drag plays a nontrivial role in the total momentum budget of the atmosphere.

See also

Buoyancy and Buoyancy Waves: Optical Observations; Theory. **Downslope Winds**. **Dynamic Meteorology:** Waves. **Lee Vortices**. **Wave Mean-Flow Interaction**.

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LIDAR

Contents

Atmospheric Sounding Introduction

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Introduction

Lidar (an acronym for light detection and ranging) is a remote sensing technique used predominately for measuring atmospheric parameters, such as temperature, composition and wind. Lidar operates on the same principle as radar; in fact, it is sometimes called laser-radar. Both these techniques operate by transmitting a beam of electromagnetic radiation and subsequently detecting any radiation scattered back to the instrument. The scattered radiation is analyzed in order to determine some property or properties of the medium through which the radiation traveled. Lidar and radar differ in the wavelength of the radiation utilized. Radar uses wavelengths longer than about 1 cm, in the radio band, while lidar uses light in the ultraviolet, visible, and infrared, which in modern lidar systems is generated by lasers. The different wavelengths used by radar and lidar leads to the very different forms the actual instruments take.

The range of atmospheric parameters measurable with lidar includes temperature, wind velocity, atomic and molecular species concentration, and aerosol and cloud properties.

In addition to its atmospheric applications, lidar is also used in ocean research and military applications, including the detection of chemical and biological agents and the remote identification and tracking of vehicles. Lidar-equipped binoculars are used by hunters and golfers as they provide accurate range measurements.

Evolution

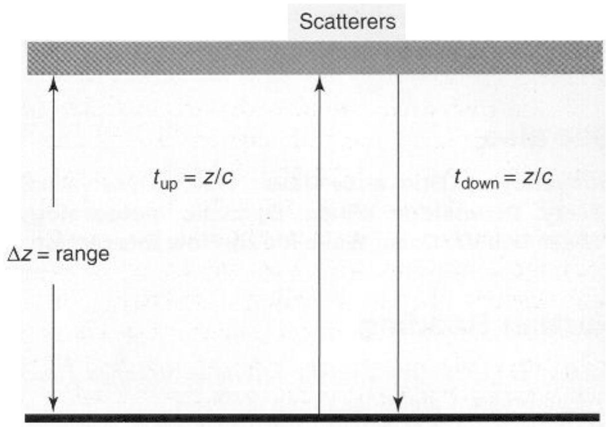
The principle of lidar was first proposed in 1930. The original proposal suggested the measurement of atmospheric density profiles by the detection of scattering from a beam of light projected into the atmosphere. This proposed scheme suggested an antiaircraft searchlight as the source of the beam and a distant large telescope for the receiver. In this configuration, now known as bistatic, the range of the scattering can be determined by geometry. In the bistatic configuration, shown in **Figure 1**, the field of view of the receiver is scanned along the transmitted beam in order to obtain an altitude profile of the scattered light.

The first results obtained using this principle were reported in the late 1930s when photographic recordings of light scattered from a searchlight beam were made.

Typically, modern lidar systems are monostatic in configuration, with the transmitter and receiver co-located. Monostatic systems can be subdivided into two categories: coaxial systems, where the laser beam is transmitted coaxially with the receiver's field of view, and biaxial systems, where the transmitter and receiver are located adjacent to each other. Monostatic lidar systems use pulsed light sources, thereby enabling the range at which scattering occurs to be determined from the round-trip time of the scattered light (**Figure 2**).

By the early 1950s, refinements in technique and improved instrumentation, including electrical recording of the intensity of the backscattered light, allowed the measurement of atmospheric density profiles up to altitudes of around 67 km. These measured density profiles were then used to derive temperature profiles using the Rayleigh-lidar technique, which is described later.

The invention of the laser in 1960 and the giant pulse, or Q-switched, laser in 1962 provided a powerful new light source for lidar. The first use of a laser in a lidar system was reported in the early 1960s and since then developments in lidar have been linked closely to advances in laser technology.



$$t_{total} = t_{up} + t_{down} = 2\,\Delta z/c$$

$$\Delta z = (t_{total} \cdot c)/2$$

Figure 2 Schematic illustrating the process of ranging based on timing the returned signal.

Instrument Basics

Lidar hardware can be conveniently divided into three subsystems: the transmitter, the receiver, and the detection and recording systems. **Figure 3** is a block diagram of a generic lidar system, which shows how these subsystems work together to form a complete lidar.

