WORLD METEOROLOGICAL ORGANIZATION

INSTRUMENTS AND OBSERVING METHODS

REPORT No. 12

INDIRECT SENSING

METEOROLOGICAL OBSERVATIONS

BY

LASER INDIRECT SENSING TECHNIQUES

by

A.O. Van Gysegem
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SECRETARIAT OF THE WORLD METEOROLOGICAL ORGANIZATION

GENEVA, SWITZERLAND

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At its seventh session (Hamburg, 1977) the Commission for Instruments and Methods of Observations had charged its rapporteur on the use of lasers in meteorology with preparing a contribution toward a joint technical note on the use of radars and lasers in meteorology (Resolution 12(CIMO-VII)). However, it became apparent that a better approach was to prepare separate reports for radar and lasers.

This report therefore provides the technical background necessary for the use of lasers for making meteorological measurements. The first chapter provides a summary of the physical interactions between laser radiation and the atmosphere which are useful for understanding which techniques and methods of observation should be used and which types of meteorological information can be obtained.

The basic principles and techniques of observation, which can be used for obtaining meteorological information, are described in chapter two. A general overview of existing meteorological applications, together with a summary of new developments (up to 1979) is provided in the third chapter.

In chapter four the state of the art of laser-based meteorological measurements is described. In particular, eye safety and calibration problems are considered in some detail, as these factors can limit the practical usefulness of these new observation techniques for operational measurements by meteorological services.
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INTRODUCTION

Electromagnetic energy is scattered by atmospheric gas molecules and particulate and droplet constituents. In the case of the energy at the optical and near-optical wavelengths generated by lasers, such scattering is sufficient to permit the application of the radar principle to making observations of the atmosphere itself. The remote atmospheric probing by lasers using the radar principle is called LIDAR, from the acronym: Light Detection And Ranging.

Considerable work has been done in recent years on the development of lidars in attempting to demonstrate their capability to measure atmospheric conditions indirectly. These experimental devices are now approaching a stage of maturity that will soon enable operational quantitative measurements of meteorological parameters from ground stations. Laser systems for cloud height determination can be considered almost operational. Meteorological lidar systems, capable of measuring vertical profiles of temperature, water vapour and wind, horizontal and slant range visibilities, concentration of various atmospheric constituents at different heights, cloud and aerosol structures in the troposphere and the stratosphere are not yet operational but substantial progress has been made in demonstrating feasibility.

The purpose of this report is to extract from the already extensive literature, information relevant to lidar, and to present this in a form which describes the basic principles of laser observation of the atmosphere in such a way that future or prospective meteorological users can acquire a knowledge of the actual and future possibilities. The first chapter provides a summary of the physical interactions between laser radiation and the atmosphere, and indicates the type of meteorological information which can be obtained by laser exploration of the atmosphere.

The second chapter describes the basic techniques and methods of observation while the third chapter gives an overview of actual applications and of new developments, together with some general considerations. The final chapter describes the state of the art in lidar and discusses the limitations which may accrue from eye-safety and calibration considerations.
CHAPTER I

OPTICAL INTERACTIONS BETWEEN THE LIDAR SIGNAL AND THE ATMOSPHERE

INTRODUCTION

As a transmitted laser beam passes through the atmosphere, the gas molecules and particles or droplets encountered change the directional distribution of the radiation by a physical process called "scattering". The magnitude and nature of atmospheric scattering depends upon the wavelength of the electromagnetic radiation and on the number, size and other properties of the particles, droplets and gaseous molecules present. Some portion of the laser energy is backscattered toward the lidar receiver and is there available for detection. It is mostly this scattered light that is used to obtain information concerning the atmosphere.

Optical scattering can be divided into two types, called inelastic and elastic scattering. When the laser energy scattered by atmospheric constituents differs in wavelength (and frequency) from the incident wavelength, the process is called inelastic scattering; examples are Raman scattering and fluorescence. For elastic processes the scattered and incident wavelengths are the same. The two elastic scattering processes which are detected by laser radars are Rayleigh and Mie scattering, depending on the species and size of scatterers with respect to the incident wavelength. A useful measure of the scattering efficiency is the scattering cross section which is defined most simply as the quotient resulting from the division of the energy scattered per unit time per scatterer by the incident energy crossing unit area per unit time. When the scattering is isotropic the scattering cross section per unit solid angle and per scatterer is given by:

\[ \sigma / 4 \pi \]

In general, an angular dependence is specified through a differential cross section:

\[ \sigma (\theta, \phi) = \frac{d\sigma}{d\Omega} \quad (m^2 \text{ster}^{-1}) \]  \hspace{1cm} (1)

where \( \theta \) is taken as the scattering angle and \( \phi \) is the angle of polarisation (for unpolarised light \( \sigma (\theta, \phi) = \sigma (\theta) \)).

A volume backscattering coefficient \( \beta \) is defined by:

\[ \beta = N \sigma (\theta) \quad (m^{-1} \text{ster}^{-1}) \]  \hspace{1cm} (2)

where \( N \) is the number of scatterers per unit volume (m\(^{-3}\)).

The scattering of energy out of the propagated beam and the absorption by gases and particles both reduce the intensity of the beam, which is said to be attenuated. Attenuation of the lidar radiation, and scattering are the most important parameters in the equations used for analysing the results of laser monitoring, and enabling the extraction of quantitative information on the profiles of the characteristics of atmospheric gases, particles and droplets. The intensity \( I (\lambda, L) \) of a laser beam with wavelength \( \lambda \) and initial intensity \( I_0 (\lambda) \) after the radiation passes through a homogeneous layer of thickness \( L \) is described by BOURGUER's law as expressed in equation 3:
\[ I(\lambda, L) = I_0(\lambda) \exp(-\alpha(\lambda)L) \]  

(3)

where \(\alpha(\lambda)\) is the volume extinction coefficient and accounts for all the interactions that extract energy from the laser beam. The exponent \(\alpha(\lambda)L\) is called the optical thickness \(r(\lambda)\) of the atmospheric layer. For atmospheric investigations it is common to separate \(\alpha(\lambda)\) into its three major components:

\[ \alpha(\lambda) = \alpha_{m,a}(\lambda) + \alpha_{m,s}(\lambda) + \alpha_p(\lambda) \]  

(4)

where the subscripts m, a, s and p stand respectively for molecules, absorption, scattering and particles; \(\alpha_{m,a}(\lambda)\) is the extinction due to absorption by molecules; \(\alpha_{m,s}(\lambda)\) is the extinction caused by molecular scattering and \(\alpha_p(\lambda)\) the extinction by particle scattering and absorption. Other scattering processes, such as Raman scattering are much weaker and are negligible when considering extinction coefficients.

In the next paragraphs, a quantitative description of the most important interaction processes is given: molecular absorption, inelastic Rayleigh and Mie scattering and elastic Raman scattering. In addition, multiple scattering and the effects of atmospheric turbulence and aerosol scintillation are discussed, as these interactions have a direct influence on the usefulness of laser sounding techniques.

I.1 Molecular absorption

The resonant interaction between an electromagnetic wave and an atom or molecule causes energy absorption. Within an atom, the electrons are arranged in orbits about the nucleus, each invoking a discrete energy level as dictated by the fundamental laws of quantum mechanics. A photon of energy, \(\hbar\gamma\), corresponding to the energy difference between the ground state and an allowed state can excite an electron to the higher energy state. Similarly a molecule containing two or more atoms can be excited from its ground state into a number of states characterised by the discrete levels of energy of the rotational, vibrational and electronic states of the molecules. In general, the energy of the molecular system is given by:

\[ E = E_e + E_v + E_r + E_t \]  

(5)

where the subscripts refer to electronic, vibrational, rotational and translational states of the molecule. These states are quantised, i.e. they can take only certain discrete levels. Absorption occurs whenever the incident radiation has a wavelength \(\lambda\) corresponding to the difference between two allowed states, i.e. \(E = \frac{hc}{\gamma}\). In the visible and UV regions, photon energies are of the same order as the energy level differences between the electronic states of atoms. Energy differences between vibrational, rotational states of molecules correspond to photon energies at IR wavelength. The pure rotational states of molecules are separated by energies equivalent to that of far IR microwave radiation.

Only certain gases in the atmosphere absorb radiation, since the interaction with an electromagnetic field must involve an electric or magnetic dipole or quadrupole moment. A further restriction arises from the fact that the permis-
sible transitions are governed by selection rules which limit the changes in quantum numbers between initial and final states. Transitions between discrete states occur at discrete frequencies giving rise to line spectra. These exhibit a regular structure in the case of atomic absorption involving bound electronic states, which are characterized by narrow lines spaced at intervals governed by the fundamental atomic constants and quantum numbers. Molecular spectra are more complex than atomic spectra because simultaneous changes in the vibrational and rotational states as well as the electronic states are possible. The absorption which arises from a transition between two discrete molecular energy levels \( (n\) and \( m)\), is never completely sharp in frequency. The expression

\[
\gamma_{nm} = \frac{E_n - E_m}{h}
\]

(6)
gives the centre frequency of the absorption line. Its width results from natural relaxational processes (arising from the finite lifetime of the excited state), and from collisions between atoms or molecules or from Doppler broadening processes. The strength of the absorption process, which depends essentially on the dipole moment for the transition, and the linewidth are both temperature and pressure dependent. The main absorbing gases in the atmosphere for the UV, visible and IR are water vapor, carbon dioxide, ozone and oxygen. The atmosphere also contains minor constituents that absorb radiation in the wavelength range considered; these are primarily carbon monoxide, methane and nitrogen oxides. In addition, various gases of industrial origin may be present in localised regions. The very intense absorption in the centre of certain bands in the region 0.2 to 20 \( \mu \)m practically excludes the possibility of applying these bands for the purpose of most laser monitoring of the atmosphere, irrespective of whether the wavelength of the laser radiation is near the central part of the absorption band. Within absorption bands, laser monitoring can be accomplished only in the upper layers of the atmosphere where the concentration of absorbing molecules is sufficiently small. The most useful wavelengths for laser monitoring are generally those in intervals between absorption bands; these windows are clearly depicted in Fig. 1 in which two low resolution absorption spectra of solar radiation are shown. The upper curve characterizes the absorption spectrum of solar radiation reaching the earth’s surface; the lower one was obtained at an altitude of 11 km. The positions of the centres of the most important absorption bands of atmospheric gases are also indicated.

![General picture of absorption spectra of solar radiation: Upper curve: earth's surface; Lower curve: altitude of 11 km (Zuev, 1976)](image-url)
Figure 2
Infrared absorption spectra for atmospheric gases
It follows that the molecular absorption coefficient $\alpha_{m,\lambda}(\lambda)$ is very strongly wavelength dependent, becoming the dominant component of the extinction coefficient $\alpha(\lambda)$ in the vicinity of absorption lines and bands of the various atmospheric gases. These spectral features may be exploited in the differential absorption technique to provide remote measurements of specific gaseous constituents as described in chapter II. As an example, the IR absorption spectra for some atmospheric gases is shown in Figure 2.

The most complex spectrum which we have to deal with in normal atmospheric gases is that of $\text{H}_2\text{O}$; its complication is such that it is impossible to give a single formula covering all vibrational-rotational spectra. Figure 3 shows atmospheric absorption in the region near the ruby laser line (Long, 1967).

![Figure 3](image-url)

**Figure 3**
Atmospheric absorption spectrum 0.6934 - 0.6945 $\mu$m using the sun as a source (Long, 1967)

Although these absorptions are weak, they are used by various workers for the remote measurements of the water vapor content of the atmosphere (see Chapter III).

I.2 Elastic scattering

I.2.1 Rayleigh scattering

Scattering from gaseous molecules and from particles which are very small compared with the wavelength of the laser radiation, varies directly with the number...
of the particles and with the sixth power of their diameter, and is inversely proportional to the fourth power of the wavelength. The scattering process involves an interaction between the molecules and the incident photons, during which the molecules undergo a double transition by first absorbing, and then emitting a photon. The absorption of the photon will raise the energy of the molecule from its initial energy state, but the molecule will return within an extremely short time to a stationary state through the emission of a photon. If this stationary state is the initial state, the frequency of incident and emitted photon are the same and the process is said to be elastic and is referred to as Rayleigh scattering.

The Rayleigh scattering cross section \( \sigma_R \) can be expressed on a per molecule basis as (Penndorf, 1957):

\[
\sigma_R = \frac{8\pi^3}{3}\left(\frac{m_s - 1)^2}{N_s^2}\right) \cdot \frac{6 + 3\delta}{6 - 7\delta}
\]

where \( N_s \) is the number of gas molecules per unit volume, \( m_s \) is the refractive index, \( \lambda \) is the wavelength of the scattered light and \( \delta \) is the depolarization factor to account for the anisotropy of the polarizability of air molecules (\( \delta \approx 0.035 \)).

The Rayleigh extinction coefficient, \( \alpha_R(h) \), is given by

\[
\alpha_{m,s} = \alpha_R(h) = N_m(h) \sigma_R
\]

where \( N_m(h) \) is the density of air molecules at height \( h \). The scattering is not isotropic and an angular scattering function is given by (Panofsky and Phillips, 1955):

\[
\psi_R = \frac{3}{8\pi} \left( \frac{\cos^2 \theta \cos^2 \phi + \sin^2 \phi}{2} \right)
\]

where \( \theta \) is the scattering angle, and \( \phi \) is the angle of polarization. For unpolarized light \( \psi_R \) is averaged over the angle \( \phi \) and:

\[
\psi_R = \frac{3}{8\pi} \left( \frac{\cos^2 \theta + 1}{2} \right)
\]

The scattering cross section per unit angle is then given by:

\[
\sigma(\theta, \phi) = \sigma_R \psi_R
\]

In the case of Rayleigh backscattering (\( \theta = \pi \)) the extinction coefficient and the backscattering coefficient are uniquely related:

\[
\beta_m = \beta_R = N_m \sigma_R(\pi) = N_m \frac{3}{8\pi} \sigma_R = \frac{3}{8\pi} \alpha_R
\]

so that a measurement of either \( \beta_R \) or \( \alpha_R \) may immediately be converted to the other. The relation also shows that a measurement of \( \beta_R \) can be used to provide a measure of the atmospheric density of the scatterer, through \( N_m \). In the troposphere where the energy backscattering by particles is frequently comparable to, or larger than that by gases, this type of inference is not possible; but it has proven useful in the upper atmosphere (Chapter III: Aerosols). For a mixture of atmos-
pheric gases which occurs below about 100 km:

\[
\sigma_R(\pi) = 5.45 \left( \frac{\lambda (\mu m)}{0.55} \right)^4 \times 10^{-28} \text{ cm}^2 \text{ ster}^{-1}
\]

At sea level, where the molecular density \( N_g = 2.55 \times 10^{19} \) cm\(^{-3} \):

\[
\beta_R = 1.39 \left( \frac{\lambda (\mu m)}{0.55} \right)^4 \times 10^{-8} \text{ cm}^{-1} \text{ ster}^{-1}
\]

(13)

(14)

I.2.2 Mie scattering

At visible wavelengths near 550 nm where gaseous absorption is small the Rayleigh scattering extinction coefficient is:

\[
\alpha_{m,s} = \alpha_R = 0.0116 \text{ km}^{-1}
\]

(15)

The meteorological range \( V_M \) is given by the Koschmieder relation:

\[
V_M = \frac{3.91}{\alpha}
\]

(16)

It can be seen that for a purely Rayleigh scattering atmosphere \( \alpha = \alpha_R \) the sea level visibility would exceed 250km. Since, even under exceptionally clear conditions this is impossible, it is evident that the purely gaseous scattering component of the atmosphere normally makes a very small contribution to the actual attenuation of visible light near 550 nm. The reduction of visibility is there due to the presence in the atmosphere of various solid and liquid particles. The extinction coefficient for particles can be written as the sum of:

\[
\alpha_p(\lambda) = \alpha_{p,s}(\lambda) + \alpha_{p,a}(\lambda)
\]

(17)

where \((s)\) and \((a)\) refer to scattering and absorption. The extinction properties of atmospheric particles can be quite reliably described in terms of equivalent spheres. In this formulation, the volume extinction coefficient for light of wavelength \( \lambda \) is given by:

\[
\alpha_p(\lambda) = \int \sigma_E(a, \lambda, m) N_p'(a) da
\]

(18)

where \( \sigma_E(a, \lambda, m) \) is the extinction cross section for a particle of radius \( a \) and refractive index \( m \); \( N_p'(a) \) is number density of particles per unit radius interval. \( \sigma_E = \sigma_s + \sigma_a \) emphasises that the extinction cross section includes contributions from both scattering and absorption. For homogeneous spherical particles, the dependence of the extinction cross sections on \( a, \lambda \) and \( m \) is given by the Mie scattering theory. This theory yields the following expression for extinction
cross sections for scattering and absorption by a single particle in terms of efficiency factors (Mie, 1908):

\[ \pi a^2 Q_s(x,m) = \sigma_s(a, \lambda, m) \]  
(19)

\[ \pi a^2 Q_a(x,m) = \sigma_a(a, \lambda, m) \]  
(20)

\[ \pi a^2 Q_E(x,m) = \sigma_E(a, \lambda, m) \]  
(21)

where \( x \) is the particle size parameter defined by:

\[ x = \frac{2\pi a}{\lambda} \]  
(22)

These efficiency factors of scattering, \( Q_s \), absorption, \( Q_a \), and total extinction, \( Q_E \), are numerically equal to the ratio of the energy scattered, absorbed and attenuated, respectively, by a particle, to the energy incident onto its geometrical cross section \( \pi a^2 \). The functions \( Q_s, Q_a \) and \( Q_E \) have been tabulated in detail for a set of parameters \( x \) and \( m \) encompassing the conditions of optical wave propagation in real aerosol systems such as clouds, fogs, hazes and precipitations (Van der Hulst, 1957).

The volume backscattering coefficient of a suspension of homogeneous spheres of varying size when illuminated by light of wavelength \( \lambda \) is given by:

\[ \beta_p(\lambda) = \int_0^\infty \sigma_B(a, \lambda, m) N^s_p(a) \, da \]  
(23)

Similarly to that for extinction, the backscattering cross section may be written as:

\[ \sigma_B(a, \lambda, m) = \pi a^2 Q_B(x,m) \]  
(24)

where \( Q_B \) is the backscattering efficiency. For a number of model size distributions \( N^s_p(a) \), computational results for \( \beta_p(\lambda) \) have been tabulated and plotted in several standard books (e.g. Deirmendjian, 1969).

