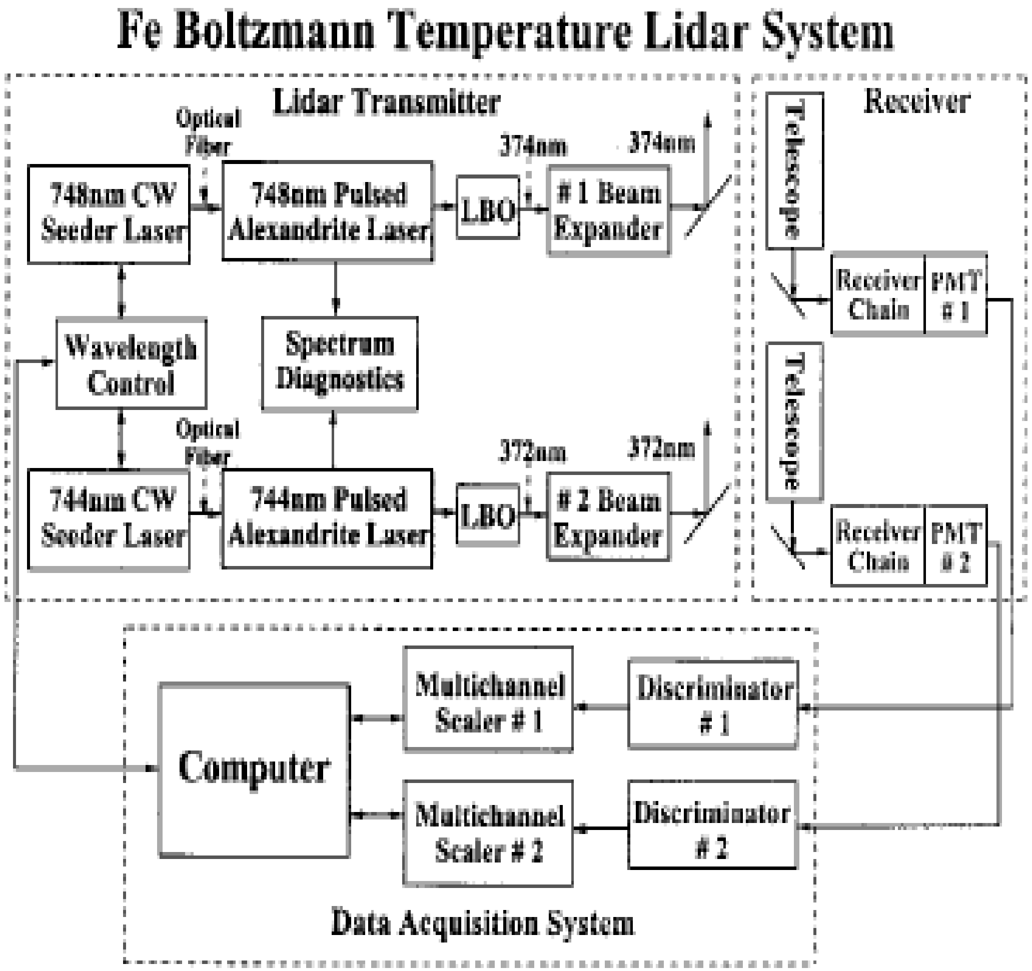
(a)

(b)

Fig. 6. (a) Temperature profiles measured by Fe Boltzmann temperature lidar over the North Pole on 21 June 1999 and over the South Pole on 24 December 2000 and 29 December 2000 along with MSISE-00 model data for 21 June 1999 at the North Pole. (b) The 372-nm ground-state Fe density profiles corresponding to the temperature profiles plotted in Fig. 6(a).

$$T = \frac{\Delta E / k_B}{\ln\left[\frac{g_2}{g_1}\frac{\rho_{\mathrm{Fe}}(372)}{\rho_{\mathrm{Fe}}(374)}\right]}$$

ρ_{Fe}372 and ρFe374 are the associated Fe number densities, ΔE is the energy difference between the two levels

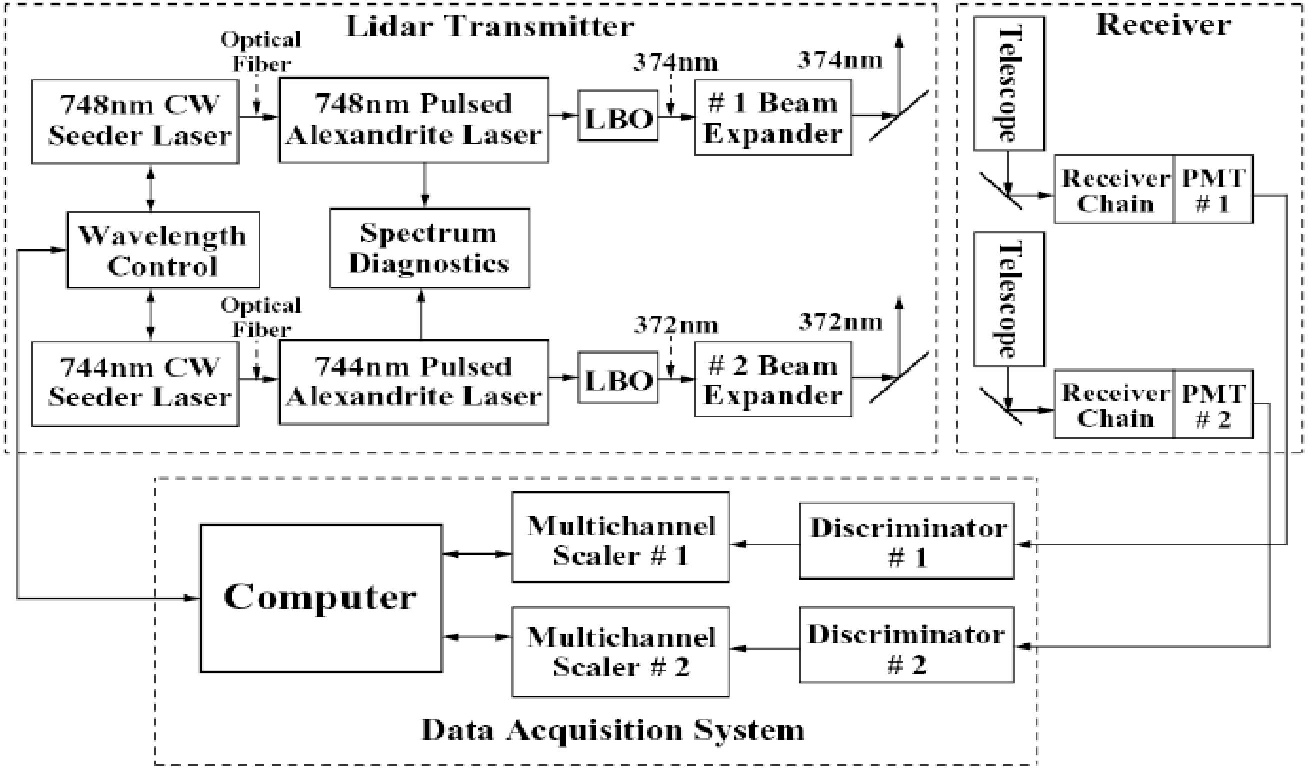


Fe Boltzmann Temperature Lidar System

Diagram of Univ. of Illinois Fe Boltzmann Temperature Lidar System

J.Appl. Opt. 41, 2002.

Fe Boltzmann Lidar Schematic



Lidar Transmitter

748nm CW Seeder Laser

Optical Fiber

748nm Pulsed Alexandrite Laser

LBO

374nm

1 Beam Expander

374nm

Wavelength Control

Spectrum Diagnostics

744nm CW Seeder Laser

Optical Fiber

744nm Pulsed Alexandrite Laser

LBO

372nm

2 Beam Expander

372nm

Receiver

Telescope

Receiver Chain

PMT # 1

Telescope

Receiver Chain

PMT # 2

Computer

Multichannel Scaler # 1

Discriminator # 1

Multichannel Scaler # 2

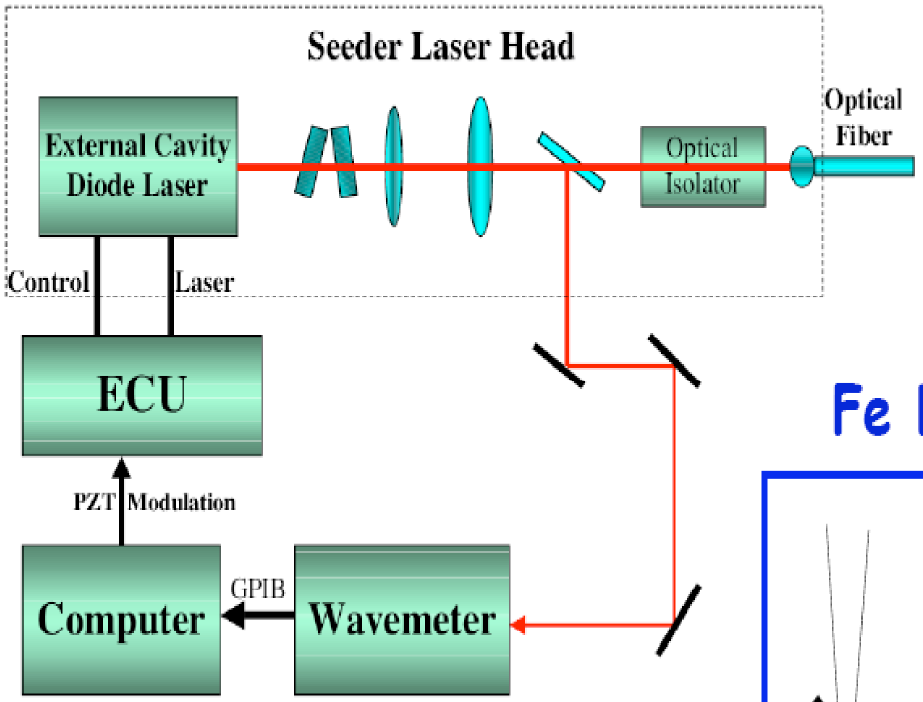
Discriminator # 2

Data Acquisition System

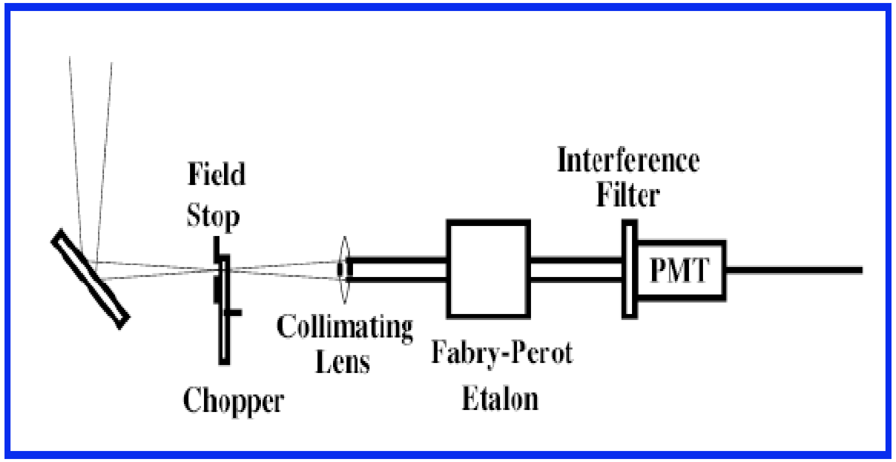
- Based on injection-seeded, frequency-doubled, pulse Alexandrite laser systems (372 and 374 nm output)

Fe Lidar Seeder Laser System

Seeder Laser Structure and Wavelength Control



Fe Boltzmann Lidar Receiver



Aerosol Lidar

Motivations to Study Aerosols

Atmospheric aerosols play an important role in many atmospheric processes:
- Aerosols have appreciable influence on the Earth's radiation budget, air quality and visibility, clouds, precipitation, and chemical processes in the troposphere and stratosphere.

Their occurrence, residence time, physical properties, chemical composition as well as the resulting climate-relevant optical properties are subject to large diversity especially in the troposphere because of their widely different sources and meteorological processes.

Therefore, vertically resolved measurements of physical and optical properties of particles such as the mean particle size, and the volume extinction coefficient are of great interest.

Routine (long-term), range-resolved observations of these parameters can only be carried out with lidar.

(3) Aerosol LIDAR:
Elastic-Scattering, Raman, HSRL

Elastic-Scattering for Lower Atmos

- Lidar equation for elastic backscatter by air molecules and aerosols

$$\boxed{P(R) = \frac{E_o \eta}{R^2} O(R) \beta(R) \exp\left[-2\int_0^R \alpha(r) dr\right]}$$

O(R) - overlap between laser and FOV
$\beta(R)$ - backscatter coefficient ($km^{-1}sr^{-1}$)
$\alpha(R)$ - extinction coefficient (km^{-1})

- Backscatter and extinction are contributed by aerosols and molecules

$$\boxed{\begin{aligned} \beta(R) &= \beta_{aer}(R) + \beta_{mol}(R) \\ \alpha(R) &= \alpha_{aer}(R) + \alpha_{mol}(R) \end{aligned}}$$

Index aer refer to aerosol particles
Index mol refer to air molecules

- Combining above equations, we obtain

$$P(R) R^2 = E_0 \eta_L \left[\beta_{aer}(R) + \beta_{mol}(R)\right] \exp\left[-2\int_o^R \left[\alpha_{aer}(r) + \alpha_{mol}(r)\right] dr\right]$$

Note: backscatter is local effect while extinction is integrated effect

- Recall the Rayleigh scattering from air molecules $\beta_{mol}(R)$ can be determined from atmosphere temperature and pressure

$$\boxed{\beta_{mol}(\lambda, z_R) = 2.938 \times 10^{-32} \frac{P(z_R)}{T(z_R)} \cdot \frac{1}{\lambda^{4.0117}}}$$

z_R is altitude for range R

In general, both the volume extinction coefficient α and backscattering coefficient β_T are unknown. it is therefore necessary to assume some kind of relation between the extinction α and the backscattering coefficient β_T (extinction-to-backscattering ratio); where the volume backscaterring coefficient is $\beta=\beta_T/4\pi$ ($m^{-1}.Sr^{-1}$)

Extinction-to-backscattering ratio:

Let $S(R)= Ln[R^2.P(R)]$ and let S(Ro) be the signal at the reference range R_0, we have:

$$S(R) - S(R0)= Ln[\beta(R)/\beta(R_0)]-2\int_{R_0}^{r}\alpha.dr$$

In differential form:

$$dS(R)/d(R)=1/\beta(R).d\beta(R)/dR - 2\alpha(R)$$

Slope method of inversion: assumes that the scatterers are homogeneously

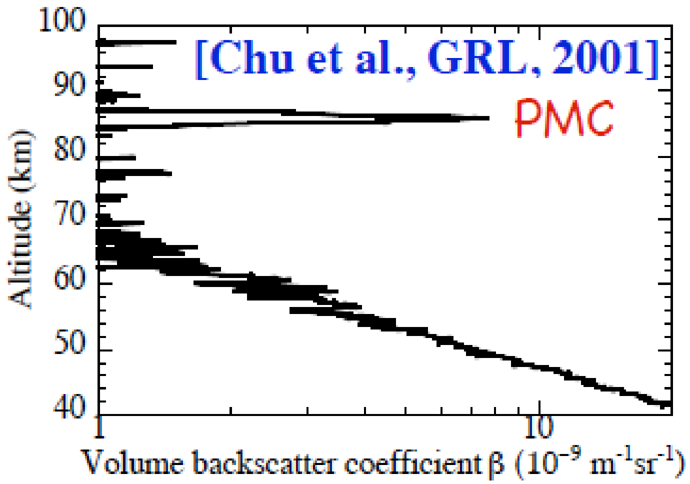
Distributed along the lidar path so $d\beta(R)/dR \sim 0$

Thus $dS/dR = 2\alpha(R)$ is estimated from the slope of the plot S vs. R

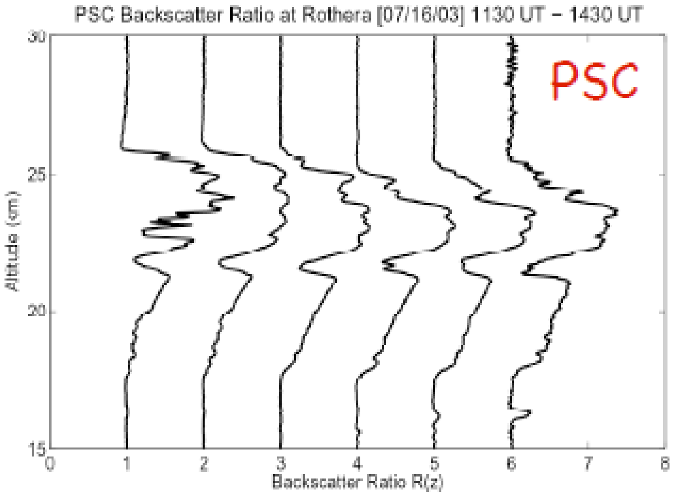
Limitations: applicable for a homogeneous path only.

