Lecture 05. Fundamentals of Lidar Remote Sensing (3) – "Physical Processes in Lidar"

- Overview of physical processes in lidar
- Light transmission through the atmosphere
- Light interaction with objects
  - Elastic and in-elastic scattering
  - Absorption and differential absorption
  - Fluorescence and resonance fluorescence
  - Comparison of backscatter cross section
- Summary

General Lidar Equation in β and α

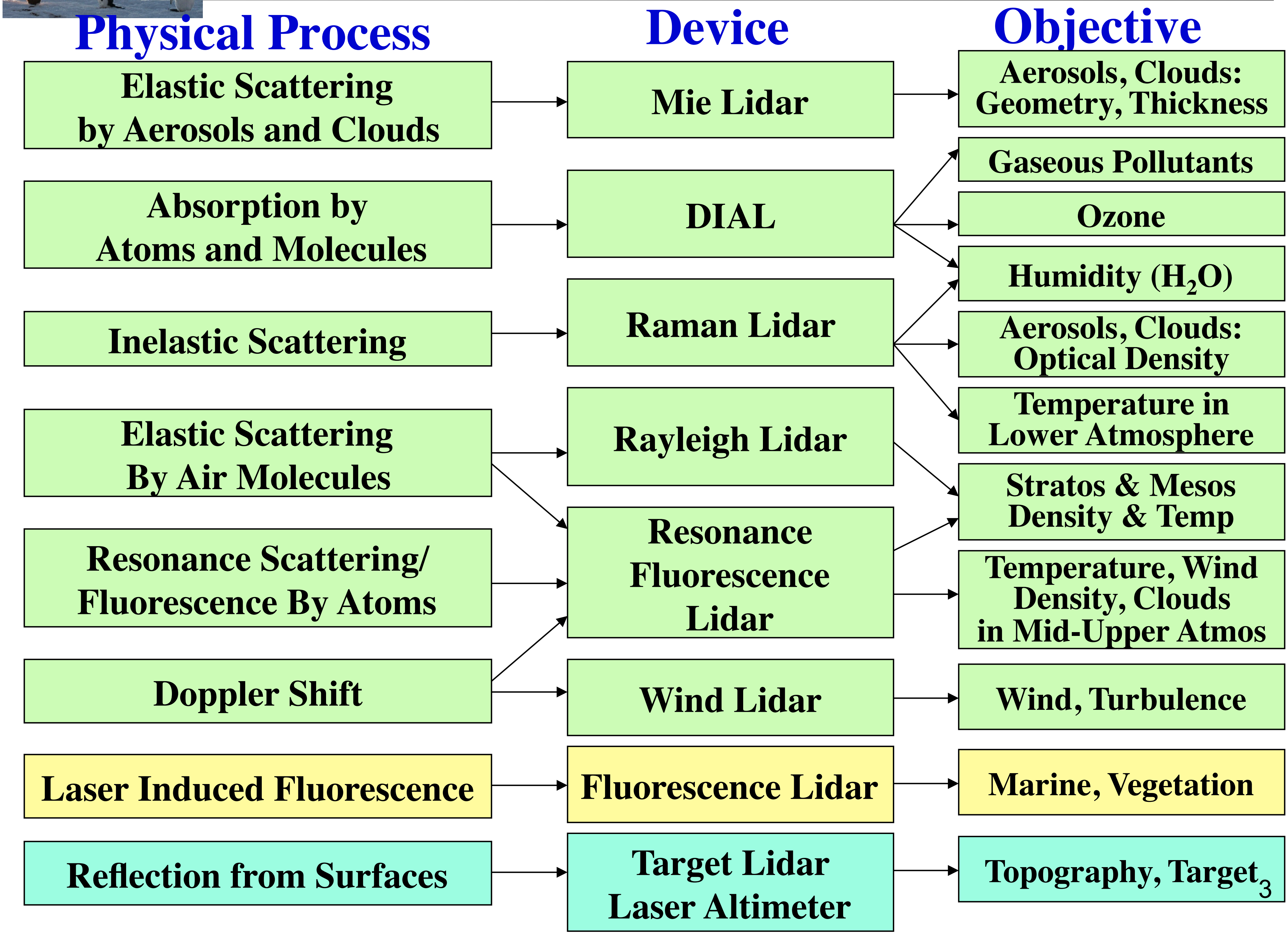
$$N_S(\lambda,R) = \left[\frac{P_L(\lambda_L)\Delta t}{hc/\lambda_L}\right]\left[\beta(\lambda,\lambda_L,\theta,R)\Delta R\right]\left(\frac{A}{R^2}\right) \cdot \exp\left[-\int_0^R \alpha(\lambda_L,r')dr'\right]\exp\left[-\int_0^R \alpha(\lambda,r')dr'\right]\left[\eta(\lambda,\lambda_L)G(R)\right] + N_B \tag{4.17}$$

β is the volume scatter coefficient

α is the extinction coefficient

Volume scatter coefficient $$\beta(\lambda,\lambda_L,R) = \sum_i \left[\frac{d\sigma_i(\lambda_L)}{d\Omega} n_i(R) p_i(\lambda)\right] \tag{4.5}$$

Transmission $$T(\lambda_L,R)T(\lambda,R) = \exp\left[-\left(\int_0^R \alpha(\lambda_L,r)dr + \int_0^R \alpha(\lambda,r)dr\right)\right] \tag{4.18}$$



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

Overview of Physical Processes in Lidar

- Light propagation in the atmosphere or medium:
  - Light transmission vs. light extinction (attenuation)
  - Extinction (attenuation) = Absorption + Scattering (Total)
- Interaction between light and objects

(1) Scattering (instantaneous elastic & inelastic):

