Exploring the Atmosphere with Lidars

2. Types of Lidars

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In Part 1[1], we described the basic principle of the lidar (Light Detection and Ranging), the different scattering processes in the atmosphere and the Mie and Rayleigh lidars. In this part, we describe three other types of lidars: Raman lidar, differential absorption lidar (DIAL) and doppler lidar.

A lidar system consists of a pulsed laser which sends out pulses of laser light and a sensor that senses the scattered light from the different molecules and aerosols in the atmosphere. The characteristics of the scattered light are used to determine the nature and amount of the constituents.

1 Part 1. Basics and Applications, *Resonance*, Vol.8, No.4, pp. 33-43, 2003.

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Lidar, scattering, absorption.

Raman Lidar

The Raman technique has the greatest potential for measuring atmospheric gases, water vapor, temperature, etc. The transmitter should have a high energy and a high repitition rate. The receiver needs to incorporate a spectrometer or interference filter matched to the Raman shifted wavelength. The recent resurgence of activity in Raman scattering measurements of water vapor in the troposphere, after the earlier work in the late 1960s and early 1970s, can be attributed to advances in laser technology and the availability of interference filters which are capable of rejecting the strong Rayleigh and Mie scattered signals. Simultaneous measurements of water vapor and nitrogen can be made by using the frequency tripled output of a Nd: YAG laser at 355 nm and interference filters centered at 387 nm and 408 nm to record vibrational bands of nitrogen and water vapor, respectively. With this type of system, measurements up to the tropopause require integration times of several hours. The incorporation of XeF excimer laser operating at 351 nm would yield an average power larger by almost two orders of magnitude and, hence a reduction in sampling time by a factor of about ten.

The water vapor mixing ratio (q) is derived by the ratio of water vapor Raman to oxygen Raman backscatter signals, which is given by

$$q(z) = \frac{P_{H_2O}(z)}{P_{O_2}}.K.T(z_0, z), \tag{1}$$

where K is, the calibration constant obtained from a model measurement, $P_{O_2}(z)$ and $P_{H_2O}(z)$ are Raman backscattered signals by oxygen and water molecules at height z, respectively and $T(z_0, z)$ is the transmission correction term (ratio of atmospheric transmissivity at oxygen Raman backscattering to that of water vapor Raman scattering from the lidar at height z_0 to height z).

Differential Absorption Lidar (DIAL)

A DIAL system is similar to a LIDAR except that the laser must be tunable. By analysing the return signal with a fast digitizer (as in LIDAR) the radiation scattered back from any particular range along the beam can be measured. If we consider the size of the return signal at say 10 ms after the firing of the laser we know that this must correspond to radiation which has travelled to a distance of 1.5 km ($= C \times 10^{-6}/2$) and has been scattered back. The size of this signal will thus depend, apart from fixed geometric factors, on the amount of backscattering at 1.5 km range and on the absorption produced by the pollutant over the round trip to 1.5 km and back. The scattering is in general unknown but can be eliminated by repeating the measurement at a slightly different wavelength where the absorption coefficient of the pollutant is different but the scattering intensity is virtually the same. The change in signal between the two wavelengths thus corresponds entirely to the different amounts of absorption at the two wavelengths, and if the absorption coefficients of the pollutant at these two wavelengths are known, the total burden of pollutant between the measuring site and 1.5 km range can be

Box 1. Absorption methods

In absorption methods, observations are made at the wavelength of the incident radiation in the absorption lines or bands characteristic of a particular gas. Different experimental configurations are used for absorption measurements. Conventional long path absorption measurements can be made by using an optical receiver at the far end of the path. Also long path absorption system can be made single ended by the using optical retro-reflector or topographical targets as reflectors at the other end. These methods are capable only of measuring the total concentration, or column content of the molecules along the entire optical path. But they cannot provide range resolved data as in the backscattering pulsed lidar system. The most sensitive and effective absorption method for the measurements and monitoring of minor constituents is the DIAL technique. This method is based on backscattering from a continuous distribution of elastic scatterer in their path and provides range resolved data on a continuous basis. The absorption caused by the molecule and thereby its concentration, is obtained by measuring the backscattering produced by these scatterers at two wavelengths, one on the absorption line and the other one out side the absorption line. For this purpose the pulsed laser transmitter emits signals at two nearby wavelengths, on and off corresponding to a peak and trough respectively, in the absorption spectrum of the species of interest. The difference in the two received signals due to backscattering corresponds to the absorption produced by the species in the range cell defined by the laser pulse duration and receiver gate. This DIAL method is used for range resolved measurement of a number of minor constituents like ozone, water vapor, methane, etc.