Lidar Detection of Aerosols/Clouds

- ❑ Aerosols and clouds are shown as distinct peaks above the Rayleigh scattering background in range-resolved lidar profiles.
- ❑ The common way to detect aerosols and clouds is to use elastic scattering lidar with Rayleigh and Mie scattering detection capability.
- ❑ Virtually this can be done by any lidars that receive scattering signals, including resonance fluorescence, DIAL, Raman, Rayleigh, & Mie.



Polar mesospheric clouds
Noctilucent clouds



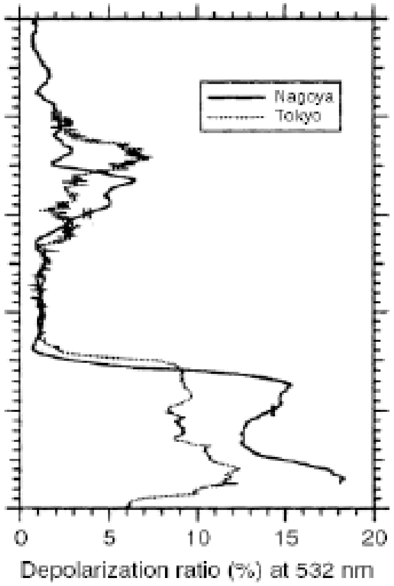
Polar stratospheric clouds

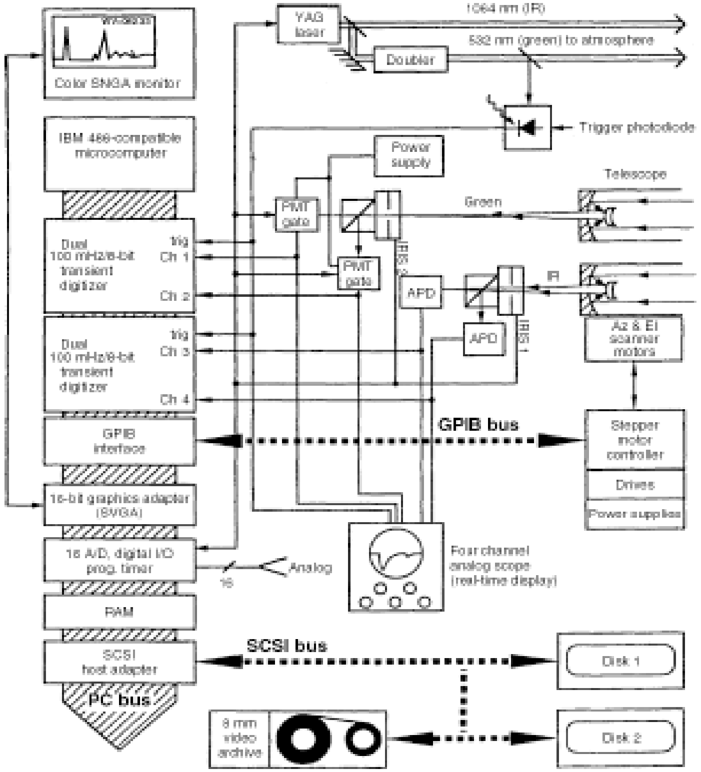
Polarization Lidar Detection

- ❑ Backscattering from a spherical particle does not change the polarization, but the non-spherical particle changes the polarization. Thus, by monitoring the polarization status of the scattered light, information on the shape of the aerosol particles can be obtained.

- ❑ Depolarization is defined by

$$\boxed{\delta = I_{\perp} / I_{\parallel}}$$





(2) Wind Lidar

Motivations for Wind Measurements

Global atmospheric wind profiles from ground to 120 km are important for validation of the output of global atmosphere models, and for study of the atmosphere dynamics, as wave information can be inferred from the wind measurements.

Wind/velocity measurements have much more applications in industry, environment, and defense business. For example,
(1) Aircraft true airspeed, aircraft wake vortices
(2) Clear air turbulence, wind shear, gust fronts
(3) Air pollution monitoring
(4) Vibration of objects
(5) Laboratory, machine shop, production facility, wind tunnel

Techniques for Wind Measurements

Use wind-dependent effects or use definition of wind

- ☐ Direct Motion Detection Technique:

(using the definition of velocity)

$$\vec{v} = \frac{d\vec{r}(t)}{dt}$$

(1) Tracking aerosol/cloud motions
(2) Laser Time-of-Flight Velocimetry
(3) Laser Doppler Velocimetry

- ☐ For non-resonant scattering
  - ☐ The Doppler frequency shift is given by

$$\boxed{\Delta\omega_{scattering} = \omega_2 - \omega_1 = -(\vec{k}_1 \cdot \vec{v}_1 - \vec{k}_2 \cdot \vec{v}_2)}$$

  - ☐ Therefore, for forward scattering, $\vec{k}_2 \approx \vec{k}_1, \vec{v}_2 \approx \vec{v}_1$, so $\Delta\omega = 0$
  - ☐ For backward scattering, $\vec{k}_2 \approx -\vec{k}_1, \vec{v}_2 \approx \vec{v}_1$, so $\Delta\omega = -2\vec{k}_1 \cdot \vec{v}_1$

(4) Constituent Lidar

- Motivations to study atmosphere constituents
- Lidar detection of atmospheric constituents

(spectroscopic signatures to distinguish species)

- Metal atoms by resonance fluorescence lidar
- DIAL detection of molecules and pollutant

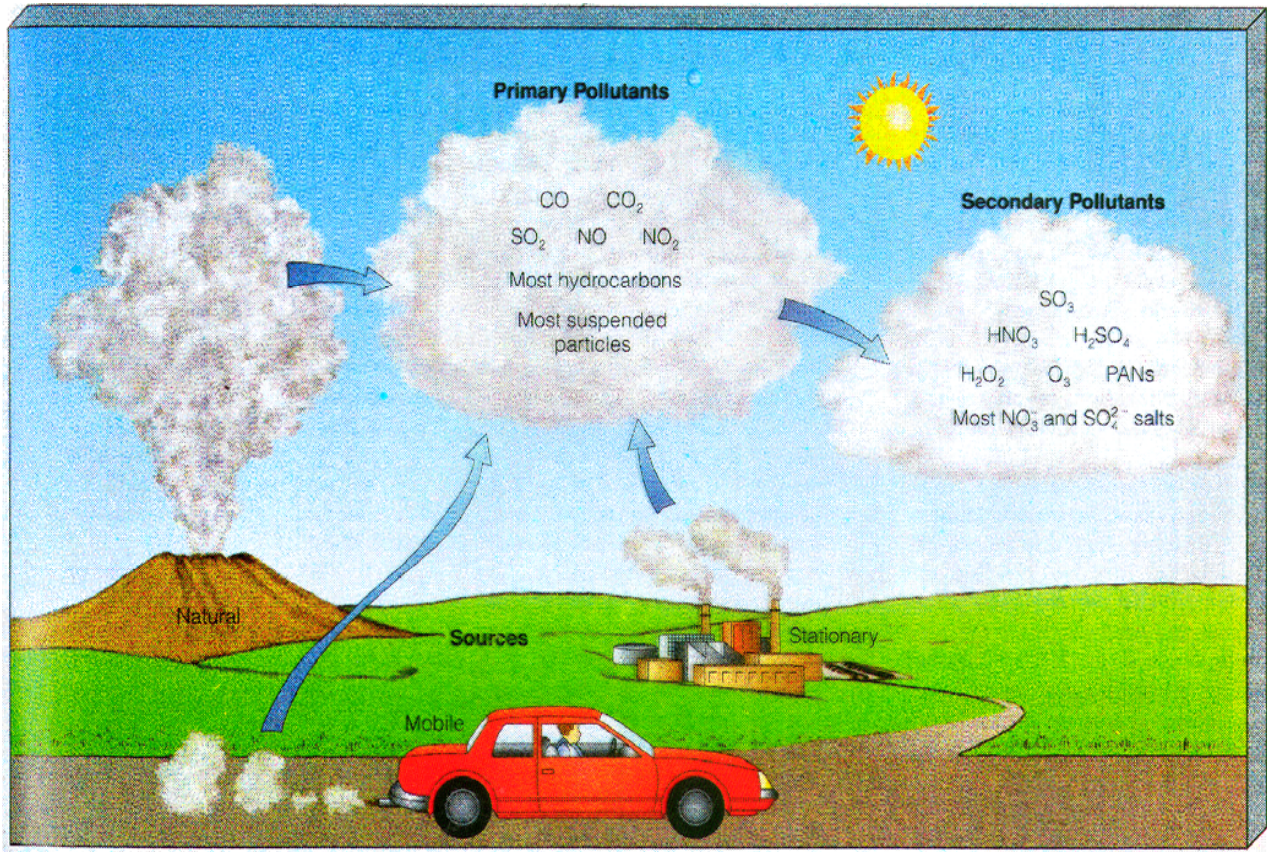
(DIAL Equation and Solution)

- Raman Lidar detection of molecules and pollutant

(Raman Equation and Solution)

Motivations to Study Constituents

- Atmospheric constituents are referred to the trace gases that occur in relatively small but sometimes highly variable concentrations. In our class, constituents mean the atomic or molecular trace gases in the atmosphere, excluding aerosols and clouds.


Primary Pollutants
CO CO_2
SO_2 NO NO_2
Most hydrocarbons
Most suspended particles
Secondary Pollutants
SO_3
HNO_3 H_2SO_4
H_2O_2 O_3 PANs
Most NO_3^- and SO_4^{2-} salts
Natural
Sources
Stationary
Mobile

Pollutant Gases in Earth Atmosphere

Note: the absorption cross-sections of molecules are about 6 orders of magnitude smaller than the metal atoms such as Na, Fe, K .

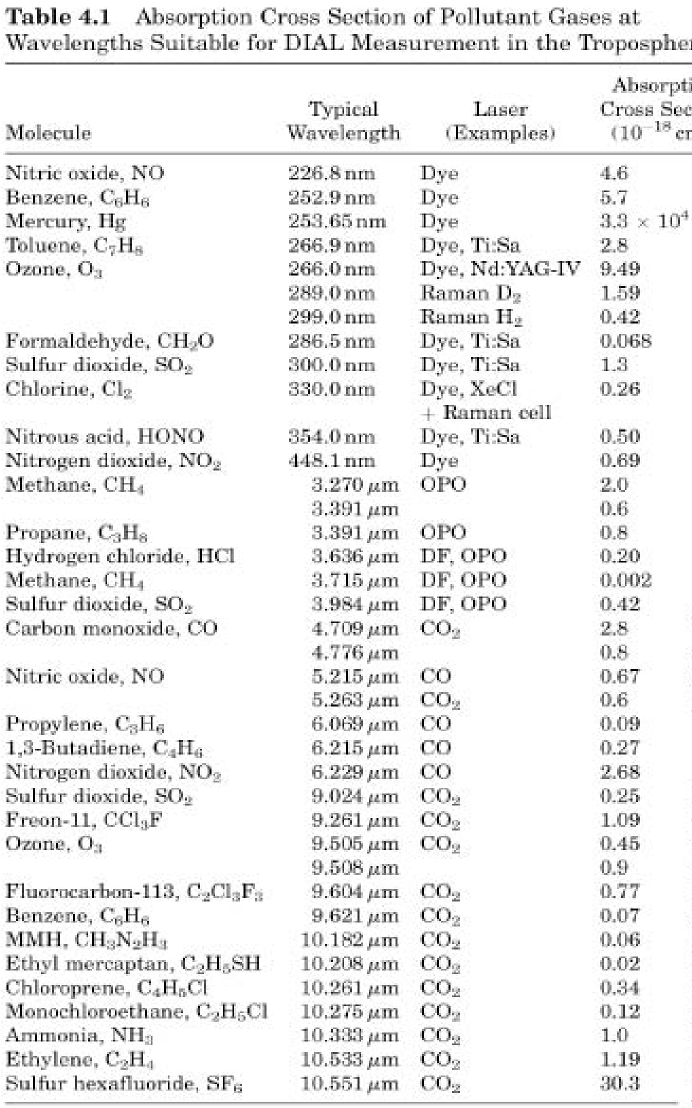


Table 4.1 Absorption Cross Section of Pollutant Gases at Wavelengths Suitable for DIAL Measurement in the Troposphere

