# Lecture 07. Fundamentals of Lidar Remote Sensing (5) "Physical Processes in Lidar"

- Light interaction with objects (continued)
- Polarization of light
- > Polarization in scattering
- Comparison of lidar equations
- Comparison of backscatter cross-sections
- Light transmission through the atmosphere
- Summary and question

# **Polarization of Light**

Light, as a photon stream, is also an electromagnetic wave – "Wave-particle duality". It is a transverse EM wave.
 There are both electric and magnetic fields associated with the light wave vector. The electric field E defines the polarization of light.





https://www.youtube.com/watch?v=Q0qrU4nprB0



## **Polarization of Light**

> For every single photon regarded as a plane wave,  $\vec{E} = \vec{A}_{o}e^{i(\omega t - kz)}$ its complex amplitude vector can be written as For unpolarized light the phases  $\phi_x$  and  $\phi_y$  are uncorrelated and their difference fluctuates statistically. For linearly polarized light in x,

 $\vec{A}_{o} = \begin{cases} A_{ox} e^{i\phi_{x}} \\ A_{ox} e^{i\phi_{y}} \end{cases}$ 

 $A_{oy}$  = 0; in a direction  $\alpha$  against x,  $\phi_x = \phi_y$  and  $\tan \alpha = A_{oy}/A_{ox}$ . For circular polarization  $A_{ox} = A_{oy}$  and  $\varphi_x = \varphi_y \pm \pi/2$ .

> The different states of polarization can be characterized by their Jones vectors, which are defined as  $\vec{E} = \begin{cases} E_x \\ E_y \end{cases} = \left| \vec{E} \right| \cdot \begin{cases} a \\ b \end{cases} \cdot e^{i(\omega t - kz)}$ where the normalized vectore {a, b} is the Jones vector.

The Jones representation shows its advantages when we consider the transmission of light through optical elements such as polarizers, wave plates, or beam splitters that can be described by 2x2 Jones matrices. The polarization state of the transmitted light is then obtained by multiplication of the Jones vector of the incident wave by the Jones matrix of the optical element.  $\vec{E}_{t} = \begin{cases} E_{xt} \\ E_{wt} \end{cases} = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \cdot \begin{cases} E_{xo} \\ E_{wo} \end{cases}$ 

ightarrow E<sub>x</sub> and E<sub>y</sub> form the orthogonal basis.



#### Jones Vectors and Jones Matrices

Table 2.1. Jones vectors for light traveling in the z-direction and Jones matrices for polarizers



#### **Stokes Vectors and Mueller Matrices**

Jones vectors and Jones matrices are used in laser spectroscopy to describe the polarization state of light, which is usually coherent light. They are good descriptions of the single photon behaviors.
 Stokes vectors and Mueller Matrices are formulated to represent incoherent (and coherent) light consisting of many photons, in terms of its total intensity (I), degree of polarization (p), and polarization ellipse.

$$\vec{S} = \begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix} = \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}$$

$$S_0 = I$$

$$S_1 = pI \cos 2\psi \cos 2\chi$$

$$S_2 = pI \sin 2\psi \cos 2\chi$$

$$S_3 = pI \sin 2\chi$$

$$I = S_0$$

$$p = \frac{\sqrt{S_1^2 + S_2^2 + S_3^2}}{S_0}$$

$$2\psi = \operatorname{atan} \frac{S_2}{S_1}$$

$$2\chi = \operatorname{atan} \frac{S_3}{\sqrt{S_1^2 + S_2^2}}$$

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#### **Stokes Vectors and Mueller Matrices**

>Stokes parameters do not form a preferred basis of the space, but rather were chosen for easy to be measured or calculated.



# **Polarization Lidar Equation**

Obeying the same physics picture of lidar remote sensing as scalar lidar equations, polarization lidar equation uses Stockes vectors and Mueller matrices to describe the polarization states and changes along with the instrument properties on polarization, etc. Due to the matrix calculation, the polarization lidar equation is written from right to left.



