Lecture 22

Principles of active remote sensing: Lidars

Objectives:

1. Optical interactions of relevance to lasers.
2. General principles of lidars.
3. Lidar equation.

Required reading:

G: 8.4.1, 8.4.2

Additional/advanced reading:

R.M. Measures, Laser remote sensing, 1984.

1. Optical interactions of relevance to lasers.

- Laser is a key component of the lidar.

Lidar (LIght Detection And Ranging)

Laser (**L**ight **A**mplification by **S**timulated **E**mission of **R**adiation)

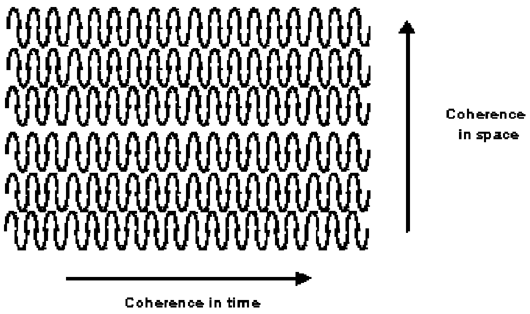
Basic principles of laser: stimulated emission in which atoms in an upper energy level can be triggered or stimulated in phase by an incoming photon of a specific energy. The emitted photons all possess the same wavelength and vibrate in phase with the incident photons (the light is said to be COHERENT).

The emitted light is said to be INCOHERENT in time and space if

- the light is composed of many different wavelengths
- the light is emitted in random directions
- the light is emitted with different amplitudes
- there is no phase correspondence between any of the emitted photons

Properties of laser light:

- Monochromaticity
- Coherence



A TRAIN OF COHERENT PHOTONS

- Beam divergence:

  All photons travel in the same direction; the light is contained in a very narrow pencil (almost COLLIMATED), laser light is low in divergence (usually).
- High irradiance:

  Let’s estimate the irradiance of a 1 mW laser beam with a diameter of 1 mm. The irradiance (power per unit area incident on a surface) is

$$F = P/S = 1\text{x}10^{-3}\ \text{W}/(\pi\ (1\text{x}10^{-3}\ \text{m})^2/4) = 1273\ \text{W/m}^2$$

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

Inelastic scattering is when there is a change in the frequency.

<u>Optical interactions of relevance to laser environmental sensing</u>

- Rayleigh scattering: laser radiation elastically scattered from atoms or molecules with no change of frequency
- Mie scattering: laser radiation elastically scattered from particulates (aerosols or clouds) of sizes comparable to the wavelengths of radiation with no change of frequency
- Raman Scattering: laser radiation inelastically scattered from molecules with a frequency shift characteristic of the molecule

- Resonance scattering: laser radiation matched in frequency to that of a specific atomic transition is scattered by a large cross section and observed with no change in frequency
- Fluorescence: laser radiation matched in frequency to a specific electronic transition of an atom or molecule is absorbed with subsequent emission at the lower frequency
- Absorption: attenuation of laser radiation when the frequency matched to the absorption band of given molecule

Types of laser relevant to remote sensing :

- solid state lasers (e.g., ruby laser, 694.3 nm)
- gas lasers (e.g., CO2, 9-11 μm)
- semiconductor lasers (GaAs, 820 nm)

2. General principles of lidars.

There are three basic generic types of lidar:
Backscatter lidars measure backscattered radiation and polarization.

DIfferential Absorption Lidar (DIAL) is used to measure concentrations of chemical species (such as ozone, water vapor, pollutants) in the atmosphere.
Principles: A DIAL lidar uses two different laser wavelengths which are selected so that one of the wavelengths is absorbed by the molecule of interest whilst the other wavelength is not. The difference in intensity of the two return signals can be used to deduce the concentration of the molecule being investigated (see lecture 26).

Doppler lidar is used to measure the velocity of a target. When the light transmitted from the lidar hits a target moving towards or away from the lidar, the wavelength of the light reflected/scattered off the target will be changed slightly. This is known as a Doppler shift - hence Doppler Lidar. If the target is moving away from the lidar, the return light will have a longer wavelength (sometimes referred to as a red shift), if moving towards the lidar the return light will be at a shorter wavelength (blue shifted). The target can be either a hard target or an atmospheric target - the atmosphere contains many microscopic dust and aerosol particles which are carried by the wind.