  Mie, Rayleigh, and Raman scattering

(2) Absorption and differential absorption

(3) Laser induced fluorescence

(4) Resonance fluorescence

(5) Doppler shift and Doppler broadening

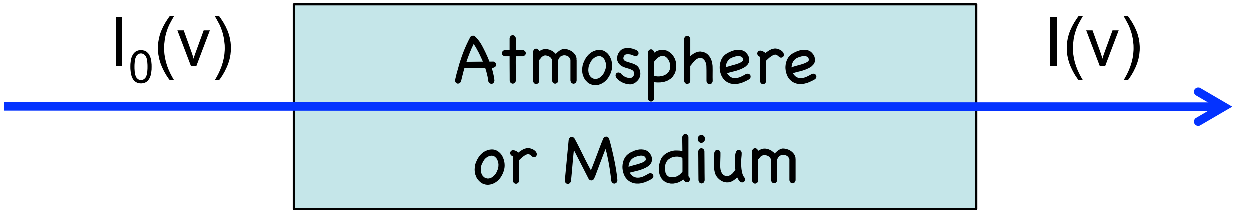
(6) Boltzmann distribution

(7) Reflection from target or surface

Light Propagation through the Atmosphere

- When light propagates through the atmosphere or medium, it experiences attenuation (extinction) caused by absorption and scattering of molecules and aerosol particles.

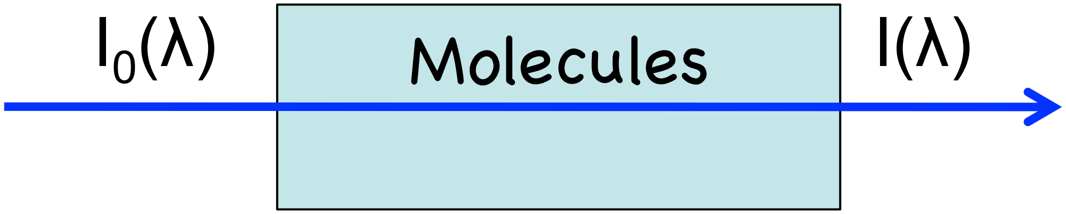
Transmission + Extinction = 1

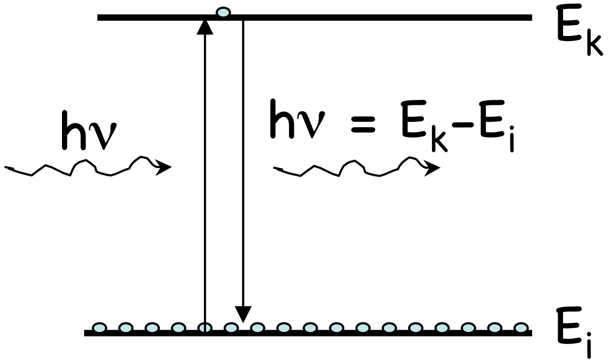


$$Transmission = \frac{I(\nu)}{I_0(\nu)} \quad (5.1), \qquad Extinction = \frac{I_0(\nu) - I(\nu)}{I_0(\nu)} \quad (5.2)$$

- The energy loss of a laser beam propagating through the atmosphere is due to molecular absorption, molecular scattering, aerosol scattering and aerosol absorption.

Molecular Absorption





➢ The intensity change dI of a light propagating through an absorbing sample is determined by the absorption coefficient $\alpha_{mol,abs}$ in the following manner:

$$dI(\lambda) = -I(\lambda)\alpha(\lambda)dz = -I\sigma_{ik}(\lambda)(N_i - N_k)dz \qquad (5.3)$$

$\alpha(\lambda) = \sigma(\lambda)(N_i - N_k)$ is absorption coefficient caused by transition E_i → E_k

Here, σ_{ik} is the absorption cross section, N_i and N_k are the populations on the energy levels of E_i and E_k, respectively.

➢ If $\Delta N = N_i - N_k$ is independent of the light intensity I, the absorbed intensity dI is proportional to the incident intensity I (linear absorption). Solving the above equation, we obtain

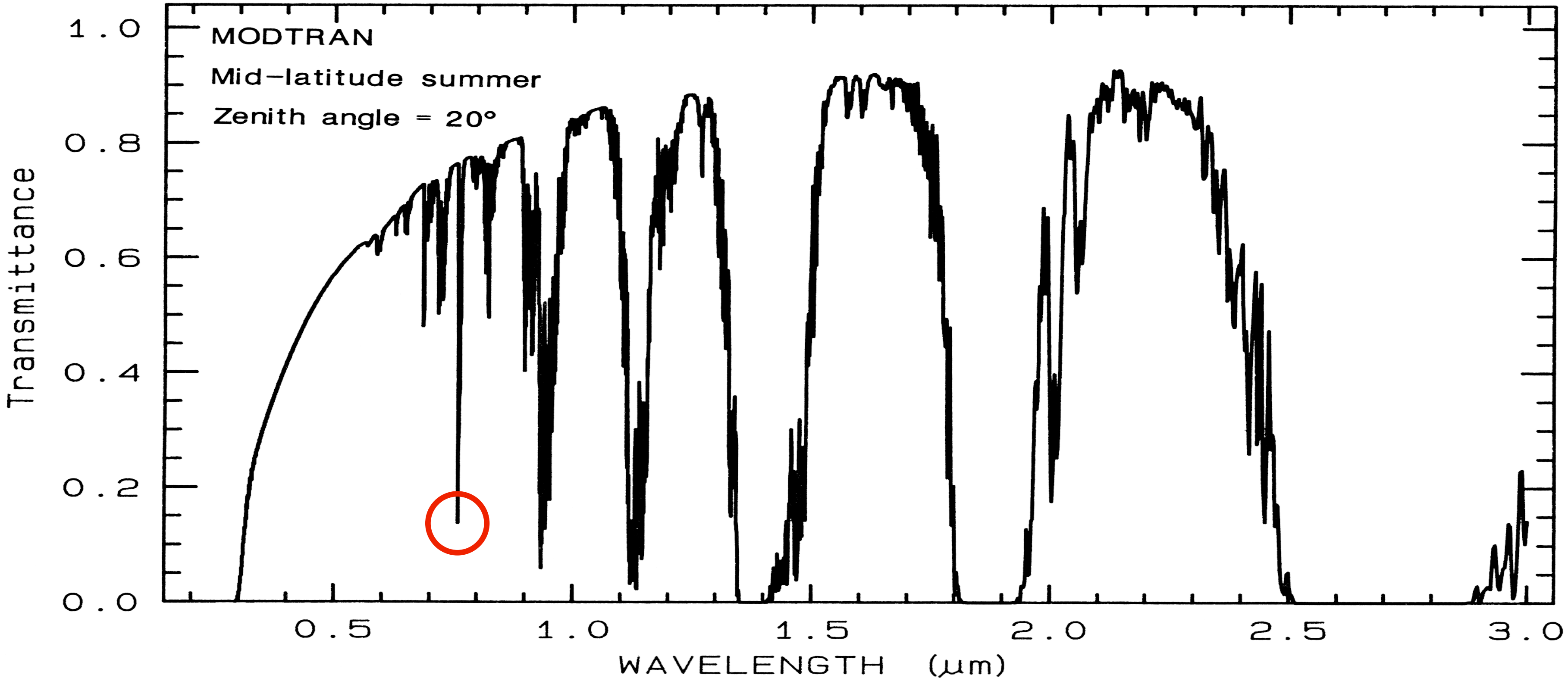
$$I(\lambda,z) = I_0 \exp\left[-\int_0^z \sigma_{ik}(\lambda)(N_i - N_k)dz\right] \qquad (5.4)$$