The dependence of the efficiency factor on the size parameter \( x \) for non-absorbing particles of refractive index 1.33 is shown in Figure 4. The maximum of the curve occurs when the particle radius is approximately equal to the wavelength and for large radii, resonances occur due to the interference between transmitted and diffracted radiation. The form of the extinction curve for absorbing particles is shown in Figure 5. The effect of absorption is to damp out the oscillations for particle radii greater than the wavelength. This damping increases with the absorption coefficient. For large size parameters \( (x \gg \lambda) \) expressions for the scattering efficiency are more conveniently derived from geometrical optics. The curves on Figure 4 and Figure 5 apply to a single spherical particle or an assembly of equally sized droplets of well-defined refractive index. However, atmospheric scatterers are generally irregular in shape, occur over a wide size range and have varying absorption properties. The effect of non-sphericity can be accounted for by extension of the theory and solutions exist for spheroidal and cylindrical particles.
When a range of particles exists or a wide spectral band is considered, the size parameter takes on a range of values. As a consequence curves of scattering coefficients versus wavelength, as shown in Figure 6 for typical atmospheric scattering assemblies, do not exhibit those distinct resonances of Figure 5; these are smoothed out by averaging over size and wavelength.

![Figure 4](image)

**Figure 4**
Extinction efficiency factor for non absorbing water spheres

![Figure 5](image)

**Figure 5**
Extinction efficiency factor for absorbing water spheres

![Figure 6](image)

**Figure 6**
Attenuation by scattering as a function of wavelength for various atmospheric conditions (Farrow, 1975)
Mie scattering is far from isotropic and exhibits an interdependence among scattering intensity, size parameter and direction. For small water droplets the scattering coefficient for a given angle, $\theta$, is a function of the number and size of particles, the index of refraction of the particles, the wavelength and polarization of the incident light. Figure 7 gives an example of the angular effect on the intensity which may be calculated from Mie theory.

The aerosol scattering is not symmetric with respect to forward and backward scattering. The ratio of forward scattering to backscattering increases with increasing size parameters $x = 2\pi a/\lambda$ and so will increase for hazes, clouds and precipitations in that order for the visible wavelengths.

In particular for precipitation, the main part of scattered radiation is concentrated in a narrow range of angles close to $0^\circ$ or the forward direction. As an example $I(\theta)$ for fog decreases by 3 to 7 orders of magnitude with a change in scattering angle from $0.2^\circ$ to $7^\circ$.

The size distribution of naturally occurring scatterers cannot be uniquely specified; it is therefore necessary to substitute an empirical expression for $N'(a)$ into the equations 18 and 23 and to replace the integral by a summation over droplets size intervals, for which the particle density may be found by experimental sampling techniques. Assuming that all optically significant particles have a size distribution given by the power-law or Junge model expressed by:
\[ N'(o) = Q_o - (p+1) \]

where \( p \) is a dimensionless fitting parameter, it can be shown that:

\[ \beta_p(\lambda) = Q\lambda - (p+1) \]

For atmospheric haze, typical values of the exponent fall in the range \( 2.5 < p < 4 \) and hence the exponent for \( \beta_p(\lambda) \) varies between 0.5 and 2. Thus, the wavelength dependence of particulate scattering by haze is less pronounced than that of molecular scattering, a fact which can be used to separate the two contributions. Backscattering of visible light by fog and cloud droplets is virtually independent of wavelength because the large size parameter \( (25 < x < 400) \) places the process nearly in the geometric optics region where the extinction efficiency \( Q_E(x,m) \approx 2 \) and the backscatter-to-extinction ratio has a very weak wavelength dependence.

In further contrast with the Rayleigh scattering, the ratio of Mie backscattering to Mie extinction is also a function of particle size distribution and refractive index. Results computed for a number of typical aerosol size distributions and refractive indices fall in the range (Harrison, 1972):

\[ 0.01 < \frac{\beta_p}{\alpha_p} < 0.1 \text{ ster}^{-1} \]

which is smaller than the value:

\[ \frac{\beta_R}{\alpha_R} = \frac{3}{8x} = 0.12 \text{ ster}^{-1} \]

obtained for Rayleigh scattering. This results from the increased proportion of light scattered into near forward angles with increasing particle size. So the analysis of scattering into different angles will permit the separation of the particulate and molecular contributions.

Particle shape effects lead to important differences with respect to the predictions of Mie theory. Laboratory measurements of the angular distribution of light scattered by ice crystals have shown (Huffman, 1970) that the backscatter-to-extinction ratio could be an order of magnitude or more smaller than the values predicted by Mie theory for the same refractive index and an equivalent size distribution; these measurements are in accordance with the results of computations (Liou, 1972) that model the ice crystals as infinitely long circular cylinders, a shape for which an analytical solution can be obtained.

Another characteristic of Mie backscattering which is used in lidar investigations, is polarization. If the incident light is linearly polarized, the backscattered light retains the linear polarization of the incident light and the backscattering cross section is independent of the incident light polarization (spherical symmetry of the Mie scatterers). However, the polarization properties
of aspherical particles differ markedly from those of spheres. In general the polarization of backscattered light by aspherical particles differs from that of the incident light. Moreover, if the aspherical particles are aligned in some fashion, the size of the volume backscatter coefficient $\beta_p$ can depend on the direction of polarization and incidence with respect to the alignment direction or plane. These effects are especially evident in light scattering by ice crystals (Liou, 1974; Sasson, 1974). This particle shape effect is of considerable utility in the remote sensing of cloud droplet phases (see Chapter III).

I.3 Inelastic scattering

I.3.1 Raman scattering

A spectral analysis of scattered radiation reveals the existence of a series of sideband frequencies $\gamma_R$ shifted up and down by an amount equal to the vibrational-rotational $\tilde{\gamma}_R$ frequencies of the molecule irradiated:

$$\gamma_R = \gamma_0 \pm \tilde{\gamma}_R$$  \hspace{1cm} (29)

where $\gamma_0$ is the frequency of the incident wave. Sideband frequencies below $\gamma_0$ are called Stokes lines while those above $\gamma_0$ are called anti-Stokes lines. The two processes, which produce the Stokes lines and the anti-Stokes lines, constitute the Raman scattering effect which results in a net energy transfer between molecules and photons. Stokes lines appear when a molecule, excited by an incident photon, returns to an intermediate excited state so that the emitted photons have lower frequencies. Similarly, if the incoming photon interacts with a molecule in an excited state the molecule may either return to the same state with the emission of a photon of the same frequency (Rayleigh line) or return to a lower or a ground state with the emission of a photon of higher frequency (anti-Stokes lines).

An important characteristic of Raman scattering is the fact that the frequency shift is independent of the incident frequency $\gamma_0$. Each molecular species exhibits a characteristic frequency shift, so that (in principle) the observation of the Raman spectra permits the identification of the molecule. An estimate of the absolute concentration of each molecular species can be performed by comparing the Raman backscattered energy with that of the Raman lines from $N_2$ molecules which occupy the same volume. Detailed explanations and listings of Raman lines are found in textbooks, for example Herzberg (1960). The frequency shifts of the vibrational-rotational Raman spectra of typical molecules present in the atmosphere with respect to the transmitted laser frequency are summarized in Figure 8.

The selection rules of Raman transitions for diatomic and linear molecules are known to be $\Delta V = 0, \pm 1$ and $\Delta J = 0, \pm 2$ where $V$ and $J$ indicate the vibrational and rotational quantum numbers, respectively. The transition specified by $\Delta V = 0, \Delta J = 2$ corresponds to pure rotational Raman lines, the transitions $\Delta V = \pm 1, \Delta J = 0, \pm 2$ to vibrational-rotational Raman scattering; whereas the transition $\Delta V = 0, \Delta J = 0$ gives rise to Rayleigh scattering. As an example, the theoretical distribution of a typical vibrational-rotational Raman spectrum for the $N_2$ molecule at a temperature of 300K as a function of the wave-
Figure 8
Frequency shifts of Q-branch of Raman spectra of typical molecules relative to the exciting laser frequency (Inaba, 1976)

number corresponding to the Stokes shift is shown in Figure 9 in which the ordinate gives the value of differential scattering cross section under the excitation of incident radiation at 337.1 nm. In this figure, which corresponds to the vibrational transition \( V = 0 \rightarrow 1 \), all lines in the Q-branch lie very close to each other, and cannot be resolved except with extremely high resolution spectroscopy. The S- and O-branches, however, are well separated in energy and appear as sidebands on either side of the intense Q-branch. The calculated distribution of pure rotational Raman scattering at 300 K for the \( \text{N}_2 \) molecule excited at the wavelength

Figure 9
Calculated distribution of vibrational-rotational Raman spectrum at 300 K

Figure 10
Calculated distribution of pure rotational Raman and Rayleigh spectra at 300 K

(Inaba H. and Kobayasi, 1971)
of 337.1 nm is shown in Figure 10. Two components, S- and O-branches, are also positioned symmetrically on either side of the central Rayleigh component. Since the rotational and vibrational degrees of freedom are sensitive to the molecular temperature, Raman scattering offers a method for the remote measurement of temperature.

Intensity calculations relative to a Raman-Stokes band can be performed using formulae derived by Placzek (1934). These formulae are expressed in terms of differential Raman scattering cross sections. Characteristics of Raman scattering of the principal atmospheric consituents and for an incident wavelength $\lambda_0 = 347.1$ nm (double ruby laser) are given in Tables I and II.

Table I
Theoretical values of the differential Raman backscattering cross section ($\text{cm}^2/\text{sr}$) for Q-branch, O- and S-branches and total of these three branches for the vibrational transition $V = 0 \rightarrow 1$ excited at 337.1 nm, together with the Raman frequency shift $\gamma_j$ (Hz) (Inaba, 1976)

<table>
<thead>
<tr>
<th>Molecule</th>
<th>$\gamma_j$</th>
<th>$\left(\frac{d \sigma}{d \Omega}\right)_Q^{\text{RAM}}$</th>
<th>$\left(\frac{d \sigma}{d \Omega}\right)^{\text{O+S}}_{\text{RAM}}$</th>
<th>$\left(\frac{d \sigma}{d \Omega}\right)^T_{\text{RAM}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>N$_2$</td>
<td>2329.66</td>
<td>$2.9 \times 10^{-30}$</td>
<td>$0.55 \times 10^{-30}$</td>
<td>$3.5 \times 10^{-30}$</td>
</tr>
<tr>
<td>O$_2$</td>
<td>1556.26</td>
<td>3.3</td>
<td>1.3</td>
<td>4.6</td>
</tr>
<tr>
<td>CO$_2$(V$_1$)</td>
<td>1388.15</td>
<td>3.4</td>
<td>0.73</td>
<td>4.2</td>
</tr>
<tr>
<td>CH$_4$(V$_1$)</td>
<td>2914.2</td>
<td>21.0</td>
<td>0</td>
<td>21.0</td>
</tr>
</tbody>
</table>

Table II
Theoretical values of differential cross sections ($\text{cm}^2/\text{sr}$) for Rayleigh, pure rotational Raman backscattering and total backscattering (Inaba, 1976)

<table>
<thead>
<tr>
<th>Molecule</th>
<th>Rayleigh</th>
<th>Pure rotational</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>N$_2$</td>
<td>$3.90 \times 10^{-27}$</td>
<td>$1.14 \times 10^{-28}$</td>
<td>$4.01 \times 10^{-27}$</td>
</tr>
<tr>
<td>O$_2$</td>
<td>3.28</td>
<td>1.96</td>
<td>3.47</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>9.02</td>
<td>8.3</td>
<td>9.85</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>8.60</td>
<td>0</td>
<td>8.60</td>
</tr>
</tbody>
</table>

The Raman scattering cross-section varies with the 4th power of the output frequency, so that Raman experiments are best conducted with UV lasers; the angular dependence of the scattering is similar to Rayleigh scattering.
I.3.2 Resonance Raman scattering

When the exciting frequency $\lambda_1$ is tuned to the absorption band of the molecule, but lies outside the line widths of absorption levels, a great increase in the Raman scattering cross section is obtained. An enhancement of three to six orders of magnitude over the ordinary Raman cross sections for the $\text{N}_2$ molecule is reported. This process is conventionally called resonance Raman scattering. Although this effect has been recognised for many years, only the recent availability of tunable laser sources has opened the way for quantitative measurements using the effect. The significantly improved scattering efficiency will be useful to allow indirect detection of lower concentrations of atmospheric constituents as long as the transmitted beam is not severely attenuated by absorption.

I.4 Multiple scattering

The main assumption made when formulating the lidar equation (see Chapter II) consists in stating that the particles scatter electromagnetic radiation independently of each other and that all scattered photons, except those which are backscattered, are permanently removed from the transmitted and received lidar beams. In reality a fraction of the scattered photons travels in near forward directions and so never leaves the lidar beam; in addition some photons that are scattered out of the lidar beam may later be scattered back in. Thus the received lidar signal includes photons that have been scattered more than once, an effect called multiple scattering. The increased noise signal due to multiple scattering depends on the optical thickness and optical properties of the scattering medium, the distance to the volume being sampled, the viewing angle of the receiving system, the width of transmitted and received beams and the laser wavelength. The theoretical treatment of multiple scattering in lidar applications is complex. For detailed information, see for instance (Zuev, 1979; Eloranta, 1979). Only some general conclusions will be given here.

Multiple scattering affects the polarisation of the laser beam; the received lidar signal is partially depolarized, even when all of the scatterers are spherical; depolarisations of up to 40% have been attributed to multiple scattering. For laser sounding of a haze layer or monitoring through a haze layer, the effects of multiple scattering can usually be neglected (Zuev, 1976), whereas in connexion with the sounding of clouds, fog and rain, the effect tends to be much more significant because of the larger probability of scattering by particles into near forward directions.

For clouds and fog the effect can be ignored (Zuev, 1976) only for limited optical thicknesses whose values depend on the angle of divergence of the source and the viewing angle of the receiving system. In fog, clouds and rain multiple scattering effects are readily observable experimentally and tend to exceed the theoretical estimates. Multiple scattering is considered as a serious problem for applications of laser sounding techniques, since it limits the interpretation of received signals. Several researchers have published proposed theoretical solutions, elaborating approximate lidar equations taking into account double or even $n^{th}$ scattering (Eloranta, 1979).

I.5 Effects of atmospheric turbulence and aerosol scintillation

Laser pulses propagating through the atmosphere not only suffer energy
losses due to absorption and scattering, but also are influenced by atmospheric turbulence. Turbulent fluctuations of the refractive index lead to a fluctuating distortion of the initial laser beam parameters, and to signal fluctuations which limit the interpretation of results of laser soundings. Detailed considerations of the effect of atmospheric turbulence are presented by Lawrence (1970) and Khmelevtsov (1973).

The interaction between a beam of radiation and turbulent eddies of varying dimensions and refractive index may be considered qualitatively as follows:

(a) if the beam cross-section is much smaller than the size of the eddy, the entire beam is steered by refraction;
(b) eddy sizes of the same order as the beam diameter cause focussing and defocussing and hence alter the power density across the beam;
(c) if the size of the eddy is considerably less than the beam diameter, the eddy will act as a diffraction centre and multiple scattering will cause the beam to spread beyond its initial divergence.

The movement of such inhomogeneities across the path will produce amplitude fluctuations (scintillation) at the receiver at frequencies which are dependent on the frequency with which eddies cross the path. The variation of refractive index between sections of the wavefront and the spatial coherence will be degraded.

Finally, at the receiver the focus will be shifted by small amounts (image dancing) due to differences in the angle of arrival of the rays. Since eddy dimensions vary from millimeters to tens of meters and since the beam diameters of laser systems lie typically within this range, all of the above mentioned effects might be expected to occur in practical systems.

Laser beam intensity fluctuations in the atmosphere is also connected with aerosol particle concentration variations, their mutual spacing, size distribution, shape and orientation. Solution of the general scintillation problem leads to very complicated equations for the intensities.

Experimental investigations are only preliminary, and existing data indicate that these phenomena will have to be taken into account when interpreting lidar results. Further theoretical and experimental studies are greatly needed. For long-path propagation, turbulence can cause the laser beam to break-up and change direction thereby causing partial loss of signal at the receiver optics. In the case of wind measurements using Doppler methods (see Chapter III) the degree of focussing of the radiation determines the minimum volume which can be sounded, and random shifts of the laser beam position restrict the confidence with which the sounded volume can be defined; both of these parameters are functions of turbulence.
CHAPTER II

ATMOSPHERIC LIDAR SYSTEMS

INTRODUCTION

Indirect sensing of the atmosphere can be defined as sensing qualitatively and/or quantitatively a chemical or physical variable in the atmosphere where the monitoring instrument and the variable under investigation are spatially separated. For atmospheric applications, indirect sensing techniques can be divided into two categories: passive and active, depending on the source of radiation. Passive techniques make use of available radiation in the atmosphere (e.g. solar, earth-reflected or emitted radiation). They will not be further discussed in this report. Active systems, on the other hand, are characterized by the introduction of specific radiation into the atmosphere; for example, a laser can be used as the source of radiation. The interaction with the atmosphere (e.g. scattering and absorption) is observed in order to infer information of meteorological significance. Active techniques are subdivided into single-ended and double-ended systems. All single-ended lidar systems consist of at least one laser and receiver whose optical axes are aligned such that the receiver telescope field-of-view includes the laser beam as it propagates through the atmosphere. Different lidar systems exist depending on the selection of the laser wavelength, the receiver wavelength and the data analysis methodology; e.g. the classical Mie or Rayleigh lidar, the Raman lidar and the Differential Absorption Scattering Lidar (DIAL). The feasibility of other systems such as those based on resonance Raman scattering and fluorescence is not fully demonstrated; physical and technological difficulties continue to limit the practical application of these schemes for meteorological investigations. Double-ended systems may either have the laser transmitter and receiver located separately or may have the laser transmitter and receiver co-located, and make use of a physical reflector located at a distance. Absorption and total attenuation are measured by these systems, which include the bistatic lidar and long path absorption techniques.

The optimum selection of the components and their integration into a complete lidar system is determined by the application for which the system is intended. A variety of systems have been developed corresponding to the range of meteorological applications intended. Most of these are still in a feasibility phase, while a small number are the object of laboratory or field evaluations, and only a few can be considered as almost operational. Taking into account this state of the art, basic principles and general descriptions will be given below for those techniques and methods which are generally used and for those which are considered as very promising for meteorological purposes. A more detailed description is given of the Mie or Rayleigh lidar, referred to simply as lidar, including the general configuration with its distinct parts and the lidar equation which is the basic relation for understanding how laser radars obtain information about the atmosphere. The lidar is the basic system from which the other above-mentioned laser systems are, to some extent, derived.
II.1 Single-ended systems

II.1.1 Rayleigh or Mie lidar

II.1.1.1 Configuration

In a lidar, the detector wavelength is matched to the laser wavelength, so the received energy is due to Rayleigh and Mie backscattering. The detected signal is recorded as a function of time to provide a range-resolved measurement of atmospheric backscattering. Analysis of the data then provides an indication of the aerosol distribution in the troposphere and stratosphere. Figure 11 gives a schematic diagram of the fundamental lidar configuration, consisting of a lidar transmitter, a lidar receiver and data processing equipment.

