Lecture 06. Fundamentals of Lidar Remote Sensing (4) "Physical Processes in Lidar"

- Light interactions with objects (continued)
- > Resonance fluorescence
- Laser induced fluorescence
- > Doppler effect (Doppler shift and broadening)
- Boltzmann distribution
- > Reflection from target or surface
- > Multiple scattering
- > Polarization in scattering
- Comparison of backscatter cross-sections
- Comparison of lidar equations
- Summary



Resonance Fluorescence

□ In the middle and upper atmosphere, there exist meteoric metal atoms and atomic ions. They have large absorption cross sections, 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. F



$$hv = E_2 - E_1$$





Laser Induced Fluorescence

Because of the strong intermolecular interactions, solids and liquids exhibit broad absorption and emission spectra. □ 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 excitedstate fluorescence lifetime of some ns. The decay then occurs to different sublevels of the ground state giving rise to a distribution of fluorescence light.





Chlorophyll fluorescence spectra (Chapter 6 and references therein) 3

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.

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

$$(6.2)$$
Here, $\alpha(\lambda, R)$ is the extinction coefficient caused by the absorption.

$$\alpha_c(\lambda, R) = \sigma_{eff}(\lambda, R) n_c(R)$$
 (6.3)

Doppler Shift and Broadening

Doppler Effects – 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)



Doppler Shift and Broadening in Atmospheric Scattering Signals



6

Boltzmann Distribution

Maxwell-Boltzmann distribution is the law of particle population distribution according to energy levels (under thermodynamic equilibrium)



N₁ and N₂ – particle populations on energy levels E₁ and E₂ g₁ and g₂ – degeneracy for energy levels E₁ and E₂, $\Delta E = E_2 - E_1$ k_B – Boltzmann constant, T – Temperature, N – total population

Population Ratio ⇒ **Temperature**

Fe Boltzmann Technique



Atomic Fe Energy Level [Gelbwachs, 1994; Chu et al., 2002] Example: Fe Boltzmann

$$\frac{N(J=4)}{N(J=3)} = \frac{g_1}{g_2} \exp\{\Delta E/k_B T\}$$
(6.9)

$$g_1 = 2 * 4 + 1 = 9$$

$$g_2 = 2 * 3 + 1 = 7$$

$$\Delta E = 416(cm^{-1})$$

$$= hc \times 416 \times 100(J)$$

$$\Delta E / k_B = 598.43K$$

For
$$T = 200$$
,
 $\frac{N(J=4)}{N(J=3)} = \frac{9}{7}e^{598.43/200} = 25.6$

Example Lidar Signals from Antarctica



Taken from [Chu et al., Geophysical Research Letters, 2011]

LIDAR

Reflection from Target or Surface

- Specular reflection from water or ice or target surface;
- Laser non-specular reflection from ground;
- Laser non-specular reflection from target surface;
- Solar reflectance from ground or target surface.
- For laser altimeter, laser scattering from ice sheet ...

How roughness and slope of surfaces affect the reflectance, angular distribution, broadening of the return pulses, etc.





Backscatter Cross-Section Comparison

| Physical Process | Backscatter Cross-Section | Mechanism |
|---|---|---|
| Mie (Aerosol) Scattering | 10 ⁻⁸ - 10 ⁻¹⁰ cm ² sr ⁻¹ | 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 4π times backscatter cross-section. 11

□ Lidar equations developed in Lecture 4 were developed under the single-scattering assumption. That is, all scattered photons except those scattered in the direct backward direction ($\theta = \pi$) are permanently removed from the transmitted and received lidar beams.

$$N_{S}(\lambda,R) = \left[\frac{P_{L}(\lambda_{L})\Delta t}{hc/\lambda_{L}}\right] \left[\beta(\lambda,\lambda_{L},\theta,R)\Delta R\right] \left(\frac{A}{R^{2}}\right)$$

$$\cdot \exp\left[-\int_{0}^{R} \alpha(\lambda_{L},r')dr'\right] \exp\left[-\int_{0}^{R} \alpha(\lambda,r')dr'\right] \left[\eta(\lambda,\lambda_{L})G(R)\right] + N_{B}$$
(4.17)

Multiple scattering is a natural phenomenon, occurring in the lower atmosphere, especially in fog, cloud and rain.

Multiple scattering has three major effects on the lidar return signals:

- 1) increasing the received power,
- 2) causing larger depolarization, and
- 3) delaying the time of flight.