$$\rightarrow \quad I(\lambda,z) = I_0 e^{-\sigma(\lambda)(N_i - N_k)L} = I_0 e^{-\alpha(\lambda)L}$$

-- Lambert-Beer's Law (5.5)

Light Transmission through the Atmosphere

$$\text{Transmission} \quad T(\lambda,R) = \frac{I(\lambda,R)}{I_0(\lambda)} = \exp\left[-\int_0^R \alpha(\lambda,r)dr\right] = \exp\left[-\int_0^R \sigma(\lambda)\Delta N(r)dr\right] \quad (5.6)$$



Taken from http://speclab.cr.usgs.gov/PAPERS.refl-mrs/refl4.html

- Absorption cross section, scatter concentration, and path length all matter to the light transmission. Zenith angle is related to path length.
- MODTRAN provides a good resource for calculating light transmission.

Light Transmission through the Atmosphere

For λ<200nm, atmosphere is totally opaque due to Schumann-Runge absorption of O_2

For 200nm<λ<350nm, significant attenuation due to O_3 absorption

For 400-700nm, visible light – good transmission (350-850 nm)

For near IR, mid-IR, far-IR, CO_2 and H_2O have strong absorption bands.

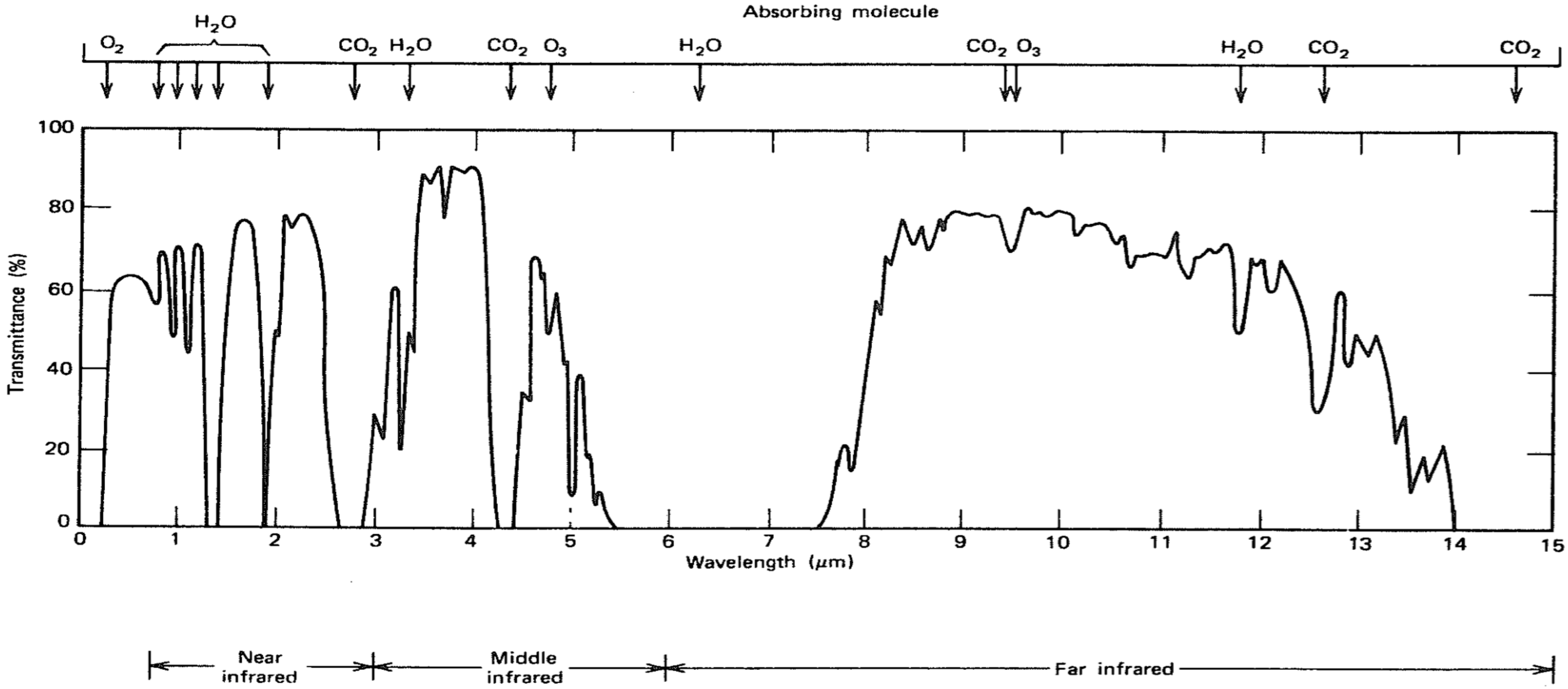


Fig. 4.6. Transmittance through the earth's atmosphere (horizontal path at sea level, length 1828 m) (Hudson and Hudson, 1975).

