Exploring the Atmosphere with Lidars

1. Basics and Applications

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Lidar is a powerful technique for the study of atmospheric structure and dynamics. The spatial and temporal variability of minor constituents of the atmosphere such as aerosols, dusts, clouds, water vapour, and wind speed and temperature structure of the upper atmosphere can be studied using lidar. This article describes the basic principle of lidar operation, types of laser used for the remote sensing of the atmosphere and mechanism of scattering/absorption processes when the laser interacts with the atmosphere. Part 1 gives the basics and applications of lidar. Also, one type of lidar – Mie and Rayleigh lidar is described.

Introduction

The remote sensing of the atmosphere can be classified broadly into two categories, namely passive remote sensing and active remote sensing methods. In passive remote sensing methods, the source is beyond the control of the observer, e.g. radiometer, photometer, spectrometer, etc. In active remote sensing methods, the source can be controlled by the observer e.g. lidar, radar, sodar, sonar, etc. In the field of remote sensing [1], lasers play an important role due to their inherent capability of generating well-collimated beams with outstanding characteristics in high coherence, monochromaticity, and directivity. Laser remote sensing techniques provide powerful tools for scientific studies of the atmosphere, environmental monitoring, measurement of air quality parameters, remote sensing of oceans and rivers, remote assessment of vegetation, etc. Developments in laser technology such as second harmonic generation, high power, compact diode pumped solid-state lasers, and tunable solid-state lasers, etc. have opened new possibilities of laser remote sensing to explore the Earth's atmosphere. One of the newest

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lidar innovations known as 'volume imaging lidar' is a technique that finds use in many strategic areas apart from its applications in studying the inhomogeneities in the atmosphere.

Laser remote sensing of the atmosphere is generally referred as LIDAR, the acronym for LIght Detection And Ranging. Similar to radar, in lidar, a laser pulse is sent into the atmosphere and is used as a spectroscopic probe of its physical state and chemical composition. The emitted laser beam interacts with the atmospheric constituents causing alterations in the intensity, polarization, and wavelength of the backscattered light. From the measurements of these parameters of the received backscattered light, one can deduce the properties of the atmosphere and its constituents. The lidar allows range resolved measurement to obtain a vertical profile of the atmospheric parameters. The distance of the scattering medium can be deduced with high accuracy from the time delay of the return signal. Lidar systems can be operated in the wavelength range extending from the ultraviolet to the infrared (UV to IR) by using different types of lasers. Using the techniques of scattering, absorption, resonance and fluorescence, lidar can measure solid particulate matter such as aerosols [2], species of very low concentrations such as ozone [3], water vapour and metal atoms [4] such as Na, K, etc. Lidar measurements of the Rayleigh scattering from a neutral atmosphere can be used to determine neutral density, pressure, temperature, and wind speed. Studies in the past decade have demonstrated the reliability of Rayleigh lidar technique for measuring the temperature and dynamics of the atmosphere in the altitude region of 30-80 km.

Principle of Lidar Operation

A lidar system essentially comprises a transmitter, a receiver, and a lidar controller. The transmitter is a laser source, whereas receiver is an optical telescope. Lidar controller provides accurate timing and control pulses for the operation of the different channels, while simultaneously providing synchronization with the laser transmitter pulse. In general, lidars are used for the study of aerosols in the atmosphere in either monostatic or bistatic configuration depending upon the application or experimental requirements. In the monostatic configuration, the transmitter and receiver are arranged either co-axially in which the axis of the laser beam is coincident with that of the receiver optics, or in a bi-axial arrangement in which the laser beam only enters the field of view of the receiver optics beyond some predetermined range. In the case of bistatic configuration, the transmitter and receiver are spatially separated according to experimental requirements. Although monostatic lidars are suitable for the development of mobile systems for vehicles, aircraft and spacecraft installations besides their ground based applications, bistatic lidars, on account of their angular scattering measuring capabilities, possess advantages over monostatic lidars.