Molecule	Typical Wavelength	Laser (Examples)	Absorption Cross Section (10^{-18} cm^2)
Nitric oxide, NO	226.8 nm	Dye	4.6
Benzene, C_6H_6	252.9 nm	Dye	5.7
Mercury, Hg	253.65 nm	Dye	3.3×10^4
Toluene, C_7H_8	266.9 nm	Dye, Ti:Sa	2.8
Ozone, O_3	266.0 nm	Dye, Nd:YAG-IV	9.49
	289.0 nm	Raman D_2	1.59
	299.0 nm	Raman H_2	0.42
Formaldehyde, CH_2O	286.5 nm	Dye, Ti:Sa	0.068
Sulfur dioxide, SO_2	300.0 nm	Dye, Ti:Sa	1.3
Chlorine, Cl_2	330.0 nm	Dye, XeCl + Raman cell	0.26
Nitrous acid, HONO	354.0 nm	Dye, Ti:Sa	0.50
Nitrogen dioxide, NO_2	448.1 nm	Dye	0.69
Methane, CH_4	3.270 μm	OPO	2.0
	3.391 μm		0.6
Propane, C_3H_8	3.391 μm	OPO	0.8
Hydrogen chloride, HCl	3.636 μm	DF, OPO	0.20
Methane, CH_4	3.715 μm	DF, OPO	0.002
Sulfur dioxide, SO_2	3.984 μm	DF, OPO	0.42
Carbon monoxide, CO	4.709 μm	CO_2	2.8
	4.776 μm		0.8
Nitric oxide, NO	5.215 μm	CO	0.67
	5.263 μm	CO_2	0.6
Propylene, C_3H_6	6.069 μm	CO	0.09
1,3-Butadiene, C_4H_6	6.215 μm	CO	0.27
Nitrogen dioxide, NO_2	6.229 μm	CO	2.68
Sulfur dioxide, SO_2	9.024 μm	CO_2	0.25
Freon-11, CCl_3F	9.261 μm	CO_2	1.09
Ozone, O_3	9.505 μm	CO_2	0.45
	9.508 μm		0.9
Fluorocarbon-113, $C_2Cl_3F_3$	9.604 μm	CO_2	0.77
Benzene, C_6H_6	9.621 μm	CO_2	0.07
MMH, $CH_3N_2H_3$	10.182 μm	CO_2	0.06
Ethyl mercaptan, C_2H_5SH	10.208 μm	CO_2	0.02
Chloroprene, C_4H_5Cl	10.261 μm	CO_2	0.34
Monochloroethane, C_2H_5Cl	10.275 μm	CO_2	0.12
Ammonia, NH_3	10.333 μm	CO_2	1.0
Ethylene, C_2H_4	10.533 μm	CO_2	1.19
Sulfur hexafluoride, SF_6	10.551 μm	CO_2	30.3

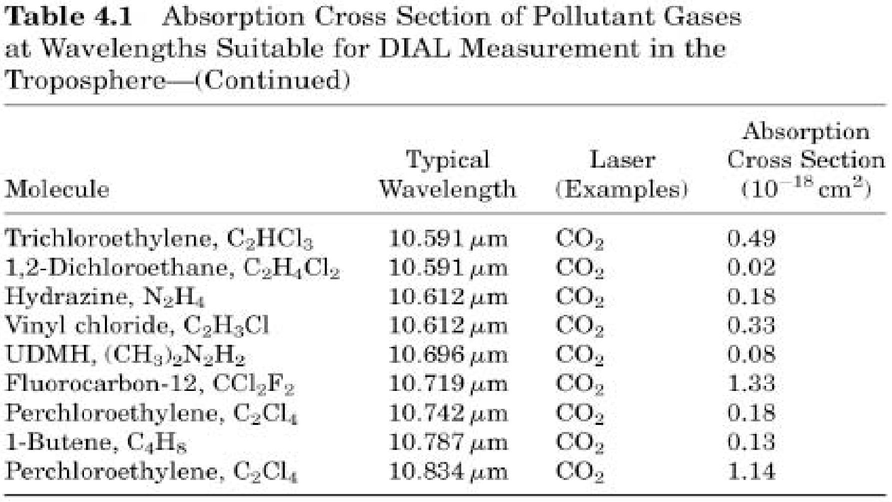


Table 4.1 Absorption Cross Section of Pollutant Gases at Wavelengths Suitable for DIAL Measurement in the Troposphere—(Continued)

Molecule	Typical Wavelength	Laser (Examples)	Absorption Cross Section (10^{-18} cm^2)
Trichloroethylene, C_2HCl_3	10.591 μm	CO_2	0.49
1,2-Dichloroethane, $C_2H_4Cl_2$	10.591 μm	CO_2	0.02
Hydrazine, N_2H_4	10.612 μm	CO_2	0.18
Vinyl chloride, C_2H_3Cl	10.612 μm	CO_2	0.33
UDMH, $(CH_3)_2N_2H_2$	10.696 μm	CO_2	0.08
Fluorocarbon-12, CCl_2F_2	10.719 μm	CO_2	1.33
Perchloroethylene, C_2Cl_4	10.742 μm	CO_2	0.18
1-Butene, C_4H_8	10.787 μm	CO_2	0.13
Perchloroethylene, C_2Cl_4	10.834 μm	CO_2	1.14

Differential Absorption Lidar

- For the molecular species to be detected by DIAL, usually they have strong absorption, however, nearly none resonance fluorescence due to strong relaxation processes other than fluorescence (e.g., frequent collisions with surrounding atmosphere molecules can make molecules decay from excited states to ground state without giving fluorescence).
- Thus, in the lidar equation for DIAL, the influence of molecular species is in the extinction (atmosphere transmission) part, not in the backscatter part. In other words, the molecular absorption contributes to the extinction of light when incident light and scattered light propagate through atmosphere, while the return signals are from the scattering of laser light by air molecules and aerosols.

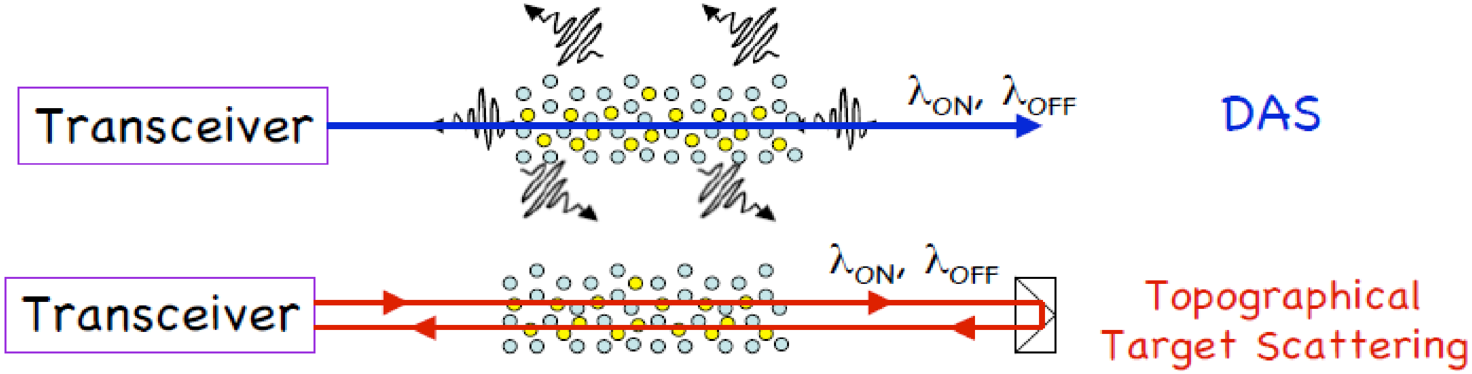
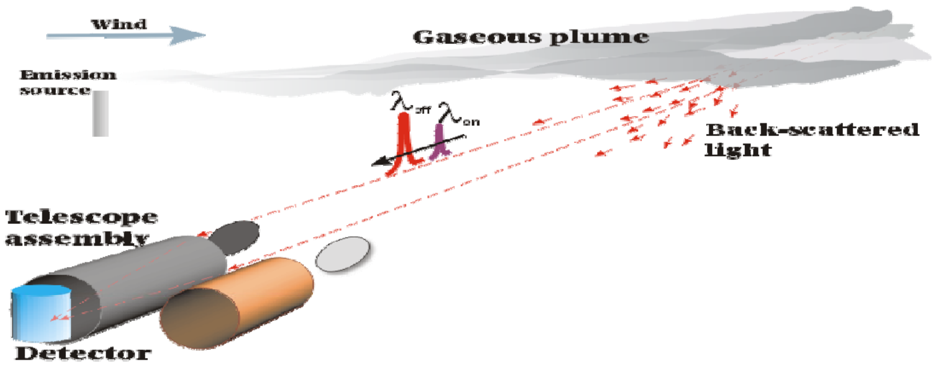


Illustration of the DIAL Concept

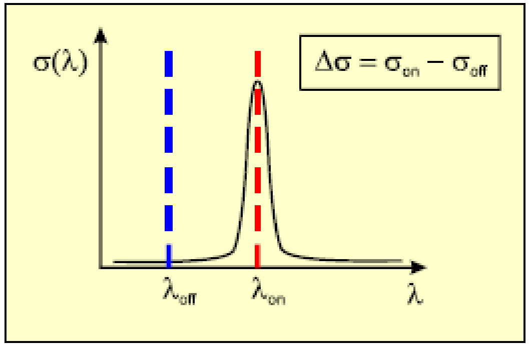


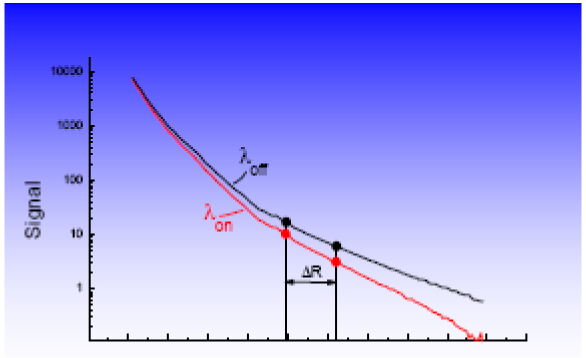
Case I: DIAL Elastic scattering from diffuse reflector (Mie & Rayleigh Scattering)

Elastic scattering is when the scattering frequency is the same as the frequency of the incident light (e.g.,Rayleigh scattering and Mie scattering)

$$N(R)=\frac{1}{2\Delta\sigma}\left[\frac{d}{dR}\left\{\ln\left[\frac{P(\lambda_{off},R)}{P(\lambda_0,R)}\right]-\ln\left[\frac{\beta(\lambda_{off},R)}{\beta(\lambda_0,R)}\right]\right\}+\overline{\kappa}(\lambda_{off},R)-\overline{\kappa}(\lambda_0,R)\right]$$

Where





Case II: Elastic scattering from a topographical target

$$\int_0^{R_T} N(R)dR = \frac{1}{2\Delta\sigma}\left[\ln\left[\frac{E(\lambda_{off}, R_T)}{E(\lambda_0, R_T)}\right] + \bar{\kappa}(\lambda_{off}, R) - \bar{\kappa}(\lambda_0, R)\right]$$

Lidar Equation for DIAL

❑ DIAL lidar equation

$$P_S(\lambda,R) = P_L(\lambda)\left[\beta_{scatter}(\lambda,R)\Delta R\right]\left(\frac{A}{R^2}\right)\exp\left[-2\int_0^R \overline{\alpha}(\lambda,r)\,dr\right]$$

$$\times\exp\left[-2\int_0^R \boxed{\sigma_{abs}(\lambda,r)n_c(r)}\,dr\right]\left[\eta(\lambda)G(R)\right]+P_B$$

Extinction caused by interested constituent absorption

Extinction caused by other molecules and aerosols

❑ Compared to resonance fluorescence, the main difference in DIAL is that the backscatter coefficient is from the elastic-scattering from air molecules and aerosols, not from the fluorescence of interested molecules.

$$\beta_{Scatter}(\lambda,R) = \beta_{aer}(\lambda,R) + \beta_{mol}(\lambda,R)$$

❑ The parameter in the DIAL equation

$$\overline{\alpha}(\lambda,r) = \alpha_{aer}(\lambda,r) + \alpha_{mol}(\lambda,r) + \sigma_{IG}(\lambda,r)n_{IG}(r)$$

Aerosol Extinction   Air Molecule Extinction   Interference gas absorption

DIAL Equation Cont'd

- ❑ Notice that the constituent information is already included in the extinction part. If the lidar parameters and aerosol/air molecule backscatter and extinction are known, we can derive the constituent number density from the lidar equation directly.
- ❑ Unfortunately, most of these parameters are unknown. So the DIAL technique is to utilize two wavelengths - one tuned to strong molecular absorption and another one detuned off the absorption line. Thus, most of the parameters can be cancelled or estimated to a much better degree, allowing the constituent information to be derived more truthfully.

$$\boxed{\begin{aligned} P_S(\lambda_{ON},R) = {} & P_L(\lambda_{ON})\left[(\beta_{aer}(\lambda_{ON},R)+\beta_{mol}(\lambda_{ON},R))\Delta R\right]\left(\frac{A}{R^2}\right)\exp\left[-2\int_0^R(\alpha_{aer}(\lambda_{ON},r)+\alpha_{mol}(\lambda_{ON},r))dr\right] \\ & \times\exp\left[-2\int_0^R\sigma_{IG}(\lambda_{ON},r)n_{IG}dr\right]\exp\left[-2\int_0^R\sigma_{abs}(\lambda_{ON},r)n_c(r)dr\right]\left[\eta(\lambda_{ON})G(R)\right]+P_B \end{aligned}}$$

$$\boxed{\begin{aligned} P_S(\lambda_{OFF},R) = {} & P_L(\lambda_{OFF})\left[(\beta_{aer}(\lambda_{OFF},R)+\beta_{mol}(\lambda_{OFF},R))\Delta R\right]\left(\frac{A}{R^2}\right)\exp\left[-2\int_0^R(\alpha_{aer}(\lambda_{OFF},r)+\alpha_{mol}(\lambda_{OFF},r))dr\right] \\ & \times\exp\left[-2\int_0^R\sigma_{IG}(\lambda_{OFF},r)n_{IG}dr\right]\exp\left[-2\int_0^R\sigma_{abs}(\lambda_{OFF},r)n_c(r)dr\right]\left[\eta(\lambda_{OFF})G(R)\right]+P_B \end{aligned}}$$

Solution for DIAL Equations

- To derive solution for DIAL equations, we take the ratio between the ON and OFF wavelength equations and take the logarithm of the ratio:

$$\boxed{\begin{aligned}\ln\left[\frac{P_S(\lambda_{ON},R)-P_B}{P_S(\lambda_{OFF},R)-P_B}\right] &= \ln\left[\frac{P_L(\lambda_{ON})\big(\beta_{aer}(\lambda_{ON},R)+\beta_{mol}(\lambda_{ON},R)\big)\eta(\lambda_{ON})}{P_L(\lambda_{OFF})\big(\beta_{aer}(\lambda_{OFF},R)+\beta_{mol}(\lambda_{OFF},R)\big)\eta(\lambda_{OFF})}\right]\\ &\quad -2\int_0^R\left[\alpha_{aer}(\lambda_{ON},r)-\alpha_{aer}(\lambda_{OFF},r)\right]dr\\ &\quad -2\int_0^R\left[\alpha_{mol}(\lambda_{ON},r)-\alpha_{mol}(\lambda_{OFF},r)\right]dr\\ &\quad -2\int_0^R\left[\sigma_{IG}(\lambda_{ON},r)-\sigma_{IG}(\lambda_{OFF},r)\right]n_{IG}dr\\ &\quad -2\int_0^R\left[\sigma_{abs}(\lambda_{ON},r)-\sigma_{abs}(\lambda_{OFF},r)\right]n_c(r)dr\end{aligned}}$$

- Note: several factors have been eliminated from the equation: ΔR, A/R^2, $G(R)$, as the ON and OFF wavelength laser lights are transmitted and received through the save transmitter and receiver, so share the same geometry factor and the same receiver aperture.