Taken from "Laser Remote Sensing" book by Measures

Molecular Absorption, Molecular Scattering, Aerosol Scattering, and Aerosol Absorption

$$\alpha = \alpha_{mol,abs} + \alpha_{mol,sca} + \alpha_{aer,sca} + \alpha_{aer,abs} \qquad (5.7)$$

- Here, the scattering extinction coefficients are the scattering coefficient integrated over the entire 4π solid angle, as all-direction scatterings are attenuation to the laser light.
- The extinction coefficient has the meaning of the percentage change of laser intensity per unit distance

$$\alpha = -\frac{dI/I}{dz} \qquad (5.8)$$

- In approximation of constant α over distance, the laser transmission is given by

$$T = e^{-\alpha L} \qquad (5.9)$$

- Total scattering cross section of atm molecular for z < 100 km is given by

$$\boxed{\sigma_{m,total}(\lambda) = 4.56 \cdot \left(\frac{550}{\lambda(nm)}\right)^4 \times 10^{-31} m^2} \qquad (5.10)$$

- Given a sea-level $N_m = 2.55 \times 10^{19}$ cm^{-3}, the molecular scattering extinction coefficient is -- a sea-level visibility exceeding 250 km!

$$\alpha_m = 0.0116 \ \ km^{-1} \qquad (5.11)$$

- The main attenuation of mid-visible light is due to the presence in the atmosphere of various solid and liquid particles – aerosols.

Atmospheric Attenuation Coefficient

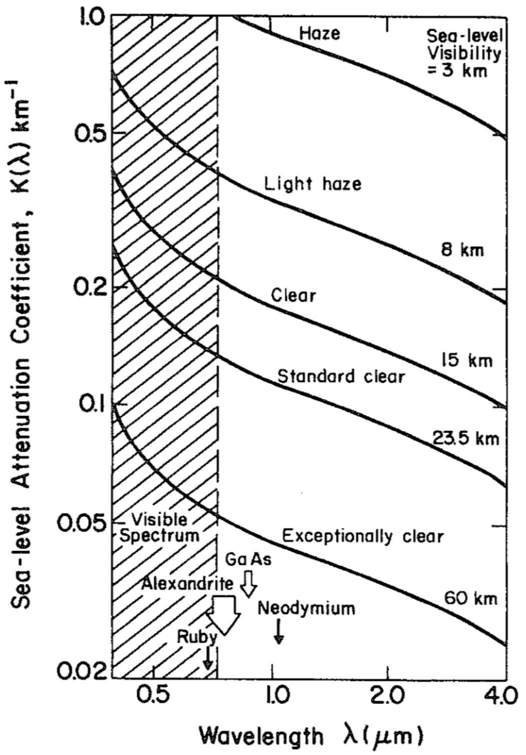


Fig. 4.9. Variation of sea-level attenuation coefficient $\kappa(\lambda)$ with wavelength for various atmospheric conditions. Also shown are wavelengths of some relevant lasers (Pressley, 1971).

Taken from "Laser Remote Sensing" book by Measures

Empirical formula for atmospheric extinction coefficient

$$\kappa_{Mie}(\lambda) \approx \frac{3.91}{R_v}\left(\frac{550}{\lambda}\right)^{q} km^{-1} \tag{5.12}$$

$$q = 0.585 R_v^{1/3} \quad for \quad R_v \le 6km \tag{5.13}$$

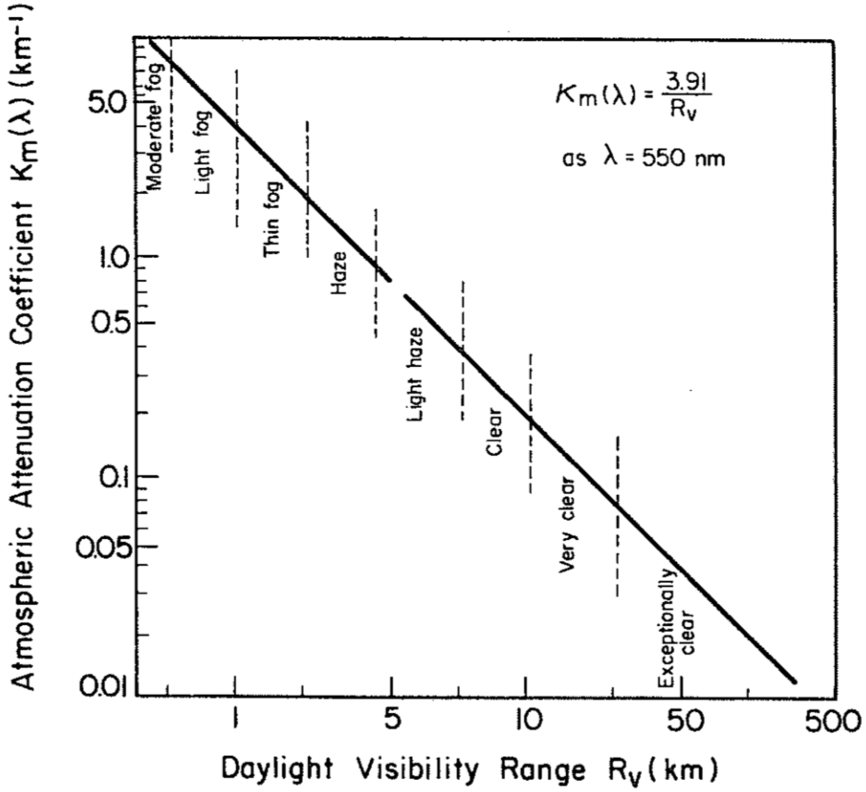


Fig. 4.10. Variation of atmospheric attenuation coefficient $\kappa_m(\lambda)$ with visibility range R_v, at a wavelength of 550 nm (Pressley, 1971).

