Lidar probing of the atmosphere*

1 Introduction

The early use of lasers in atmospheric measurements by Fiocco and Smullin\(^1\) served to demonstrate the advantages of these sources over searchlights employed in previous active probing experiments\(^2\). Specifically, the introduction of Q-switching provided short light pulses of high power for range-resolved measurements, and the monochromatic nature and ease of beam collimation of lasers facilitated discrimination against background radiation. After almost three decades of development, the lidar (light detection and ranging) technique finds a wide range of applications in ground-based measurements of atmospheric parameters\(^3,5\), has been employed on airborne platforms\(^4,6\), and its use for possible deployment in space\(^6\) has been widely examined.

To date, the applications of the technique have been largely confined to visible and ultraviolet wavelengths. Wavelengths near 720 nm are suitable for observations of water-vapour concentration in the troposphere\(^7\) and greater sensitivity would be provided by stronger absorption lines in the 930-960 nm range. The relatively high efficiency of infrared lasers and the improved signal-to-noise ratio offered by coherent detection over incoherent detection favours an extension of operations to still longer wavelengths. However, as will be pointed out in Section 2, atmospheric scattering of wavelengths greater than about 3 \(\mu\)m depends on the presence of aerosols. Thus the upper height limit probed with CO\(_2\) laser systems operating at 10.6 \(\mu\)m is about 20 km (Ref. 8). However, wavelengths in this region are the leading contenders for a satellite-borne laser atmospheric wind measurement system\(^9\)-\(^11\).

The purpose of the present paper is to describe some of the ground-based and airborne lidar observations of the atmosphere, with particular attention being paid to middle atmospheric heights. The principle of the technique, the interactions involved at ultraviolet and visible wavelengths, and the corresponding height ranges probed are outlined in Section 2. The applications of the technique in studies of particulates, composition, structure and dynamics are considered in Sections 3, 4 and 5, respectively, with attention being concentrated on those applications which relate to current problems, such as the role of clouds in global warming, the depletion of stratospheric ozone, and gravity wave effects in the upper stratosphere and mesosphere. Finally, to emphasise the maturity of the technique, consideration is given in Section 6 to current plans to deploy lidar systems in space and the associated technical developments.

2 Outline of technique and optical interactions

The lidar technique involves the emission of a short pulse of radiation from an appropriate laser, the collection and measurement of the radiation backscattered by atmospheric gases and particles, and the recording of its delay relative to the transmission and, hence, the path length traversed. The radiation collected is passed through a spectrum an-
alyser and the component with the required wavelength is passed to a detector, normally a photomultiplier for the visible or ultraviolet spectral range, and processed by digital or analogue techniques.

For a vertically directed system, in which there is a complete overlap of the transmitter and receiver fields of view, the number of photoelectrons $n_\lambda(\lambda, h)$ generated by a pulse of radiation backscattered from a height interval $\Delta h$ at a height $h$ is given for a single scattering species by

$$n_\lambda(\lambda, h) = P_\lambda(\lambda) \frac{A}{h^2} N_\lambda(h) \frac{\partial \sigma_\lambda(\lambda)}{\partial \Omega} \eta \Delta h \times \exp \left[ -2 \int_0^h (N_a \sigma_a + k(h)) dh \right]$$

where $P_\lambda(\lambda)$ represents the number of photons in the emitted laser pulse, $A$ the area of the receiving mirror, $N_\lambda(h)$ the number density of the scattering species, $\partial \sigma_\lambda(\lambda)/\partial \Omega$ the corresponding differential backscattering cross-section, $N_a$ and $\sigma_a$ the number density and absorption cross-section of absorbing molecules, $k(h)$ the total extinction coefficient excluding the effect of absorbing molecules, and $\eta$ the optical efficiency of the receiver system, including the quantum efficiency of the photomultiplier. In this form, it is assumed that no change of wavelength is associated with the scattering process. The atmospheric measurements are concerned with the quantities $N_\lambda \partial \sigma_\lambda/\partial \Omega$ and the exponential term.

The range of values of $\partial \sigma_\lambda/\partial \Omega$ for the types of interactions employed, to date, in lidar investigations are illustrated in Fig. 1(a), with the corresponding constituents or parameters measured and the relevant height ranges being shown in Fig. 1(b). A distinction is drawn between elastic and inelastic scattering processes.