A fraction of the light in the transmitted pulse is scattered back to the receiver by the molecules and particles (aerosols) in the atmosphere, which act as distributed scatterers. The received radiation is collected by an optical system (telescope) and is focused on to the cathode of a optical detector preferably a photo multiplier tube (PMT). The electrical signal from PMT is amplified, digitized, stored, and analyzed using a computer. Since the transmitted pulse has a finite duration τ, it illuminates a finite geometrical length $C\tau$ (C is the velocity of light) of the atmosphere at any instant. However, since the received energy must travel a two-way path, the atmospheric length (or range increment) from which signals received at any time is $C\tau/2$. This method allows a range resolved measurement. All the backscattered photons arriving in the time range $\tau \pm \Delta\tau/2$ are stored in one range bin. A typical range resolution of 75 m requires a 500 ns range bin. A single profile is recorded for each laser shot. The single shot profiles are added together at each altitude to build up a sufficient signal at the corresponding altitude. For example if a laser fires 1000 shots at the rate of 10 pulses per second, then time required to build up a single statistically significant profile is 100 s.

Types of Laser and their Properties Relevant to Lidar Applications

The laser is the most critical part of any lidar system. The laser needs to be easy to operate, reliable, rugged and reasonably compact. It is necessary that its operation is controlled through a personal computer (PC) so that the synchronization of various experimental settings can be done. Lasers, which are capable of emitting pulses of high peak power, narrow bandwidth, and short duration and that propagate with a low degree of divergence are ideal for probing the environment (*Box* 1, *Table* 1). Lasers used for these applications should be capable of operating at high repetition rate when the return signal is very weak and for studying short-term phenomena. The importance of some of these laser parameters are explained below.

Pulse Energy: The higher the laser pulse energy, the better the signal to noise ratio for a given range.

Pulse Length: This sets a limit to the range resolution. For example, a 10 ns pulse length can provide a 1.5 m range resolution. For atmospheric measurements, a pulse length of 100 ns is adequate.

Beam Quality: A beam divergence of 1 mr or less is required for the output beam. For UV lidar system, the field-of-view of the telescope has to be kept small in order to reduce the amount of background light seen by the detector. For an IR system, it is necessary to have small area detector to reduce noise. Beam divergence can be improved by expanding the beam with a telescope and this also makes the beam more eye-safe. Beam expansion is required particularly for higher altitude (above 70 km) studies in order to improve the signal-to-noise ratio as well as to increase the spatial resolution in the horizontal plane.

Repetition Rate: A high repetition rate speed means that the time required to average over the required number of pulses is

Box 1. Types of Laser for atmospheric Studies

There are different types of lasers available for atmospheric measurements. Also the wavelength range is further extended by the use of second, third or even fourth harmonic generation. The development of new lasers operating over a broader range of frequencies has made use of other techniques like DIAL (DIfferential Absorption Lidar) as powerful methods for many other measurements in the atmosphere. *Table* 1 summarizes some of the important lasers that find wider use in the atmospheric studies.

Laser	Wavelength	Energy (J)	PRF (Hz)	Range (Km)	Parameter studied
Ruby	0.694mm	2-3	0.5	up to 40	Aerosols, volcanic ash, dust.
Nd: YAG	1.06mm	1	10	up to 80	Aerosols, volcanic ash, dust, clouds.
CO_2	9-11 mm multi-line	1-10	1-50	up to 15	H_2O, CH_4, NO_2, SO_2, etc.
CO	5-6.5 mm	Not very popular for pulsed operation		up to 15	CO, Hg, CO_2, etc.
Dye lasers flash lamp pumped	0.35 – 1.06 mm	0.1 to 20	10-100	up to 90	Temperature, pressure.

Table 1. Characteristics of pulsed lasers for atmospheric studies.

less. Some atmospheric measurements need high repetition rate to study fast varying phenomena or parameter having time scales of few seconds to few minutes. Typical repetition rates used in atmospheric lidars vary from few Hz to few tens of Hz. However, rates greater than 20 Hz would cause problems in acquiring the data. The system is difficult to align for pulse rates less than 1 Hz.