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

(There are confusions in definitions of these scatterings.)

- Inelastic scattering:

scattering with apparent change of wavelength

Raman scattering

Pure rotational Raman and vibration-rotational Raman

Definitions for Different Scatterings

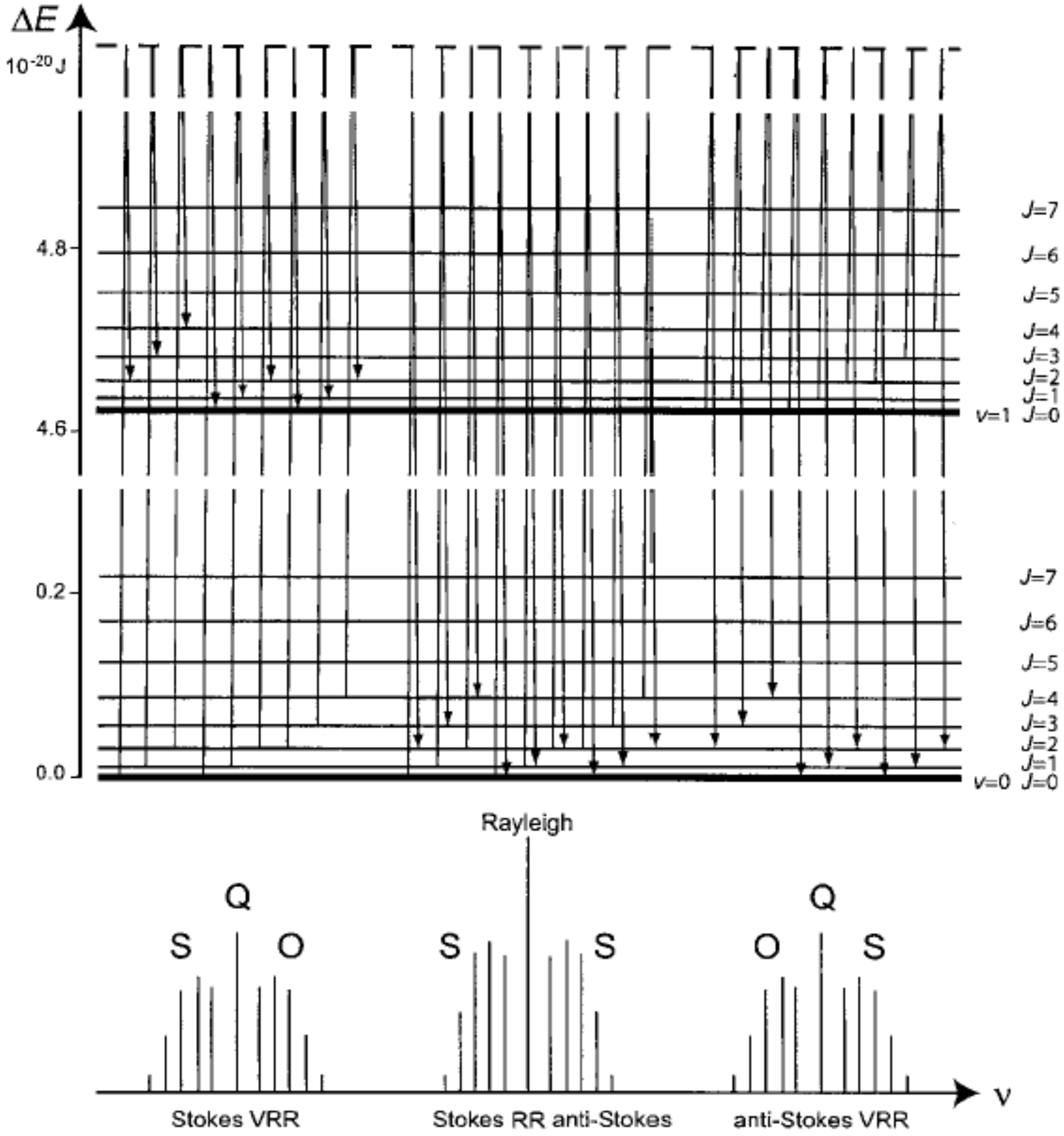


Fig. 9.1. Vibration–rotation energy levels of the N_2 molecule, Raman transitions, and resulting spectrum.