Solution for DIAL Cont'd

- Take the differentiation of the equation, we obtain the number density of the constituent that we are interested in

$$
\begin{array}{ll}
n_c(R) = \dfrac{1}{2\Delta\sigma_{abs}}\dfrac{d}{dR}\left\{
\begin{array}{l}
\ln\left[\dfrac{P_S(\lambda_{OFF},R)-P_B}{P_S(\lambda_{ON},R)-P_B}\right] \\
-\ln\left[\dfrac{P_L(\lambda_{OFF})\eta(\lambda_{OFF})}{P_L(\lambda_{ON})\eta(\lambda_{ON})}\right] \\
-\ln\left[\dfrac{\beta_{aer}(\lambda_{OFF},R)+\beta_{mol}(\lambda_{OFF},R)}{\beta_{aer}(\lambda_{ON},R)+\beta_{mol}(\lambda_{ON},R)}\right]
\end{array}
\right\}
&
\begin{array}{l}
\text{A} \\[2em]
\text{B} \\[2em]
\text{C}
\end{array}
\\
\qquad -\dfrac{1}{\Delta\sigma_{abs}}\left\{
\begin{array}{l}
\left[\alpha_{aer}(\lambda_{ON},R)-\alpha_{aer}(\lambda_{OFF},R)\right] \\
+\left[\alpha_{mol}(\lambda_{ON},R)-\alpha_{mol}(\lambda_{OFF},R)\right] \\
+\left[\sigma_{IG}(\lambda_{ON},R)-\sigma_{IG}(\lambda_{OFF},R)\right]n_{IG}
\end{array}
\right\}
&
\begin{array}{l}
\text{D} \\
\text{E} \\
\text{F}
\end{array}
\end{array}
$$

- Here, the $\Delta\sigma_{abs}$ is called the differential absorption cross-section

$$
\begin{aligned}
\Delta\sigma_{abs}(R) &= \sigma_{abs}(\lambda_{ON},R)-\sigma_{abs}(\lambda_{OFF},R) \\
&= \sigma_{abs}(\lambda_{ON})-\sigma_{abs}(\lambda_{OFF})
\end{aligned}
$$

DIAL Solution in Simple Case

- ☐ In the case that the ON and OFF wavelengths have small separation, the laser power, lidar efficiency, aerosol/molecule backscatter coefficient and extinction coefficient are close to be the same for the ON and OFF wavelengths. Therefore, terms B-E are zero. Also, assume there is no interference gas present, so term F is zero. Then we have

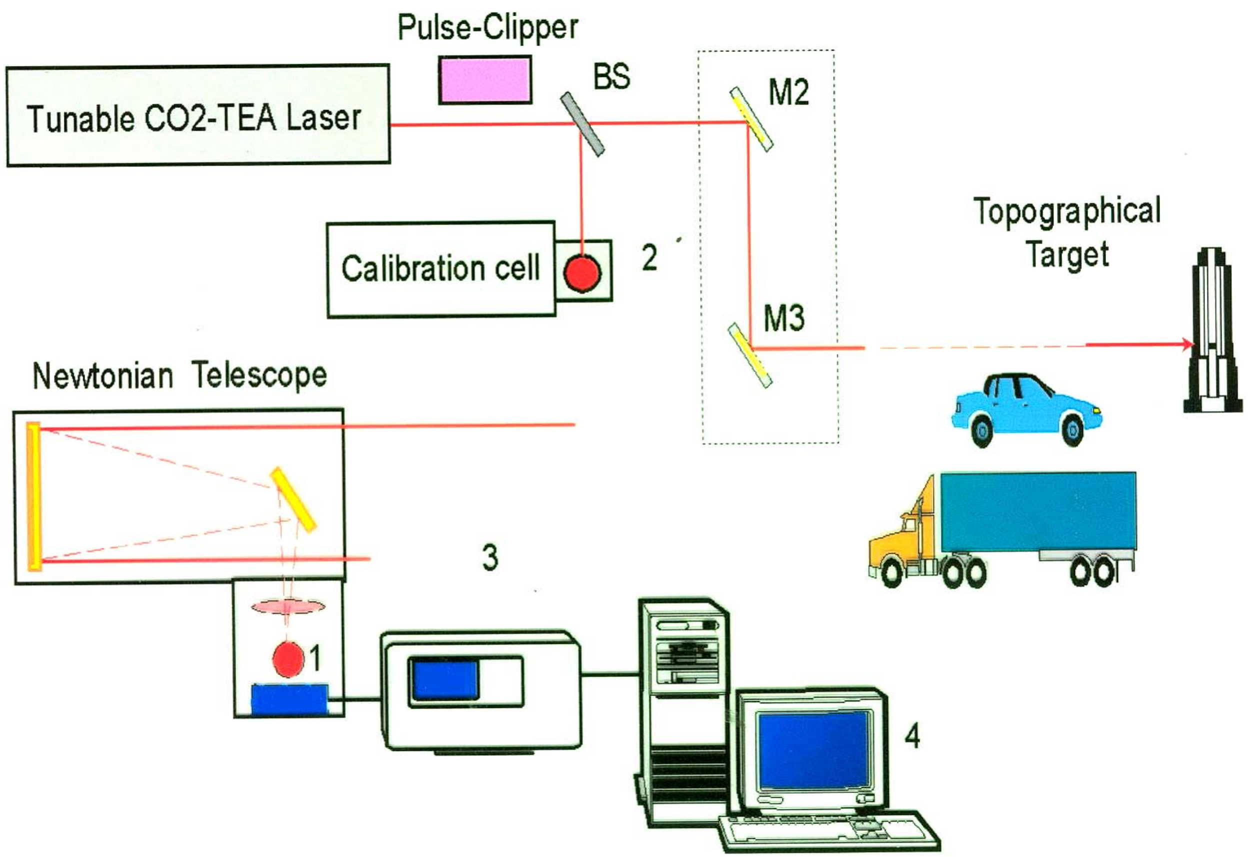
$$\boxed{n_c(R) = \frac{1}{2\Delta\sigma_{abs}} \frac{d}{dR}\left\{ \ln\left[\frac{P_S(\lambda_{OFF}, R) - P_B}{P_S(\lambda_{ON}, R) - P_B} \right] \right\}}$$

- ☐ In practice, lidar signals are not recorded or analyzed as continuous functions, but rather as values in discrete range bins. Thus, the above solution should be expressed in terms of a range increment ΔR:

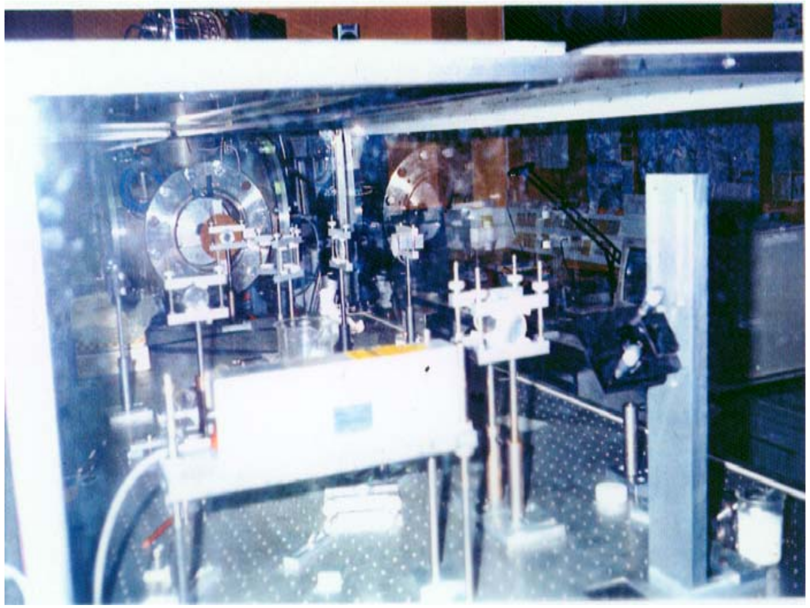
$$\boxed{n_c(R) = \frac{1}{2\Delta\sigma_{abs}\Delta R} \ln\left[\frac{P_S(\lambda_{OFF}, R+\Delta R) - P_B}{P_S(\lambda_{ON}, R+\Delta R) - P_B} \cdot \frac{P_S(\lambda_{ON}, R) - P_B}{P_S(\lambda_{OFF}, R) - P_B} \right]}$$

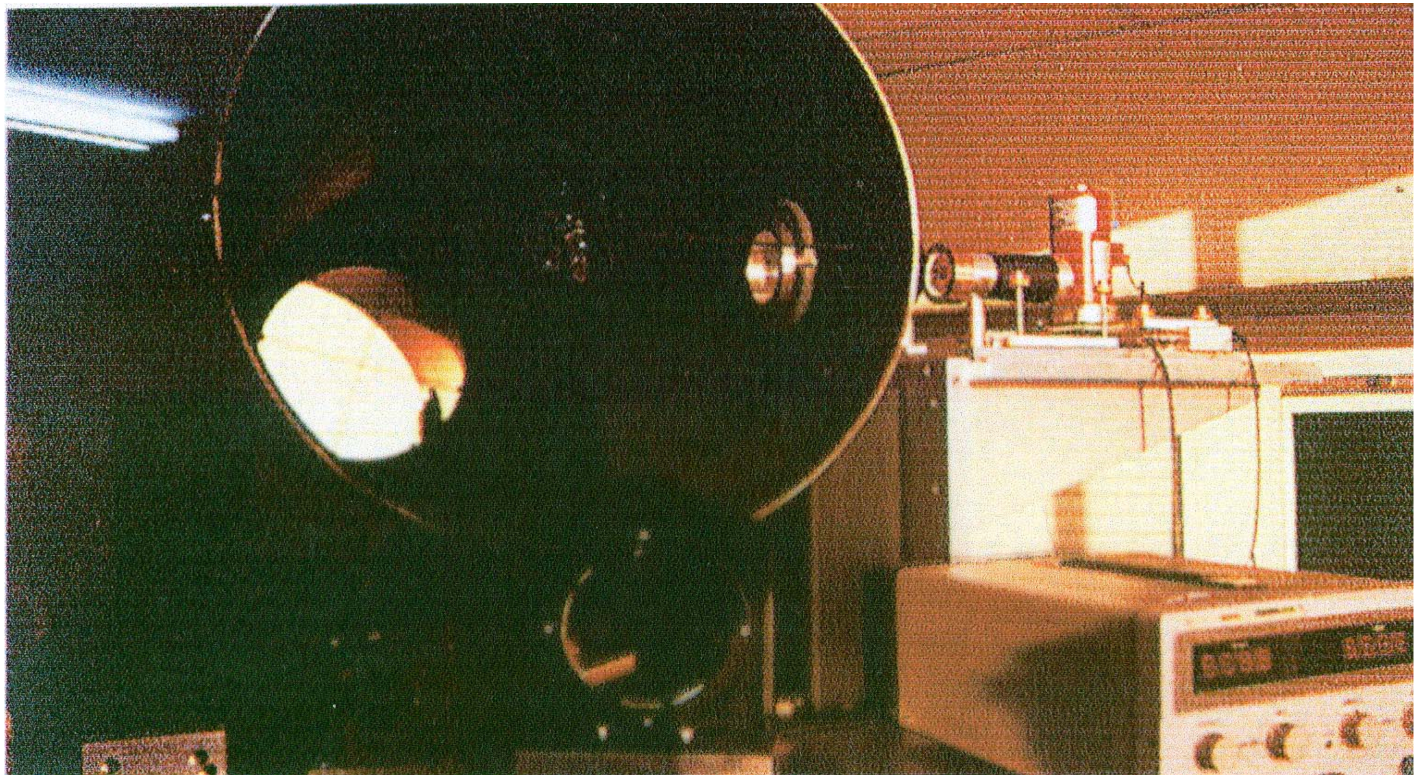
- ☐ Number density average between range R_1 and R_2

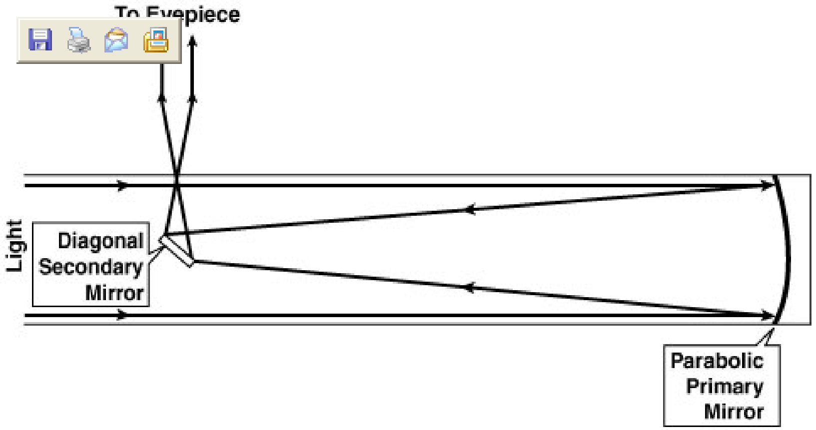
$$\boxed{n_c = \frac{1}{2\Delta\sigma_{abs}\Delta R} \ln\left[\frac{P_S(\lambda_{OFF}, R_2) - P_B}{P_S(\lambda_{ON}, R_2) - P_B} \cdot \frac{P_S(\lambda_{ON}, R_1) - P_B}{P_S(\lambda_{OFF}, R_1) - P_B} \right]}$$