Figure 11
Rayleigh or Mie lidar

(a) Lidar transmitter

Lasers: Since the development of the first lasers in the early 1960's most applications have relied on their power, low beam divergence, and short pulse characteristics. Lasers are generally several orders of magnitude brighter than thermal sources and have inherently better resolution. The choice of a particular laser is a function of the type of measurement to be made and is also affected by signal-to-noise considerations. The received signal, which is a function of the wavelength and of the energy and the pulse duration of the laser, is used in calculations involving the lidar equation. The geometry of the beam, the pulse frequency and radiation quality of the laser are the most important factors contributing to noise. In general two types of lasers are used in meteorological investigations; fixed frequency lasers and tunable lasers. In most cases the lasers are pulsed,
combining a very high output power with an extremely short pulse duration. For special purposes, continuous wave lasers are also used.

Commonly used fixed frequency lasers include the following types:

(i) Ruby lasers: the earliest lidar employed a solid state ruby laser ($\lambda = 694.3\text{nm}$) or its first harmonic ($\lambda = 347\text{nm}$) obtained with a conversion efficiency of about 20%, delivering pulses of 5 to 50 nanoseconds duration with a power of 10 to 100 megawatts. The beam divergence was less than one minute arc with a repetition frequency up to 10 Hz. The laser was pumped optically by a Xenon flash tube and the ruby crystal was cooled by water or air circulation. Ruby lasers are mostly used for Rayleigh-Mie scattering at 694nm and for Raman scattering at 347nm.

(ii) Neodymium lasers: the technology is similar to that of the ruby laser; emission takes place at 1060nm. Two frequency doublings can be obtained, the first at 530nm with an efficiency of 30% followed by a line at 265nm with an efficiency of only 5%. Constraints on the cooling of the rod limit the pulse repetition frequency to less than that of the ruby laser. In an other version of this laser, the YAG (yttrium, aluminium, garnet), much faster cooling is possible, resulting in pulse repetition rates of up to 100 Hz. The output power is of the order of a megawatt. This laser is used for Mie scattering measurements at 1060nm. The advantage of the harmonic at 265nm is that it operates in the UV region of the electromagnetic spectrum.

(iii) Nitrogen gas lasers: the nitrogen gas laser does not have the same spectral and geometric qualities as the above-mentioned lasers; however, it operates directly in the UV ($\lambda = 337\text{nm}$), with a pulse repetition rate of between 5 and 500 Hz and an output power of about a megawatt at pulselengths of the order of nanoseconds. The pumping of this laser is accomplished during the propagation of an electrical discharge in the gas. The energy efficiency is about 1%. Nitrogen lasers are used in Raman lidar, but only for small ranges.

The laser output wavelength is important for different reasons: firstly because the proportion of energy scattered by atmospheric constituents depends upon wavelength, and secondly because of eye safety considerations. Scattering by atmospheric particles and gases is much stronger at visible and UV wavelengths than in the IR; on the other hand, the probability of eye damage is greatly reduced in the IR. The laser output wavelength is especially critical for differential absorption techniques (see paragraph II.1.2). Such an application usually requires the capability of "tuning" or varying the output wavelength. Tunable lasers are now available from the near UV to the far IR as illustrated in the following Figure 12. Further details on tunable lasers can be found in Walther (1976) and Hinkley (1976).

Most of the important lasers in use are summarized in Table III. In this table $\lambda$ means: the wavelength in $\mu$m; CW: continuous wave output signal; PRF: the pulse repetition frequency in Hz; PV: peakpower in watts; $V$: power in watts; and PL: pulselength in ns.

Low power continuous wave (CW) gas lasers are being applied in lidars. With such lasers, range information is obtained by modulating the CW energy with a characteristic frequency variation pattern, normally a sawtooth frequency modulation (fm). Such fm-CW systems operate at a very low instantaneous power level and are eye-safe. In meteorology a particular application of the CW operation is the making of wind measurements by Doppler lidar.
### Table III

<table>
<thead>
<tr>
<th>Type</th>
<th>$\lambda$ (\textmu m)</th>
<th>$\nu$ (CW)</th>
<th>$\Delta f$ (Hz)</th>
<th>$P_{\nu}$ (W)</th>
<th>$P_{L}$ (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ruby + 2° harm.</td>
<td>0.6943 and 0.3472</td>
<td></td>
<td>1-10</td>
<td>$3 \times 10^9$</td>
<td>30</td>
</tr>
<tr>
<td>Nd : YAG + 2° harm</td>
<td>1.06 and 0.53</td>
<td>200 on 1.06 \textmu m</td>
<td>up to 100</td>
<td>$10^9$</td>
<td>30</td>
</tr>
<tr>
<td>Nd : glas</td>
<td>1.06</td>
<td></td>
<td>10-50</td>
<td>$10^{10}$</td>
<td>15</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>tunable at 10.6</td>
<td>50</td>
<td>2</td>
<td>$10^8$ up to $10^9$</td>
<td>40-200</td>
</tr>
<tr>
<td>N$_2$</td>
<td>0.3371</td>
<td>20</td>
<td>5-500</td>
<td>$10^5$</td>
<td>10</td>
</tr>
<tr>
<td>Ar$^+$</td>
<td>0.488 and 0.5145</td>
<td>10</td>
<td>up to $2 \times 10^3$</td>
<td>50</td>
<td>30</td>
</tr>
<tr>
<td>He - Cd</td>
<td>0.325 and 0.4416</td>
<td>$50 \times 10^{-3}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kr$^+$</td>
<td>0.6471</td>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>He - Ne</td>
<td>0.6328</td>
<td>$100 \times 10^{-3}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO</td>
<td>5.2</td>
<td></td>
<td>2</td>
<td>$10^8$</td>
<td>40</td>
</tr>
<tr>
<td>Semi-conductor</td>
<td>0.6 — 30</td>
<td>$10^{-3}$</td>
<td>up to $10^4$</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>DYE</td>
<td>0.2 — 1.4</td>
<td>$10^{-1}$</td>
<td>30</td>
<td>$10^5$</td>
<td>500</td>
</tr>
<tr>
<td>Parametric oscillator</td>
<td>0.4 — 4</td>
<td>$10^{-3}$</td>
<td>$10^4$</td>
<td>$3 \times 10^3$</td>
<td></td>
</tr>
<tr>
<td>Sum and difference frequency</td>
<td>0.2 — 0.4 (+)</td>
<td>$10^{-3}$</td>
<td></td>
<td>$10^3$</td>
<td></td>
</tr>
<tr>
<td>Spin Flip Raman</td>
<td>around 5 and 9 — 15</td>
<td>1</td>
<td>up to 120</td>
<td>$10^4$</td>
<td></td>
</tr>
</tbody>
</table>
Available tunable laser sources (J. Kuhl and W. Schmidt, 1974)
In the wavelength regions where the black bars are interrupted, tunable lasers are still under development or proposed

Transmitter: A pulsed laser transmitter normally consists of a laser head, housing the solid state lasing material and a powerful irradiating light source, front and rear reflectors, a power supply and a control circuit for the light source. A "Q" switching mechanism reduces irregular laser pulsations and at the same time greatly increases the peak intensity by regulating regeneration in the laser through artificial impairment of the optical path. A beam expander is located near the output of the transmitter.

(b) Lidar receiver

As the transmitted energy passes through the atmosphere, the gas molecules and aerosols encountered cause scattering. A small fraction of this energy is backscattered in the direction of the lidar and is there available for detection. At the lidar, backscattered energy is collected in a suitable receiver by means of an optical telescope, which is analogous to a microwave antenna; its function is to collect electromagnetic radiation from a narrow field. Keplerian, Newtonian and Cassegrainan types of telescopes or modified versions thereof are suitable for use in the receiver.

Background radiation: The radiation received by the telescope is the sum of that scattered back from the outgoing laser pulse and that originating from various background sources. The major source of background radiation is the irradiation from the sky and terrain (i.e. from natural sources). An example of the spectral radiance of the sky under clear daytime conditions is given in Figure 13 (Kildal, 1971).

Figure 12
Available tunable laser sources (J. Kuhl and W. Schmidt, 1974)

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Although pulsed lidars employ direct photodetection, which cannot distinguish between signal and noise (e.g. background) photons, the background counts can be reduced by spatial and spectral filtering in the optical telescope. The number of background photons, \( n_b(\gamma_r) \), is usually estimated using the equation:

\[
n_b(\gamma_r) = B(\gamma_r) \tau_d \eta(\gamma_r) K' A_r \Omega_r \Delta \lambda
\]

where \( B(\gamma_r) \) is the spectral radiance of the background source; \( \Omega_r \), the solid angle of the receiver field of view; \( \Delta \lambda \), the bandwidth of the receiving system; \( K' \), the efficiency of the optical system; \( \eta(\gamma_r) \), the quantum efficiency of the photodetector; \( \tau_d \), the gate time interval and \( A_r \), the receiver detecting area.

This expression for \( n_b(\gamma_r) \) indicates that background intensity can be reduced by decreasing the field of view, the receiver spectral bandwidth and the effective receiving area. The spectral radiance has a peak in the visible region due to scattered solar radiation. Below about 300 nm the \( O_3 \) absorption in the upper atmosphere screens out all solar radiation so that operation without sun interference (effective night condition) is possible in this "solar-blind" wavelength region; below about 250nm atmospheric transmittance is decreased by elastic scattering and absorption due to oxygen, so that the useful UV region is limited to 250-300 nm.

In the IR the spectral radiance again peaks due to thermal radiation around 13 \( \mu \)m. Background noise due to elastic backscattering is important for Raman scattering in the UV and visible regions. Calculations show that laser Raman measurements could be severely hindered if the background photoelectron rate is greater than \( 10^5 \); therefore daylight measurements are almost impossible to perform, at least for the present state of the art, while night-time operation might be expected to give practical results. In a real atmosphere containing a large number of different compounds, fluorescent scattering might be induced; generally, a fluorescent spectrum consists of discrete spectral spikes super-imposed on a broad continuum which can mask the Raman signals from molecules to an extent depending upon the irradiation wavelength, the chemical composition of the atmosphere, fluorescence quenching and other factors. Experiments demonstrate that such fluorescence effects severely reduce the Raman capability of measuring atmospheric gases.

**Detector:** The collected electromagnetic energy is directed onto a photodetector; at visible and shorter wavelengths (\( \lambda \approx 200 \) to 700 \( \mu \)m) a multi-stage photomultiplier is most efficient, while at IR wavelengths (i.e. above 800 \( \mu \)m) photoconductive solid state detectors have been used successfully. In photoconductive solid state detectors the absorption of a quantum of electromagnetic radiation will produce a current if its energy is greater than the threshold value of the photosensitive area. The ratio of the current carriers, each with charge \( e \), produced per incident photon is always less than unity and is called the quantum efficiency. The dark current in a photomultiplier consists of random thermionic emission of electrons from the cathode surface and dynodes, of leakage current and of other minor sources and it limits the performance of the laser system. In order to extend the dynamic range, the postdetection gain in the receiver can be varied either with the intensity of the incident light (e.g. logarithmic response) or with time (e.g. time-programmed gain).

Weak signals (such as in Raman lidars and stratospheric measurements) detected by photomultipliers take the form of series of photoelectron pulses rather than a continuous current. For the region encompassing the UV to the near IR,
which is accessible to photomultipliers, two types of detection methods are customarily employed: digital photon counting and analogue boxcar integration. Both of these have sufficient speed of response to enable good range resolution and they permit increasing the signal-to-noise ratio by signal averaging. A schematic block diagram of the basic setup for both the analogue (a) and digital detection methods (b) appear in Figure 14 (Inaba, 1972).

The return signal, from a distance R, received by a photomultiplier (PM) and processed by a pulse amplifier is sampled at time 2R/C during a specified time interval or by using a range gate. The gating pulse is controlled by a pulse generator, triggered by the transmitted laser pulse, but shifted by a delay circuit in order to coincide with the arrival of the signals scattered at distance 2R/C. In the boxcar integration scheme, the signal current sampled by the gating pulse is integrated and stored, to be displayed on a recorder or sent to an analogue-to-digital transient recorder. In the photon counting scheme the number of photons converted from received photons, is counted during a fixed sampling time after passing through a discriminator, which rejects noise electrons on the basis of their height distribution. The dynamic range of the counting method is limited by the electronic bandwidth, so that boxcar techniques are preferable for detecting wider ranges of returned signals, whereas photon counting has better sensitivity for very weak intensities.

Laser heterodyne detection systems, using lasers as local oscillators, are used for detecting weak radiation signals which have a narrow spectral line width, e.g. thermal radiation from gases, laser radiation which has been scattered from gas molecules or aerosols, or laser radiation transmitted from a distant source. In this technique, the received laser radiation is mixed in a wideband infra red detector with that from a local laser source. The local laser can operate at a fixed frequency, or be tunable so that it scans across the emission line of interest; a beat frequency is produced whenever the difference frequency is within the bandpass range of the electronics. Under ideal conditions, using photoconductive detectors, the minimum detectable power is (Keyes, 1970):
where $B$ denotes the IF bandwidth, $\eta$ is the quantum efficiency of the IR detector and $\tau$ is post-detection integration time. For a 1 GHz IF bandwidth, a one second integration time and $\eta \approx 0.5$, one obtains $P_{\text{min}} = 10^{-15}$ W in the 5-10 $\mu$m spectral region. This sensitivity is significantly better than that obtained using incoherent detection of thermal radiation. Laser heterodyne techniques can also be used in a passive mode (without a transmitting laser). Gases radiate at their resonant absorption frequencies and since thermal radiation is strongest in the IR, this is the ideal spectral range for viewing the thermal properties of atmospheric constituents. When a heterodyne radiometer is used to detect IR laser radiation in active atmospheric monitoring systems, it is generally several orders of magnitude (typically 4) more sensitive than direct detection methods. At the present time, only a few practical atmospheric measurements have been made, but the results of laboratory experiments are encouraging. The rapid evolution of improved components and the accumulation of experience point toward an interesting measurement capability in the future.

(c) Data processing equipment

![Figure 15](image_url)

**Figure 15**
A-type oscilloscope traces of lidar returns with (A) fixed post detection gain and (B) time programmed gain, which corrects for the inverse square law and atmospheric losses (see lidar equation)

The electrical signal from the detector contains information on the presence, range and concentration of atmospheric scatterers and absorbers. Various forms are used for analysing and presenting the information content of such signals. In the simplest form the signals are presented on an oscilloscope in a coordinate system showing the received signal intensity as a function of time or range; since such signals are very transient, it is necessary to photograph such oscilloscope displays to obtain an adequate data presentation. A typical return signal is shown in Figure 15.
Sequences of observations in a given direction, or in various scan directions can be used to provide information on the atmospheric condition on an extended scale in space or time. Figures 16 and 17 illustrate such visualisations. Aerosols and clouds in the atmosphere are studied in the simplest way by pointing the lidar into the vertical direction and displaying the backscattered signal on an oscilloscope (intensity modulation) using a suitable time base, as shown in the example given in Figure 16.

Figure 16
Height/time cross section of the aerosol structure over St. Louis (13.8.71) as observed by the SRI/EPA Mask VIII lidar system (Uthe, 1974)

Figure 17 shows an intensity modulated vertical cross section generated by making a series of observations while scanning in different directions. The rate at which such information can be collected depends upon the pulse repetition frequency of the laser system. Although photography (particularly Polaroid photography) of signals remains in common use, more sophisticated techniques of data processing are now commonplace, and are significantly enhancing the utility of the lidar data.

Figure 17
Intensity modulated vertical cross section (Collis, 1976)
Analogue signals of high intensities are converted to digital signals by transient recorders, stored on magnetic tape or disc storage media and processed by mini computers. Weak signals which have the form of a series of pulses can readily be processed in digital form.

II.1.1.2 The lidar equation

The basic relation for understanding how laser radars obtain information about the atmosphere is the lidar equation. This equation is valid for a one wavelength monostatic single-ended lidar and describes the system and atmospheric parameters which contribute to the signal measured by the lidar. Figure 18 shows the geometry of a classical lidar.

![Lidar geometry of a classical Mie or Rayleigh lidar](image)

Figure 18

Lidar geometry of a classical Mie or Rayleigh lidar

An atmospheric cell of length $L$ at range $R$ or height $h$ is illuminated by the laser transmitter which has a solid angle of $\Omega_t$. The receiver system has an opening angle of $\Omega_R$ and an effective detecting area of $A_R$. The laser transmitter and receiver are located as close to each other as possible so that the transmitted and backscattered beams overlap over almost the entire atmospheric path.
The receiver is gated in time so that it receives photons only during the time period corresponding to the arrival of backscatter from a particular atmospheric cell with volume

\[ L A_t = L \Omega_t R^2 \]  

(32)

\( L \) can be as large as desired by simply keeping the receiver time gate open longer, but can only (usefully) be as small as:

\[ \frac{c \tau}{2} \]  

(33)

which is the optimal radar range resolution where \( c \) is the velocity of light and \( \tau \) the laser pulse duration.

The number of photons \( N_t \) transmitted per laser pulse is given by:

\[ N_t = \frac{p_t \tau}{h \gamma_t} \]  

(34)

where \( h \gamma_t \) is the energy per photon (\( h = \) Planck's constant and \( \gamma_t \) the transmitter frequency), \( \tau \) is the pulse width and \( p_t \) is the laser power.

The number of photons incident on the atmospheric cell is:

\[ N_t \eta_t \exp \left(-\int_0^R \alpha(r) \, dr \right) \]  

(35)

where \( \eta_t \) is the optical efficiency factor of the optical system required to collimate the laser and \( \alpha(r) \) is the volume extinction coefficient for the transmitted wavelength (see Chapter I).

The signal returned to the receiver from the cell is determined by the volume backscattering coefficient. The total backscattering per steradian is proportional to:

\[ N(R) \sigma(\pi) L \]  

(36)

where \( N(R) \) is the number density \((m^{-3})\) of scatterers and \( \sigma(\pi) \) the backscattering cross section (see Chapter I).

The fraction of photons reaching the receiver is:

\[ \frac{A_R}{R^2} \exp \left(-\int_0^R \alpha'(r) \, dr \right) \]  

(37)

where \( \frac{A_R}{R^2} \) is the solid angle at the receiver as seen from the atmospheric cell, \( \alpha'(r) \) is the volume extinction coefficient of the return signal; \( A_R \) is the
effective receiver area. The number of signal photons, \( N_R \), counted by the receiver will be the number incident on the receiver times an optical efficiency \( \eta_R \).