Virtual
Energy Levels

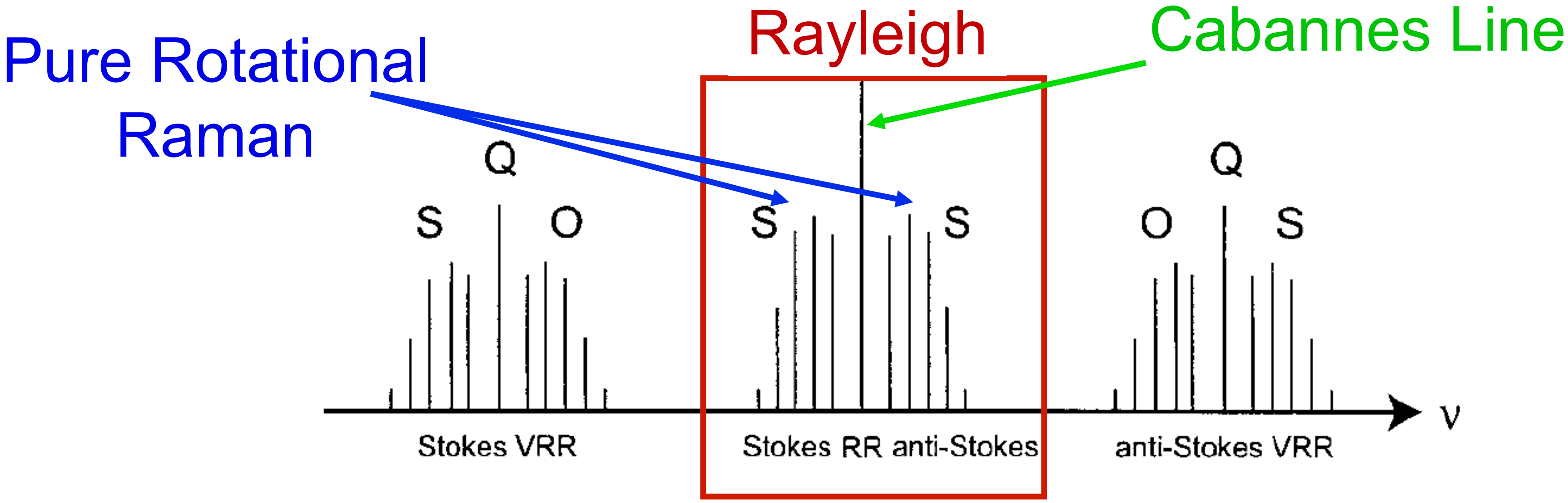
Real
Energy Levels

Real
Energy Levels

$$\Delta v = 0, \qquad \Delta J = 2$$
$$\Delta v = \pm 1, \qquad \Delta J = 0, \pm 2$$

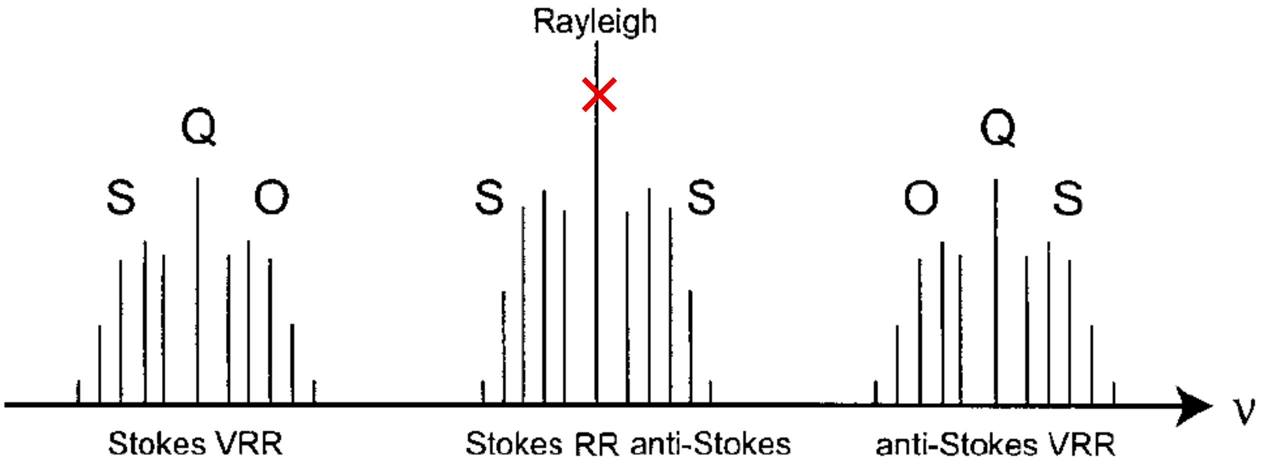
Rayleigh (Molecular) Scattering

- Rayleigh scattering is referred to the elastic scattering from atmospheric molecules (particle size is much smaller than the wavelength), i.e., scattering with no apparent change of wavelength, although still undergoing Doppler broadening and Doppler shift.
- However, depending on the resolution of detection, Rayleigh scattering can consist of the Cabannes scattering (really elastic scattering from molecules) and pure rotational Raman scattering.



Raman Scattering

- ☐ Raman scattering is an inelastic scattering with rotational quantum state or vibration-rotational quantum state change as the result of scattering.



- ☐ Separation between Cabannes line and the nearest pure rotational Raman (O_2 and N_2) is about 10 cm^{-1} = 300 GHz.
- ☐ For vibration-rotational Raman, Q branch is not a single line, but consists of many lines with very small separations, < 0.1 cm^{-1} = 3 GHz, due to the different splitting of the rotational levels in the lower and upper vibrational levels.

Mie (Aerosol/Cloud) Scattering

- Strictly speaking, Mie scattering is an elastic scattering from spherical particles [Mie, 1908], which includes the solution of Rayleigh scattering.
- However, in lidar field, Mie scattering is referred to the elastic scattering from spherical particles whose size is comparable to or larger than the wavelength.
- Furthermore, Mie scattering is generalized to elastic scattering from overall aerosol particles and cloud droplets, i.e., including non-spherical particles.
- To precisely calculate the scattering from non-spherical particles, Mie scattering theory has to be replaced by non-spherical particle scattering theories. This is a complicated issue in the elastic lidar field.

Rayleigh Backscatter Coefficient

- Precise equations should be obtained from Rayleigh theory and experimental measurements of parameters.
- In lidar field, a common practice is to use the equation

$$\boxed{\beta_{Rayleigh}(\lambda, z, \theta = \pi) = 2.938 \times 10^{-32} \frac{P(z)}{T(z)} \cdot \frac{1}{\lambda^{4.0117}} \left(m^{-1} sr^{-1}\right)} \quad (5.14)$$

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 β_{Rayleigh} is the backscatter coefficient (angular).

- Total scatter coefficient β_T has relationship:

$$\boxed{\beta(\theta) = \frac{\beta_T}{4\pi} P(\theta) = \frac{\beta_T}{4\pi} \times 0.7629 \times (1 + 0.9324 \cos^2 \theta)} \quad (5.15)$$

Rayleigh Backscatter Cross Section

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

$$\boxed{\frac{d\sigma_m(\lambda)}{d\Omega} = 5.45 \cdot \left(\frac{550}{\lambda}\right)^4 \times 10^{-32} \left(m^2 sr^{-1}\right)} \qquad (5.16)$$

where λ is the wavelength in nm.