deduced. Total burden is the integrated concentration

$$\int_0^r n(r')dr', \tag{2}$$

where $n(r)$ is the concentration at range r. Since the DIAL return signal is in fact continuous we can make this calculation at a whole series of ranges and determine the total burden as a function of range. This is the basic principle of DIAL. A more precise treatment can be given starting with the LIDAR equations (given in Part I) for the two wavelengths, which are traditionally known as the on-resonance and off-resonance wavelengths (on-resonance referring to the wavelengths at which the absorption is largest – usually the peak of an absorption line or feature).

The atmospheric absorption coefficient can be expressed in terms of its component:

$$\alpha_{\text{on}}(r) = \alpha_{\text{M}}(r) + \alpha_{\text{R}}(r) + \sigma_{\text{on}}\, n(r)$$
$$\alpha_{\text{off}}(r) = \alpha_{\text{M}}(r) + \alpha_{\text{R}}(r) + \sigma_{\text{off}}\, n(r).$$

Here Mie and Rayleigh scattering coefficients, α_M and α_R are nearly the same for the on and off resonance wavelengths. If σ is the absorption cross-section of the pollutant and $n(r)$, the concentration of pollutant in molecules/unit volume then $\sigma n(r)$ represents the absorption produced by the pollutants. The concentration of pollutants $n(r)$ can be obtained knowing the received power levels at the on-resonance and off-resonance wavelengths.

Using this method most of the trace gases and air pollutants such as O_3, CO, CH_4, OH and OCS can be measured.

Doppler Lidar

Mean wind profiles can be measured using Doppler lidars, which are similar in principle to Doppler radars, but operate at optical and infrared wavelengths (typically from 0.3 to 10 μm). At these wavelengths scattering in the troposphere and lower stratosphere is primarily from airborne particulate (e.g., sea salt, dust, smoke, spores, water droplets, and ice particles). These aerosol particles have radii ranging from 0.001 to 10 μm, remain suspended in the atmosphere on the order of days, and moves with the background wind providing a useful target for lidar wind sensing. Lidar wind profile measurements are usually obtained by scanning the lidar about the vertical axis at a fixed zenith angle. Since the Doppler shifts are generally small, they are measured by the optical heterodyne technique, i.e., the returned signal is mixed with another laser signal operating at a nearby wavelength and the difference or beat frequency between the mixed signal and the original signal is detected. Doppler lidar has distinct advantages over the Doppler radar. Because of shorter wavelength, it can operate on several atmospheric tracers and clear air operation is possible. It does not require large antenna, hence has better steerability, and is more suitable for mobile systems like aircrafts and satellites. It has both military and scientific applications. It is useful for atmospheric dynamics studies and is capable of giving true wind speeds and wind shears from airborne systems. If deployed from a satellite platform, it gives the global wind field with high accuracy, spatial and temporal resolution on a routine basis. It requires lasers with high frequency stability (a velocity of 1 ms^{-1} produces a Doppler shift of 200 kHz at a laser wavelength of 10 mm. Hence, frequency stability better than 10^{-8} is needed).

Future Perspectives

The field of remote sensing of the atmosphere using lasers has made tremendous progress in the recent years through the development of practical, new eye-safe lasers and simultaneous progress in the solution of inverse problems concerning the composition and physical state of the atmosphere. Lasers are quite useful because of their compact size and tunability. Diode lasers will facilitate further reduction of lidar system complexity and size so that more portable lidar systems would be available in future for multidimensional mapping of air pollutant concentrations. The existing ground based, airborne, ship-borne and space-borne lidar systems would offer an unique opportunity to obtain global observation of many atmospheric parameters on continuous basis. The development in laser technology will bring out new laser-based systems for better understanding of the secrets of our planet and its atmosphere.

Suggested Reading

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