Main Scattering/absorption Process of Laser-atmosphere Interactions

Several scattering/absorption mechanisms are present when the laser energy interacts with the atmosphere. The term backscattering refers to the case where the scattered radiation is at an

Table 2. Main scattering/absorption process of laser-atmosphere interactions.

angle 180° to the incident radiation, the lidar configuration being monostatic with the transmitter and receiver collocated. *Table* 2 describes the important scattering/absorption processes

Technique	Cross-section of the scatterer (m^2)	Principle	Application
Rayleigh scattering	~ 10^{-31}	Dimensions of scatterer << laser wavelength.	Higher altitude density of air molecules, temperature.
Mie scattering	~ 10^{-14} (Depends upon the size distribution of scatterers).	Dimensions of scatterer >> laser wavelength.	Aerosols, clouds, smog, smoke, dust.
Resonance scattering	$10^{-17} - 10^{-21}$	Excitation with a laser produces emission of photon at same wavelength.	High altitude atomic species (K, Na, Li...).
Fluorescence	$10^{-24} - 10^{-32}$	Wavelength of laser coincides with absorption line or band in sampled material. Transition to a lower state of higher energy occurs followed by emission of light at wavelength similar to or less than the laser wavelength.	Trace species (Na, K, Li, OH, etc.).
Raman scattering	~ 10^{-34}	Wavelength of scattered radiation shifts with respect to the laser wavelength. Positive and negative shifts represent stokes and anti-Stokes Raman scattering, respectively.	CO_2, H_2O, N_2 (Lower altitude water vapour and temperature measurements).
Differential absorption	~ 10^{-23}	Excitation with laser at two wavelengths (one coincides with maximum and other with minimum absorption of the gas of interest) provides concentration of the constituent.	Trace species (O_3, NO_2, SO_2, CH_4, CO, H_2O).

Box 2. Scattering Processes

The different scattering processes are:

- Rayleigh scattering
- Mie scattering
- Resonant scattering
- Fluorescence
- Raman scattering

The first two scattering processes are elastic process in which no appreciable energy exchange takes place between the scatterer and the incident photons. Elastically scattered energy has the same wavelength as the incident radiation. It is customary to differentiate between the Rayleigh regime, in which the scatterer is much smaller than the illuminating wavelength, and the Mie regime, in which scatterer is comparable to or larger than the wavelength. In the case of inelastic scattering, there is an exchange of energy between the scatterer and the incident photons resulting in a scattered radiation at a wavelength differing from that of the incident radiation. Inelastic scattering includes resonant scattering, ordinary fluorescence, and Raman scattering. Resonant scattering entails absorption at a wavelength corresponding to an electronic transition and re-emission at the same wavelength. It is applicable for atomic species at higher altitudes such as Na. K, etc. Fluorescence usually refers to absorption of radiation at a particular wavelength and re-radiation at one or more longer wavelengths, and can apply to either atoms or molecules. Fluorescence cross-sections are quite large at low pressure, but in the lower atmosphere the effective cross-sections get reduced by many orders due to collisional quenching. Some of the atmospheric constituents like OH radicals are measured using the laser induced fluorescence technique. Raman scattering (including resonant Raman scattering) is very useful for the study of minor constituents such as N_2, H_2O, etc. Raman scattering results from excitation of either the vibrational-rotational or the pure rotational transitions. Re-emission takes place at wavelengths lower and higher than the wavelength of the incident radiation. The shift from the wavelength of incident radiation is characteristic of the scattering molecules and is thus useful for its measurement of composition. Raman scattering technique also provides a means of identifying unknown constituents like pollutants.

that take place when the laser energy interacts with the atmosphere. The different scattering processes are described in *Box* 2.

Details of Types of Lidar Systems for Atmospheric Studies

The lidar systems are used mainly for the study of

i. Atmospheric gas densities and dynamic structures up to an altitude of about 80 km using the Rayleigh scattering.

ii. Aerosol characteristics in the lower troposphere using Mie scattering.