Putting all these factors together (equations 32 to 37) and assuming \( \alpha(r) = \alpha'(r') \), the lidar equation is given by:

\[
N_R = N_t \eta_t N(R) \sigma(r) L \frac{A_R}{R^2} \eta_R \exp \left( -2 \int_0^R \alpha(r) \, dr \right)
\]

This equation can also be written as:

\[
P_R(R) = \frac{K \beta(R) T^2(R)}{R^2}
\]

where \( \beta(R) \) is the volume backscattering coefficient, \( P_R(R) \) is the received backscattered power from a scattering volume at range \( R \) and:

\[
T^2(R) = \exp \left( -2 \int_0^R \alpha(r) \, dr \right)
\]

\( T^2(R) \) is called the two way atmospheric extinction function, \( K \) is a constant equal to \( \xi P_t L A_R \) where \( \xi \) stands for the overall optical and quantum efficiency of the lidar and can be determined from a knowledge of the system instrumental parameters or from a previous calibration (e.g. using a short distance and a reflector with well known wavelength characteristics). However, in pulsed laser systems the power \( P_t \) is not always constant, so it is better to determine \( K' = \xi L A_R \) and to measure (by an electronical way) \( P_R \) for each pulse. The distance \( R \) can be calculated from the time difference between the start of the laser pulse and the time of the received signal.

II.1.1.2.1 Solution of the lidar equation

The first step in deriving quantitative information from the lidar equation is to solve the equation. However, successful implementation of this technique does require that certain plausible a priori assumptions or constraints be made, regarding the physical properties of the aerosol particles. Referring back to the lidar equation, the two unknowns which relate the lidar response from any range \( R \) to the atmospheric scatterers are the backscattering coefficient \( \beta(R) \) and the transmission term \( T^2(R) \), where \( T^2(R) \) in turn, depends on the integral of the extinction coefficient \( \alpha(r) \) over range from 0 to \( R \). As a single lidar return provides only one measurement at any range \( R \), it is evident that \( \beta(R) \) and \( T^2(R) \) cannot be uniquely determined without the aid of supplemental information or some a priori knowledge about the relationship between \( \beta(R) \) and \( T^2(R) \) or \( \alpha(r) \). One of the most direct methods for solving the lidar problem is the "slant path" technique described by Hamilton (1969). This technique is based on the assumption that the atmosphere is horizontally homogeneous over the region probed by the lidar. If this is the case, the lidar response, \( P(R) \), from any range, \( R \), along a slant path at an angle, \( \theta \), with respect to the zenith can be expressed in terms of ver-
tical height $z$ and zenith angle $\theta$ by:

$$P_R(R) = \frac{K \beta(z)}{z^2 \text{sec}^2 \theta} \exp(-2 \tau(z) \text{sec} \theta)$$

where $R = z \text{sec} \theta$, $K$ is the system constant and $\tau(z)$ is the partial optical depth from ground level to height $z$. $\tau(z)$ is related to $T^2(R)$ and $\alpha(r)$ by

$$T^2(R) = \exp -2 \int_0^{R} \alpha(r) \, dr = \exp(-2 \tau(z) \text{sec} \theta)$$

(42)

The backscattering coefficient is assumed to be only a function of height. From equation (41) it can be seen that $\beta(z)$ or $\tau(z)$ may be uniquely separated if short path measurements are made at several zenith angles. A convenient graphical solution may be obtained by plotting the natural logarithm of $P_R(z \text{sec} \theta)$, $z^2 \text{sec}^2 \theta$ versus $2 \text{sec} \theta$ for a given height, for series of zenith angles using:

$$\ln(P_R(z \text{sec} \theta) z^2 \text{sec}^2 \theta) = \ln(K \beta(z)) - 2 \tau(z) \text{sec} \theta$$

(43)

The crossing of the best fit line with the ordinate yields $K \beta(z)$ while the slope gives $\tau(z)$. Horizontal inhomogeneities that may be present will cause scatter in the data points and contribute to errors in the interference of $\tau(z)$ and $K \beta(z)$. An example plot obtained by Spinherine et al (1974) is shown in Figure 19.

**Figure 19**
Example of short-path determination of $\tau(z)$ and $K \beta(z)$ made with a ruby laser at Tucson, Arizona, August 13, 1974 at a height of $z = 1.6$ km (Spinherine, 1974)

The vertical distribution of aerosol optical depth may also be determined by subtracting the molecular partial depth $\tau_m(z)$, which is known theoretically, from $\tau(z)$ to obtain the aerosol partial optical depth $\tau_a(z)$. If $z$ is chosen
sufficiently high to include most of the aerosols in the atmosphere, $\tau_\alpha(z)$ to this height may be used directly as an indicator of the "optical loading" or turbidity due to aerosols.

Optical depth data, obtained via this method or by some other method, such as a narrow-wavelength solar radiometer (Shaw et al, 1973), may be used to extract additional information from lidar return. For example, given $\tau(z)$ to some reference height $z_r$, the round trip lidar equation transmission factor $r^2(z_r)$ to height $z_r$ is also known. With this information, an analysis scheme developed by Fernald et al (1972) may be employed to solve the lidar equation and to determine $\alpha(z)$ and $\beta(z)$ for any height between 0 and $z_r$. This reduction method requires that the system calibration constant $K$ must be known. The calibration constant can be obtained by using the target technique described by Hall (1970), or by referencing to lidar signals from a height where the scattering is due approximately to molecules only. An other requirement is that the aerosol attenuation coefficient $\alpha_\alpha(z)$, divided by the aerosol backscattering coefficient $\beta_\alpha(z)$, be a constant, defined here as $S$, for all heights between 0 and $z_r$. This constraint physically requires that the relative shape of the aerosol particle size distribution and particle refractive index remain constant with height. Self-consistency checks reported by Fernald et al (1972) indicate that $S$ is sufficient constant with height so that $S$, $\alpha_\alpha(z)$ and $\beta_\alpha(z)$ can typically be determined with an error of 30% or less as long as there are sufficient particles in the atmosphere to insure that $\beta_\alpha(z)$ is at least comparable in magnitude to the molecular backscattering coefficient.

The aerosol parameters which one may hope to determine from single wavelength lidar measurements then include $\tau_\alpha(z)$, $S$, $\alpha_\alpha(z)$ and $\beta_\alpha(z)$. These parameters may be used directly in certain applications, or they may be used to infer at least limited information about the physical properties of aerosols. For example, assuming $S$ constant with height, then $\alpha_\alpha(z)$ and $\beta_\alpha(z)$ both provide a relative measure of the vertical aerosol number density profile. If the aerosol particle refractive index is known or if a representative value is assumed, $S$ and $\alpha_\alpha(z)$ or $\beta_\alpha(z)$ can be used to obtain a simple Junge model fit for the aerosol particle size distribution (Fernald, 1972). The inferred size distribution may in turn be used to determine, on an absolute basis, the vertical distribution of aerosol particle number density and mass per unit volume. A number of assumptions are obviously involved in estimating some of these physical quantities, but useful information can still be obtained. Lidar may be used to infer more information about the physical properties of aerosols if probing techniques are employed which provide additional independent measurements. One possible approach is the use of a multi-wavelength lidar. Another approach, that has already been used to some extent, is the bistatic lidar technique which can make scattering measurements at several scattering angles. Herman (1971) has shown that it is possible to invert bistatic lidar measurements to recover aerosol size distributions of fairly arbitrary shape. Reagan (1972) and Palmer (1972) use a bistatic lidar to infer real aerosol particle size distributions through the use of model fitting procedures.

Solution techniques to enable evaluation of the single-scattering lidar equation for quantitative purposes are also described by Barrett (1967), Johnson and Uthe (1971) and Davis (1969). Further solutions for the lidar equation will be given in Chapter III: visibility ("slope" method and "ratio" method). In the case of turbid atmospheres (fog or clouds) multiple scattering occurs and solutions which assume single-scattering are invalid. In such cases more sophisticated form-
ulations of the lidar equation must be used, although useful evaluations of lidar observations in fog have been made by Viezee (1973) using a semi-empirical approach. In less turbid atmospheres and in clear air, the assumption of single scattering appears to be wholly acceptable for lidar data.

II.1.2 Raman lidar

In a Raman lidar the receiver is made sensitive to Raman-shifted wavelengths. As mentioned in the foregoing chapter, the Raman wavelength shift is unique to each type of scattering molecule and the intensity of the Raman signal is proportional to the concentration of scattering molecules. Raman lidars are used to obtain absolute measurements of atmospheric molecular concentrations and to infer vertical profiles of humidity, ozone concentrations, temperature and visibility.

The basic concept of the Raman lidar for remote detection of atoms and molecules in the atmosphere is illustrated schematically in Figure 20. The transmitted optical laser beam passes through a transmitting telescope and is backscattered from mixtures of particulate scatterers and gaseous constituents dispersed in the air. The spectrum of the backscattered energy arriving at the receiving telescope is composed of Rayleigh and Mie scattered components of a frequency, centered at $\gamma_0$, identical with the transmitted frequency as well as the Raman-shifted frequencies at $\gamma_1, \gamma_2, \ldots, \gamma_n$. These spectral components are analysed and detected simultaneously by a spectrum analyzer in conjunction with optical filtering devices and sensitive photodetectors.

![Figure 20](image)

**Figure 20**

Raman lidar basic concept

Although for Raman scattering, selective excitation at a particular frequency is not required, the backscattered signal includes Raman scattered spectra from all Raman-active constituents in the air, with intensities proportional to their concentrations. For resonance Raman scattering, the transmitted laser fre-
quency must be tuned into or close to resonance with a specific transition of the species under study. At present, tunable lasers include dye lasers and their second harmonics for the wavelength region covering the near UV to the near IR and non-linear optical devices such as parametric oscillators for the range from the visible VI to the middle IR (30 µm). The received power \( P_r (R, \gamma) \) of a spectral component of frequency \( \gamma \) backscattered from a scatterer at range \( R \) is described as follows by the lidar equation:

\[
P_r (R, \gamma) = \frac{K \beta_{\text{RAM}} (R) T(R, \gamma_0) T(R, \gamma)}{R^2}
\]

(44)

with:

\[
K = \xi P_t (\gamma_0) L A_R
\]

(45)

\[
T(R, \gamma_0) = \exp (- \int_0^R \alpha (\gamma_0, \tau) \, d\tau)
\]

(46)

\[
T(R, \gamma) = \exp (- \int_0^R \alpha (\gamma, \tau) \, d\tau)
\]

(47)

\( T(R, \gamma_0) \) is the atmospheric attenuation of the transmitted beam with frequency \( \gamma_0 \)

\( T(R, \gamma) \) is the atmospheric attenuation of the scattered beam with frequency \( \gamma \)

\( \beta_{\text{RAM}} (R) \) is the volume backscattering Raman coefficient which can be assumed the same for both wavelengths

The night-time detection limit versus height is demonstrated in Figure 21 for several molecules which occur in the atmosphere, together with their concentration profiles, using a typical Raman lidar with output power of one Joule and a receiver detecting area of 0.5 m².

The minimum detectable concentration or maximum detectable altitude can be obtained at the intersection of the concentration profiles, with the straight line representing the detection limit. It can be seen that \( \text{N}_2 \) and \( \text{H}_2\text{O} \) molecules are detectable up to about 50 km and 9 km respectively by photon counting, up to heights of about 40 km for \( \text{O}_2 \) and 15 km for \( \text{CO}_2 \). So valuable information can be obtained about the mixing ratios of oxygen-nitrogen and oxygen-carbon dioxide in the atmosphere as a function of altitude, water vapour transport, cloud formation and atmospheric humidity, for example.

In addition, since the receipt of detectable Raman signals from atmospheric \( \text{N}_2 \) appears possible throughout the troposphere, there is a potential for using this spectral information for remote temperature sensing in three dimensions. A common method for obtaining molecular concentrations in the atmosphere, which minimizes uncertainties due to instrumental and physical parameters in the lidar equation, is
to calculate the ratio of the return signals from nitrogen and another gas, since 
the concentration distribution of the former is assumed to be both known and con-
stant in the atmosphere.

\[
\frac{P(R)_{\text{gas}}}{P(R)_{\text{N}_2}} = \frac{\beta_{\text{gas}} N_{\text{gas}}(R) T_{\text{gas}}(R)}{\beta_{\text{N}_2} N_{\text{N}_2}(R) T_{\text{N}_2}(R)}
\]

(48)

If the Raman returns of the gas and nitrogen are sufficiently close in frequency,
the atmospheric scattering losses and absorption losses can be assumed to be the 
same for both frequencies; then the random uncertainties in obtaining the molecular 
concentration occur only in the power measurements and may be reduced by pulse aver-
going without concern for atmospheric fluctuations. Error sources in Raman scattering 
are largely due to the overlapping of the Raman spectra of different species. 
To retain specificity, narrow band filters with high rejection ratios should be 
used. Typical Raman signals are small (see Chapter I) and the signal to noise 
ratio is low so that night-time operation provides a greater sensitivity and range; 
daytime operations would be improved if the measurements could be made in the solar 
blind region below 3000 A, but at shorter wavelengths the Raman lines are closer 
together so that the filtering requirements are greater and the errors due to the 
overlapping of Raman spectra of different gases increase.

The use of the resonance Raman effect appears promising because of en-
hancement of the scattering cross section by resonance. However, when the laser 
is tuned to resonance, the resonance absorption and superposed fluorescense 
will reduce severely the received beam power, rendering detection very difficult 
or almost impossible; thus, near-resonance Raman scattering is considered to be a 
preferable interaction process. The theoretical system sensitivity in near reso-
nance Raman scattering is evaluated in Figure 22 by considering a \text{N}_2 \text{ gas laser} 
(337.1 nm) and the 4th Harmonic of a Nd-Yag laser (266.0 nm) (as a possible high-
power laser), as a function of range, for several different values of the resonance
Minimum detectable concentration as a function of range for lidars based on the near-resonance Raman scattering utilizing the resonance enhancement of the scattering cross section (\( \Lambda \)) (Inaba, 1976).

Parameter, \( \Lambda \) (an enhancement factor of the Raman scattering cross section of the specific molecule of interest relative to the cross section of the N\(_2\) molecule (Inaba, 1976)). It is seen that the sensitivity expected by the use of the N\(_2\) laser is limited by the sky background for daytime operation, while this is not the case for the 4th Harmonic Nd-Yag laser. This phenomenon is primarily due to the location of the latter's wavelength in the solar blind region, which provides remarkable characteristics during practical operation of the lidar irrespective of the time of day or night.

It can also be seen from this figure that resonance enhancements \( \Lambda \) of \( 10^2 \) to \( 10^3 \) in scattering cross section, relative to that for the N\(_2\) molecule, would be enough to realize remote detection of minor atmosphere constituents. The maximum range, however, is limited to a few hundred meters with range resolutions of the order of 10. The remote detection of the major molecular constituents (see Figure 21) by this resonantly enhanced scheme is not inherently feasible through the lower atmosphere, because their excitation wavelengths are located close to or at those of resonance lines, which are mostly in the wavelength ranges of highly absorptive or significantly low atmospheric transmittance in the UV. The estimated value of the resonance Raman scattering cross section for O\(_3\), excited by its very intense Hartley dissociation band between 250 and 300 nm, could be sufficiently large (Penney, 1974) \((10^{-24} \text{ cm}^2/\text{sr})\) to allow range-resolved detection of ambient levels of the order of 10 ppb in environmental air. Spatially-resolved probing of the atmospheric ozone layer (about 10 and 35 km altitude) (see Figure 22) seems to be experimentally feasible by means of resonance Raman scattering. Penney (1974) estimated that the number of detectable photons per joule of transmitted energy from this altitude is about 1 photon (assuming a wavelength near 300 nm, \( A_\tau = 10 \text{ m}^2 \); \( K = 0.1 \) and \( n = 0.2 \) and two way transmission \( T^2 \approx 0.1 - 0.2 \)). Higher sensitivity should be expected.
from high altitude observatories having large receiving optics.

The advantages of Raman lidar include:

(a) no requirement for a particular frequency nor for a tuned frequency laser beam; a laser frequency can be selected in a spectral region which is free from atmospheric absorption; shorter wavelengths are preferable for higher scattering efficiency;

(b) a spatially resolved measurement of preselected atmospheric constituents can be performed from a single station; the wavelength can be tuned, in order to observe isolated Raman spectra of each molecular species with almost no interference;

(c) ambiguity in the backscatter due Rayleigh and Mie scattering can be avoided; this assures measurements of density profiles of molecular species independently of aerosol distributions;

(d) the absolute concentration of each minor species is obtainable by referring to the Raman echo intensities of N$_2$ and O$_2$ since backscattering signals always include Raman echoes from major components (such as N$_2$ and O$_2$) at exactly the same location; thus complex atmospheric and instrumental parameters which arise in the lidar equation can be eliminated using known concentrations of N$_2$ or O$_2$.

The disadvantages include:

(a) the lack of detection sensitivity over long ranges owing to the small scattering cross sections; thus the normal Raman method is difficult to use for detecting minor constituents;

(b) the requirement for high power lasers in the visible and UV regions may lead to serious eye-safety problems in practical applications.

II.1.3 Differential absorption scattering lidar (DIAL)

The DIAL technique, first proposed by Schotland (1964), makes use of at least two laser beams with different wavelengths which are sequentially or simultaneously transmitted along the same path in the atmosphere. The laser wavelengths are chosen so that one coincides with a molecular absorption band, while the other, at a nearby wavelength, is not strongly absorbed. Figure 23 is a schematic diagram for a typical DIAL system, using a tunable IR laser radiation source and a heterodyne receiver. In other systems, two different lasers are used or a ruby laser is tuned to two frequencies by changing the temperature of the laser rod.

Since the beams are spectrally separated by only a small wavelength difference, the aerosol scattering may be considered identical for each. Thus, the difference in scattering intensity is assumed to arise from the difference in absorption by the molecule under investigation. Analysis of both signals provides a measurement of the absorbing molecule's concentration. This technique is generally considered to be a most promising technique for atmospheric measurements. The dependence of the received lidar signal on the two way attenuation term (exp. (-2 $\int a \, dz$)) can be exploited to provide range resolved measurements of specific gaseous constit-
vents at appreciable ranges and with potentially high sensitivity, as illustrated in Figure 24.
Referring to Chapter I the atmospheric extinction coefficient at wavelength $\lambda$ is the sum of the extinction coefficient due to absorption by a gas, $\alpha_g$, and that due to scattering and absorption by all other gases and particles, $\alpha_A$:

$$\alpha(\lambda) = \alpha_g(\lambda) + \alpha_A(\lambda)$$

with:

$$\alpha_g(\lambda) = N \sigma(\lambda)$$

where $N$ is the gas concentration (in molecules per unit volume) and $\sigma$ is the absorption cross section.