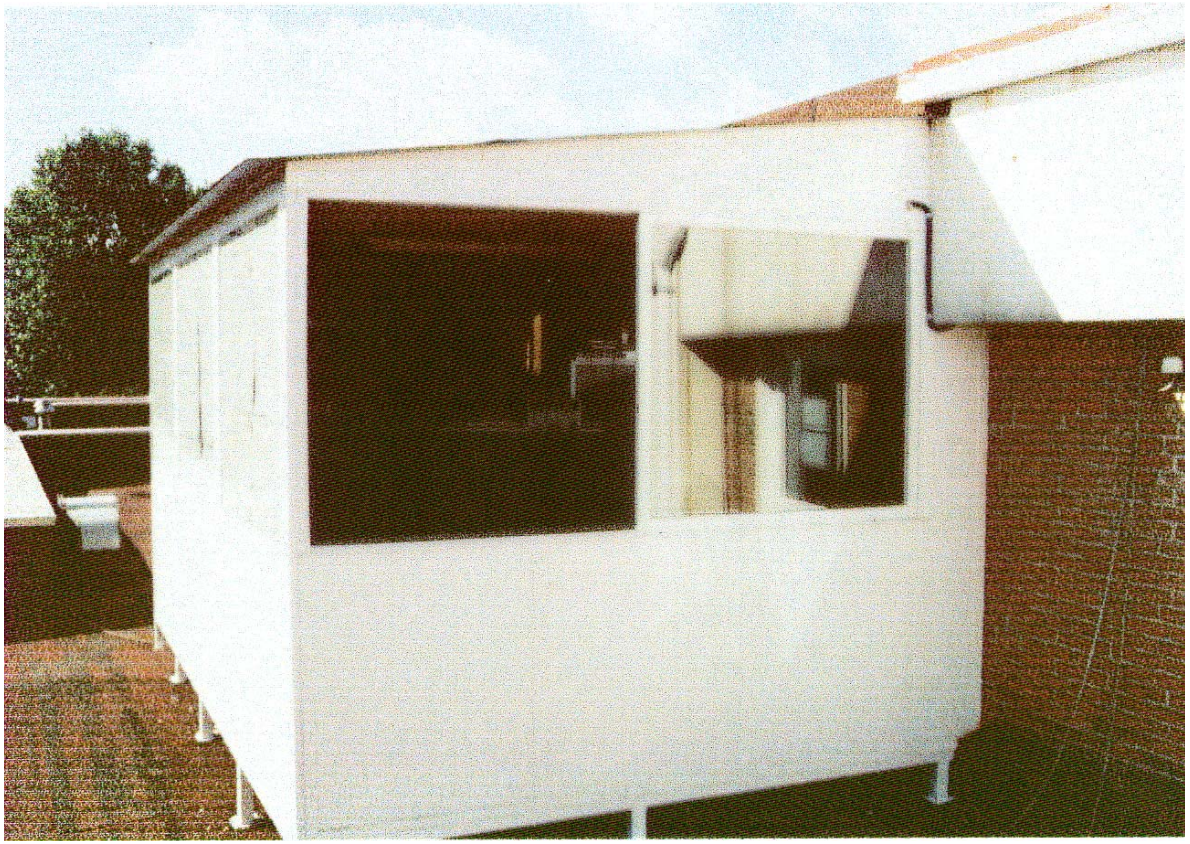


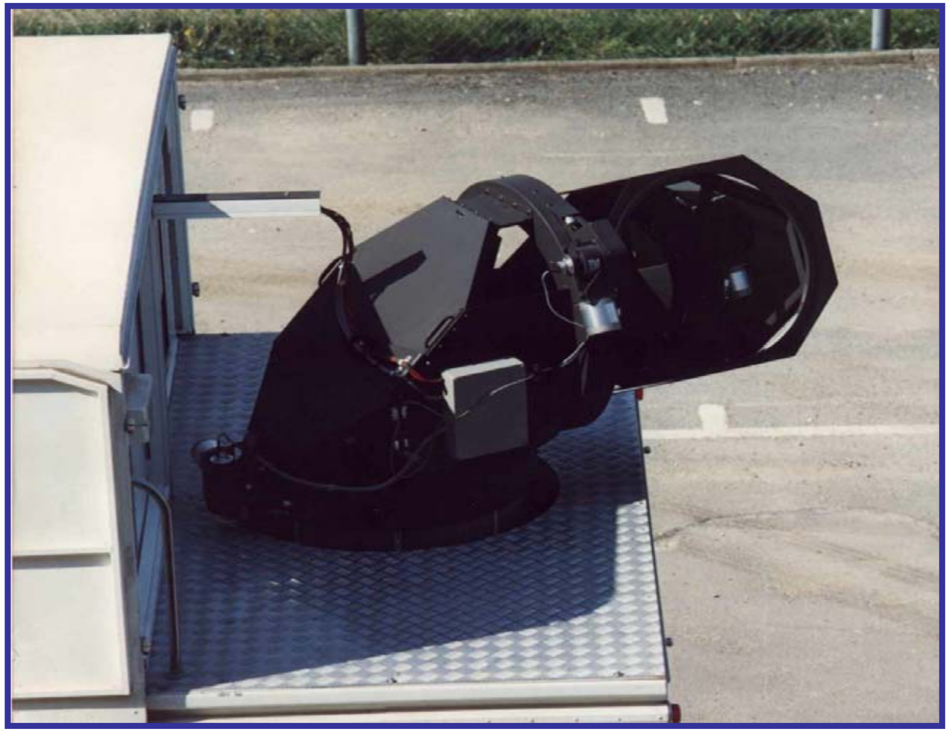
Schematic diagram of the Dial system:
1) Photo-detection and signal boosting stage, **2)** Signal calibration, **3)** Signal digitization, **4)** Data processing and storage, M2-M3: Steering mirrors, BS: Beam splitter, **5)** Topographical target.



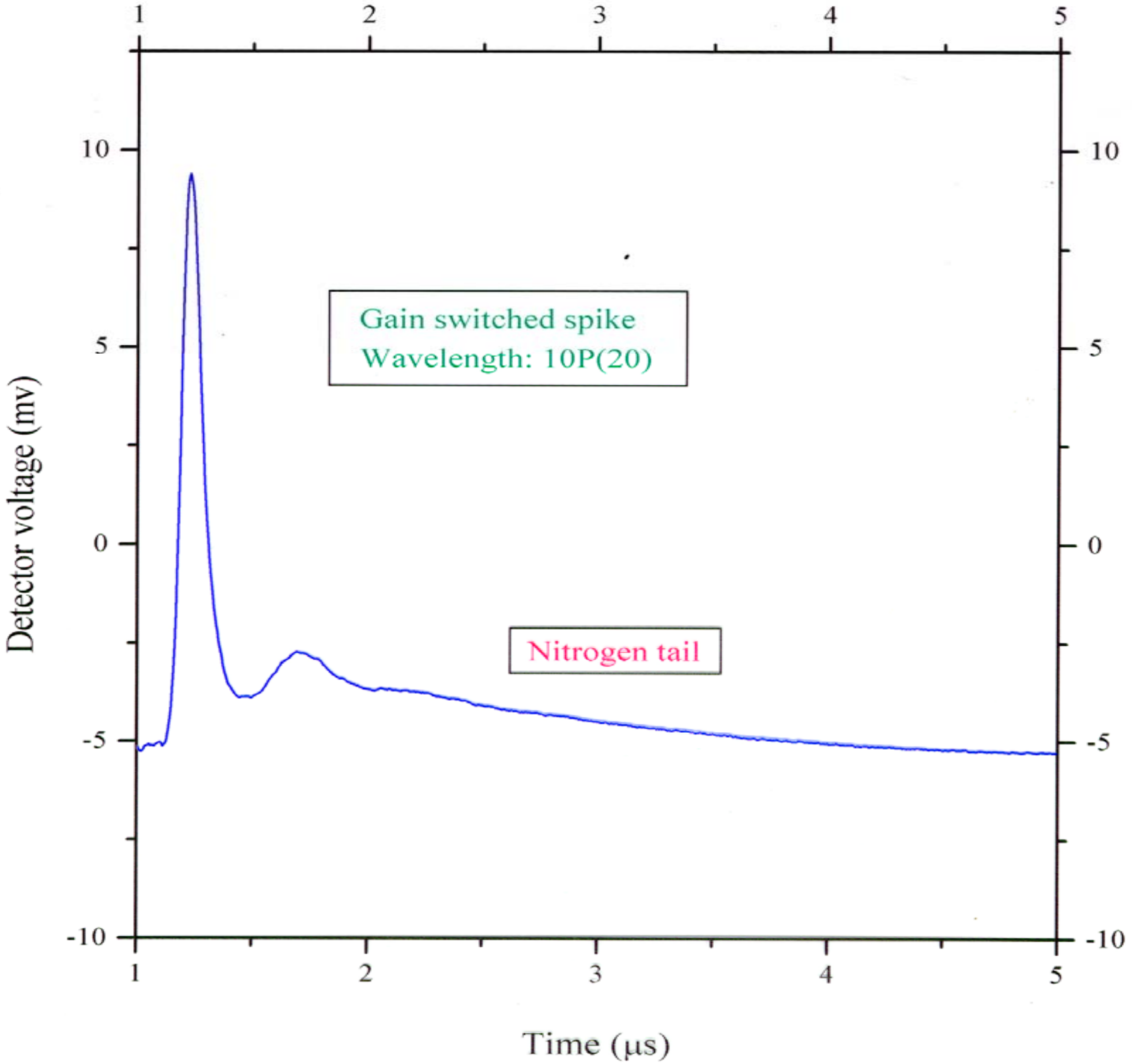


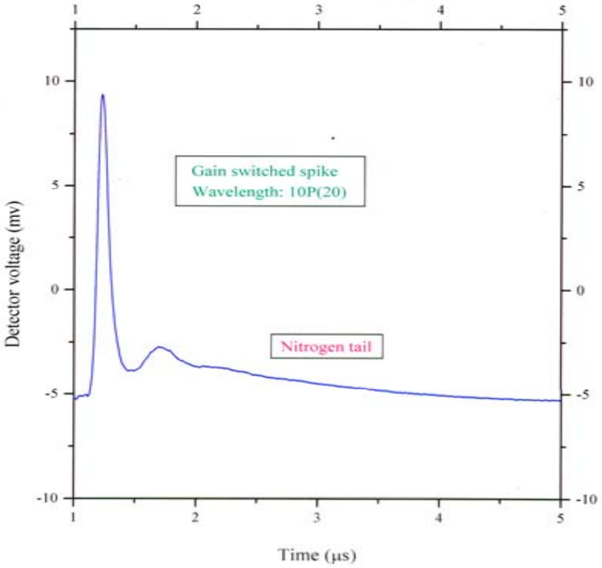

To Eyepiece
Light
Diagonal Secondary Mirror
Parabolic Primary Mirror

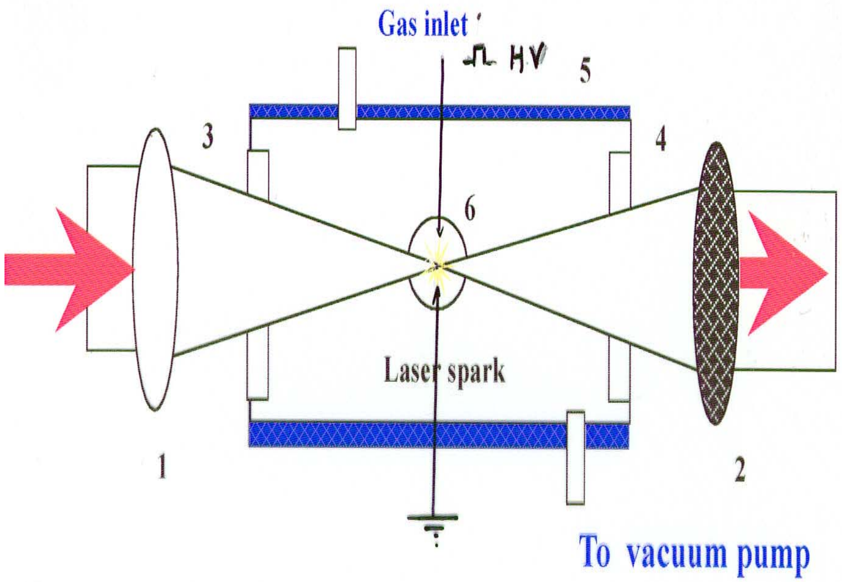




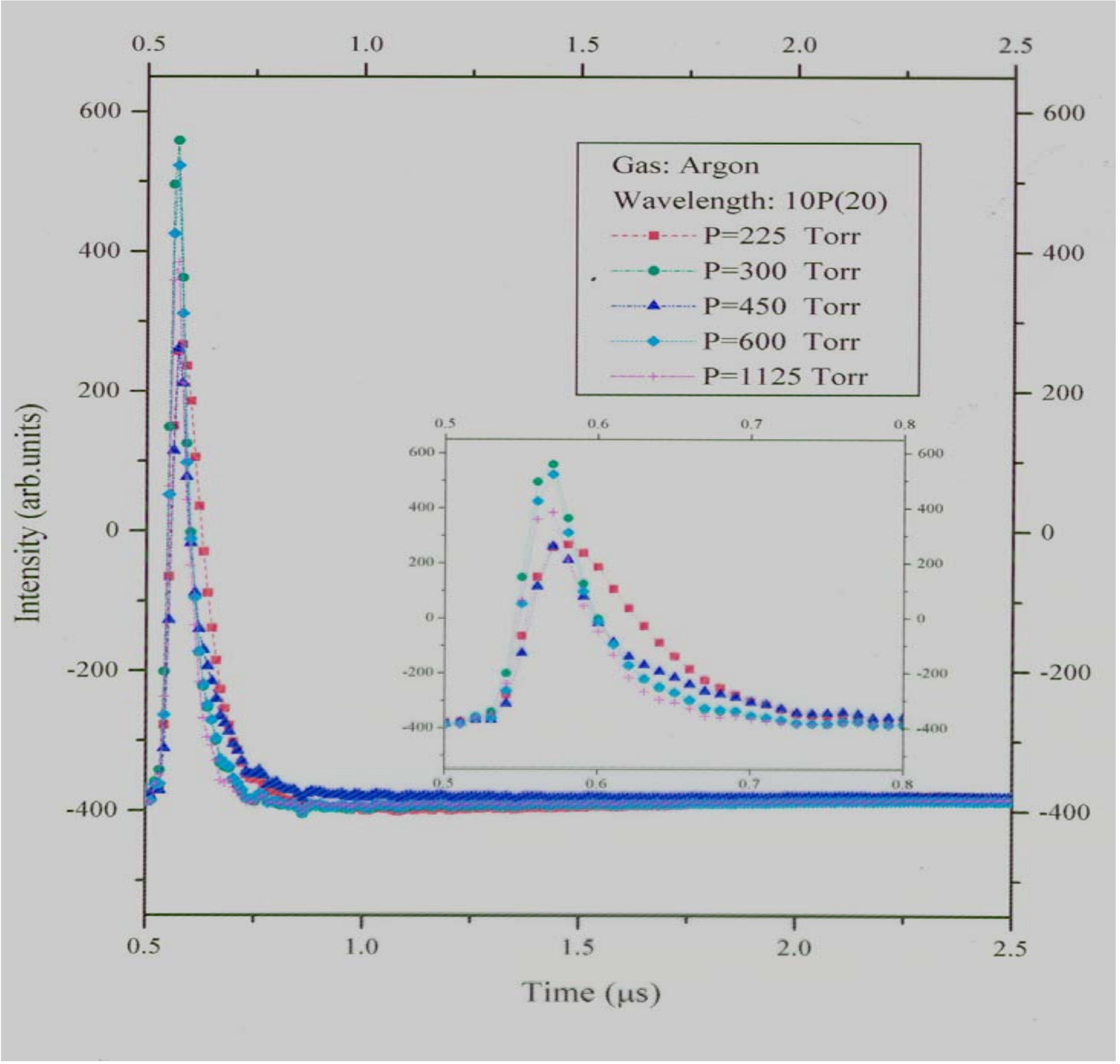
View of the 3-D scanner

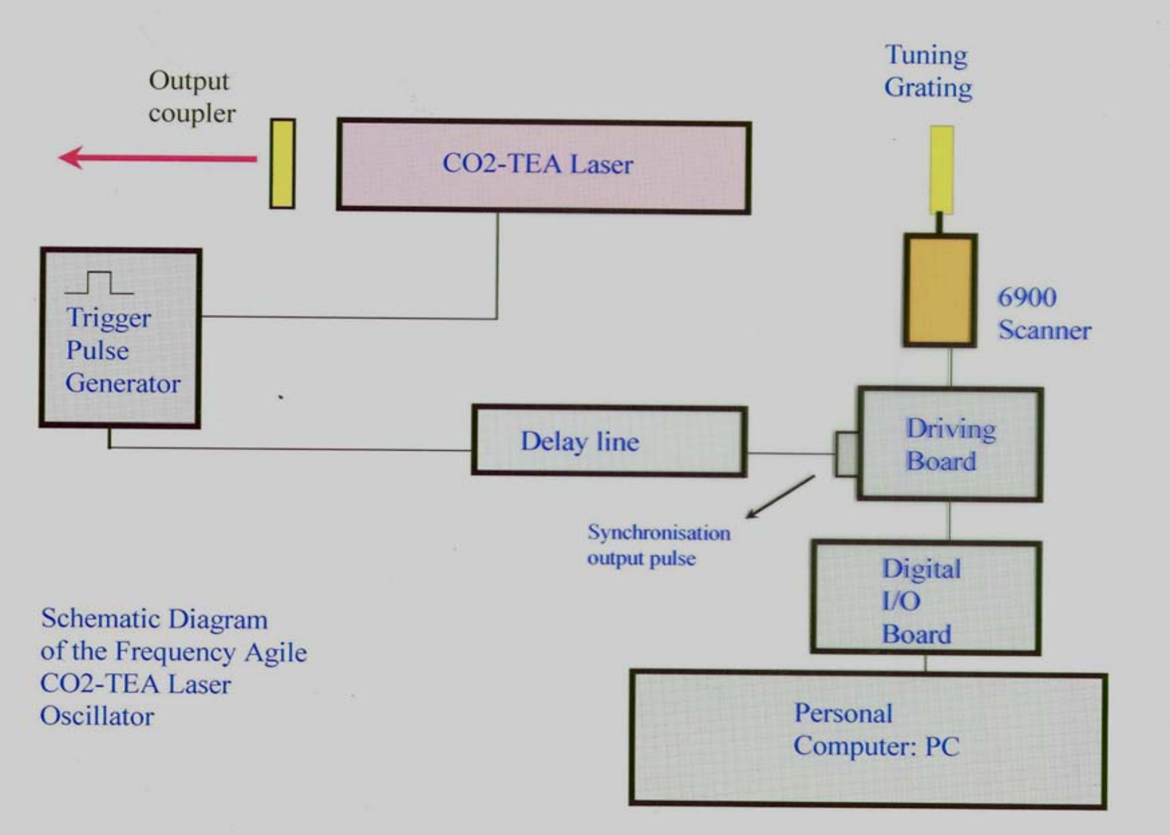

1
2
3
4
5
10
5
0
-5
-10
Detector voltage (mv)
Gain switched spike
Wavelength: 10P(20)
Nitrogen tail
Time (μs)