Transmitter

The transmitter generates light pulses with the required properties and directs them into the atmosphere. Pulsed lasers, with their inherently low divergence, narrow spectral width, and short, intense pulses are ideal as the light sources for lidar systems.

In addition to a laser, the transmitter of a lidar often includes a beam expander, whose purpose is to reduce the divergence of the beam being transmitted into the atmosphere. This allows a reduction in the background measured by the lidar. At night, the background is due to light from the Moon, stars, airglow, and artificial lights. During the day, background is predominately due to the Sun. Background can enter the lidar receiver either directly or after scattering in the atmosphere. A reduction in the divergence of the

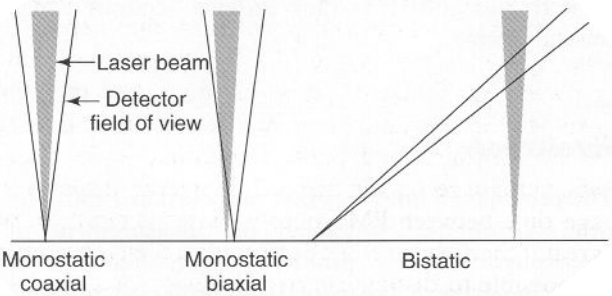


Figure 1 Three possible alignment arrangements of a lidar's transmitted beam and receiver field of view.

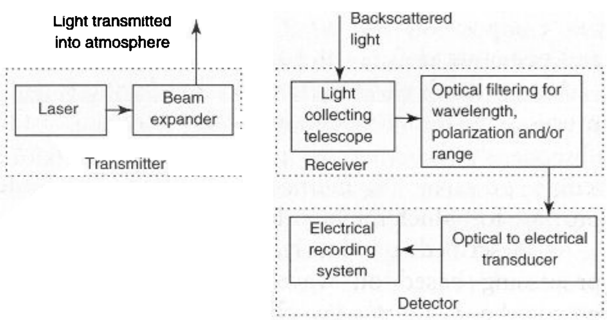


Figure 3 Schematic of a generic lidar.

transmitted beam allows the field of view of the receiver to be reduced, resulting in a lower background.

The narrow spectral width of the laser has been used to advantage in a variety of ways in lidar systems. It allows the spectral filtering of light by the lidar receiver. A bandpass filter tuned to the laser wavelength selectively transmits photons backscattered from the laser beam, while rejecting photons at other wavelengths, thereby enabling a reduction in the background by several orders of magnitude. The pulse properties of pulsed lasers allow ranging to be achieved by timing the backscattered signal, thus allowing the simpler monostatic configuration.

The major influence on the type of laser used in a lidar is the parameters the lidar is being designed to measure. Some measurements require a very specific wavelength and/or tunability, i.e. resonance–fluorescence and differential-absorption lidar (DIAL). These types of lidars can require complex laser systems to produce the required wavelengths, while other simpler lidars, such as Rayleigh, Raman, and aerosol lidars, can operate over a wide wavelength range. Although it may be possible to specify the exact performance characteristics of the laser required of a particular lidar measurement, these characteristics often need to be compromised in order to select from the types of lasers available.

Receiver

The receiver of a lidar collects and processes the scattered laser light before directing it onto the detector. The first optical component, the primary optic in the receiver usually has a large diameter, enabling it to collect a large amount of the scattered laser light.

Lidar systems typically utilize primary optics with diameters ranging from about 10 cm up to a few meters in diameter. Optics at the smaller end of this scale are used in lidar systems that are designed to work at close range – a few hundred meters – and may be lenses or mirrors. Optics at the larger end of this range are used in systems designed to probe the middle and upper atmosphere and are typically mirrors.

After collection by the primary optic, light is usually processed in some way before being directed to the detector system. Processing can be based on wavelength, polarization, and/or range, depending on the purpose for which the lidar has been designed.

As described previously, the simplest form of processing based on wavelength is the use of a narrow-band interference filter to reduce the background. Much more sophisticated spectral filtering schemes are employed in Doppler and high-spectral-resolution lidar systems.

Signal separation based on polarization is a technique often used in the study of atmospheric aerosols. Information on aerosol properties can be obtained from the degree to which light scattered from a polarized laser beam is depolarized.

Processing of the backscattered light based on range can be performed in order to protect the detector from the intense near-field returns of high-power lidar systems. This protection is achieved by using a fast shutter that closes the optical path to the detector while the laser is firing and for a short time afterward. The shutter opens again in time to allow transmission of light backscattered from the altitude range being studied.