Substituting from equations (49) and (50) into the lidar equation and formulating the difference of the logarithms of $P(\lambda_o, R)$ and $P(\lambda_o, R + \Delta R)$ for both the wavelengths $\lambda_o$ within an absorption line, and $\lambda_w$ on the "tail" of the line (or outside the main absorption peak), an expression for \(\bar{N}(R)\) averaged over the range cell $\Delta R$ can be obtained:

$$\ln P(\lambda_o, R) - \ln P(\lambda_o, R + \Delta R) = \frac{\ln (\lambda_o/\lambda_o + R)}{\ln (\lambda_o/\lambda_o + R)} + \frac{2\Delta R}{R} + 2\Delta \bar{N}(R) \sigma(\lambda_o) - \bar{\alpha}_A(\lambda_o)$$

$$\ln P(\lambda_w, R) - \ln P(\lambda_w, R + \Delta R) = \frac{\ln (\lambda_w/\lambda_w + R)}{\ln (\lambda_w/\lambda_w + R)} + \frac{2\Delta R}{R} + 2\Delta \bar{N}(R) \sigma(\lambda_w) - \bar{\alpha}_A(\lambda_w)$$

with $\bar{\alpha}_A$ being the averaged value of $\alpha_A$ over $\Delta R$. Equations (51) and (52) can be solved to yield:

$$\bar{N}(R) = \frac{\ln P(\lambda_o, R) - \ln P(\lambda_o, R + \Delta R)}{\ln P(\lambda_o, R + \Delta R) - \ln P(\lambda_w, R + \Delta R)} + B + T$$

where

$$B = \ln \left[ \frac{\beta(\lambda_o, R + \Delta R)}{\beta(\lambda_o, R)} \right] - \ln \left[ \frac{\beta(\lambda_w, R + \Delta R)}{\beta(\lambda_w, R)} \right]$$

$$T = -2 \left[ \bar{\alpha}_A(\lambda_o, R) - \bar{\alpha}_A(\lambda_w, R) \right] \Delta R$$

$$\bar{\alpha}_A(\lambda_o, R) - \bar{\alpha}_A(\lambda_w, R)$$
If it can be assumed that the spectral dependences of $\alpha_A$ and $\beta$ are weak in the wavelength region $\lambda_o - \lambda_w$ and that the measurements are made nearly simultaneously to avoid temporal changes in $\alpha_A$ and $\beta$, then $B$ and $T$ can be taken to be zero. In this case, the minimum detectable concentration $N_{\min}$ of gas is given by:

$$N_{\min} = \frac{\delta}{2 \Delta R (\sigma(\lambda_o) - \sigma(\lambda_w))}$$

(56)

where $\delta$ is the minimum value of the logarithmic difference which can be reliably detected. Given typical detection and digitalization equipment, a reasonable value for $\delta$ is about 0.02. This value, combined with the differential absorption coefficients of several atmospheric constituents, results in the minimum detectable concentrations shown in Table IV.

### Table IV

Minimum detectable concentrations of various atmospheric gases using DIAL techniques (Collis, 1976)

<table>
<thead>
<tr>
<th>Species</th>
<th>Wavelength $\lambda$ ($\mu$m)</th>
<th>Differential absorption coefficient (cm$^{-1}$ atm$^{-1}$)</th>
<th>Minimum detectable concentration per 100 m range cell (ppm)</th>
<th>Typical atmospheric concentrations</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_2O$ vapour</td>
<td>0.6944</td>
<td>0.00035</td>
<td>3000</td>
<td>4000-30000 4000-30000</td>
</tr>
<tr>
<td>$CO$</td>
<td>2.3</td>
<td>0.4</td>
<td>2.5</td>
<td>1-100 0.3-1.0</td>
</tr>
<tr>
<td>$CO$</td>
<td>4.74</td>
<td>10</td>
<td>0.1</td>
<td>0.01-0.3 0.001-0.005</td>
</tr>
<tr>
<td>$NO_2$</td>
<td>0.45</td>
<td>7.2</td>
<td>0.4</td>
<td>0.01-0.3 0.01</td>
</tr>
<tr>
<td>$SO_2$</td>
<td>0.30</td>
<td>26</td>
<td>0.04</td>
<td>0.01-0.3 0.01</td>
</tr>
<tr>
<td>$C_6H_6$</td>
<td>7.4</td>
<td>16</td>
<td>0.06</td>
<td>0.01-0.3 0.01</td>
</tr>
<tr>
<td>$C_6H_6$</td>
<td>8.88</td>
<td>1</td>
<td>1</td>
<td>0.01-0.3 0.01</td>
</tr>
<tr>
<td>$C_6H_6$</td>
<td>0.25</td>
<td>33</td>
<td>0.03</td>
<td>0.04-0.5 0.03-0.06</td>
</tr>
<tr>
<td>$CO$</td>
<td>0.29</td>
<td>12</td>
<td>0.08</td>
<td>0.04-0.5 0.03-0.06</td>
</tr>
<tr>
<td>$O_3$</td>
<td>9.48</td>
<td>10.8</td>
<td>0.1</td>
<td>0.04-0.5 0.03-0.06</td>
</tr>
<tr>
<td>$NH_3$</td>
<td>10.7</td>
<td>30</td>
<td>0.03</td>
<td>0.04-0.5 0.03-0.06</td>
</tr>
<tr>
<td>$NO$</td>
<td>0.226</td>
<td>7</td>
<td>0.14</td>
<td>0.04-0.5 0.03-0.06</td>
</tr>
<tr>
<td>$NO$</td>
<td>5.2</td>
<td>4</td>
<td>0.25</td>
<td>0.04-0.5 0.03-0.06</td>
</tr>
<tr>
<td>$NO$</td>
<td>5.31</td>
<td>10</td>
<td>0.1</td>
<td>0.04-0.5 0.03-0.06</td>
</tr>
<tr>
<td>$NO$</td>
<td>5.5</td>
<td>1.2</td>
<td>0.8</td>
<td>0.04-0.5 0.03-0.06</td>
</tr>
<tr>
<td>$CH_4$</td>
<td>3.39</td>
<td>15</td>
<td>0.07</td>
<td>0.04-0.5 0.03-0.06</td>
</tr>
</tbody>
</table>
In differential absorption measurements, the minimum detectable concentration is independent of range, R, which is in marked contrast to corresponding expressions for experiments which measure the concentration through its contribution to the backscattering coefficient \( \beta \), such as those employing Raman scattering (where the minimum detectable concentrations increase at least as rapidly as \( R^2 \)). This range independency is valid as long as the backscattering signal from all atmospheric particles and gases at both on-line and off-line wavelengths is large enough to provide a measurable difference term which exceeds \( \delta \). The range over which this condition holds, depends on the transmitter and receiver characteristics, the transmitted wavelength (UV, visible or IR) and the atmospheric particulate content. Several tunable lasers (dye lidars) exist for which the received signal meets these criteria over ranges of several km and more, in the UV and visible region. At longer wavelengths (where many useful absorption lines occur) the decreased atmospheric scattering coefficient \( \beta \) reduces the possible range for spatially resolved measurements, but the use of reflectors may permit path-integrated measurements in these cases.

Potential errors in the DIAL methods have been investigated in some detail by Schotland (1974) and Wright (1975). Schotland evaluated the uncertainties in the measured concentration arising from uncertainties in the differential backscatter and transmission terms, the absorption coefficient and the measured power. He showed that for a typical gaseous absorption line with a frequency difference \( \Delta \gamma \leq 0.3 \text{ cm}^{-1} \) between the line center and its tail, the wavelength dependence of \( \beta \) and \( \alpha \) is weak enough, so that in exactly simultaneous measurements, the difference terms \( \beta (\lambda_o) - \beta (\lambda_w) \) and \( \alpha (\lambda_o) - \alpha (\lambda_w) \) are negligible (relative differences \( < 10^{-4} \)) provided that the absorption by other gases is constant for \( \lambda_o < \lambda < \lambda_w \).

Consideration of the temporal variations of \( \alpha \) and \( \beta \) due to natural fluctuations in atmospheric particulate content is important; Schotland showed that, if a relative accuracy in \( N(R) \) of 10% or better is desired, the time interval between line and tail shots should be less than a few milliseconds. Schotland obtained expressions for the uncertainties in \( \alpha \) and \( \beta \) and applies them to the ground-based measurements of a vertical water vapor profile using a ruby lidar. He showed that the uncertainty in \( \alpha \) arising from uncertainties in the temperature and pressure of the atmospheric volume being probed introduces a relative error of about 1% for a single measurement pair, while the uncertainty in \( \alpha \) due to uncertainties in the ruby laser output wavelength are more significant, ranging from 3% at sea level to 6% at an altitude of 3 km (temperature dependence of the ruby laser output wavelength). At an altitude of 3 km power measurement errors begin to dominate as the received lidar signal becomes small in comparison to the sky background, producing relative errors in \( N \) of 9%, even when the variance is deduced by averaging 25 measurement pairs. Wright (1975) has presented an error analysis which not only includes the terms considered by Schotland, but also the effects of interfering absorption by other gases and of signal digitalization errors; in addition, explicit terms for several different types of power measurements and signal detection errors were included. His analysis shows that the uncertainties arising from a given source, which may be insignificant in one particular type of measurement may be the dominant source of error in another type of measurement. Interference effects, which occur when a material other than the gas of interest has a significant wavelength dependence in the region \( \lambda = \lambda_o \) to \( \lambda_w \) tend to occur more frequently in the IR and UV than in the visible. In many practical cases interference effects may indeed be significant. They may be circumvented by using more than one absorption line of the gas of interest; however, this method complicates the analysis, and requires more elaborate equipment. Digitalization and other signal processing errors are a fundamental aspect of any practical system and may become the dominant...
source of error when a lower limit is set for the attainable $\delta$ in equation (56).

II.2 Double-ended systems

As already mentioned, double-ended systems are those in which the laser transmitter and receiver are located separately, or those having the laser transmitter and receiver co-located, but using a physical reflector at some distance. From a practical point of view, these arrangements present a number of disadvantages; however, they open new possibilities which would be impossible with single-ended systems. The two principal double-ended systems are known as the bistatic lidar and long path absorption.

II.2.1 Bistatic lidar

In bistatic lidars both the laser and receiver optics are oriented toward the same volume in the atmosphere. By carefully varying the pointing angles of the laser and the receiver, measurements of scattering at a fixed altitude can be observed for a variety of scattering angles. The obtained scattering data can be used to infer the refractive index and/or the size distribution of atmospheric aerosols, as already discussed in Chapter I.

II.2.2 Long path absorption

This technique makes use of the measured absorption of a laser beam as it propagates through the atmosphere to infer molecular concentrations. The averaged concentration of a particular molecular species over a path can be measured using the differential absorption technique. Receiver and transmitter are separated by a path distance $R$; in most existing systems this is accomplished by co-locating the laser and receiver with their optical axes aligned and pointed toward a retro-reflector. As in the differential absorption scattering lidar at least two beams at slightly different wavelengths are used.

Consider the transmission of two laser wavelengths $\lambda_1$ and $\lambda_2$, "on" and "off" the spectral absorption line to be monitored (i.e. $\sigma(\lambda_1) = \sigma$ and $\sigma(\lambda_2) \approx 0$, where $\sigma$ is the peak molecular absorption cross section). If the laser radiation is transmitted over an atmospheric path of length $L$ to a remote reflector, the power arriving at the receiver is:

$$P_r(\lambda_1) = K'(\lambda_1) P_o(\lambda_1) \exp(-2\int_0^L N(z)dz) \exp(-2\int_0^L a(\lambda_1, z)dz)$$

(57)

$$P_r(\lambda_2) = K'(\lambda_2) P_o(\lambda_2) \exp(-2\int_0^L a(\lambda_2, z)dz)$$

(58)

where $P_o(\lambda)$ is the transmitted power, $K'(\lambda)$ the overall system efficiency, and $a(\lambda, z)$ the effective extinction due to "tail" absorption from other constituents.
and scattering from particles and aerosols (see equation (49)). The average concentration $\bar{N}$ over the path is thus given by:

$$\bar{N} = \frac{1}{L} \int_0^L N(z) \, dz$$

$$= \frac{1}{2 \sigma L} \ln \left[ \frac{P(\lambda_2)}{P(\lambda_1)} \right] + \frac{1}{\sigma L} \int_0^L \left( a(\lambda_2, z) - a(\lambda_1, z) \right) \, dz$$

(59)

Assuming that the wavelength dependence of the interferences is low enough to make the last term of equation (59) negligible, that the system efficiency is also independent of wavelength over the range of interest and that $P_o(\lambda_2) = P_o(\lambda_1)$ we obtain:

$$\bar{N} = \frac{1}{2 \sigma L} \ln \left[ \frac{P(\lambda_2)}{P(\lambda_1)} \right]$$

(60)

In the limit where $2 \sigma N L \ll 1$ we can rewrite this equation in the following form:

$$\bar{N} \approx \frac{1}{2 \sigma L} \left[ \frac{\delta P}{P_r} \right]$$

(61)

where $\delta P = P(\lambda_2) - P(\lambda_1)$ represents the differential absorbed power collected by the detector system. Experimentally, changes in received power equal to 0.003 $P_r$ have been detected over outdoor paths (Ku, 1875). For CO monitoring this corresponds to a minimum detectable concentration of 0.2 ppb for a 0.1 mW laser. This sensitivity is clearly adequate for CO, whose concentration is generally above 50 ppb, and for most other pollutants as well. Although long-path monitoring employing a remote reflector has the very important advantage of requiring only low-power laser radiation (less than 0.1 mW usually), attempts have been made to use topographical targets in order to achieve greater versatility and range resolution by beam steering because of the cost of a double-ended system.

The system sensitivity remains the same, but much greater transmission power is needed as the transmitter/receiver system efficiency includes the factor $\frac{\rho A}{\pi L^2}$ which takes into account Lambertian scattering from the target; A is the receiver area and $\rho$ is the effective target reflectivity. Uncertainties in $\rho$ reduce the system performance. Fortunately, $\rho \approx 1$ in the IR, although it is approximately 0.1 in the UV and visible regions of the spectrum. Using IR heterodyne detection, the ultimate sensitivity of this type of monitoring system can be improved. Besides the discrete frequency "on-off" absorption, discussed above, other modes of operation include: first derivative detection, second derivative detection and direct line scan with a tunable laser. For a good description of these methods, see E.D. Hinkley, 1976.
CHAPTER III

METEOROLOGICAL APPLICATIONS OF LASER SYSTEMS

III.1 Atmospheric temperature profiles

Laser techniques have the potential to become the most useful and precise means for obtaining unperturbed three dimensional measurements of temperature. Most developments have made use of Raman lidar methods, although recent developments are directed toward the use of the differential absorption scattering lidar and measuring techniques based on Doppler broadening.

The Raman lidar offers a single-ended method for instantaneous measurement of temperature profiles in the atmosphere. This is possible because Raman scattering signals provide a direct measure of the relative population distribution among the internal molecular modes; in thermal equilibrium these relative distributions correspond to the fundamental definition of temperature. Several Raman techniques can be used for remote temperature measurements; these are based on rotational or vibrational Raman scattering and employ different means for analyzing the spectra. The rotational Raman scattering methods include: analysis of line-by-line intensity profiles, comparison of the envelope shape of all the lines in an observed band, comparison of frequency shifts of the band peak intensity, and examination of the intensity ratio of selected spectral regions of the band using a monochromator or filters. For the vibrational Raman scattering method, in addition to those already mentioned measurements can be made of the intensity ratio between Stokes and anti-Stokes components, and also an examination can be made of the width of a specific Q-branch band profile (such as the ground state band, which provides a convenient estimate of rotational excitation temperature) when available. One advantage of the use of rotational scattering rather than the vibrational scattering is the relative strength of the total rotational spectrum as is evident from the differential scattering cross sections depicted in Tables I and II (Chapter I). Special care should be taken to reject the overlapping interference because the pure rotational spectra distribute much more closely to the excitation frequency than do vibrational spectra (see Figures 9 and 10 in Chapter I, and, for example, Dye Lasers, in Topics in Applied Physics (ed. Springer), 1973).

Among the possible rotational Raman scattering techniques, the examination of the intensity ratio of selected spectral regions is particularly attractive for single-ended measurements. This technique was proposed by Cooney (1972) and used by Salzman et al (1972).

The shape dependence of the envelope of the spectrum for three different temperatures is illustrated qualitatively in Figure 25. Comparison of the intensities of appropriately-chosen portions of the rotational Raman spectrum, backscattered from a given volume of the atmosphere, provides a measure of the temperature of that volume; this can be accomplished through the use of two optical interference filters \( F_1 \) and \( F_2 \). A signal representing either the difference or ratio of the two intensities seems to be much more sensitive to changes in the shape of the spectral envelope than signals which could be obtained by an analysis of line-by-
Figure 25
Shape changes of the envelope for pure rotational Raman spectra with temperature in the vicinity of the exciting frequency $V_0$.

line intensity profiles or by comparisons of the envelope shape of all the lines in the observed band or by comparisons of frequency shift of the band peak intensity. Furthermore, high temporal and spatial resolution can be obtained, and real time measurements are possible. Also since the rotational Raman spectra of the major atmospheric molecular species (e.g. $N_2$ and $O_2$) are customarily confined to a narrow wavelength region, they are, to a good approximation, affected equally by most extraneous and uncalibrated effects, such as the atmospheric transmittance and the response characteristics of the detection system. Accordingly, when an intensity ratio is taken along with the spectra, these unknown factors are cancelled and the result depends only on the rotational temperature to be measured.

Zuev (1979) approximated the temperature dependence of the ratio $R(T)$ of the backscattered intensities in two regions by the formula:

$$R(T) = \exp \left( \frac{\alpha}{T} + \beta \right)$$

Calculations were made for four positions of spectral intervals (with 4 cm$^{-1}$ shifts) in the S branch of the pure rotational Raman spectra of $N_2$ and $O_2$ molecules in the air, with their width and spectral separation being constant. The values obtained for $\alpha$ and $\beta$ are given in Table V along with their root mean square (r.m.s.) Computations were made at 5°K increments over the temperature region of 210°-350°K (Zuev, 1979).

Table V
Coefficients $\alpha$ and $\beta$ for S-branch Raman spectra of $N_2$ and $O_2$

<table>
<thead>
<tr>
<th>Interval position</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>r.m.s. deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>702.118</td>
<td>-1.0082</td>
<td>0.025</td>
</tr>
<tr>
<td>2</td>
<td>640.476</td>
<td>-0.9315</td>
<td>0.019</td>
</tr>
<tr>
<td>3</td>
<td>578.409</td>
<td>-0.8487</td>
<td>0.017</td>
</tr>
<tr>
<td>4</td>
<td>519.748</td>
<td>-0.7926</td>
<td>0.012</td>
</tr>
</tbody>
</table>

The results indicate that the assumed approximation formula is adequate (i.e. the maximum error in temperature measurements, due to this approximation, does not exceed 1°K in the temperature region 210°-350°K). Zuev pointed out that this formulation enables the calibration of a Raman lidar for temperature measurements.
only at two temperatures, which significantly simplifies the calibration procedure. A thorough study of the method by Petitpa (1977) resulted in the following practical recommendations: a ruby laser (\( \lambda = 694.3 \text{ nm} \)) could be used (for a smaller wavelength it becomes difficult to separate the Raman bands from the intense Rayleigh-Mie line) and to avoid interference due to absorption by water vapour, the anti-Stokes part of the spectrum is more convenient. The same study proposes optimal wavelengths for the filters \( F_1 \) and \( F_2 \). In Table VI the uncertainties in temperature due to noise in the Raman signals are estimated (second column) for a typical lidar installation (Petitpa, 1977).