1- Incoming beam is focussed by lens 1 to an intensity very close to gas breakdown
2- High voltage pulse triggers the breakdown
3- Plasma once generated absorbs the remaining energy of the laser pulse
4- Lens 2 collimates the beam

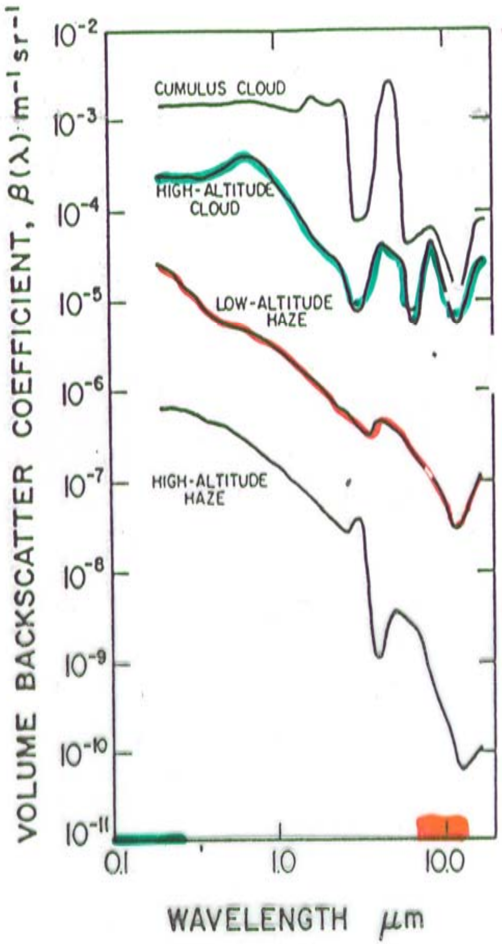

Gas: Argon
Wavelength: 10P(20)
P=225 Torr
P=300 Torr
P=450 Torr
P=600 Torr
P=1125 Torr
Intensity (arb.units)
Time (µs)
0.5
1.0
1.5
2.0
2.5
600
400
200
0
-200
-400
0.6
0.7
0.8



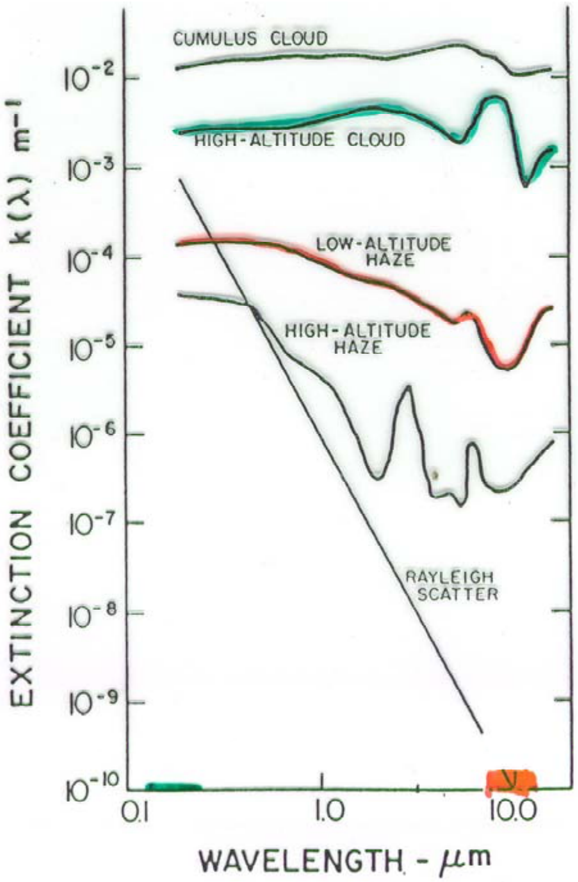
Schematic Diagram of the Frequency Agile CO2-TEA Laser Oscillator

Characteristics and performance of the CO_2-TEA DIAL

Parameters	Specifications
Transmitter	
Laser	Tunable, pulsed CO_2-TEA Lumonics 370XT upgraded at 20 Hz
Pulse width	Unclipped pulse: 3.5 µs Clipped with plasma shutter:<70 ns
Energy	1.2 J (gain-switched spike at P20)
Repetition rate	2-20 Hz
Wavelength	9.2 to 10.8 µm
Tuning	Scanner computer controlled
Receiver module	
Telescope	Newtonian φ=40cm. F=183cm, F#/4.5
Field of view	<5 mrad.
Detector	EG&G LN cooled: J15-D12
Data acquisition	
Computer	PC 3 GHz, 1Gb Ram
Software language	C++
Digitization	Tektronix TDS 540-200 MHz
Interfaces	IEEE-488



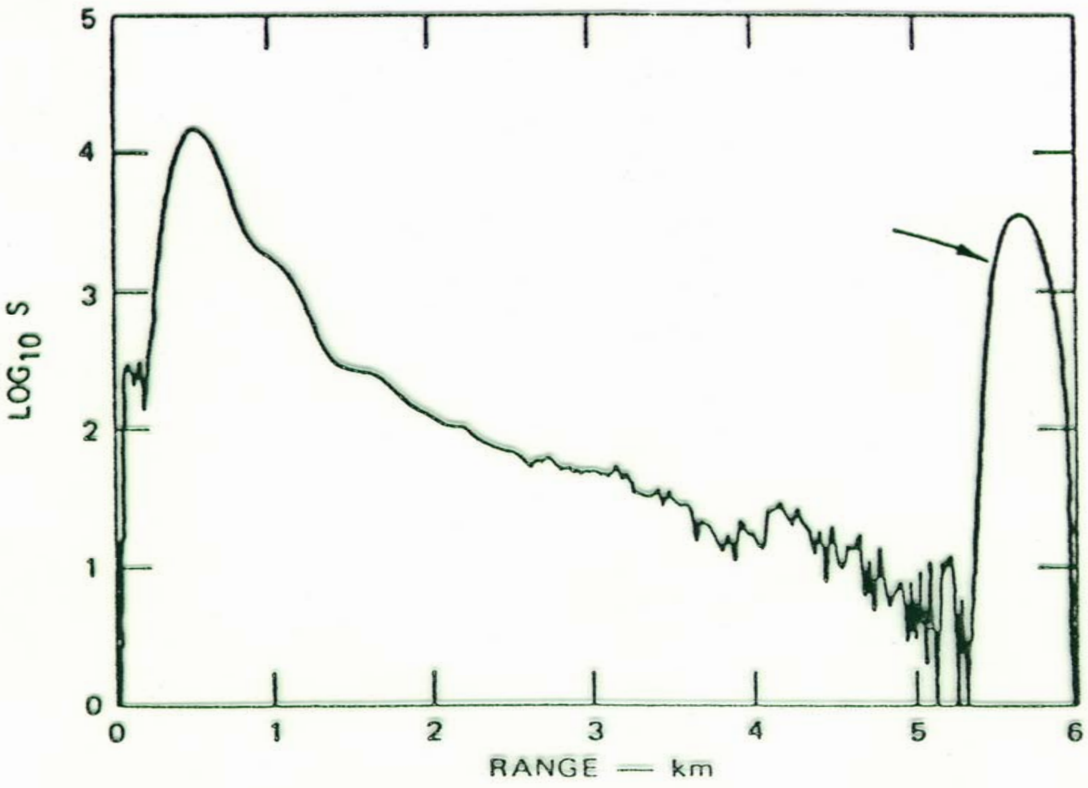
Aerosol volume backscattering coefficient as a function of wavelength (Wright et al



Aerosol extinction coefficient as a function of wavelength (Wright et

Aerosol Volume Backscattering and Extinction Coefficients in the NIR

(CO_2 laser wavelengths and others)



Backscattered signal measured with the ir lidar system.

Logarithmic Amplification of IR LIDAR Return Signal. SNR~300

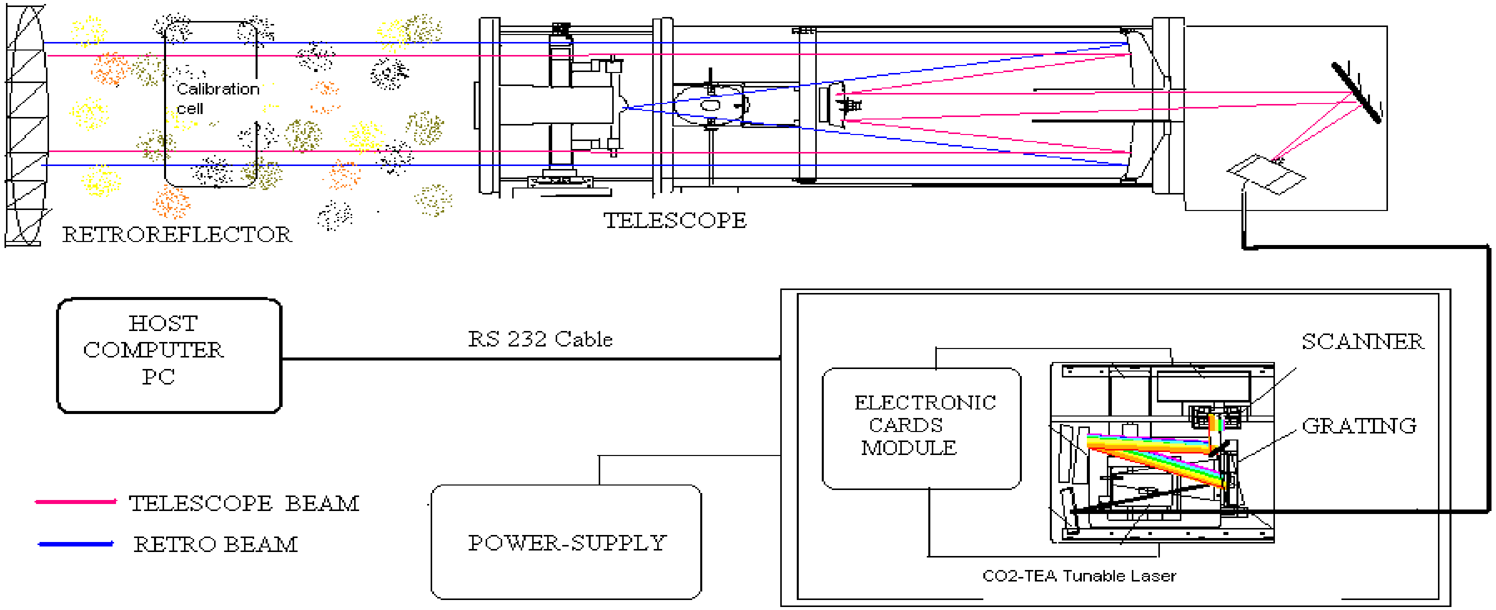
Atmospheric Ammonia

It is produced by a combination of natural and anthropogenic sources.
Concentration of ambient NH_3 varies between 3ppb and 10ppb.

Detection and measurement of Ammonia are important:

- Concentration of NH_3 is critical parameter in the rates of formation, transport, transformation and removal of sulfur and nitrogen oxides.
- Nitrogen aerosols play an important role in the generation of acid rain.

LIDAR Calibration using Ammonia

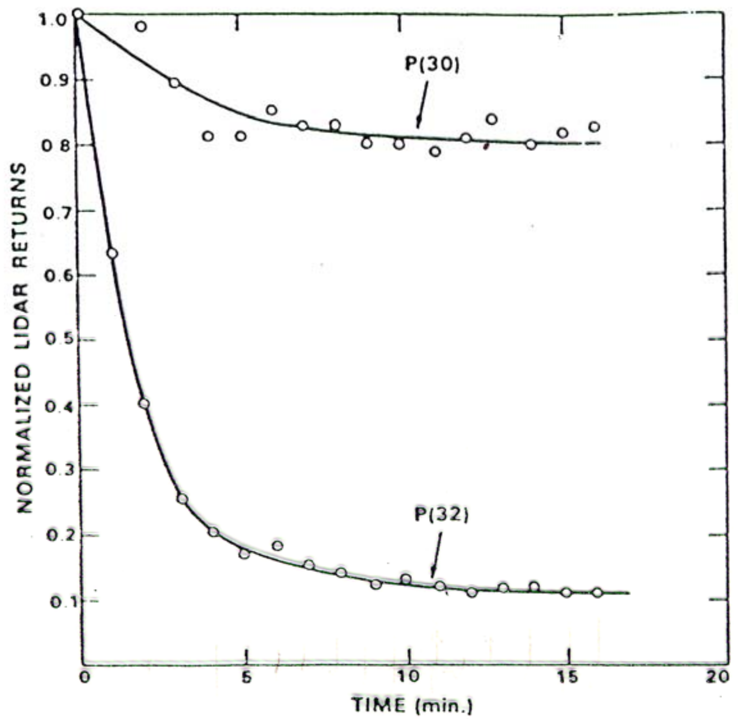


Ammonia Measurements Near a Corn Field

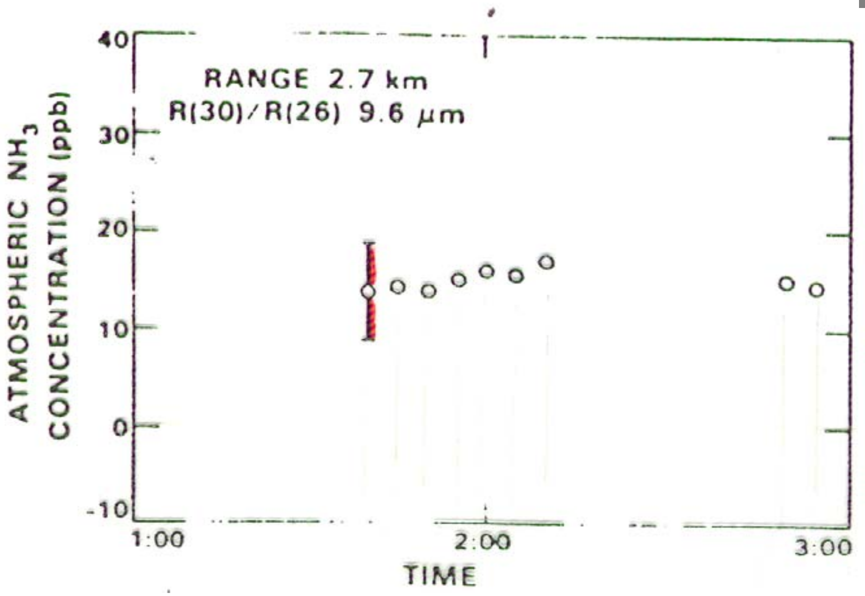
$\alpha(P30) = 1.1 \ (\text{atm. cm})^{-1}$

