Lecture 22

Principles of active remote sensing: Lidars.

Lidar sensing of gases, aerosols, and clouds.

1. Optical interactions of relevance to lasers.

2. General principles of lidars.

3. Lidar equation.

Required reading:

S: 8.4.1, 8.4.2, 8.4.3, 8.4.4

Weitkamp: Ch 1

Additional/advanced reading:

CALIPSO: http://www-calipso.larc.nasa.gov/

CALIPSO Data User's Guide:

http://www-calipso.larc.nasa.gov/resources/calipso_users_guide/

Browse Image Tutorial:

http://www-calipso.larc.nasa.gov/resources/calipso_users_guide/browse/index.php

Winker, D. M., and Coauthors, 2010: The CALIPSO Mission: A Global 3D View of Aerosols and Clouds. Bull. Amer. Meteor. Soc., 91, 1211–1229.

Young, S. A., M. A. Vaughan, R. E. Kuehn, D. M. Winker, 2013: The Retrieval of Profiles of Particulate Extinction from Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) Data: Uncertainty and Error Sensitivity Analyses. J. Atmos. Oceanic Technol., 30, 395–428

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)

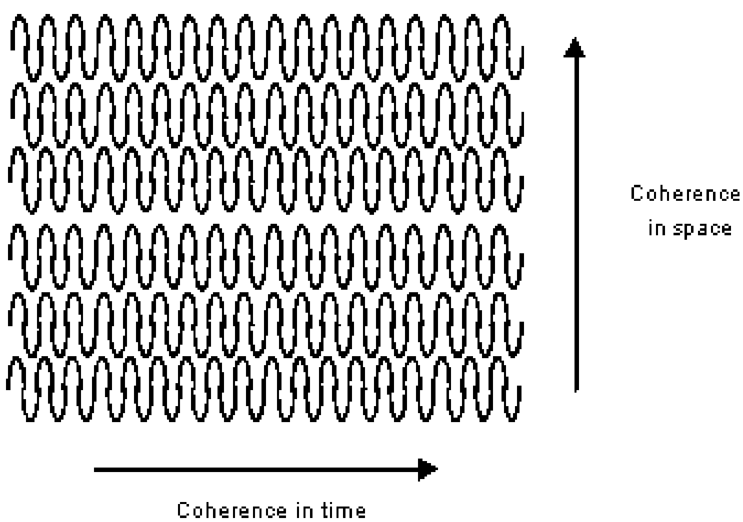
Basic principles of laser: stimulated emission in which atoms in an upper energy level can be triggered (or stimulated) in phase by an incoming photon of a specific energy. The emitted photons all possess the same wavelength and vibrate in phase with the incident photons (the light is said to be COHERENT).

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.

Optical interactions of relevance to laser environmental sensing

- 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 atmospheric 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 several main types of lidars:

Backscatter lidars measure backscattered radiation and polarization (often called the Mie lidar)

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 while 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.

Raman (inelastic backscattering) Lidars: detect selected species by monitoring the wavelength-shifted molecular return produced by vibrational Raman scattering from the chosen molecules.

High Spectral Resolution Lidar (HSRL) measures optical properties of the atmosphere by separating the Doppler-broadened molecular backscatter return from the unbroadened aerosol return. The molecular signal is then used as a calibration target which is available at each point in the lidar profile. This calibration allows unambiguous measurements of aerosol scattering cross section, optical depth, and backscatter phase function (see S 8.4.3).

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, but radar signals can penetrate heavy clouds (and precipitation).
- In optically clear air, radar return signals may be obtained from insects and birds, and from air 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 <u>elastic</u> 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 ($h=ct_p$)