Table VI

Estimated uncertainty in temperatures obtained using Raman signals

<table>
<thead>
<tr>
<th>Altitude (meters)</th>
<th>Density method</th>
<th>Raman Spectra</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.2°C</td>
<td>0.2°C</td>
</tr>
<tr>
<td>500</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>1000</td>
<td>2.0</td>
<td>2.1</td>
</tr>
<tr>
<td>2000</td>
<td>5.0</td>
<td>4.4</td>
</tr>
<tr>
<td>3000</td>
<td>10.0</td>
<td>6.8</td>
</tr>
</tbody>
</table>

The table indicates that precise measurements are only possible in the lower layers of the atmosphere. Gill (1979), using a ruby laser as transmitter and measuring the Raman backscattered radiation in two separate channels with centre wavelengths at 6916 and 6890 A, indicates, in a preliminary note, that the average absolute departure from the radiosonde temperature profile was only 0.85°C and that useful data has been obtained beyond 2 km; results obtained on 31 October 1977 are presented in Figure 26.

Figure 26
Comparison of lidar measurements with radiosonde measurements
In Gill's experiments the lidar profile has been normalised to the sonde at 1475 m. Gill believes that the implementation of improvements, suggested by the field trials, will further reduce the error at 2 km to the order of ± 0.5°C.

In addition to the above rotational Raman technique for absolute determination of temperature, Strauch et al (1971) found that the backscattered vibrational Raman signal from atmospheric N₂, correlated closely with temperature fluctuations. This method originates from the well known relation (ideal gas law):

\[
\frac{\Delta P(R)}{P(R)} \text{N}_2 = \left[ \frac{\Delta \rho(R)}{\rho(R)} \right] \text{N}_2 + \frac{\Delta T(R)}{T(R)}
\]  

(63)

where \( P(R) \text{N}_2 \) is the partial pressure, and \( \rho(R) \text{N}_2 \), the density of N₂ at a distance R; T is the absolute temperature. Assuming that for a fixed altitude the partial pressure of N₂ is constant for the duration of the measurements, one obtains:

\[
\frac{\Delta \rho(R)}{\rho(R)} = - \frac{\Delta T(R)}{T(R)}
\]

(64)

The signal received by a lidar system measuring the Raman backscattering from N₂ would indicate:

\[
\frac{\Delta R \text{N}_2(R)}{R \text{N}_2(R)} = - \frac{\Delta T(R)}{T(R)}
\]

(65)

where R is the backscattering Raman signal and is proportional to \( \rho \text{N}_2(R) \). Thus at any altitude where the partial pressure of N₂ is approximately constant the Raman backscattering provides a direct indication of temperature fluctuations. By measuring the atmospheric pressure at the laser site and assuming that the hydrostatic equation predicts pressure at greater heights, the technique can be extrapolated to measure temperature profiles. In a feasibility study, such Raman backscattering signals were compared with the temperature data obtained by thermistors mounted on a tower at a height of 30 meters. An example of the results (Strauch, 1971) is shown in Figures 27a and 27b.

![Figure 27 (a) & (b)](image)

Comparison of Raman backscattered intensity with temperature
Renault (1977), in an attempt to measure vertical temperature profiles using this method, came to the conclusion that although the influence of aerosols is not negligible, it would be possible to correct for it, if two lasers with different wave-length were used, together with an analysis of the Rayleigh-Mie signal from N₂; additional assumptions on the optical influence of aerosols are necessary. Uncertainties in the temperature resulting from noise in the Raman signal, are estimated and given in Table VI (column one).

Taking into account the estimations given in Table V both methods give acceptable results only over the first few hundred meters of the atmosphere and can be used for instance, for measurements of low-level inversions. As Raman back-scattering can be obtained from altitudes of up to 10 km (see Figure 21, Chapter II) investigations should probably be undertaken to enable a more practical use of this (relatively inexpensive) approach to vertical temperature profile measurements.

In addition, other developments are under way. For instance, the work of L. Lading et al (1979) leading to the design of an experimental setup for remote measurements of temperature on the basis of the Doppler broadening of the Rayleigh spectrum using a cavity-dumped argon laser as the light source; the major problem seems to be to find an efficient opto-electronic processor for the return signal, as this contains different components (narrow band aerosol scattered light, molecularly scattered light and broad-band skylight).

A different approach for measurements of temperature using lidar was proposed by Mason (1975), who showed that the thermal distribution of rotational states within a molecular absorption band of a gas can be probed, by means of lidar differential absorption techniques, to obtain measurements of the gas temperature. An expression was derived giving the temperature in terms only of constant line parameters and ratio's of the measured power returns from the probed region. In fact, a theoretical expression was derived giving the temperature as a function of the ratio of the differential cross sections at two different lines in the absorption spectrum. This ratio can be obtained using the differential absorption lidar technique. As a result, the temperature at any height in the atmosphere could be calculated from experimental data.

The elements of this lidar system include a laser source capable of simultaneous emission at three wavelengths and a receiver capable of independently resolving and detecting each wavelength. Since only ratios of the measured power of the returned signals are necessary some of the difficulties associated with absolute measurements are avoided. A further analysis of temperature measurements by triple wavelength lidar is given by Schwammer et al (1979).

A new dual wavelength lidar technique for the measurement of atmospheric temperature profiles has been developed by C. Korb and C. Weng (1979). The technique makes use of a lidar system in a differential absorption experiment with differential ranging. A highly sensitive temperature measurement is obtained by locating one wavelength on a high J-line (for Raman scattering) in the oxygen A band near 770 nm. A second reference wavelength located within 0.1 nm, is used to normalise the effects of atmospheric scattering and of continuum absorption common to both wavelengths. For these lines, the absorption has been calculated as a function of altitude and temperature; this set of data is then used to obtain the absolute temperature at a given altitude. Simulations show that accuracies better than 1°K can be obtained, with a vertical resolution as fine as 200 m, for altitudes up to 5 km. This technique should provide an order of magnitude increase in sensitivity over the triple wavelength technique.
III.2 Humidity profiles

Two laser techniques have been investigated for possible measurement of atmospheric water vapour profiles: Raman lidar and Differential Absorption Scattering Lidar. Interesting results have been obtained with both techniques; however, more attention has been directed to the second technique in recent years.

Raman scattering offers the possibility of the selective measurement of molecular concentrations; Cooney (1968) has carried out Raman lidar measurements of the major atmospheric constituents. More recently, several research groups have applied the Raman technique to the specific measurement of vertical humidity profiles (e.g. Cooney (1971), Melfi (1972), Strauch (1971) and Orszag (1977)).

The vertical profile of the water vapour mixing ratio can be obtained by comparison of the backscattered Raman signals from water vapour and nitrogen. Following the lidar equation the ratio of the two signals can be expressed by:

$$\frac{I_R(H_2O)}{I_R(N_2)} = \frac{N(H_2O)}{N(N_2)} \cdot \frac{T(\lambda_{H_2O}, R)}{T(\lambda_{N_2}, R)} \cdot k$$  (66)

where $\lambda_{H_2O}$ and $\lambda_{N_2}$ are the Raman wavelengths of water vapour and nitrogen respectively, and $k$ is a calibration constant. In addition to the unknown concentration $N(H_2O)$, the equation also contains the ratio of the unknown transmission functions ($T$) at the two wavelengths. This last ratio can be estimated for a standard atmosphere with visibilities ranging from 2 to 25 km; the calculated values lying between 1.06 and 1.2 for a range of 3 km, so that a lack of precision for this ratio has only a small influence on the value $\frac{N(H_2O)}{N(N_2)}$. Since mixing ratio of nitrogen is known over the range of altitudes which can be explored by the Raman lidar, the absolute value of the humidity can be obtained as a function of altitude.

A frequency doubled ruby laser operating in the UV region of the electromagnetic spectrum, ($\lambda = 347.1$ nm), appears to be one of the most convenient radiation sources. The factors influencing this choice include the available optical energy, the intensity of the backscattered light (taking into account the backscattering frequency dependence), the transmission of the atmosphere for the transmitted and backscattered light, the performance of optical filters and the quantum efficiency of photomultipliers. However, noise considerations almost limit the application to night time measurements. Background noise due to the sky is almost $10^5$ times higher during the day than at night for wavelengths greater than 300 nm. The corresponding noise is much higher than the Raman signals, as can be seen in Figure 28. Better conditions exist in the spectral interval 250 to 300 nm, where light absorption by the lower atmosphere is not excessive and where solar radiation is absorbed by the ozone layer. However, in practice, the problem is further complicated: the neodymium quadrupled laser ($\lambda = 265$ nm) is suitable, but its output efficiency is low (only 5%), aerosol fluorescence effects degrade the measurements and optical filtering becomes more difficult as the UV Raman spectrum is compressed due to the equal frequency shift.
An example of typical results is given in Figure 29 as obtained by Melfi (1972); the ground based lidar ratio data are compared with radiosonde data.

A frequency doubled beam of a Q-switched laser with an output power of 0.04J at 347.2 nm and a Newtonian receiving telescope of 40 cm diameter were employed to obtain this data. Cooney (1971) also measured vertical profiles of atmospheric absolute humidity with a frequency doubled ruby laser. The comparison with data obtained by radiosondes and helicopters, taken at essentially the same time...
and place, showed strong qualitative similarities; the relative accuracy was 10%, and the absolute accuracy was estimated to be 13%.

A direct comparison of the Raman backscattering intensity from atmospheric water vapour, using a pulsed N\textsubscript{2} laser (100 kW peak power at 337.1 nm) with a microwave refractometer was performed by Strauch (1972). The refractometer was located at the 30 m level of a meteorological tower and the laser beam passed approximately 1 meter from the microwave cavity. The relative Raman intensity is compared with the observed partial pressure of water vapour in Figure 30. The good agreement demonstrates the feasibility of remote measurements, not only of humidity as a function of position, but also of the fluctuations, and hence, the structure functions of atmospheric water vapour in the lower atmosphere.

![Figure 30](image)

Comparison of relative Raman backscattered intensity from H\textsubscript{2}O molecules with a standard humidity meter (Strauch, 1972)

More recently, results of similar experiments were obtained in France (Orszag, 1977); good results can be obtained up to altitudes of 1500 m as shown in Figure 31. However, the accuracy degrades with range.

![Figure 31](image)

Comparison of water vapour mixing ratios obtained by a Raman lidar and radiosondes (Orszag et al., 1979)
The method of lidar sounding using differential absorption by scattering is the most promising method for indirect sensing of the spatial humidity distribution in the atmosphere.

This method, in contrast to that based on the Raman scattering, allows the measurement of humidity to be made through the whole troposphere, where the basic water reserves are concentrated. A knowledge of the latter is important when discussing the problems of using lidars for practical meteorology. Most systems (Schotland, 1964, Zuev 1979, and Zhao Yan-Seng et al (1979)) are based on the absorption lines of H$_2$O in the visible part of the electro-magnetic spectrum close to the ruby laser wavelength as shown on Figure 3 in Chapter I. In general two ruby lasers are employed, one tuned on, or close to, the peak of a H$_2$O absorption line and one off the line. In most cases the ruby wavelength is tuned by changing the ruby crystal temperature in accordance with the expression:

$$\lambda = 694.325 + 0.008 (T_C - 20)$$  \hspace{1cm} (67)

where $T_C$ is the temperature of the ruby crystal in degrees celsius. DIAL lidars are also designed in which the ruby laser is operated in a double pulse, double wavelength mode, with an assembly of crystals installed in the cavity to change the wavelength from the first pulse to the second. In all systems both laser beams are emitted during a very short interval: less than 1 millisecond, so that the assumption that the atmosphere remains unchanged along the optical path remains valid.

The preliminary results obtained by the above-mentioned groups are very promising. Zuev (1979) reported success in obtaining a humidity distribution up to altitudes of 3 km.

The method is a powerful one, but also delicate, as the peak of the absorption line is influenced by the pressure and temperature conditions at each altitude. However, several research groups are now developing optimized systems, and one may expect that in the near future operational systems may become available for routine meteorological measurements.

III.3 Visibility

Horizontal visibility can be measured by human observers directly, or through the use of transmissometers and videometers, the operation of which is based on the scattering and absorption properties of the atmosphere. The determination of visibility using such local measurements are only representative for relative homogeneous atmospheres. The flexibility of lidars in sampling the atmosphere in different directions and at specific ranges offers possible advantages for assessing the visibility over extended remote paths especially above the surface. A careful measurement of the Slant Visual Range (SVR) may be important for safe and regular aircraft operations. Most recent lidar investigations have been aimed at providing such data.

The distance $r$ at which the apparent contrast $C_r$ between a source and its background has decreased to 5% of the value pertaining under ideal visibility conditions, $C_0$, is, by convention, taken to be the Meteorological Optical Range, $V_M$, and is usually quoted for a wavelength of 0.55 $\mu$m. It can be shown that, in a wide range of conditions:
\[ C = C_0 e^{-\sigma x} \]  
\[ V_M = \frac{1}{\sigma \ln 0.05} \approx \frac{3.00}{\sigma} \]  

This expression gives the relation between \( V_M \) and the extinction coefficient \( \sigma \); it represents the preferred approach for making instrumental determinations of visibility. The extinction coefficient may be expressed as a function of wavelength in the following form, if the predominant loss mechanism is by atmospheric scattering:

\[ \sigma(\lambda) = \frac{3.00}{V_M} \cdot \left[ \frac{0.55}{\lambda} \right]^q \]  

where \( q = 0.639 \frac{V_M^3}{M^4} \) for \( V_M \leq 7.8 \text{ km} \)

\[ q = 1.3 \text{ for average conditions} \]

The visual range of lights at night, \( V_L \), is a function of the intensity \( I \) of the light and \( E_t \), the threshold illumance detectable by the eye, according to the equation:

\[ V_L = \frac{1}{\sigma} \left( \ln(\frac{1}{E_t}) - 2 \ln V_L \right) \]  

The determination of \( \sigma \) as a function of range by lidar observations could open new methods for the determination of visibility. So far, two methods have been proposed and tested: Raman lidar and the classical Mie or Rayleigh lidar. The method of measuring the attenuation by Raman lidar was suggested by Melfi (1973). The Raman backscattered signal from oxygen or nitrogen is used. As the concentrations of these gases are reasonably constant, the backscattering coefficient can be determined by means of the standard atmosphere or by radiosonde measurements. The received signal then provides a measure of the two-way atmospheric transmittance. If the Raman wavelength does not differ much from the laser wavelength, the attenuation coefficient can be deduced together with the corresponding horizontal visibility. A comparison of the Raman lidar signal \((\Delta)\) from nitrogen with the signal which should be obtained in a perfect transparent atmosphere is shown in Figure 32; the corresponding horizontal visibility is shown in Figure 33.

The method is limited by the small Raman backscattering cross section, so that high power lasers are necessary and operation is limited mostly to night time operation in order to avoid background noise problems. A different approach for visibility determination involves obtaining the attenuation coefficient \( \sigma(x) \) from the return from a short-pulse, single-wavelength lidar, without any additional information. Two methods have been commonly investigated, the "ratio" method (Brown (1973); Lifsitz (1974)) and the "slope" method (Viezee and Uthe (1968); Collis et al (1970); Lifsitz (1974); Ruger (1976)). A discussion of the interpretation problem encountered in single-wavelength lidar transmissometers is given by R.H. Kohl (1978). The ratio method of determining \( \sigma(x) \) from the return signal from a short pulse lidar, arises from a derivation of the lidar equation in the form
appropriate for a homogeneous dispersion and seeks to obtain \( \sigma \) at \( r = r_i \) from:

\[
\sigma(r_i) = \frac{1}{2\Delta r_i} \ln \left( \frac{r_i^2 R(t_i)}{r_{i+1}^2 R(t_{i+1})} \right)
\]

where \( r_i = \frac{ct}{2} \); \( r_{i+1} = r_i + \Delta r_i \) and \( \Delta r_i \) is ideally a small differential; \( R(t) \) is the return signal at time \( t \). The slope method of determining the average \( \sigma(r) \) uses an \( S \) function defined as:

\[
S(r) = \ln \left( r^2 R(t) \right)
\]

where \( r = \frac{ct}{2} \) and seeks to obtain the average "\( \sigma(r) \)" from \( r_a \) to \( r = r_e \) from:

\[
\sigma_{ae} = -\frac{1}{2} \cdot \frac{\Delta S}{\Delta r}
\]

where \( \Delta S / \Delta r \) is the slope of the least-squares straight line fit to \( S(r) \) between \( r_a \) and \( r_e \). Both methods cease to be applicable when the atmosphere is inhomogeneous, and particularly when the density of scatterers increases with range. In these cases it is necessary to attempt other solutions for the lidar equation. Only very limited success has been reported due to the difficulties encountered.

Interesting results were reported by X.J. Zhou (1979), using a method in which the lidar equation is solved, based on an assumption of linear relationship between the attenuation coefficient and the backscattering coefficient.

Since 1972, the relation between visibility \( R(\text{km}) \) and the attenuation co-
efficient $\sigma$ (km$^{-1}$) has been exhaustively examined using a ruby laser in China. The results obtained are shown in Figure 34 and a relation is derived for the ruby laser:

$$\nu = \frac{3.4}{\sigma} \text{ (km)}$$

(75)

It is noticed that the atmosphere departs from this formula for a visibility lower than 1 km; this is ascribed to multiple scattering. For this reason, a lidar equation taking into account the double scattering effect and a method for determination visibility under this condition has been proposed (Lü, Da-Ren, 1979).

![Figure 34](image)

**Figure 34**
Relation between atmospheric horizontal visibility and extinction coefficient (Zhou, 1979)

III.4 Observation of clouds

In recent years considerable attention has been paid to the observation of clouds by lasers. The measurements can be divided into measurements of the cloud-base (laser ceilometers) and cloud observations in general.

III.4.1 Laser ceilometer

The measurement of cloud-base height by lidar is very straightforward, particularly when the lower surface of the cloud is well defined. In this case, the rapid increase of signal that marks the backscattered return from the cloud-base can be readily distinguished and by measuring the time taken for a laser pulse to travel from the transmitter to the cloud-base and back to the receiver the height of the cloud-base is determined. The technique can be considered as almost operational and already several laser ceilometers are commercially available and in use. In general, low power lasers with a high pulse repetition frequency are used as for instance the gallium-arsenide laser which operates in the near infra-red. Such
lasers will not cause eye damage and comply with local standard practices for the safe use of lasers. However, for low powered lasers the backscattered signal from clouds is very small; in order to improve the signal-to-noise ratio, the return from a number of laser transmissions is commonly integrated to achieve adequate average signal levels. In addition, digital signal processing techniques are used to determine the cloud-base height and to reject noise. On Figure 35 a typical chart recording of the cloud-base height is shown (Winstanley, 1977).