$\alpha(P32) = 12 \ (\text{atm. cm})^{-1}$

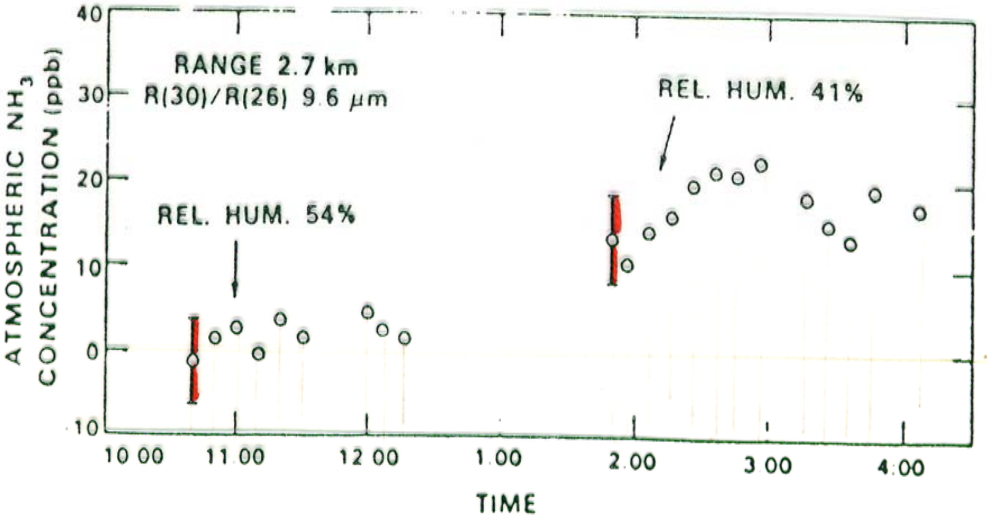
Time variation of LIDAR returns of 10.69-μm P(30) and 10.71- μm P(32) radiation passing through the tank and reflected from a topographic target at a range of 2.7 km after injecting 0.2 cm^3 of 28% aqueous NH_3



Ammonia Measurements Near a Corn Field



Single-laser DIAL measurement of ambient atmospheric NH_3 using 9.24-μm R(26) and 9.22-μm R(30) CO_2 laser lines over a 2.7-km range with 26% relative humidity



DIAL measurement of ambient atmospheric NH_3 using 9.24-μm R(26) and 9.22-μm R(30) CO_2 laser lines over a 2.7-km range showing the effect of a change in relative humidity from 54 to 41%

Ozone and Ozone Layer:

-Ozone is a naturally occurring gas found in the Earth's atmosphere that absorbs certain wavelengths of the sun's UV radiation.

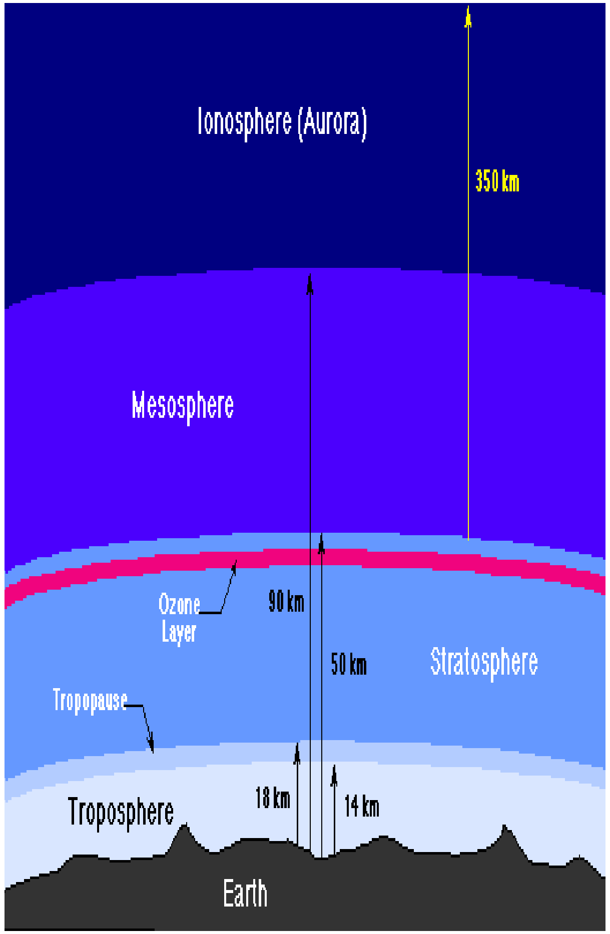
-Ozone Layer: around 15-35 Km above the earth's surface.

-10% of the total ozone is found in the troposphere.

-The troposphere contains 90% of the atmosphere and nearly all the atmosphere's water vapor.

Tropospheric Ozone:

-the layer between the earth's surface and tropopause (border between troposphere and stratosphere) contains only a fraction of the ozone. Due to multiple scattering (dust and aerosols) of rays within this layer, the solar UV is absorbed there more efficiently than within an equal amount of stratospheric ozone.



-In spite of this benefit, tropospheric ozone is often referred to as "bad ozone" or "bad Nearby" because of its adverse effects.

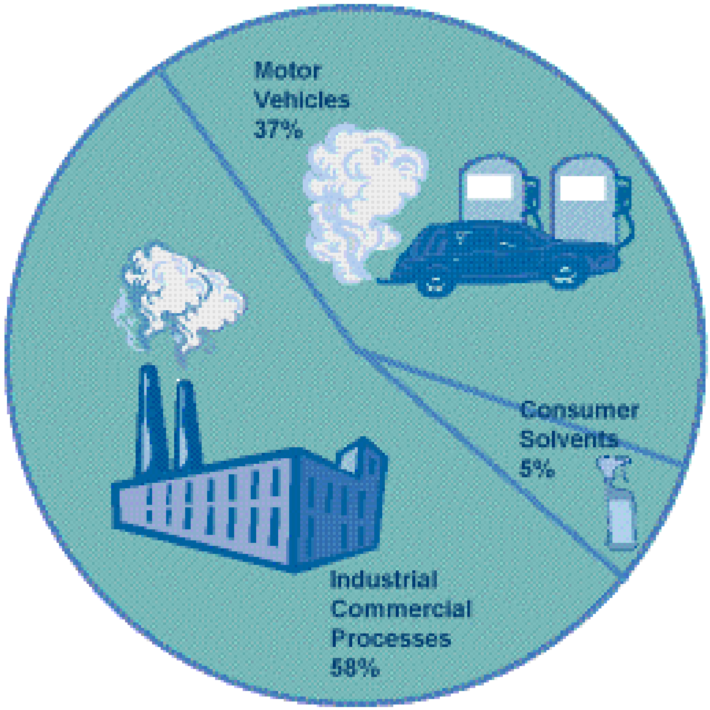
Ozone in the Troposphere
“Bad Nearby”