Lidars compared to radars:

- Lidar uses laser radiation and a telescope/scanner similar to the way radar uses radio frequency emissions and a dish antenna.
- Optically thick cloud and precipitation can attenuate the lidar beam. On the other hand, radar scatterers may consist of clouds and hydrometeors (e.g., rain or frozen precipitation, which have a definite fall velocity).
- In optically clear air, radar return signals may be obtained from insects and birds, and from radio refractive index variations due to humidity, temperature, or pressure fluctuations.
- Lidar beam divergence is two to three orders of magnitude smaller compared to conventional 5 and 10 cm wavelength radars.
- The combination of the short pulse (of the order of 10^{-8} s) and the small beam divergence (about 10^{-3} to 10^{-4} radiant) gives a small volume illuminated by a lidar (about a few m^3 at ranges of tens of km).

3. Lidar equation.

In general, the form of a lidar equation depends upon the kind of interaction invoked by the laser radiation.

Let's consider elastic scattering. Similar to the derivation of the radar equation, the lidar equation can be written as

$$P_r(R) = \frac{C}{R^2}\frac{h}{2}\frac{k_b}{4\pi}\exp(-2\int_o^R k_e(r')dr') \qquad [22.1]$$

where C is the lidar constant (includes P_t, receiver cross-section and other instrument factors);

$\kappa_b/4\pi$ (in units of $km^{-1}sr^{-1}$) is called the backscattering factor or lidar backscattering coefficient or backscattering coefficient;

κ_e is the volume extinction coefficient; and t_p is the lidar pulse duration ($h=ct_p$)

NOTE: From Eqs.[21.1]-[21.4], we have

$$k_b = k_s P(\Theta = 180) \qquad [22.2]$$

where κ_s is the volume scattering coefficient.

Solutions of the lidar equation:

In general, both the volume extinction coefficient κ_e and backscattering coefficient κ_b are unknown

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it is necessary to assume some kind of relation between κ_e and κ_b (called the extinction-to-backscattering ratio)

To eliminate system constants, the range-normalized signal variable, S, is introduced as

$$S(R) = \ln(R^2 P_r(R)) \qquad [22.3]$$

If S_o is the signal at the reference range R_0, from Eq.[22.1] we have

$$S(R) - S(R_0) = \ln\left(\frac{k_b}{k_{b,o}}\right) - 2\int_{R_0}^{R} k_e(r)dr$$

or in the differential form

$$\frac{dS}{dR} = \frac{1}{k_b(R)}\frac{dk_b(R)}{dR} - 2k_e(R) \qquad [22.4]$$

Slope method of inversion: assumes that the scatterers are homogeneously distributed along the lidar path so $\dfrac{dk_b(R)}{dR} \approx 0$

Thus $\dfrac{dS}{dR} = -2k_e$ and κ_e is estimated from the slope of the plot S vs. R

Limitations: applicable for a homogeneous path only.

Techniques based on the **extinction-to-backscattering ratio:**

use *a priori* relationship between k_e and k_b typically in the form

$$k_b = bk_e^n \qquad [22.5]$$

where ***b*** and ***n*** are specified constants.

Substituting Eq.[22.5] in Eq.[22.4], we have

$$\frac{dS}{dR} = \frac{n}{k_e(R)}\frac{dk_e(R)}{dR} - 2k_e(R) \qquad [22.6]$$

with a general solution at the range R

$$\boxed{k_e = \frac{\exp\left(\frac{S-S_0}{n}\right)}{\frac{1}{k_e} - \frac{2}{n}\int_{R_o}^{R}\exp\left(\frac{S-S_0}{n}\right)dr}} \qquad [22.7]$$

NOTE:

- Eq.[22.7] is derived ignoring the multiple scattering
- Eq.[22.7] requires the assumption on the extinction-to-backscattering ratio
- Eq.[22.7] is instable with respect to k_e (some modifications were introduced to avoid this problem. For instance, use the reference point at the predetermined end range, R_m, so the solution is generated for $R < R_m$ instead of $R > R_o$)