□ Multiple scattering increases the lidar received power by two major factors: Forward scattered photons never leave the lidar beam, and some photons that are scattered out of the lidar beam may later be scattered back in. Thus, the actually received lidar signal includes photons that have been scattered more than once.

As a result, the received power somewhat exceeds the value given by Eq. (4.17) or the other lidar equations given in Lecture 04. Equivalently, the effective value of the scattering extinction coefficient is somewhat smaller than the single-scattering values.



Fig. 3.1. Schematic diagram of multiple scattering in the lidar geometry. The thick gray line represents the outgoing laser pulse; the arrows, the scattering events; and the two pairs of thin lines, the limits of two receiver fields of view, a narrow one for near-single-scattering detection, and a wider one for multiple-scattering detection.

Figure taken from "Lidar and multiple scattering" by Bissonnette in the book of "Lidar"



□ The paths of received multiply-scattered photons can lie on many different planes, and thus can transfer the plane of the electric vector. As a result, multiple scattering causes the received lidar signals partially depolarized, even when all the scatters are spherical.

□ The radiation backscattered exactly 180° by spherical particles conserves the linear polarization of the original laser beam. However, within 2° off the exact backscatter direction, the depolarization could jump from 0 to as much as 60%.

□ Multiple scattering causes depolarization mainly via the near 180° (but not exactly) single scattering. \Im

Figure taken from "Lidar and multiple scattering" by Bissonnette in the book of "Lidar"



Fig. 3.2. Single scattering linear depolarization ratio Δ integrated over all azimuth angles calculated for a model C2 Deirmendjian [15] cloud at 1.06 μ m as a function of the scattering angle near the backscattering direction of 180°.



□ The effects of multiple scattering on the received lidar signals depend on the atmospheric scattering and absorption coefficients, the size of scattering particles, the time delay, the field of view (FOV) of the lidar receiver, and the divergence of the lidar transmitted beam.

□ Larger FOV allows more chances of receiving multiply scattered photons. Thus, reducing FOV can help reduce the probability of receiving multiple scattering photons. However, the FOV is never small enough to avoid multiple scattering signals.

□ Larger scattering particles focus a much larger fraction of scattered photons in near-forward directions.

□ The theoretical treatment of multiple scattering in pulsed lidar applications is complex. Monte Carlo approach of numerical simulation can be used to predict the received power for various aerosol/cloud models.

□ The unwanted time delay caused by multiple scattering is of course an error term to laser altimeter or any laser range finders.

Have you seen multiple scattering effects even in STAR or MRI lidar?



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 $\vec{A}_{o} = \begin{cases} A_{ox} e^{i\varphi_{x}} \\ A_{oy} e^{i\phi_{y}} \end{cases}$ For unpolarized light the phases ϕ_x and ϕ_y are uncorrelated and their difference fluctuates statistically. For linearly polarized light in x, A_{oy} = 0; in a direction α 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 where the normalized vectore {a, b} $\vec{E} = \begin{cases} E_x \\ E_y \end{cases} = |\vec{E}| \cdot \begin{cases} a \\ b \end{cases} e^{i(\omega t - kz)}$ 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. > E_x and E_y form the orthogonal basis. $\vec{E}_t = \begin{cases} E_{xt} \\ E_{yt} \end{cases} = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \cdot \begin{cases} E_{xo} \\ E \end{cases}$

$$= \begin{pmatrix} a & b \\ c & d \end{pmatrix} \cdot \begin{cases} x_0 \\ E_{y_0} \end{cases}$$
 16



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.

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

$$S_0 = I$$

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

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

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

$$I = S_0$$

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

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

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

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

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

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

$$S_4 = x \sin \frac{S_4}{S_5}$$

$$S_5 = x \sin \frac{S_5}{S_5}$$

19

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 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.
- 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.

Polarization Lidar Equation

Obeying the same physics picture of lidar remote sensing as scalar lidar equations, polarization lidar equation has to use 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.



Scattering, Absorption, Fluorescence



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





Differential Absorption





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

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

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

$$T(\lambda, R) = \exp\left[-\int_0^R \alpha(\lambda, r) dr\right]_{23}$$

Differential Absorption/Scattering Form of Lidar Equation

 \Box For the laser with wavelength λ_{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 λ_{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.

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



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.

□ 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.

□ Fundamentals to understand atomic structures and energy levels are related to the interactions inside and outside an atom. Molecular structures and energy levels further include interactions among atoms within a molecule.

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.



Summary (2) 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