Detection and Recording

The signal detection and recording section of a lidar takes light from the receiver and produces a permanent record of the measured intensity as a function of altitude. In the first lidar systems the detection and recording system comprised a camera and photographic film. Today detection and recording is achieved electronically. The detector is a device that converts light into an electrical signal and the recorder is an electronic device, often involving a microcomputer, which processes and records this electrical signal.

Photomultiplier tubes (PMTs) are devices used as detectors for incoherent lidar systems working in the visible and ultraviolet. PMTs convert an incident photon into an electrical current pulse large enough to be detected by sensitive electronics. Other devices that are less commonly used as detectors in lidar systems include multianode PMTs, micro-channel-plates (MCPs), and avalanche photodiodes.

There are two ways the output of a PMT can be recorded electronically; the pulses can be counted individually (photon counting) or the average current due to the pulses can be measured and recorded (analog recording). Which method is the more appropriate depends on the rate at which the PMT produces output pulses, which is proportional to the intensity of the light incident on the PMT. If the average time between PMT output pulses is much less that the average pulse width, then individual pulses can be easily identified and photon counting is the more appropriate recording method. However, if the average time between PMT output pulses is close to, or greater than, the average pulse width, then it becomes impossible to distinguish overlapping pulses, and so analog recording becomes the more appropriate method.

Coherent Detection

There is a class of lidar systems that determine wind speed by measuring the Doppler shift of backscattered light. There are two ways these measurements can be achieved, namely incoherent and coherent detection. Incoherent systems measure the wavelength of the transmitted and received light independently, using a spectrometer, and determine the Doppler shift from these two measurements. Coherent detection systems use a local oscillator, a narrow-band continuous-wave laser, to set the frequency of the transmitted pulses. Systems incorporating coherent detection use a local oscillator on a photomixer. This arrangement results in the output of the photomixer being a radio-frequency (RF) signal whose frequency is the difference of the frequencies of the local oscillator and the backscattered light. Standard RF techniques are then used to measure and record this RF signal. The measured RF signal is used to determine the Doppler shift of the backscattered light and thus the wind speed.

The Lidar Equation

The lidar equation is used to determine the number of photons detected by a lidar system. The lidar equation takes into account both instrumental parameters and geophysical variables. The general form of the lidar equation includes all forms of scattering and it can be used to calculate the signal strength for any lidar.

The number of photons detected as pulses at the photomultiplier output, per laser pulse, is

$$A \int_{\Delta\lambda} PS(\lambda)\tau_t(\lambda)\tau_r(\lambda)Q(\lambda) \int_{R_1}^{R_2} \xi(r)\tau_a(r,\lambda)^2 \frac{1}{r^2} \times \sum_i \frac{d\sigma_i}{d\Omega}(\lambda)N_i(r)\,dr\,d\lambda \qquad [1]$$

In eqn [1] A is the area of the telescope; $PS(\lambda)$ is the convolution of $P(\lambda)$ and $S(\lambda)$, where $P(\lambda)$ is the number of photons emitted by the laser in a single laser pulse and $S(\lambda)$ is a function which takes into account any wavelength shift during scattering, including Doppler and Raman shifts; $\Delta\lambda$ is the wavelength range for which $PS(\lambda)$ is nonzero; $\tau_t(\lambda)$ and $\tau_r(\lambda)$ are the optical transmission coefficients of the transmitter and receiver optics respectively; $Q(\lambda)$ is the quantum efficiency of the photomultiplier; r is the range and R_1 and R_2 are the minimum and maximum ranges for a range bin; $\xi(\lambda)$ is the overlap factor which takes into account the intensity distribution across the laser beam and the physical overlap of the transmitted laser beam and the field of view of the receiver optics; $\tau_a(r, \lambda)$ is the optical transmission of the atmosphere along the laser path; $(d\sigma_i/d\Omega)(\lambda)$ is the backscatter cross-section for scattering of type i; and $N_i(r)$ is the number density of scattering centers, which cause scattering of type i.

The general form of the lidar equation, as expressed in eqn [1], can usually be greatly simplified when applied to a particular lidar system.