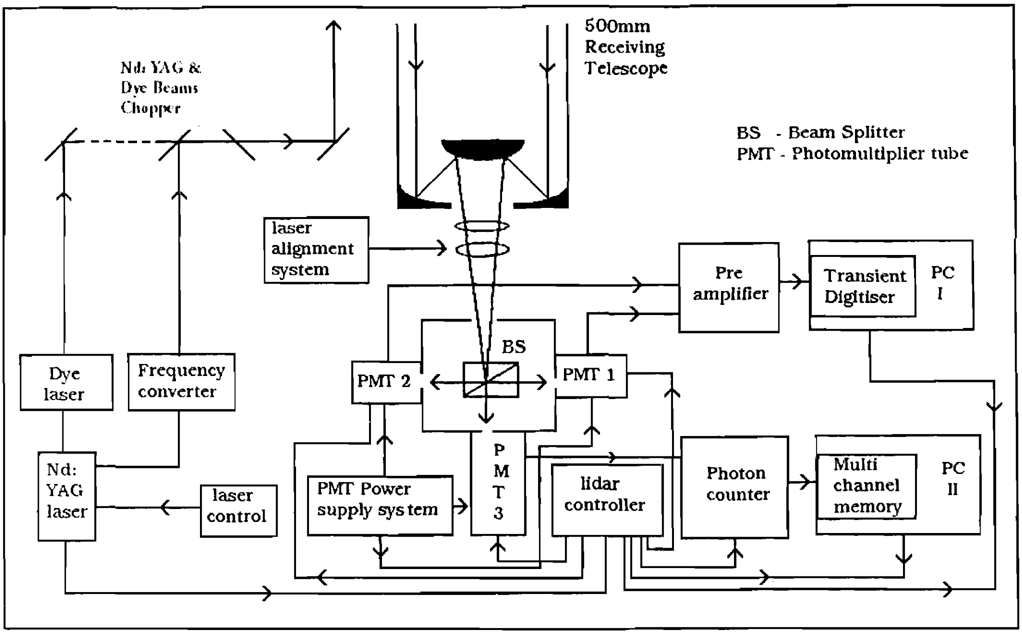
iii. Minor constituents like water vapour, ozone, etc., using Raman scattering, resonance absorption and differential absorption.

iv. Atmospheric temperature using Rayleigh and Raman scattering.

Mie and Rayleigh Lidar

Mie and Rayleigh lidar is essentially used for the study of aerosols, cirrus clouds, and temperature of the atmosphere. A typical Nd: YAG based monostatic lidar system is discussed here, which was designed and developed in-house in the Space Physics Laboratory, Vikram Sarabhai Space Centre, Trivandrum. A Quantel Model YG-581C-20 Nd: YAG laser is the main transmitting source in the lidar system (*Figure* 1). Its fundamental wavelength is 1064 nm, in the near infrared. To operate the system in the visible and UV, the second, third and fourth harmonics of the fundamental wavelength are used, viz. 532 nm, 355 nm, and 266 nm. The laser beam is transmitted vertically up

Figure 1. Schematic diagram of Multiwavelength lidar system.



into the atmosphere through a 45° mirror and a 100 mm refracting telescope (only for higher altitude studies). The backscattered radiation is collected by 500 mm Cassegrain receiving telescope. Using a post optics system, the received signal is delivered to the photo multiplier tubes. Interference filters with a bandwidth of 1 nm are used in the post optics to reduce the background noise. The receiver has three channels to cover different wavelength regions and the two data acquisition modes.

Figure 2 shows a typical aerosol extinction coefficient profile obtained in the altitude region 5 to 30 km. In general, the

Box 3. Equation for Backscattered Signal

The backscattered signal $P(r)$ received from a pulsed monostatic lidar can be expressed as

$$P_r = P_0 \frac{C\tau}{2} \eta A \frac{\beta_{(r)}}{r^2} \exp\left[-2\int_0^r \alpha_{(r')} dr'\right], \qquad \ldots(1)$$

where P_r – Received power, P_0 – Transmitted power, C – Speed of light, τ – Pulse width, r, r' – Altitude η – Optical efficiency of the transmitter and receiver, A – Effective area of the receiver, $\beta_{(r)}$ – Volume backscatter function, $\alpha_{(r)}$ – Volume extinction function.

The volume backscatter function is given by

$$\beta_{(r)} = n_a(r)\sigma_a + n_g(r)\sigma_m ,$$

where n_a and n_m are number densities of aerosols and gas molecules respectively, and σ_a and σ_m are the Mie and Rayleigh backscattering cross-sections, respectively.