These results were obtained using a GaAs laser (λ = 900 nm) with peak output power of 70 W, pulse length of 130 ns and pulse repetition frequency of 600 Hz; the cloud-base height accuracy is said to be ± 7.5 meters. A comparison between a standard cloud-base recorder (CBR) of the Meteorological Office (U.K.) and a laser ceilometer was carried out in various weather conditions, using the same laser ceilometer as above. The results are depicted in Figure 36.

While such systems perform well with well-defined cloud bases (as is also the case with conventional optical ceilometers) they do not fully exploit the lidar’s capability for providing additional information on ragged or diffuse cloud bases, and especially those with patches of cloud below. Such conditions are characteristic of low clouds, especially when the visibility at the surface is reduced by mist or fog that merges with the cloud layer aloft. Using a graphical

Figure 35
Typical chart recording of cloud-base

Figure 36
Laser ceilometer performance in precipitation and fog conditions
data presentation, lidar can provide unique information on such conditions.

III.4.2 Cloud observations in general

The observation of clouds in general and measurements of cloud thickness or of cloud top height is also readily accomplished by lidar. Even very tenuous cirrus clouds which are invisible to the eye can be detected, their structure and shape can be mapped and, within useful limits, their water content can be evaluated. An example is given in Figures 37 and 38 which show the intensity-modulated intensity as a function of height (Collis, 1976).

It is more difficult to obtain quantitative data such as the scattering coefficient, attenuation coefficient, shape and distribution of droplets, water content, etc. However, such measurements are possible through the use of complex systems making several measurements simultaneously, and in particular by lidars with different wavelengths, by bistatic lidars making measurements in different directions, by making hypotheses concerning the optical properties of the medium and by complex mathematical data reduction methods (e.g. inversion, successive approximations, etc.) As an example, Figure 39 shows the results of Platt (1974); cirrus cloud and middle altitude clouds were investigated by means of a ruby laser in conjunction with an IR radiometer (10 – 12 micron band). The backscattering coefficient in the clouds was calculated in successive steps. Such results are very useful for studying the
internal structure of a cloud and its relationship to radiation transfer.

By examining theoretically the polarization ratio, the direction of polarization, the degree of polarization, the ellipticity and the parallel and perpendicular polarization of scattered laser radiation from hydrometeors, Harris (1971) has shown that ice and water can be discriminated in clouds.

The potential of the use of the depolarization of lidar return signals for discrimination between water, ice and mixed phases in clouds was recognized by Schotland et al (1971) who observed appreciable depolarization by ice crystals of a linearly polarized lidar beam. Although depolarization ratios approaching unity have been observed in some ice clouds, they are typically about 0.4. Sassen (1974) has shown that the depolarization ratio is a function of the ratio of ice crystal concentration to water droplet concentration. The theoretical value of the depolarization ratio for light backscattered from water spheres is zero, while the measured value near the base of water droplet clouds is about 0.03 (Sassen, 1974). However, for any appreciable cloud thickness, the depolarization ratio is found to increase almost linearly with increasing cloud penetration, reaching values of 0.4 - 0.5 at a penetration depth of about 150 m (Pal and Carswell, 1973); this effect is due to multiple scattering of radiation in the lidar beam, although theoretical studies have as yet been unable to simulate the measured figures. Derr (1976) investigated the depolarization of backscattered radiation by a cumulonimbus cloud and its virga. The results obtained show that the lower part of the cloud is composed of ice crystals and that the virga are composed of oriented crystals (depolarization ratio > 1) which indicates the absence of turbulence. Another example is given by Platt (1977) in which measurements by a monostatic lidar of linear depolarization ratios and backscattering coefficients in an altostratus cloud revealed a horizontally layered structure; three different layers were observed.

The results of angular scattering and depolarization studies of water, ice and mixed phase clouds by Sassen and Liou (1979, a, b) have demonstrated that bistatic lidar polarization measurements would be quite useful for discriminating cloud composition; experimental angular scattering (left) and depolarization (right) patterns are given in Figure 40; the scattering angle is $\theta$.

![Figure 40](image)

A comparison of the angular scattering (left) and depolarization (right) pattern of pure water and ice and mixing phase clouds obtained with the use of vertically polarized incident laser light.

Sassen suggests that measurements obtained at $\theta \approx 100^\circ$, where ice crystal side scattering and depolarization are both relatively great, and at $\theta \approx 140^\circ$ where cloud droplets produce a strong cloudbow and there is little polarization induced by multiple scattering, could be used to determine the relative ice and
water content in clouds where both types of particles are present.

III.5 Atmospheric motions

Two general approaches are followed for measuring the wind and its profile by lidar techniques; the first is based upon the observation of the change with time of the location of aerosols embedded in the air, while the second makes use of the Doppler shift which occurs when the laser radiation is backscattered from air molecules and aerosols. In recent years the Doppler method has been more favoured.

In the first approach several geometric configurations have been investigated. One of these consists in firing the lidar repetitively in a fixed direction and computing the average backscattering as a function of range during an observation period. This average is then combined with the individual observations, in order to obtain fractional deviation profiles of the backscattered signal. Lag cross correlation is computed between successive profiles for each range element to obtain the radial wind for that range. An example of this method has been given by Elorante (1974). It is apparent that the technique should work best under conditions of moderate atmosphere stability as this situation will tend to establish long lived aerosol inhomogeneities. The uncertainty associated with such a wind determination appears to be of order of 1 m/sec.

An interesting demonstration of the use of inhomogeneities in a clear atmosphere to measure air flow, has been reported by Derr and Little (1970); a CW-laser beam was split to illuminate two divergent paths, these paths were intersected by two separate receiver beams in such a way that returns were received from two common volumes at the same altitude by the respective receivers. The transverse wind was then determined from the time required for an aerosol inhomogeneity to be advected from one common volume to the next. This time is determined by lag correlation of the power measured by one receiver with that of the other. A typical output of the two receivers is shown in Figure 41.

Figure 41
Typical output of two receivers:
laser A++, 2 W at 488 nm, cell separation: 4 m

The height is determined by range gating. The wind speed in the cross correlation method is determined by small fluctuations on the return signal, which places severe restrictions on the tolerable power variations of the laser. The chief limitations for its use in tropospheric wind sensing are the background noise, noise of the intervening atmosphere and detector noise. As a consequence the operational range is limited to a few kilometers. Also, in order to accommodate winds from any direction, a conical scanning arrangement was proposed.
A somewhat different approach was recently adopted by Lading (1978), that of a time-of-flight laser anemometer. Two volumes in space are illuminated by two beams from an argon laser ($\lambda = 488$ nm; output power, 0.5 to 1.0 W); the focal diameters and separation of the beams, which are proportional to range, were made 0.1 mm and 1 mm, respectively at a range of 10 m. The receiver system collects the light from each beam, directing it to separate photomultipliers, so that the times of flight of individual aerosol particles between the two beams can be inferred; in this manner the velocity component perpendicular to the optical axis can be measured with a good spatial and temporal resolution. Examples of some of the first measurements and a comparison with simultaneous wind measurements by an anemometer are provided in Figure 42.

Another approach makes use of the Doppler principle to determine the relative velocity of an atmospheric volume from which laser energy is backscattered. The Doppler frequency shift $\Delta f$ is related to the radial velocity $V$ as follows:

$$\Delta f = \frac{2V}{\lambda}$$

(76)

The mean wind of the volume determines the mean Doppler shift, but turbulence and thermally induced molecular and particle motions produce a spectral broadening of the backscattered radiation. An example of the Doppler shift of backscattered light from a $\lambda^{+}$ laser is given in Figure 43 in which the ordinate is spectral intensity (arbitrary scale) and the abscissa is frequency in cm$^{-1}$. A homogeneous
suspension of droplets is assumed and $\gamma_0$ is the transmitter frequency.

![Figure 43](image)

Figure 43
Backscattered radiation showing the Doppler shift

The broad band (a) arises from molecular scattering (for a temperature of 25°C this bandwidth (1) is $9.4 \times 10^{-2} \text{ cm}^{-1}$), while the narrow band (b) typical of particulate scattering, having a width (3) of about $10^{-6} \text{ cm}^{-1}$. Doppler winds are derived from observation of the centre of the aerosol power spectrum. For a radial wind of 10 m/sec the Doppler shift (2) is about $1.4 \times 10^{-3} \text{ cm}^{-1}$.

The detection and interpretation of such Doppler returns present considerable difficulty. Although most progress has been made in applying the concept at very short ranges (the so-called velocimetry techniques in wind tunnels, test chambers, etc.), some encouraging experimental results have been attained in atmospheric indirect probing applications.

Various techniques have been utilised for detecting the frequency shift in the energy backscattered by particles in the clear air or even by the gaseous atmosphere using CW-lasers (argon or CO$_2$) or pulsed coherent CO$_2$ lasers.

In one of these, the wavelength of the backscattered radiation is measured directly by means of a confocal spherical Fabry-Perot interferometer; in the system developed by Benedetti-Michelangeli et al (1972) the emitted frequency was controlled to within $\pm 50 \text{ MHz}$. A statistical comparison of the frequency spectrum of the returned radiation with that which was transmitted enabled the authors to determine the radial wind to claimed accuracy of 0.27 m/sec at a range of 500 m. This method is not strongly influenced by atmospheric turbulence and the limitations on the aperture size are not severe.

Detection of the Doppler shift can also be made by means of a coherent heterodyne or homodyne method, in which the backscattered signal is compared with the signal from a local oscillator. The constraint that the backscattered radiation be nearly spatially coherent with the original laser radiation at the photodetector, imposes limitations on the applications of this approach for measurements at meteorologically significant ranges (R > 100 m), since atmospheric turbulence severely distorts the phase surfaces of the transmitted and scattered radiation so that the effective area of the receiver suitable for photomixing is limited; this area ranges from $0.1 \text{ m}^2$ for visible radiation to $1 \text{ m}^2$ at 10.6 $\mu\text{m}$. Even though the backscatter
cross section decreases strongly with wavelength (varies as \( \frac{1}{\lambda^N}; 1 \leq N \leq 3 \)), the increase in coherence area and efficiency of photonmixing at longer wavelengths, as well as the availability of good IR sources, indicates that this wavelength region is more promising than others.

Both continuous wave (CW) and pulsed CO\(_2\) coherent lidar systems have achieved useful indirect wind measurements (Huffaker, 1974-1975). Range information is obtained in the CW system by using an optical depth or focus effect which limits its useful range to < 1 km for most optical configurations, while the range resolution for the CO\(_2\) pulsed system is determined by the pulse length. The winds provided by the CW CO\(_2\) lidar systems have compared well with those from other types of wind sensing systems and a CW CO\(_2\) lidar system has been used experimentally for tracking and measuring the properties of aircraft trailing vortices at airports (Huffaker, 1975). A comparison of anemometer and CW CO\(_2\) lidar sensed wind velocity data is given in Figure 44 (M.J. Post et al, 1978).

The CW CO\(_2\) Doppler lidar had a transmitted power of 3 W, a beam diameter (when focused) at 150 m of 3 cm; the sampling volume was centred at a short range of 147 m, and roughly cylindrical, 20 m long and 3 cm in diameter, and centred beneath a prop-vane anemometer. The agreement in the experiment was, in general, excellent.

A limitation of the CW Doppler lidar for indirect sensing is that it depends on natural aerosols for the scattered return, so that in perfectly clear air, no return would be obtained; however, Shwiesow (1976) estimated that aerosol concentrations typical for a clear day in rural areas with visibility in excess of 50 km are already sufficient. The other limitation is the useful range; because the length of the volume resolved by the focused lidar beam increases as the square of range, the practical maximum range of such lidar is limited to roughly 500 m. In addition, snowfall, rain or dense fog will limit the useful range by beam attenuation.

Pulsed CO\(_2\) lasers are not limited in range in this way and can be used
over very large distances. The results of an analysis of the system performance by R.M. Huffaker (1977) are shown in Figure 45, as the performance expected for the tropical model atmosphere and the listed system parameters. These results indicate the feasibility of developing a long range (20 km) pulse coherent lidar for measuring atmospheric wind velocity.

**Figure 45**
Performance of ground based pulsed coherent CO₂ lidar for various atmospheric propagation paths (Huffaker, 1977)
The meteorological application of the Doppler lidars described above is limited in that they measure only the line-of-sight wind component. However, this limitation may be eliminated by operating the laser in a VAD (Velocity Azimuth Display) mode or by using systems employing different laser beams. Shwiesow (1977) describes a concept and the results obtained using a signal processing technique for Doppler velocity measurements at ranges of at least 30 meters. The technique consists in illuminating a region of the atmosphere with two coherent focused beams converging at a small angle and intersecting at a common focus. A schematic diagram of the apparatus used is given in Figures 46(a) and 46(b).

A scatterer located in the focal volume simultaneously scatters radiation back along each transmitted beam into the other. If the scatterer is in motion, the frequency of the scattered radiation will in general be different in each direction.

At the single detector, the combined signal from the four scattering volumes is separated using a relatively powerful optical oscillator in a homodyne or heterodyne mode. For a scatterer moving in a direction at an angle $\theta$ to the lidar axis (bisector of the transmitted beam) and an incident beam convergence angle of $\phi$ between beams as shown in Figure 46(b), three Doppler frequency shifts can be determined, allowing the calculation of the wind vector. Shwiesow thus concluded that it is possible to measure simultaneously all three velocity components of a target at a distant point in the flow field, both transverse to and along the optical line of sight, by using a fully coherent optical heterodyne technique; the measurements are made effectively from a single location. The practical limits of the technique, with respect to the statistics of signal distribution in time and frequency and with respect to minimum convergence angle, remain to be determined.

Eberhard and Shotland (1979) discussed a dual-frequency Doppler lidar, using a new method to circumvent the problem of atmospheric scintillation which degrades the requisite coherence of the laser system. In this technique, the laser output is modulated to create two superimposed beams of differing frequency ($\Delta f = 10^9$ Hz) that are coherent relative to each other. Aerosols, moving with the air, backscatter energy from both beams with a Doppler shift; a nonimaging optical receiver incorporating a wide bandwidth photomultiplier detector is used. The difference in the Doppler frequency shifts from the two beams is extracted to yield the wind velocity normal to the composite wavefront of the travelling beams.

The application of scintillation theory to this method shows that the technique is relatively insensitive to optical turbulence since the frequency separation of the beams is small compared to the optical frequency so that the beams travel a nearly common path. By crossing the two beams at a small angle ($\sim 10^{-5}$ rad) the component of wind velocity at a chosen skew angle can be obtained. In principle, this crossed beam technique can be used for the indirect measurement of the three-dimensional wind velocity at a point in space remote from a single instrument site. Such a system, based upon an acousto-optically modulated argon laser, has been constructed and operated; it uses a microcomputer to provide real-time wind measurements.
Test results showed its range capability is modest (of the order of 50 m); however, the range could be markedly increased with existing technology. Both the coaxial and crossed-beam techniques were successfully demonstrated.

A laser wind sensor measuring the path averaged crosswind was developed at the Wave Propagation Laboratory (Clifford, 1975); the general configuration of the system is shown in Figure 47.

![Figure 47](Image)

General arrangement used to measure the average component of the wind across a laser beam, parallel to the spacing of two detectors

A laser beam, which is made divergent to approximate a point light source, illuminates two detectors. The temperature irregularities along the optical path produce irradiance fluctuations at each of the detectors. As the wind advects these irregularities across the laser beam, the resultant irradiance fluctuations propagate from one detector to the other. By time-lag correlation of the signals observed at the two detectors, a normalized covariance function is obtained; by computing the slope of this function at zero time lag, wind speed information is obtained. A typical laser wind sensor record is compared with conventional anemometer measurements in Figure 48; agreement between the two curves is excellent, demonstrating the feasibility of using the laser wind sensor to measure winds, and especially when a spatially-averaged value is desirable, as in determining the cross-
wind along airport runways, or the flow of pollutants through a region. Similarly, a triangular array of such sensors could be used to measure a spatially averaged divergence of the wind field.

III.6 Measurement of aerosols

III.6.1 Aerosol mapping in the boundary layer

In the same way that lidar may be used to detect cloud layers, by observing the backscattering, it may also be used to detect the suspended particles present in relatively clear air and to map certain structural features. For example, it is well known that aerosol concentrations are influenced by the thermal stability of the atmosphere; numerous authors have reported detecting the height of inversion layers by taking note of step discontinuities in the lidar returns. In mapping applications, attenuation and absorption are typically assumed to be so small that the lidar transmission $T(R)$ in the lidar equation, may be approximated as unity over ranges of a few kilometers. This allows the lidar response to be considered as being only proportional to backscatter and inversely proportional to the range squared. Range compensation of a return signal then yields a signal which provides a direct measure of atmospheric backscatter. A classical example (Uthe, 1972) is shown in the intensity display in Figure 49; a height-time sequence of the atmospheric condition at a location in downtown St. Louis (U.S.A.) is depicted during the course of a typical summer's day. At 0730, stratus cloud layers are revealed at about 2.3, 2.8 and 3.8 km and high layers of stratified haze appear below the lowest cloud layer. The stratus layers dissipate later, while surface level particulates are carried higher and higher by convection until the atmosphere is filled with haze up to about 2.3 km by 1600.

Such a display shows how lidar observations can be used to delineate the depth of the mixing layer and to establish the height of inversions. Another example is given in Figure 50, in which the boundary layer height measured by lidar...
is compared with that predicted by an inversion rise model developed by Zeeman and Tennekes (1977); the observations were made 22–23 June, 1978 at Argonne (U.S.A.) by R. Boers (1979). Other mapping applications include the tracing of the convectively induced flow of aerosols up mountain slopes, the detection of wave motions, etc.

![Figure 50](image)

**Figure 50**
Comparison of lidar measured boundary layer heights and those predicted by a Zeeman-Tennekes model (Boers, 1979)

III.6.2 Stratospheric measurements

An important factor in the balance of the global radiation budget is the presence of a layer of increased aerosol particulate concentration, typically several kilometers thick and centered near 20 km in altitude; the particles are mainly sulfates. The characteristics of this layer are strongly influenced by major volcanic eruptions. Lidar observations have made one of their most extensive and best documented contributions by making available a good detailed knowledge of this layer, beginning with the pioneering measurements of Fiocco (1964).