- For K lidar, λ = 770 nm, ⇨ 1.42×10^{-32} m^2sr^{-1}
- For Na lidar, λ = 589 nm, ⇨ 4.14×10^{-32} m^2sr^{-1}
- For Fe lidar, λ = 372 nm, ⇨ 2.60×10^{-31} m^2sr^{-1}
- For Rayleigh lidar, λ = 532 nm, ⇨ 6.22×10^{-32} m^2sr^{-1}

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

$$\boxed{N_S(\lambda,R) = \left(\frac{P_L(\lambda)\Delta t}{hc/\lambda}\right)\left(\beta(\lambda,R)\Delta R\right)\left(\frac{A}{R^2}\right)T^2(\lambda,R)\left(\eta(\lambda)G(R)\right) + N_B} \quad (5.17)$$

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

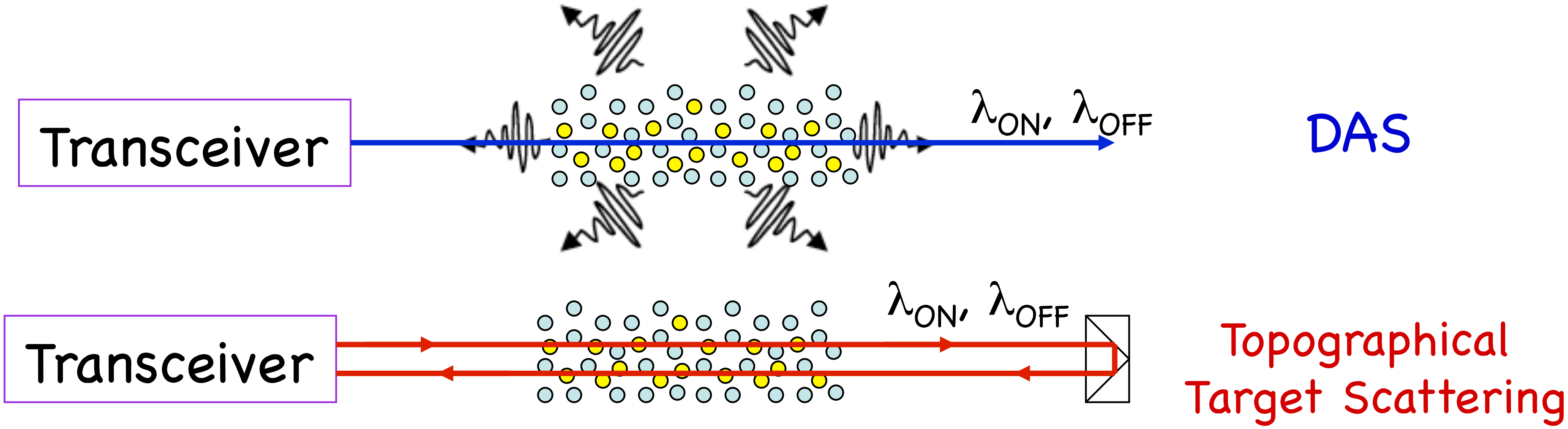
$$\boxed{N_S(\lambda,R) = \left(\frac{P_L(\lambda_L)\Delta t}{hc/\lambda_L}\right)\left(\beta(\lambda,\lambda_L,R)\Delta R\right)\left(\frac{A}{R^2}\right)\left(T(\lambda_L,R)T(\lambda,R)\right)\left(\eta(\lambda,\lambda_L)G(R)\right) + N_B}$$

$$\boxed{\lambda \neq \lambda_L, \quad p_i(\lambda) \neq 1, \quad p_i(\lambda) < 1}$$

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

Differential Absorption

- 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.



Differential Absorption/Scattering Form of Lidar Equation

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

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

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

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

- Differential absorption cross-section

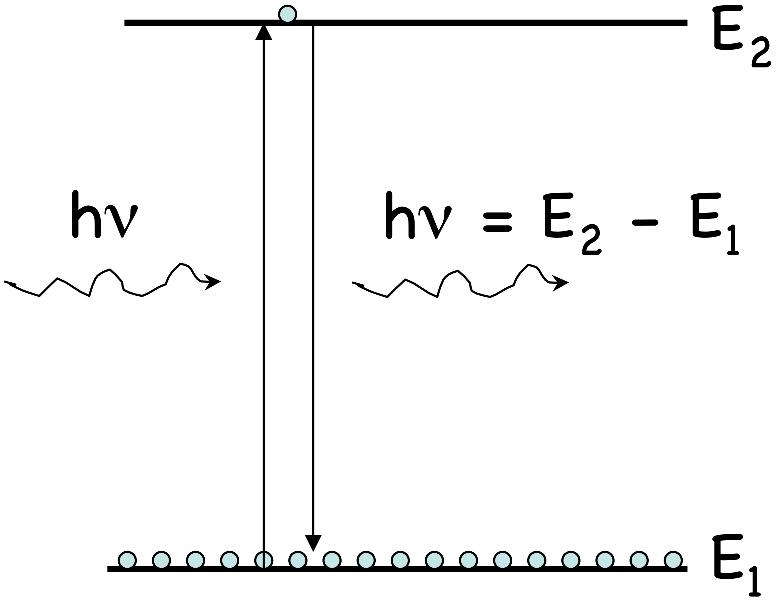
$$\boxed{\Delta\sigma_{abs}(R) = \sigma_{abs}(\lambda_{ON},R) - \sigma_{abs}(\lambda_{OFF},R)}$$

Resonance Fluorescence

- In the middle and upper atmosphere, there exist some metal atoms and atomic ions. They have large absorption cross section, and 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.