# **Polarization in Scattering**

- Depolarization is the phenomenon that the scattered photons possess polarizations different than that of the original incident laser photons. Usually the incident laser beam has a linear polarization. Depolarization means that the return photons may have polarization other than this linear polarization, e.g., linear polarizations in other directions, or elliptical polarization.
- Note that every photon possesses certain polarization, i.e., every photon is polarized. Non-polarized light or depolarized light is talked about on the statistical point of view of a large number of photons.
  - The range-resolved linear depolarization ratio is defined from lidar or optical observations as below in many lidar applications. Detailed sophisticated treatment of lidar depolarization needs to consider the optical matrix for polarization.

$$\delta(R) = \frac{P_{\perp}}{P_{\parallel}} = \frac{I_{\perp}}{I_{\parallel}}$$

where P and I are the light power and intensity detected.

# Depolarization in Scattering

- Rayleigh scattering from air molecules can cause depolarization but only a few percent or less.
- Mie scattering from spherical particles at exactly 180° will not introduce depolarization.
- Depolarization can be resulted from
- (1) Spherical particle scattering at near 180° but not exact
- (2) Non-spherical particle shape (true for both aerosol/cloud and atmosphere molecules)
- (3) Inhomogeneous refraction index
- (4) Multiple scattering inside fog, cloud or rain.



# Scattering, Absorption, Fluorescence



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





Differential Absorption



## Rayleigh Backscatter Coefficient

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

P in mbar and T in Kelvin at altitude z,  $\lambda$  in meter.

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

# **Rayleigh Backscatter Cross Section**

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

where  $\lambda$  is the wavelength in nm.

**□** For Rayleigh lidar,  $\lambda$  = 532 nm,  $\Rightarrow$  6.22 x 10<sup>-32</sup> m<sup>2</sup>sr<sup>-1</sup>



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

$$N_{S}(\lambda,R) = \left(\frac{P_{L}(\lambda)\Delta t}{hc/\lambda}\right) \left(\beta(\lambda,R)\Delta R\right) \left(\frac{A}{R^{2}}\right) T^{2}(\lambda,R) \left(\eta(\lambda)G(R)\right) + N_{B}$$

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

$$N_{S}(\lambda,R) = \left(\frac{P_{L}(\lambda_{L})\Delta t}{hc/\lambda_{L}}\right) \left(\beta(\lambda,\lambda_{L},R)\Delta R\right) \left(\frac{A}{R^{2}}\right) \left(T(\lambda_{L},R)T(\lambda,R)\right) \left(\eta(\lambda,\lambda_{L})G(R)\right) + N_{B}$$

$$\lambda \neq \lambda_L, p_i(\lambda) \neq 1, p_i(\lambda) < 1$$

$$T(\lambda, R) = \exp\left[-\int_0^R \alpha(\lambda, r) dr\right]_{12}$$

#### Differential Absorption/Scattering Form of Lidar Equation

 $\Box$  For the laser with wavelength  $\lambda_{on}$  on the molecular absorption line

$$N_{S}(\lambda_{on}, R) = N_{L}(\lambda_{on}) \Big[ \beta_{sca}(\lambda_{on}, R) \Delta R \Big] \Big( \frac{A}{R^{2}} \Big) \exp \Big[ -2 \int_{0}^{z} \overline{\alpha}(\lambda_{on}, r') dr' \Big] \\ \times \exp \Big[ -2 \int_{0}^{z} \sigma_{abs}(\lambda_{on}, r') n_{c}(r') dr' \Big] \Big[ \eta(\lambda_{on}) G(R) \Big] + N_{B}$$

 $\square$  For the laser with wavelength  $\lambda_{\text{off}}$  off the molecular absorption line

$$N_{S}(\lambda_{off}, R) = N_{L}(\lambda_{off}) \Big[ \beta_{sca}(\lambda_{off}, R) \Delta R \Big] \Big( \frac{A}{R^{2}} \Big) \exp \Big[ -2 \int_{0}^{z} \overline{\alpha}(\lambda_{off}, r') dr' \Big] \\ \times \exp \Big[ -2 \int_{0}^{z} \sigma_{abs}(\lambda_{off}, r') n_{c}(r') dr' \Big] \Big[ \eta(\lambda_{off}) G(R) \Big] + N_{B}$$