Rayleigh Lidar

Rayleigh lidar is the name given to the class of lidar systems that measure the intensity of light backscatter by molecules from altitudes between about 30 and 100 km. The intensity profiles measured by Rayleigh lidars are used to calculate relative density profiles, which are in turn used to calculate absolute temperature profiles. The terms Rayleigh scattering and molecular scattering are often used interchangeably, as are the terms Mie scattering and aerosol scattering. Rayleigh theory named after its founder, Lord Rayleigh, describes the scattering of light by molecules that are small compared with the wavelength of the incident radiation; Mie theory describes scattering by aerosols that are not small compared with the wavelength, so there is a strong connection between these two pairs of terms.

Rayleigh scattering explains the color, intensity distribution, and polarization of the blue sky in terms of scattering by atmospheric molecules. For objects with dimensions greater than about 0.003 times the incident wavelength, the more general Mie theory must be used to calculate scattering effects.

The Rayleigh backscatter ($\theta = \pi$) cross-section for the atmosphere below 90 km can be expressed as

$$\frac{d\sigma_R(\theta = \pi)}{d\Omega} = \frac{C}{\lambda^4}\ \mathrm{m^2\,sr^{-1}} \qquad [2]$$

where the value of C is between about 4.75×10^{-57} and 5.00×10^{-57}, depending on the value used for index of refraction of air. Above 90 km altitude, the concentration of atomic oxygen becomes significant, causing the refractive index of air to change, resulting in eqn [2] becoming less accurate with increasing altitude. The Rayleigh backscatter cross-section, eqn [2], can be used in conjunction with the lidar eqn [1] to determine the intensity of the backscatter that can be expected for a particular Rayleigh lidar system.

The Rayleigh lidar technique relies on the measured signal being proportional to the atmospheric density. This is not the case in any region that contains aerosols. From the surface to the top of the stratospheric aerosol layer, about 25–30 km, the atmosphere contains a significant concentration of aerosols, thus the Rayleigh technique cannot be directly applied to this region. However, the atmosphere above this altitude contains very few aerosols, allowing the application of the Rayleigh technique.

The principle of operation of a Rayleigh lidar system is quite simple. A pulse of laser light is fired up into the atmosphere, any photons backscattered and collected by the receiving system are counted as a function of range. The lidar eqn [1] can be applied directly to a Rayleigh lidar system to calculate the expected signal strength. For Rayleigh lidar a number of simplifications can be made to eqn [1], allowing it to be expressed as

$$\text{Signal} = K\frac{1}{R^2}N_a(R)\,\delta R \qquad [3]$$

where K is a constant that includes all constant terms from eqn [1], R is the range, δR is the length of a range bin, and $N_a(R)$ is the number density of air. Equation [3] shows that after correction for range a Rayleigh lidar's signal will be proportional to the atmospheric number density profile.

Due to the uncertainties in atmospheric transmission and instrumental parameters it is not possible to determine the value of the constant K in eqn [3] precisely enough to enable the determination of an absolute density profile. The measured relative density profile can be scaled to a model density profile to obtain a density profile that is well scaled.

The relative density profile is integrated, using the hydrostatic equation, to determine a relative pressure profile. This integration requires an initial or seed pressure, usually chosen from a model atmosphere, to initiate the integration at the maximum altitude of the density profile. The pressure profile calculated in this way has the same ratio to the actual pressure as the relative density profile has to the actual density, i.e. their scaling factors are the same.

An absolute temperature profile can be calculated by applying the ideal gas law to the relative density and pressure profiles. The application of the ideal gas law divides the relative pressure by the relative density so that their scaling factors, which are the same, cancel out, resulting in an absolute temperature profile.

The selection of the seed for the pressure integration may introduce an error into the calculated temperature profile. The magnitude of this error is proportional to the difference between the actual pressure and the seed pressure used. As the actual pressure is not known, the resulting error in temperature is unknown. However, the magnitude of this error reduces as the calculation of temperature proceeds downward (**Figure 4**). Users of this technique are well advised to ignore temperatures from at least the uppermost 10 km of the retrieval, since the uncertainties introduced by the seed pressure estimate are not easily quantified.