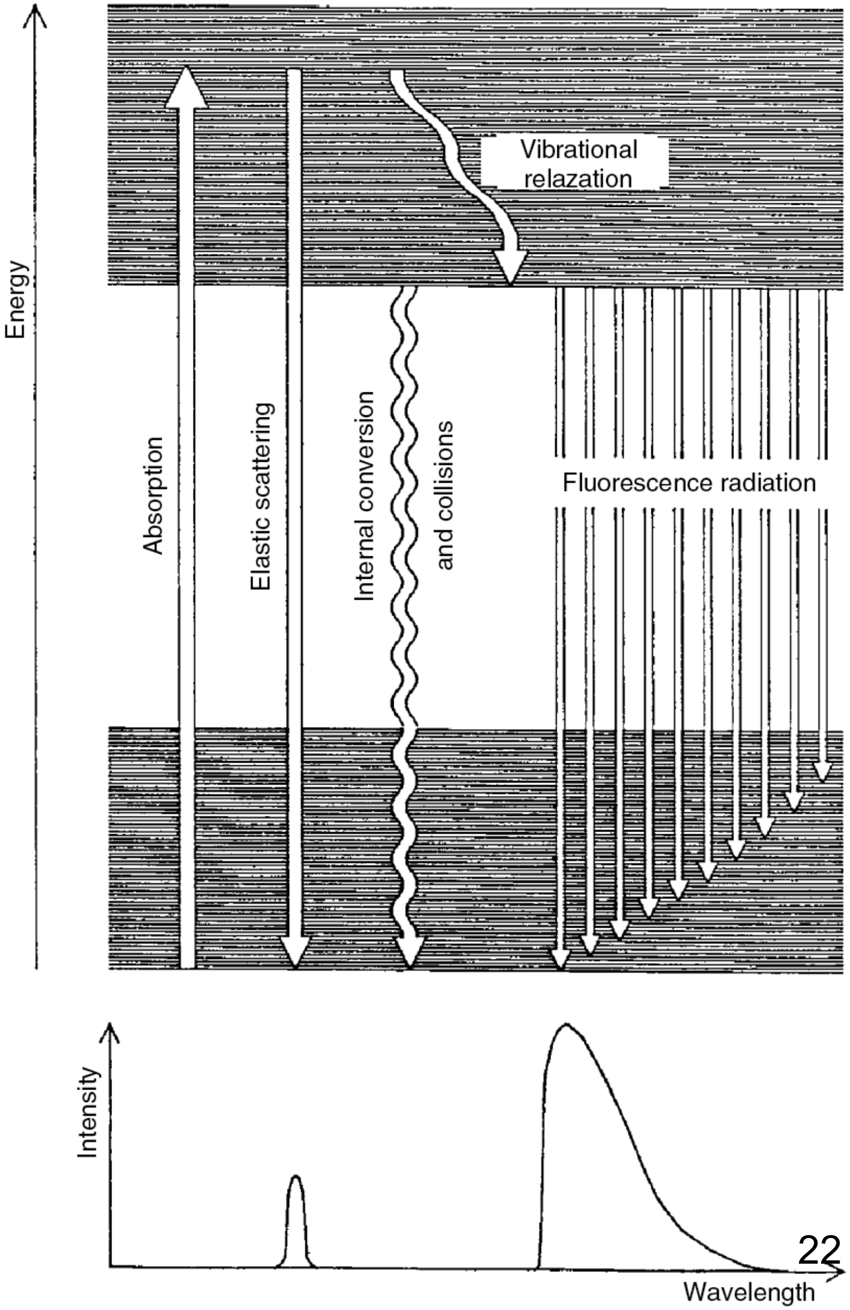
- Resonance fluorescence is a two-step process: absorption first, and then spontaneous emission. Therefore, there is finite time delay between these two steps – radiative lifetime.

- Due to frequent collisions it is hard to obtain resonance fluorescence in lower atmosphere.



Laser Induced Fluorescence

- In contrast to free atoms and molecules, solids and liquids exhibit broad absorption and emission spectra because of the strong intermolecular interactions.
- A fixed frequency laser can be used for the excitation due to the broad absorption.
- Following the excitation, there is 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.
- The decay then occurs to different sub-levels of the ground state giving rise to a distribution of fluorescence light, which reflect the lower-state level distribution.
- Fixing the excitation wavelength, we can obtain fluorescence spectra. While fixing the detection channel and varying the excitation wavelength, an excitation spectrum can be recorded.



Fluorescence Form of Lidar Equation

- Resonance fluorescence and laser-induced-fluorescence are NOT instantaneous processes, but have delays due to the radiative lifetime of the excited states.

- The lidar equation in fluorescence form is given by

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

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

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

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

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

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
Atomic Absorption and 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 (Wavelength Dependent)	10^{-27} cm^2sr^{-1}	Two-photon process Elastic scattering, instantaneous
Raman Scattering (Wavelength Dependent)	10^{-30} cm^2sr^{-1}	Two-photon process Inelastic scattering, instantaneous

Summary (1)

- Numerous physical processes are involved in lidars, including the interaction between light and objects, and the light transmission through the atmosphere or other medium.

- Light transmission through the atmosphere is mainly attenuated by molecular and aerosol absorption and scattering. When wavelengths fall in a strong molecular absorption bands, the attenuation could be significant, e.g., UV light below 200 nm or mid-infrared around 6.2 μm – the Earth's atmosphere becomes total opaque. The visibility of atmosphere is mainly dominated by aerosol scattering and absorption, therefore varies dramatically under different meteorological conditions.

- Main physical processes for interaction between light and objects include elastic and inelastic scattering, absorption and differential absorption, resonance fluorescence, laser induced fluorescence, Doppler effect, Boltzmann distribution, reflection from target or surface, and multiple scattering. There are large differences in scattering cross sections for various physical processes involved in lidar.

Summary (2)

- Understanding these physical processes precisely is the key to successful lidar simulations and applications.
- The importance of knowing the light transmission through the atmosphere or other medium is to select the most effective laser wavelength from the standpoint of energy losses under various meteorological or hydrological conditions.
- Interactions between light and objects are the basis of lidar remote sensing, because it is these interactions that modify light properties so that the light can carry away the information of the objects.
- Lidar equation may change its form to best fit for each particular physical process and lidar application.

Our Textbook – Chapter 3 for elastic scattering and polarization
Chapter 4 for differential absorption
Chapters 5 & 7 for resonance fluorescence, Boltzmann, Doppler
Chapter 6 for laser-induced fluorescence
Laser monitoring of the atmosphere (Hinkley) Ch. 3 and 4
Laser Remote Sensing (Measures) Chapter 4