Differential absorption cross-section

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

### 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. It contains two steps – absorption and then emission.

□ The lidar equation in fluorescence form is given by

$$N_{S}(\lambda,R) = \left(\frac{P_{L}(\lambda)\Delta t}{hc/\lambda}\right) \left(\sigma_{eff}(\lambda,R)n_{c}(z)R_{B}(\lambda)\Delta R\right) \left(\frac{A}{4\pi R^{2}}\right) \left(T_{a}^{2}(\lambda,R)T_{c}^{2}(\lambda,R)\right) \left(\eta(\lambda)G(R)\right) + N_{B}^{2}(\lambda,R) \left(\frac{A}{4\pi R^{2}}\right) \left(\frac{A}{4\pi R^{2}}\right) \left(T_{a}^{2}(\lambda,R)T_{c}^{2}(\lambda,R)\right) \left(\eta(\lambda)G(R)\right) + N_{B}^{2}(\lambda,R) \left(\frac{A}{4\pi R^{2}}\right) \left$$

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

$$T_{c}(R) = \exp\left(-\int_{R_{bottom}}^{R} \sigma_{eff}(\lambda, r') n_{c}(r') dr'\right) = \exp\left(-\int_{R_{bottom}}^{R} \alpha_{c}(\lambda, r') dr'\right)$$

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

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



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

The total absorption cross-section is  $4\pi$  times backscatter cross-section. 15

### 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.



□ The power/energy loss of a laser beam propagating through the atmosphere is due to molecular absorption, molecular scattering, aerosol scattering and aerosol absorption. 16

### Atomic and 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:  $\frac{dI(\lambda) = -I(\lambda)\alpha(\lambda)dz = -I\sigma_{ik}(\lambda)(N_i - N_k)dz}{dI(\lambda) = -I(\lambda)\alpha(\lambda)dz = -I\sigma_{ik}(\lambda)(N_i - N_k)dz}$ 

 $\alpha(\lambda) = \sigma_{ik}(\lambda)(N_i - N_k)$  is absorption coefficient caused by transition  $E_i \rightarrow E_k$ Here,  $\sigma_{ik}$  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

$$I(\lambda, z) = I_0 \exp\left[-\int_0^z \sigma_{ik}(\lambda)(N_i - N_k)dz\right] \rightarrow I(\lambda, z) = I_0 e^{-\sigma(\lambda)(N_i - N_k)L} = I_0 e^{-\alpha(\lambda)L}$$
-- Lambert-Beer's Law 17



### Light Transmission through the Atmosphere



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. 18

#### Light Transmission through the Atmosphere

For  $\lambda$ <200nm, atmosphere is totally opaque due to Schumann-Runge absorption of  $O_2$ For 200nm< $\lambda$ <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.



#### Taken from "Laser Remote Sensing" book by Measures

#### Molecular Absorption, Molecular Scattering, Aerosol Sc g, and Aerosol Absorption

$$\alpha = \alpha_{mol,abs} + \alpha_{mol,sca} + \alpha_{aer,sca} + \alpha_{aer,abs}$$

>Here, the scattering extinction coefficients are the scattering coefficient integrated over the entire  $4\pi$  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

>In approximation of constant  $\alpha$  over distance, the laser transmission is given by

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

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

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

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

$$\alpha_m = 0.0116 \ km^{-1}$$

$$\alpha = -\frac{dI/I}{dz}$$

$$T = e^{-\alpha L}$$

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#### **Atmospheric Attenuation Coefficient**







Empirical formula for atmospheric extinction coefficient

$$\kappa_{Mie}(\lambda) \approx \frac{3.91}{R_v} \left(\frac{550}{\lambda}\right)^q km^{-1}$$
$$q = 0.585 R_v^{1/3} \quad for \quad R_v \le 6km$$