- VOCs = volatile organic compounds

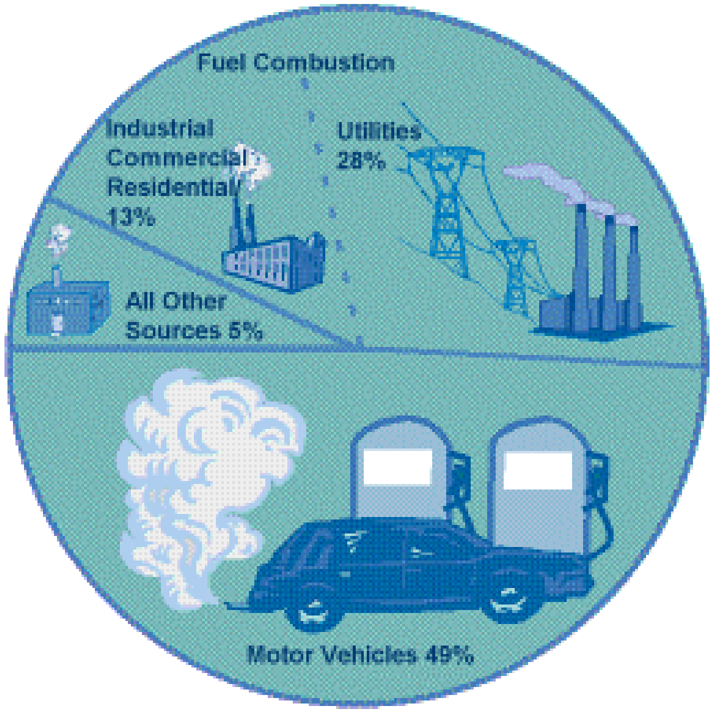
- NO_X = nitrogen oxides

VOC + NOx + Heat + Sunlight = Ozone

VOCs and NO_X result primarily from combustion of fossil fuels

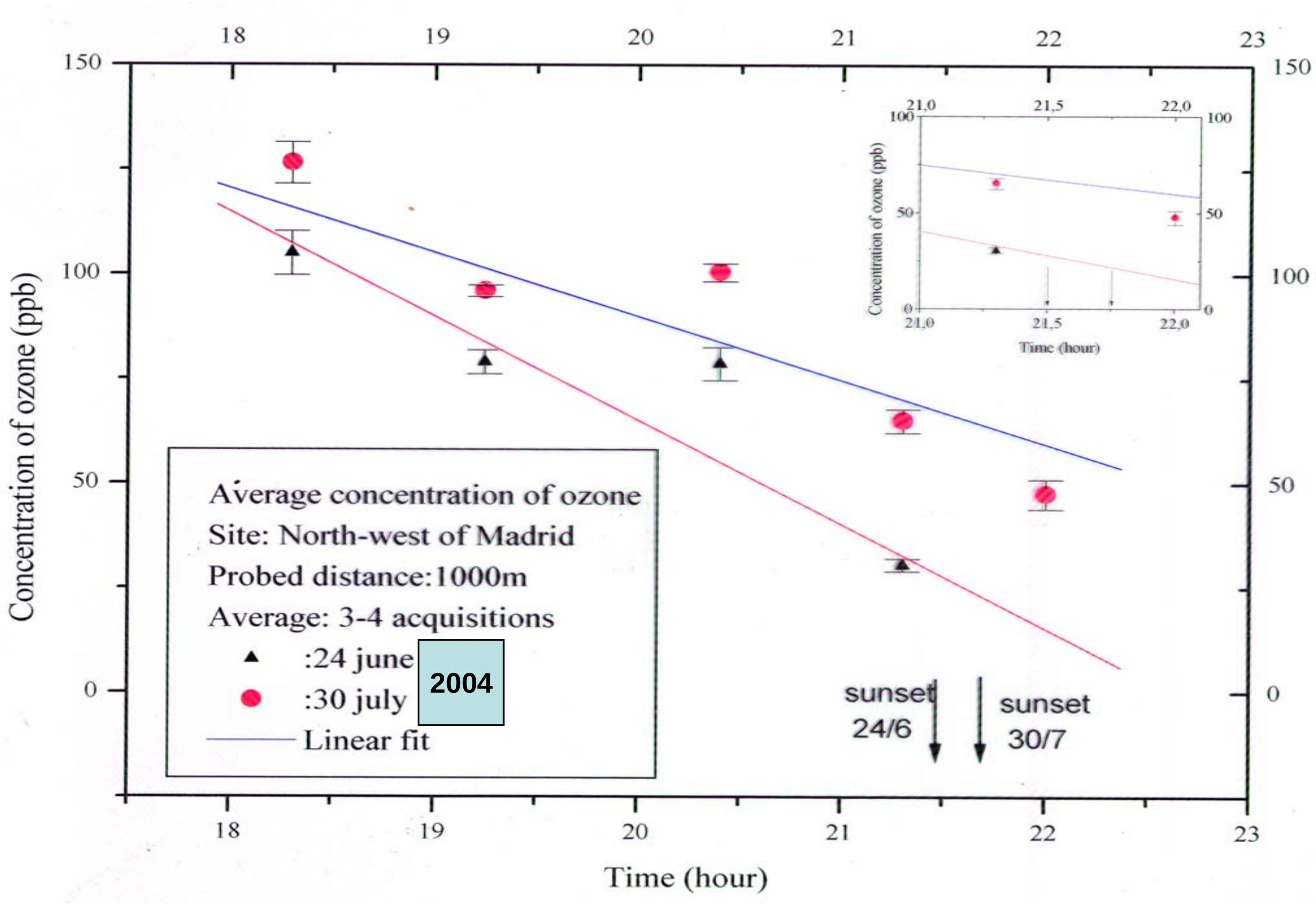


Sources of VOC



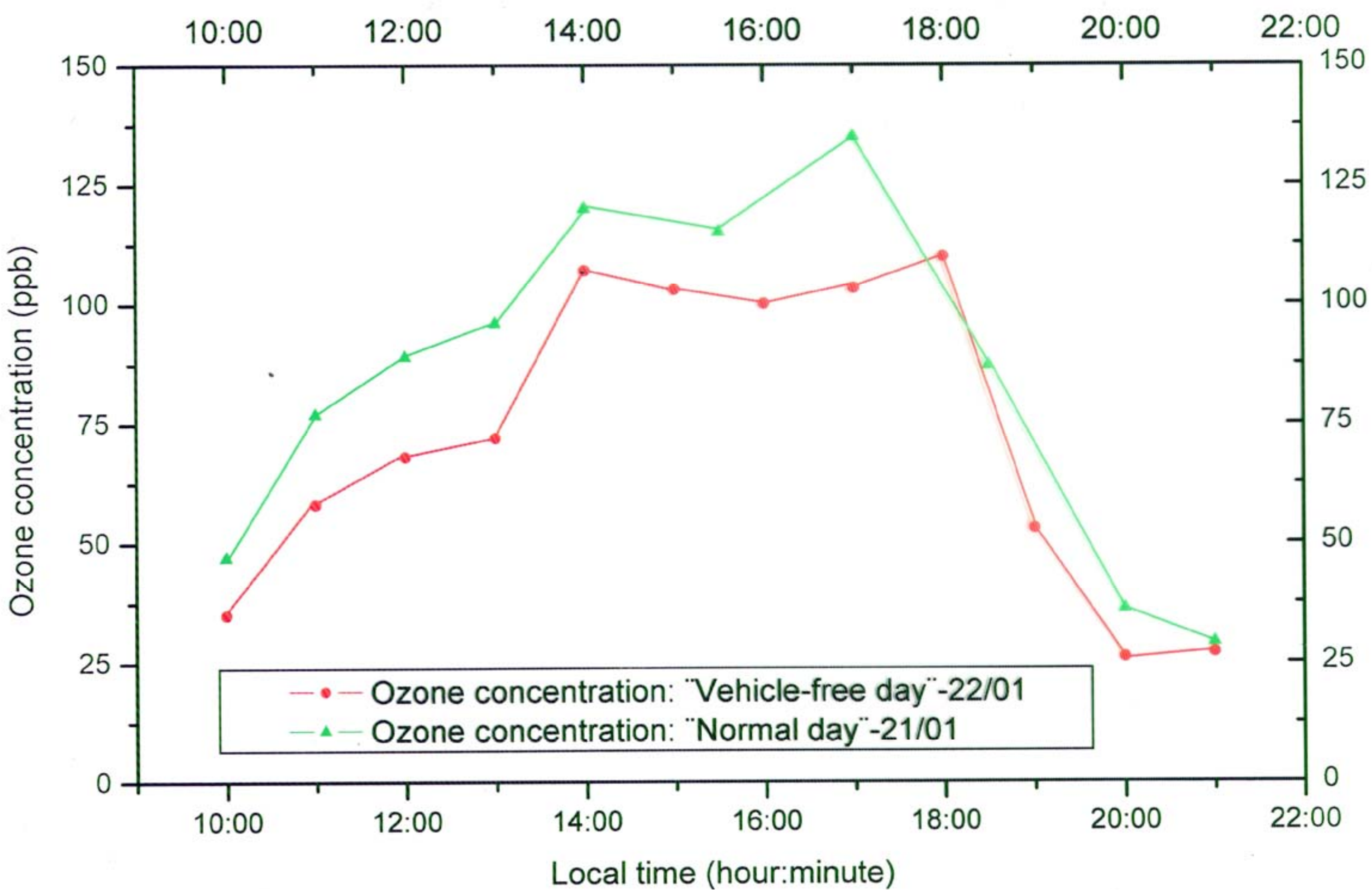
Sources of NOx

Effect of UVB Radiation on the Persistence Time of Ozone

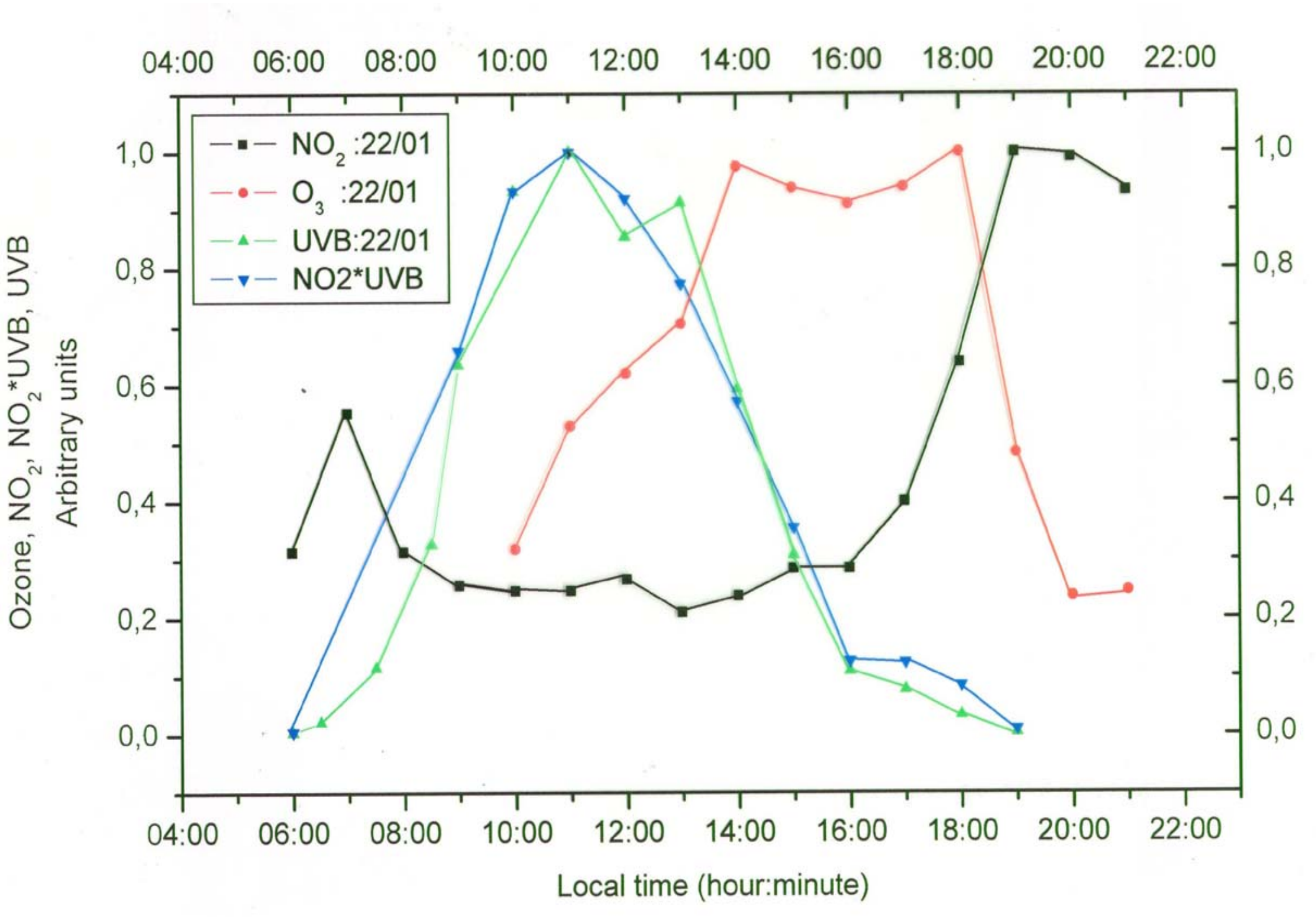


2004

Urban Ozone Measurements During a Vehicle-Free Day



Inter-relation between NO_2, O_3, UVB and NO_2*UVB



Atmospheric Ethylene as a Hydrocarbon Representative and its Relation with Ozone

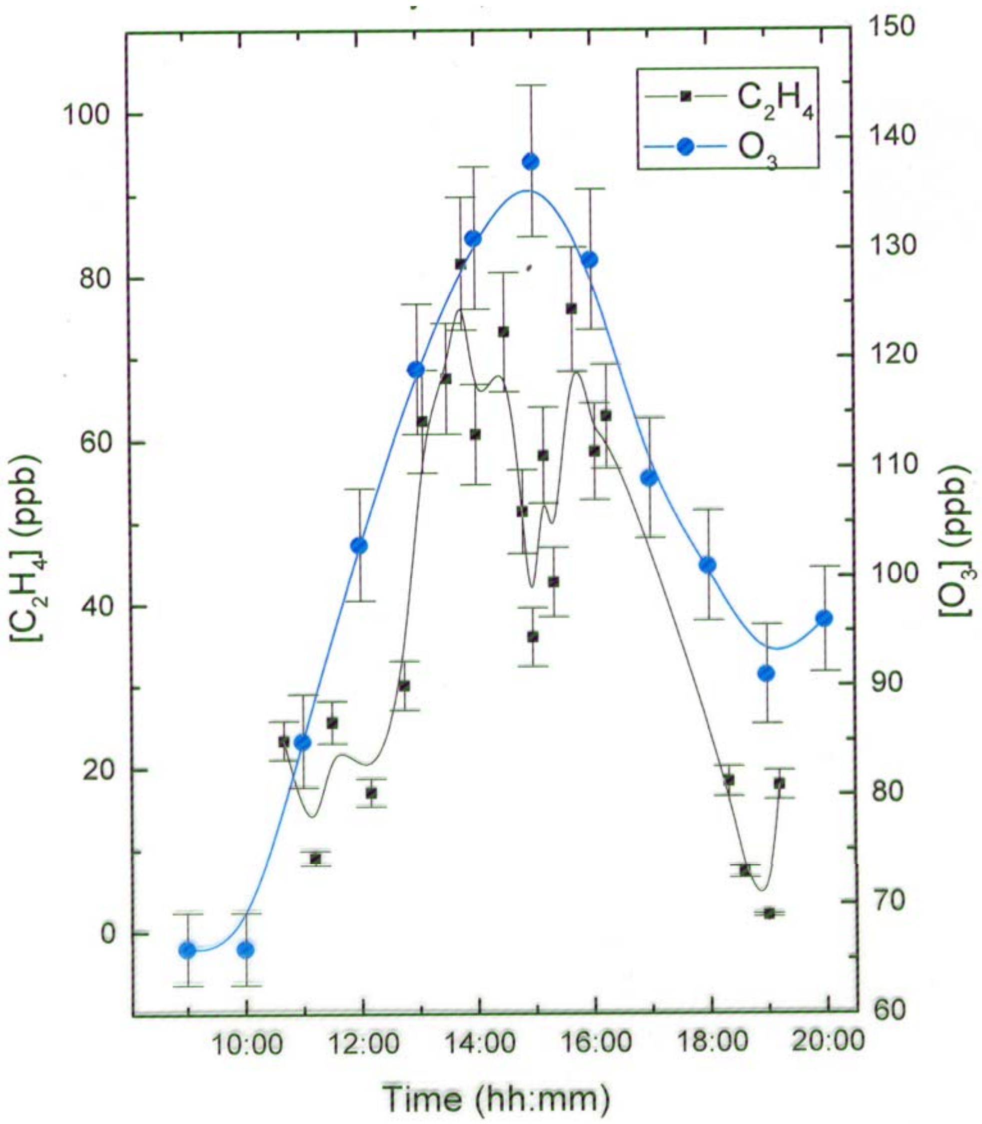
- It is an important urban air pollutant.
- It is emitted as a portion of motor vehicle exhaust
- Plants exhibit symptoms of ethylene toxicity at concentrations as low as 10 ppb.

Typical effects:

- Reduction of plant growth
- Reduction of flowering and hence fruit production
- Premature aging of plants.

Motivations:

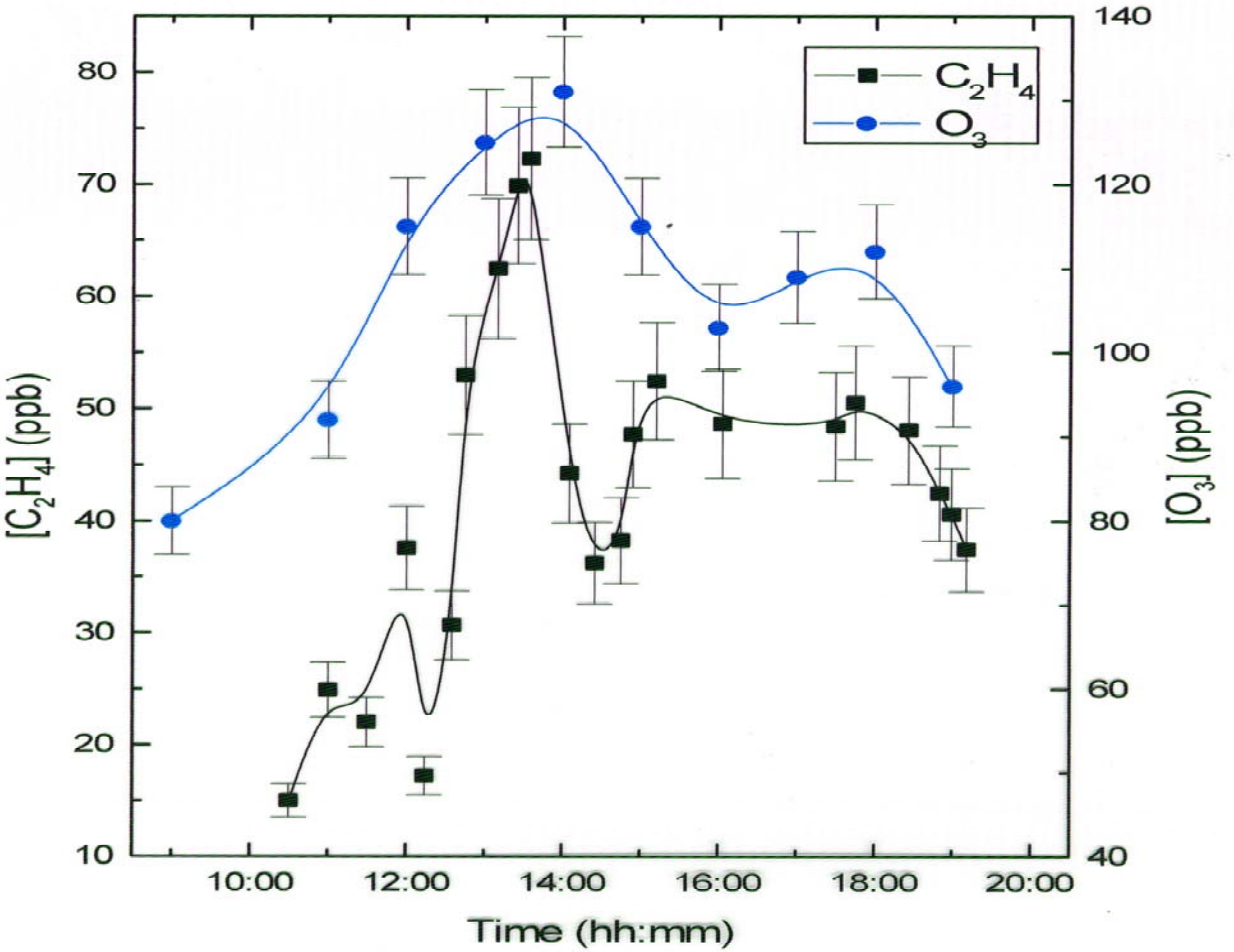
- Study the ethylene-NO_X-Ozone inter-correlation on one-day scale as a function of UV.



Ethylene DIAL measurements:

C_2H_4 with 7 ppb-correction and ozone point monitored concentration.

C_2H_4 starts at a background level of 15-20 ppb and reaches a peak of 80 ppb. Ozone, showed the same behavior namely, a slow increase then reached a maximum at around 15:00 and back to 40-50 ppb level.



7 ppb-correction ethylene and Ozone measurements of May 13.

Summary and Outlook

☐ Lidar remote sensing is an advanced technology that is not only replacing conventional sensors in science study, environmental research, and industry application, but also creating new methods with unique properties that could not be achieved before.

☐ Lidar technology has been advanced dramatically in the past 20 years, owing to the new availability of lasers, detectors, creative people involved, and the demanding needs from various aspects.

☐ Potential growing points at this stage include

(1) Solid-state resonance fluorescence lidar for mobile deployment globally

(2) Extend measurement range into thermosphere and lower mesosphere

(3) Doppler, DIAL, HSRL, and Raman lidar for lower atmosphere research

(4) Target lidar for novel applications

Material used in preparing the lectures:

-Laser Remote Sensing, Edited by Takshi Fujii and Tetsuo Fukuchi, Published by CRC Press, Taylor & Francis Group, ISBN: 0-8247-4256-7, 2005.

-Lidar: Range-resolved optical remote sensing of the atmosphere, edited by Claus Weitkamp, published by Springer, ISBN: 0-387-40075-3, 2005.

-Laser Remote Sensing: Fundamentals and Applications, by Raymond M. Measures, Wiley- Interscience, New York, ISBN: 0-89464-619-2, 1984.

- Lecture notes of Professor X. Chu; CIRES, Colorado University, USA

Thank you for your attention!