Similarly,

$$\alpha_{(r)} = n_a(r)\rho_a + n_g(r)\rho_g\rho_m ,$$

where ρ_a and ρ_m are the Mie and Rayleigh extinction cross-sections, respectively. The expression

$\exp\left[-2\int_0^r \alpha_{(r)} dr'\right]$ is replaced by $T^2(r)$, where $T(r)$ is the one-way atmospheric transmittivity. The lidar equation contains two unknowns, namely β and α. Assuming a functional form of relationship between β and α, lidar backscattered signals can be analysed to obtain altitude profiles of aerosol extinction coefficient. By measuring the aerosol extinction at different wavelengths, it is possible to invert the size index of the particulate matter/aerosol.

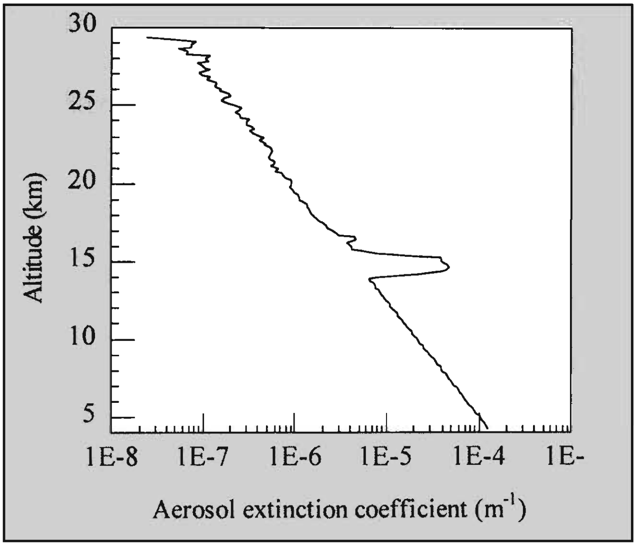


Figure 2. Altitude profile of aerosol extinction coefficient obtained using lidar system at 532 nm on 24 April 2001.

derived aerosol extinction coefficient decreases with altitude. Basically, the lidar data consists of Rayleigh scattering due to molecules and Mie scattering due to aerosols. The contribution of molecules is removed from the total extinction coefficient (aerosol+molecule) values using a model while deriving the aerosol extinction coefficient profile. The enhancement in aerosol extinction coefficient in the altitude region 13 to 16 km is

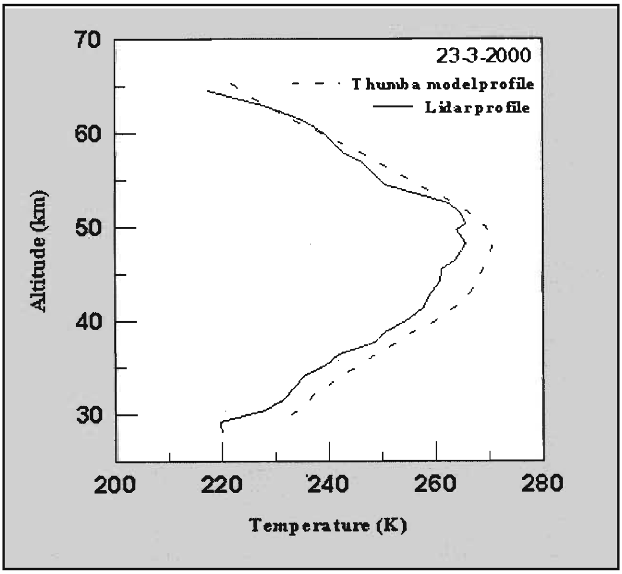


Figure 3. Temperature profile obtained using lidar system at 532 nm on March 23, 2000.

Suggested Reading

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attributed to the presence of high altitude cirrus clouds. Rayleigh lidar provides temperature measurement above 30 km. *Figure* 3 shows a typical temperature profile of the atmosphere in the altitude region 30-70 km obtained using the Rayleigh scattering technique. As the aerosol content in this region is negligible, the measured backscattered signal is completely due to Rayleigh scattering. Rayleigh scattering can be employed to determine the temperature of the atmosphere up to about 80 km if the ideal gas law and hydrostatic conditions are assumed. The method of analysis adopted for the determination of temperature profile from the lidar data is similar to the method suggested by Hauchcorne and Chanin (1991). The algorithm to derive air density and hence the temperature is, however, very sensitive to errors in the estimated background noise level. Reliable results can be obtained only if the background count level is properly estimated and subtracted from the photon count profile.

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