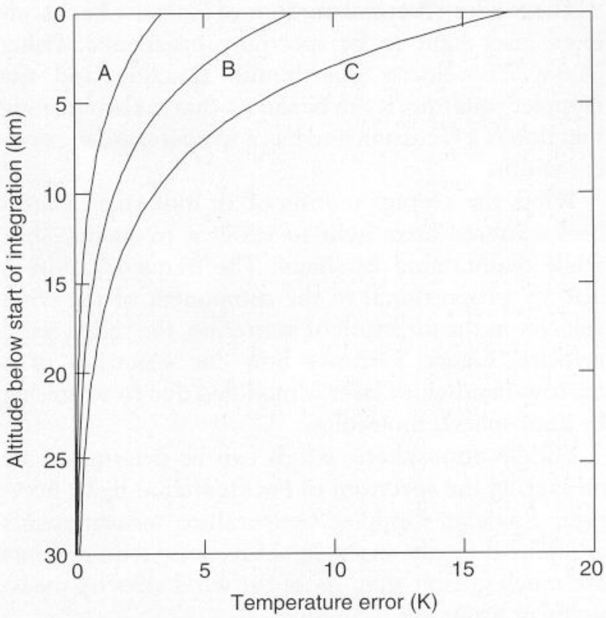


Figure 4 Propagation of the temperature error caused by a (A) 2%, (B) 5%, and (C) 10% error in the initial estimate of the pressure for the Rayleigh temperature retrieval algorithm.

Above about 90 km, changes in composition of the atmosphere cause the Rayleigh backscatter cross-section and the mean molecular mass to change with altitude. These changes lead to errors in the temperatures derived using the Rayleigh lidar technique. For the current generation of Rayleigh lidar systems other sources of error, statistical fluctuations and seeding error are generally larger than errors due to composition changes above 90 km. However, more powerful Rayleigh lidar systems may ultimately be limited in their maximum altitude extent by composition changes.

While even the most technically advanced, ground-based, middle-atmosphere lidar systems need clear skies to operate, the addition of Fabry–Perot etalons in the receiver allows daytime measurements. This daytime capability is technically complex and has been implemented on only very few Rayleigh lidar systems.

Doppler Effects

The motion of air molecules has components due to both random thermal motions and wind. When light is scattered by a molecule it suffers a change in frequency due to the Doppler effect. The magnitude and direction of the Doppler shift is determined by the component of the molecule's velocity along the direction of the lidar beam.

The random thermal motions of air cause backscattered laser light to be spectrally broadened. Using Maxwell's velocity distribution function and the Doppler equation, it can be shown that the broadening function is a Gaussian and has a temperature-dependent width.

Wind, the average motion of air molecules, causes backscattered laser light to suffer a frequency shift while maintaining its shape. The frequency shift is directly proportional to the component of the wind velocity in the direction of scattering, the radial wind velocity. **Figure 5** shows how the spectrum of a narrow-bandwidth laser is modified due to scattering by atmospheric molecules.

Middle atmospheric winds can be determined by measuring the spectrum of backscattered light; however, Rayleigh–Doppler temperature measurements are quite difficult, as the signal-to-noise requirements are much greater than those for wind velocity measurement using this technique.

Aerosol Lidar

The theory of scattering developed by Mie early in the last century is a general solution to the scattering of electromagnetic radiation by a homogeneous sphere. This early work has been extended to cover numerous other geometries and so provides a useful approximation for scattering from atmospheric aerosols.

The influence of clouds and aerosols on the atmospheric energy budget is complex, as they scatter and absorb both incoming solar and outgoing terrestrial radiation. Since the early 1960s many lidar systems have been operated at various stations around the world to study aerosols and clouds in the troposphere and lower stratosphere. Aerosols and clouds are easily detected by elastic backscatter lidar; however, instruments using multiple-wavelength transmitters and receivers and polarization techniques provide significantly more information on their properties.

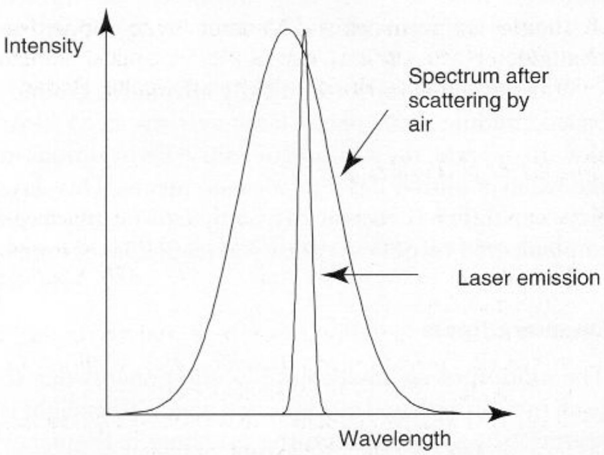


Figure 5 Doppler shift effects on Rayleigh scattering a narrow-line-width laser from atmospheric molecules. The broadening is due to thermal motion and the shift is due to wind. The intensity of the two spectra are not to scale.