The vertical profile of the received lidar signal resulting from elastic backscattering by stratospheric gases and particles is compared to the signal profile that would have resulted from the gas phase of the stratosphere alone. The result obtained from this comparison is a vertical profile of a quantity termed the "scattering ratio" defined as:

\[
R = \frac{\beta_p(z) + \beta_g(z)}{\beta_g(z)}
\]

(77)

where \( \beta_p(z) \) and \( \beta_g(z) \) are respectively the elastic particulate and molecular volume backscattering coefficients at altitude \( z \). The scattering ratio is commonly normalized to unity at the level of minimum aerosol concentration above the tropopause. Scattering ratios in excess of unity can be used to indicate the presence, vertical extent and temporal and spatial variability of particulate scattering layers. In this application, lidar observations provide a useful means of observing the variable structure and optical density of the stratospheric aerosol layer, with a coverage in space and time that would be extremely expensive to achieve with direct
sensors. Lidar observations are used extensively to probe stratospheric aerosol layers. As an example of data obtained, Figure 5.1(a) gives the average seasonal lidar profile (right side) for summer 1978 and winter 1978-79 compared with the stratospheric temperature (left side) in the same periods; the average background lidar return and the range of standard deviation for 22 observations is shown in Figure 5.1(b) (Hamill et al, 1979).

Figure 5.1(a)
Average stratosphere aerosol lidar profiles (right side) compared with the temperature profile (left side) (Hamill, 1979)

Figure 5.1(b)
Stratospheric aerosol profile and standard deviation for 22 observations (Hamill, 1979)
III.6.3 Aerosol physical properties

In addition to aerosol mapping, the measurement of the properties of the atmospheric particulates (i.e. shape distribution, size distribution, number per unit volume and their composition) is also desirable. In general this goal is somewhat elusive, since an infinity of independent measurements could be required; also it would be necessary to vary the characteristics of the lidar in such a way that independent data are measured in the presence of noise. The Mie scattering intensity for a sphere is dependent on the radius of the particle, $a$, the index of refraction, $m$, the angle of observation, $\theta$, the wavelength of the radiation, $\lambda$, and the polarization, $e$, that is $I = I(a, m, \theta, \lambda, e)$.

The radius and the index of refraction are properties of the particle but the angle of observation and the wavelength of the radiation are to some extent at the disposal of the experimenter; polarization is measurable. As a consequence, only in the special cases when the number of parameters describing the particulates is small, can the characteristics be obtained, and then only if a sufficient quantity of statistically independent data has been obtained. Thus, by a multiparameter approach it may be possible to obtain important information about the characteristics of some atmospheric particulates. Multiple wavelength, bistatic lidars combined with polarization measurements potentially could provide information on aerosol properties, but the feasibility of successful measurements has not been demonstrated.

III.7 Atmospheric constituents

The indirect measurement of the concentrations of atmospheric constituents has been investigated using classical lidars, Raman lidars and differential absorption scattering lidars; the last mentioned technique seems to offer the best possibility of success. Although most efforts in this field have been directed into the remote sensing of pollutant concentrations the techniques can be used for any atmospheric constituent, and in particular ozone, both in the troposphere and stratosphere. A summary of recent trends in this application of laser investigations of the atmosphere is provided below.

III.7.1 Tropospheric measurements of ozone

Raman backscattering of laser radiation from the major components of the atmosphere was first observed by Leonard (1967); he detected the Raman scattering signal from atmospheric $O_2$ and $N_2$ molecules using a pulsed $N_2$ gas laser having a peak power of $50 - 100$ kW and wavelength $337.1$ nm. The possibility of using Raman lidar for water vapour measurements was already discussed in section III.2. As an example of pollutant monitoring, Melfi (1973) measured the Raman scattering by $SO_2$ molecules in a plume originating at the stack of a coal-burning electric power plant; the observed relation between the apparent $SO_2$ signal count and the generating plant power output is given in Figure 52. The accuracy and sensitivity of Raman lidars is not sufficient to observe the background air pollution levels measured by WMO.

The theoretical minimum for detectable concentrations listed in Table IV (Chapter II) for a range resolution of $100$ m, indicate that the differential absorption technique is the most promising of the remote spectroscopic techniques for determining range resolved trace gas profiles at typical ambient concentrations. Moreover, if range resolution is not required, average concentrations can be measured.
over an extended path by using long path absorption techniques with artificial or topographical reflectors and quite modest laser pulse energy.

Rothe et al (1974) reported the first application of this technique for the measurements of ambient atmospheric NO₂. Actual application of the differential absorption technique to detection of trace gases does not yet match the predicted potential; however, operational systems may become available in future. The application of the differential absorption lidar technique to the indirect sensing of water vapour has been discussed in section III.2; again, most investigations have been aimed at the detection of atmospheric pollutants in the lower layers of the atmosphere. Recently, however, several research groups have developed new techniques in order to measure atmospheric constituents, and in particular ozone. A summary is given of papers presented at the 9th International Laser Radar Conference (July 1979, Munich, FRG) in order to provide a knowledge of the possibilities as of 1979.

Baumer et al developed a mobile, computer-controlled differential absorption lidar equipped with a multi-gas TEA laser, which is capable of measuring the three dimensional distribution of a variety of pollutants and of water vapour. The R(20) and R(18) lines of the 00°1-10°0 transitions of the CO₂ laser were used to study the extension of the water vapour beyond the visible plume of a power plant cooling tower, as a function of different wind directions. Kelley et al developed a system incorporating a high repetition rate CO₂ laser for operation in the 9.5-10.5 and 4.5-5.5 μm region (the latter by frequency doubling). Repetition frequencies range up to 500 Hz and an average power of several watts (doubling efficiency is 20-30%) is required to cover the range of 0 to 2.5 km. Operation at λ = 9.5-10.5 μm allowed the detection of effluents and atmospheric species such as C₂H₄, H₂O and CO₂, while frequency doubling extended the capability for detection of ambient species to the observation of minor molecular constituents. Preliminary measurements indicated that small absorption signal changes (< 1%) should be observable under conditions of moderate background extinction.

Artemov, et al described a laser system using two actively stabilised CO₂ lasers to permit the use of any pair of generated frequencies, which may, in turn, be switched by means of a chopper to diminish the influence of atmospheric turbu-
lence. The use of a diffuse reflecting surface diminishes the accuracy required in making adjustments to the optical system. For measuring ozone the sensitivity is 5 ppb along a path of 500 m.

The first measurements by Chanin et al. of vertical profiles of tropospheric and stratospheric ozone were limited to the 15 - 25 km altitude. In the years 1978-1979, using a Rhodamine 6G dye laser and differential absorption lidar, these measurements were extended downward through the troposphere to ground level. The large dynamic range of the signal requires the use of successive analogue sampling and pulse counting techniques, while the natural variability of low altitude aerosols requires either the simultaneous emission of two wavelengths or rapidly switching between them. The use of lidar to study the creation and dissipation of ozone near the ground and the vertical transfer of ozone at the tropopause have been shown to be feasible.

Asai reported range-resolved measurements of ozone in ambient atmosphere using a grating-tuned TEA CO₂ pulse laser with a pulse energy of 5.5 Joules and a 30 cm receiving mirror; the laser lines were electrically tuned using a piezoelectric transducer (the laser lines used were: P(14) in the (00°1-00°2) band as on-resonance and P(16) in the (00°1-02°0) band as off-resonance). The concentrations of ozone were measured from 0.5 km up to 2 km with a range resolution of 300 m, with a standard deviation of about ±15 ppb at 0.5 km and about ±40 ppb at 1.5 km over a period of 30 minutes. During daytime in the summer, when the photochemical smog was developed (summer, daytime), the measured values agreed well with those obtained by point monitors at the ground surface. At night, a concentration of 20-40 ppb was indirectly measured, compared to an in situ measurement of 0-5 ppb. In the ambient atmosphere the effect of the absorption of H₂O and CO₂ must be subtracted from the measured values; this effect is equivalent to that of an ozone concentration of 12-13 ppb.

III.7.2 Stratospheric measurements of ozone

Above 50 km, particulate material is a rarity, and it may be possible, with high performance lidar systems, to observe the backscattering from the gaseous atmosphere with sufficient sensitivity to make a density determination. Such a lidar (output power 10J, receiver area 10 m²) was used by Kent et al. (1971) to provide relative density measurements with an estimated accuracy of about 1% at 70 km and 10% at 90 km for periods of about 30 minutes. Although other techniques are available (rocket observations), these interesting results demonstrate the possible value of lidar for making such observations on a continuous and consistent basis.

The use of resonant elastic scattering has been applied largely to observations of the upper atmosphere where it is not quenched by molecular collisions. The most common application has been for the ground-based observation of the layer of free atomic sodium near 90 km; numerous resonance scattering observations of this layer have been reported. For example, Hake (1972) provided the vertical profile of the received scattered lidar signal (Figure 53) indicating the presence of an atomic sodium layer between 85 km and 100 km; a tunable dye-laser radar was used.
Vertical profile of received resonantly scattered lidar signal showing presence of an atomic sodium layer between 85 and 100 km.

Figure 53
CHAPTER IV
GENERAL CONSIDERATIONS

IV.1 General remarks

In the preceding chapters it has been demonstrated that the application of lasers for meteorological observation offers several possibilities which cannot be supplied by in situ sensors; the most important advantages are the possibilities of making three dimensional measurements using a single ground based system, and of making continuous measurements.

At the present time most systems which have been developed are observing the lowest layers of the atmosphere; it is anticipated that in the future this range could possibly be extended to the whole troposphere. However to extend this range the use of high power lasers would be desirable, but eye safety considerations could prevent their use. On the other hand, several new developments operate more and more in the non-visible region of the electromagnetic spectrum, where the eye safety problem is not so severe.

Many possible techniques and methods have yet to be worked out; thus, many feasibility studies and new developments are expected in the next few years. Also, existing systems are optimized using new technology, although many desired technological means remain to be developed, and when they would become available it would take some years before they would be fully integrated into an operational system. Also, detailed theoretical studies of the interaction of laser radiation with the atmosphere are required. It is not yet clear if laser systems would be practical for many of the possible uses, because of the high cost and limitations of the technology.

Most lidar systems are complex and highly sophisticated, requiring specialised personnel for development, maintenance and operation; most developments have been achieved in specialised research institutes or university laboratories, although operational systems for use by Weather Services are expected to be available in the near future. An exception to this state of affairs is perhaps the laser ceilometer which is already in operational use, although all the possibilities are not yet fully exploited.

Much progress has been made in the development of lidar systems for aerosol mapping, cloud height observation, vertical profiles of water vapour and short range visibility. Some progress has been achieved in temperature and vertical profiles of wind, atmospheric composition and cloud structure. Although some time will pass before operational lidars will be available for routine use in meteorological investigations, it is essential that solutions be found soon for the problems of calibration of lidars and the problems related to eye-safety.

IV.2 Laser safety considerations

An important consideration in evaluating the practicality of using remote
sensing laser systems in meteorology is the potential eye-safety problem. Although direct axial viewing provides the most danger, specular reflections are also a risk to eye-safety, so that considerable care must be exercised in the use of laser systems. The amount of danger for eye-safety is a function of the laser wavelength because of the wavelength-dependent optical properties of the eye.

The most sensitive region is the visible region 0.4-0.7 \( \mu \text{m} \) since both the cornea aqueous humour and the lens transmit this radiation to the sensitive retina area. Taking into account the focusing effect of the pupil in concentrating the power received by a factor of \( 10^6 \), one obtains, even for a power density of \( \text{mW/cm}^2 \) incident on the pupil, high power densities of \( \text{kW/cm}^2 \) on the retina. Such high power densities can cause severe damage to the retina and the fovea resulting in loss of visual acuity.

In the UV region, the radiation below 0.4 \( \mu \text{m} \) is absorbed by the lens, and below 0.315 \( \mu \text{m} \) it is absorbed by the cornea, so that UV hazards are mostly limited to these parts of the eye; this radiation is absorbed over a larger area than is the focused visible light on the retina, so the power density is not so high. Exposure to excessive UV results in inflammation of the cornea, conjunctivitis at the shorter wavelengths, and cataract formation at the longer wavelengths. In the IR region, up to 1.4 \( \mu \text{m} \), the ocular transmission is less than that of the visible and varies with wavelength. From 1.4 to 1.9 \( \mu \text{m} \) essentially all radiation is absorbed by the cornea and the aqueous humour. Beyond 1.9 \( \mu \text{m} \) all the radiation is absorbed by the cornea alone. The absorbed energy can be conducted to the interior of the eye, raising the temperature of the lens and resulting in the formation of cataracts.

In some countries performance standards for laser products have been proposed or adopted in order to minimize the hazards. Such standards will have an impact on the choice of laser systems for operational use in remote sensing applications. The proposed standards are somewhat complex, but may be summarized in terms of a Maximum Permissible Exposure (MPE) which varies with the laser emission duration. As an example the following values are for pulse lengths of about 0.1 \( \mu \text{s} \) (U.S.A.). It should be noted that the discontinuities in the regions near 4000 Å and 1.3 \( \mu \text{m} \) should be clarified before the standards are promulgated.

**Table VII**

Laser system eye-safety proposals in terms of maximum permissible exposure (M.P.E.)

<table>
<thead>
<tr>
<th>Wavelength region</th>
<th>M.P.E.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visible</td>
<td>( 4.10^{-7} \text{ J cm}^2 )</td>
</tr>
<tr>
<td>IR 1.06 - 1.04 ( \mu \text{m} )</td>
<td>( 2.10^{-6} )</td>
</tr>
<tr>
<td>1.4 - 13 ( \mu \text{m} )</td>
<td>( 1.55^{-4} )</td>
</tr>
<tr>
<td>UV 4000 Å</td>
<td>( 1.6 \times 10^{-2} )</td>
</tr>
<tr>
<td>3020 Å</td>
<td>( 4.8 \times 10^{-5} )</td>
</tr>
</tbody>
</table>
Additional security regulations should be applied to minimize the risk that the laser beam could inadvertently be directed at people on or in buildings or at people in an overflying aircraft. Moreover the danger may be increased by atmospheric turbulence effects which can cause intermittent local focusing of the energy beam. The MPE is insufficient by itself and a Minimum Safety Range (MSR) must be determined for each laser system. The MSR determines the safe range beyond which the beam irradiance is less than the MPE. The energy density at a given distance can be calculated approximately in the following way, assuming that the energy is uniformly distributed across the beam.

The intensity of the radiation at a distance $R$ is given by:

$$I(R) = I_0 \exp(-\alpha R) \quad (78)$$

An estimation of $\alpha$ can be obtained by the expression of the meteorological optical range ($V_M$)

$$V_M = \frac{\ln 0.05}{\alpha} \quad (79)$$

The energy density at $R$ is given by:

$$D = \frac{I(R)}{S} \quad (J/cm^2) \quad (80)$$

where $S$ is the beam surface at distance $R$ which is due to the beam divergence solid angle

$$S = R^2 \Omega \quad \text{then} \quad D = \frac{I(R)}{R^2 \Omega}$$

So when $D$ is the MPE, $R$ is the MSR or:

$$(\text{MSR})^2 = \frac{P}{(\text{MPE}) \Omega} \quad (81)$$

where $P$ is the output power of the laser in Joules.

The MSR could be reduced by increasing the laser beam divergence. A typical system divergence of 0.3 mrad results in a 0.1 m beam width at 300 m. A larger divergence of 3 mrad results in a beam width of 1 m. By computing the MSR for the promising laser techniques it appears that existing Raman lidars could not safely be used operationally in the visible region, since the beam would present a hazard even at great distance.

The existing Differential Absorption Lidars can be considered acceptable in the visible and all systems appear acceptable in the near UV and IR. It is theoretically possible to further reduce the MSR by considering the lidar equation. From this equation it is seen that, for a fixed return power $P(R)$ the transmitted power $P_t$ can be reduced by increasing the pulselength $L$. In addition the integration time of the system may be increased, so that $n$ pulses are integrated rather than
the single pulse. This enables $P_t$ to be reduced by $n^2$; but these changes would result in an increase in the minimum detectable concentrations. The problem is then to determine which modification should be executed in a specific system (Lidar, Raman, differential absorption) so that a given minimum detectable concentration is not exceeded. It should be noted that since the MPE is much larger, and hence the MSR and safe beam diameter much smaller in the near UV ($< 0.4 \mu m$) and in the IR ($> 1.4 \mu m$), systems should preferably operate in these regions, which have the additional advantage that the solar radiation background is greatly reduced or even negligible. The use of these regions appears possible for gas detection using Raman methods (in the UV) and differential absorption methods (in the UV and IR). However, for some applications (e.g. visibility), observations in the visible region are considered necessary, although visibility measurements below 0.4 $\mu m$ could probably be related to conventional visible measurements on an empirical basis.

As laser atmospheric systems are coming into operational use internationally agreed safety regulations should be worked out for meteorological observational using lasers.

IV.3 Calibration

The acquisition of quantitative meteorological information is a two step process. First, it requires the quantitative, experimental measurement of the interaction of the laser wave with the atmosphere. Second, it requires the use of a physical or mathematical model of the wave-atmosphere interaction to interpret the observed measurements in terms of meteorological parameters. Since errors may arise at each of these two stages, careful testing and calibration is absolutely necessary. Ideally, the measurement made by a laser system should be compared with an accurate measurement of exactly the same parameter, using a calibrated in situ sensor, simultaneously with the same integration time and over precisely the same volume.

In practice, this is rarely achieved. As a result, the rate of development of improved new systems is limited. The following considerations can clarify this problem:

- Almost all standard instrumentation is composed of in situ sensors which provide point measurements. Laser systems usually provide some averaging over a line, area or volume of the atmosphere which in general can be several orders of magnitude larger than that part of the atmosphere sampled by the in situ sensor.

- Due to their nature laser shots are very short (nanosecond or microsecond) exploring the atmosphere in a very short time. As a result the statistics of the two sampling systems are inherently different.

- Laser systems perform measurements over large ranges, going from decameters to almost 100 km. The difficulty is to locate standard meteorological instruments in the volume being measured by the laser system. The use of aircraft or free or tethered balloons to carry the in situ instruments often presents severe problems.

- The acquisition of comparison data aloft over a sufficiently extended period is also very difficult except perhaps in those cases where a meteorological tower can be used. However, the height of such towers is generally limited to 100 to 200 m with rare exceptions of 300 m.

- A large number of comparisons obtained during periods with different meteorological conditions are necessary to perform valid statistical analysis and to
obtain information about the response and sensitivity of the laser system in different weather conditions.

One of the major problems is the unavailability or unsuitability of standard meteorological instrumentation for the measurement of many indirectly sensed parameters, such as particle size distributions, convergence, etc.

IV.4 Comparisons

It is to be expected that in the next few years some laser systems will be put into operational use. As an example the laser ceilometer is now already manufactured by different companies and installed at many airfields. Such systems do not always have the same instrumental characteristics as for example wavelength, integration time and sensitivity. Thus intercomparisons of similar laser systems, together with existing systems, would be very useful and would help in the critical evaluation of their performance. As the field of atmospheric probing with laser systems advances, we may expect that carefully selected systems may become standard methods for measuring certain meteorological variables aloft, avoiding the need of in situ standard instruments. A critical examination of the calibration problem and its possible solutions should be performed before laser systems come into use for routine meteorological observations.
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