ਰ੍ Atmospheric Attenuation Coefficient Km(λ)(km<sup>-1</sup>)



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

### **General Case of Light Transmission**



> Transmission for single-frequency radiation propagation through an inhomogeneous medium

$$T(v,z) = \frac{I_T(v,z)}{I_0(v)} = \exp\left[-\int_{z_1}^{z_2} \alpha(v,z)dz\right] = \exp\left[-\int_{z_1}^{z_2} \sigma(v,z)\Delta N(z)dz\right]$$

> Transmission for the general case of radiation propagation through an inhomogeneous medium in the spectral interval  $[v_1, v_2]$ :

$$T(z) = \frac{\int_{v_1}^{v_2} I_T(v,z) dv}{\int_{v_1}^{v_2} I_0(v) dv} = \frac{\int_{v_1}^{v_2} I_0(v) \exp\left[-\int_{z_1}^{z_2} \sigma(v,z) \Delta N(z) dz\right] dv}{\int_{v_1}^{v_2} I_0(v) dv}$$

# **General Case of Light Transmission**

> Extinction/Attenuation for the general case of radiation propagation through an inhomogeneous medium in the spectral interval  $[v_1, v_2]$ :

$$A(z) = 1 - T(z) = \frac{\int_{v_1}^{v_2} I_0(v) \left\{ 1 - \exp\left[ -\int_{z_1}^{z_2} \sigma(v, z) \Delta N(z) dz \right] \right\} dv}{\int_{v_1}^{v_2} I_0(v) dv}$$

> In the case of homogeneous spectral dependence of the source intensity over the spectral interval  $[v_1, v_2]$ :

$$T(z) = \int_{v_1}^{v_2} \exp\left[-\int_{z_1}^{z_2} \sigma(v, z) \Delta N(z) dz\right] dv / (v_2 - v_1)$$

> In the case of homogeneous absorbing medium:  $T(z) = \int_{v_1}^{v_2} I_0(v) \exp[-\Delta N\sigma(v)L] dv / \int_{v_1}^{v_2} I_0(v) dv$ 

 $\succ$  In the case of homogeneous absorbing medium and homogeneous source spectral dependence:

$$T(z) = \int_{\nu_1}^{\nu_2} \exp\left[-\Delta N\sigma(\nu)L\right] d\nu / (\nu_2 - \nu_1)$$



# Summary (1)

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

□ The fundamentals to understand atomic structures and energy levels are related to the interactions inside and outside an atom, including electrostatic interactions, electron spin, spin-orbit angular momentum coupling, nuclear spin, mass and volume, external fields, etc. Molecular structures and energy levels further include interactions among atoms within a molecule. Liquids and solids further involve intermolecular interactions.

□ Main physical processes for interactions between light and objects include elastic and inelastic scattering, absorption and differential absorption, resonance fluorescence, laser induced fluorescence, Doppler effects, Boltzmann distribution, reflection from surfaces, multiple scattering, and depolarization. There are large differences in scattering cross sections for various physical processes involved in lidar.



# Summary (2)

Doppler effects, Boltzmann distribution, polarization properties, etc, all can be utilized in lidar applications to infer atmospheric parameters like wind, temperature, aerosol properties, etc. Multiple scattering should be considered in lower atmosphere studies, especially for cloud and aerosol research.

□ 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.

Molecular oxygen O<sub>2</sub> in the Earth's atmosphere has strong absorptions centered at 760 nm and 687 nm with O<sub>2</sub> A- and B-bands, respectively.





# Summary (3) and Questions

□ 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.

□ Understanding these physical processes precisely is the key to successful lidar simulations, design, development, and applications. Lidar equations are developed according to these physical processes.

Lidar equation may change its form to best fit for each particular physical process and lidar application.

Can you use the Boltzmann distribution in pure rotational Raman spectroscopy to measure temperatures? If yes, how?

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 Lidar (Ed. Weitkamp) Chapters 2 and 3