In September of 1994, NASA flew a space shuttle mission, STS-64, which included the Lidar In-Space Technology Experiment (LITE) instrument, the first successful space-based lidar. LITE was used to measure tropospheric and stratospheric aerosols, clouds, and surface reflectance on a global scale.

Lidar systems can utilize the backscatter from aerosols to measure wind velocity. Light backscattered from aerosols undergoes the same Doppler shift due to wind as light scattered back from molecules. However, the spectral broadening of the light backscattered from aerosols is much narrower than that backscattered from molecules, owing to the difference between the masses of the two types of scatterers. The high signal level offered by scattering from aerosols in the lower atmosphere allows the use of coherent detection for the determination of wind velocity. Steerable lidars based using this technique are capable of making high-resolution wind field maps.

Differential-Absorption Lidar (DIAL)

The differential-absorption lidar (DIAL) technique is used for measuring the concentration of trace species in the atmosphere. The DIAL method relies on sharp variations in optical transmission near an absorption line of an atmospheric constituent. A DIAL transmits two closely spaced wavelengths, one coinciding with an absorption line of the constituent of interest and the other in the wing of this absorption line. During the transmission of the two wavelengths through the atmosphere, the emission tuned to the absorption line will suffer greater attenuation than the emission in the wing of the absorption line. The intensities of the two wavelengths backscattered to the DIAL instrument can then be used to determine the optical attenuation owing to the constituent, and thus the concentration of that constituent.

The DIAL technique has proven to be useful in providing tropospheric measurements with good time and spatial resolution for a number of trace species, including NO, H_2O, O_3, SO_2, and CH_4, as well as stratospheric ozone measurements. DIAL allows mapping and wide-area monitoring of industrial effluents and pollution.

Raman Lidar

If monochromatic light, or light of sufficiently narrow spectral width, is scattered by gas or liquid then the spectrum of the scattered light can be observed to contain lines at wavelengths different from that of the incident radiation. This effect was first observed by Raman; it is due to the interaction of the radiation with the quantized vibrational and rotational energy levels of the scattering molecule. Raman scattering involves a transfer of energy between the scattered light and the molecule; it is therefore an inelastic process. As the energy levels for each type of molecule are unique, so the Raman spectrum is unique and provides a method of sensing a particular molecular species.

The term Raman lidar refers generally to a lidar that utilizes light scattered by molecules that undergo a change in their vibrational quantum number. Measurement of the intensity of the scattered Raman light allows the calculation of the abundance of the molecular species. The selection of vibrational Raman lines can be achieved with high-quality narrow-band interference filters. However, the blocking of such a filter must be made high enough for elastic backscatter from molecules and aerosols to be attenuated effectively. Owing to the small cross-sections for Raman scattering, Raman lidar is limited to molecules with a relatively high abundance, such as water vapor and molecular nitrogen. Raman lidar is generally simpler to implement than DIAL.

Raman lidar is used predominately for the measurement of atmospheric water vapor and temperature. Raman molecular nitrogen profiles can be used to determine atmospheric temperature profiles, using the Rayleigh technique described above, even in regions containing aerosols. Elastic scattering from aerosols can be separated effectively from the Raman nitrogen backscatter by spectral filtering. The Raman nitrogen signal is therefore approximately proportional to the number density profile, although a correction must be made for the optical attenuation of the atmosphere due to both aerosols and molecules.

The pure rotational Raman spectrum (PRRS), which is due to scattering involving a change in the rotational quantum state only, is difficult to measure as the spectral shift of the lines is quite small. The separation of lines in the PRRS of N_2 is about $16\,\mathrm{cm}^{-1}$, while the first vibrational transition causes a shift of about $2331\,\mathrm{cm}^{-1}$. The shape of the PPRS is temperature-dependent, allowing pure rotational Raman lidar to make atmospheric temperature measurements.

Resonance–Fluorescence Lidar

The constant ablation of meteors in the Earth's upper atmosphere leads to the existence of extended layers of alkali metals at altitudes around 90 km. These metals have low abundance but very high resonant scattering cross-sections. Resonant scattering occurs when the energy of an incident photon is equal to the energy of an allowed transition within an atom. In this elastic process, the atom absorbs a photon and instantly emits another photon at the same frequency. As resonant scattering involves an atomic transition between allowed energy levels, the probability of this process occurring is much greater than that for Rayleigh scattering, leading to the much higher scattering cross-sections. The resonant-scattering cross-section for sodium at 589 nm is about 10^{15} times larger than the cross-section for Rayleigh scattering by air at the same wavelength. As each species of alkali metal has a unique absorption and, hence, resonant-scatter and fluorescence spectrum, these may be used to identify and measure the concentration of each individual species. Although most commonly applied to sodium, resonance–fluorescence lidar has been applied to calcium (Ca and Ca^+), potassium, lithium, and iron.

Sodium lidar systems are used to measure the abundance profiles of sodium at between 85 and 105 km, with time resolution of tens of seconds and altitude resolution of a few hundred meters. Density perturbations due to wave motions are present in the sodium density profiles, enabling the determination of wave parameters in this dynamically active region of the atmosphere to be determined. Spectral resolution of resonance–fluorescence scattering from sodium allows the determination of the temperature and wind. This technique, narrow-band resonance–fluorescence lidar, allows accurate, high-resolution temperature and wind measurements in the mesopause region.

See also

Aerosols: Observations and Measurements. **Lidar:** Raman; Resonance. **Optics, Atmospheric:** Optical Remote Sensing Instruments. **Radar:** Incoherent Scatter Radar.

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Backscatter

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Introduction

This article covers several aspects of lidar backscatter. After a general introduction, various definitions pertaining to lidar backscatter are described. This is followed by a description and explanation of the scattering and backscattering phase functions, including presentation of typical scattering phase functions of molecules, water drops, and clouds. The polarized nature of the radiation and its treatment by a scattering matrix are then described briefly. The lidar equation is presented, together with a simple solution in order to point out the importance of the backscatter phase function and its relation to the extinction to backscatter ratio and its use in solving the equation. Examples of extinction to backscatter ratios of various atmospheric constituents are presented. Several examples of profiles of measured atmospheric backscatter are described, including stratospheric aerosols, cirrus clouds, and depolarizing effects in midlevel ice, water, and mixed-phase clouds. The article does not cover inelastic backscatter such as Raman scattering and fluorescence.

Lidar is used to detect and profile certain constituents in the atmosphere, such as molecules, aerosols, and clouds. The backscatter from such entities is important in lidar because most lidar (laser radar) systems are monostatic, that is, there is a telescope receiver placed close to, or coaxial with, a laser pulse transmitter. Pulses of light sent into the atmosphere are scattered in all directions by molecules, aerosols, and clouds, and a small amount scattered into the back direction is returned to the receiver. The time taken for the laser pulse to return gives the range of the atmospheric volume being studied and the amplitude of the return is proportional to the volume density of the atmospheric particles or molecules. The amount scattered in any direction forms a pattern that is described by the single scattering phase function $P(\vartheta)$ where ϑ is the angle between the scattered light and the forward direction as shown in **Figure 1**. The amount scattered by a particle is dependent on the diameter of the particle and its size compared with the wavelength of light. It is also dependent on whether the particle or molecule is absorbing as well as scattering. Thus, particles that are small compared with the wavelength scatter less than if the scatter were determined solely by the particle cross-section, and the amount is described by the scattering efficiency.

The efficiency of backscatter is very important for lidar systems and is also related to the backscatter phase function $P(\pi)$, the phase function at a scattering angle of 180° from the forward direction.

Backscatter Efficiency and Backscatter Coefficient

The scattering efficiency $Q_{sc}(\lambda, r)$ of an atmospheric particle (molecule, aerosol, water drop, or ice crystal) determines how much radiation is scattered in all directions by the particle. Here λ is wavelength and r particle dimension. Consider a uniform light beam of intensity I (W m^{-2}) incident on a particle of area of cross-section A. If I_{sc} is scattered, I_a is absorbed and I_0 passes straight through, then $I = I_{sc} + I_a + I_0$. For visible lidar scatter on spherical water drops and typical ice crystals the last two terms are close to zero. The scattering efficiency is defined as

$$Q_{sc}(\lambda, r) = \frac{I_{sc}}{I} \qquad [1]$$

Because of the nature of electromagnetic scattering $Q_{sc}(\lambda, r)$ can approach a value of 2 for non-absorbing particles large compared with the wavelength λ. This is because diffraction occurs around and outside the edges of the particle, causing the effective cross-section to be about $2A$ for large particles and less than $1A$ for