Rayleigh scattering from molecules occurs when the frequency of the radiation does not correspond to a specific electronic transition. The differential backscatter cross-section shows an inverse fourth power dependence and, consequently, this form of elastic backscatter is effective only for wavelengths shorter than about 3 $\mu$m.

The second form of elastic process is that of resonance scattering from atomic or molecular species in which the coincidence of the laser frequency with a specific transition of the species results in a large enhancement of cross-section and ensures a good sensitivity, provided collisional quenching by other constituents is not serious. The tuning facility provided by incorporating dispersive elements within dye lasers has made it possible to observe resonance scattering from neutral and ionized metal species at heights of 80-100 km, the differential cross-sections being near $10^{-16}$ m$^2$ sr$^{-1}$.

Fluorescence, shown in the inelastic category in Fig. 1(a), also requires a tunable laser. Although large cross-sections are again expected, the effective values are often reduced substantially by collisional quenching.

Mie scattering from stratospheric aerosols and water droplets or ice crystals in clouds forms the third case of elastic scattering represented in Fig. 1. The sizes of these particles vary widely but the relatively large values of cross-section account for the prominence of observations of Mie scattering from the stratospheric aerosol layer in early lidar experiments.

The second inelastic scattering process shown in Fig. 1(a) is vibrational-rotational Raman scattering in which the radiation undergoes a frequency change characteristic of the stationary states of the scattering molecule. The basic lidar equation is similar to that shown above except that the atmospheric extinction for the return path relates to the Raman-shifted wavelength corresponding to the vibrational or rotational energy. The Stokes components represented in the diagram correspond to losses of energy by the radiation to molecules; the corresponding anti-Stokes components at wavelengths shorter than the laser have not been observed for constituents in the middle atmosphere. The characteristic Raman frequency shifts serve to identify particular molecules regardless of the irradiating wavelength although, as with Rayleigh scattering, the cross-sections are proportional to the inverse fourth power of wavelength. The use of this form of scattering suffers from the relatively small cross-sections. Thus Q-branch of the nitrogen molecule, corresponding to the $\Delta \nu = 1, \Delta J = 0$ transition, has a differential Raman backscatter cross-section of $4.7 \times 10^{-35}$ m$^2$ sr$^{-1}$ at 532 nm, compared with $6.2 \times 10^{-32}$ m$^2$ sr$^{-1}$ for Rayleigh scattering.

The remaining optical interaction represented in Fig. 1(a), that of differential absorption and scattering, can provide greater sensitivity in measuring an atmospheric constituent than either Raman scattering or fluorescence, when this is affected by quenching. In this differential approach, a comparison is made between the absorption of radiation tuned to correspond to an absorption line of the constituent of interest and that tuned to the wing of the line, both radiations being returned by Rayleigh, and perhaps Mie, scattering, which provides spatial resolution. The measurement is then concerned with the contribution of molecular absorption to the extinction term in the radar equation, in contrast to the scattering measurements outlined above, which rel-
Fig. 1 — Optical interactions exploited in lidar measurements, the boxes in (a) showing the range of cross-sections involved and in (b) the height ranges over which corresponding constituents or particles have been measured.
Measurements of differential absorption at infrared wavelengths longer than 3 \( \mu m \) are dependent on Mie scattering.

3 Observations of Mie scattering—cirrus clouds, polar stratospheric clouds, and stratospheric aerosols

In the use of general circulation models to investigate global warming effects, one of the greatest uncertainties is the effects of cloud cover\(^3\). Cloud radiative forcing arises from the reflection of shortwave solar radiations, resulting in a cooling effect at the Earth’s surface, and the reduction of infrared emission to space, causing a heating or ‘greenhouse’ effect. The latter effect is believed to be large for deep cirrus clouds, such as the jet-stream cirrus clouds at mid-latitudes and monsoon cloud systems over the tropical Asian regions\(^4\). The calculation of the radiative forcing requires a knowledge of cloud amount, their optical properties and vertical structures\(^5\). Satellite-based observations of cirrus with passive instrumentation are hampered by the lack of vertical and horizontal resolution, the partially transparent nature of cirrus, and the poor understanding of the cloud spectral behaviour. Ground-based and airborne lidar and infrared radiometry can provide information on the structure, and microphysical and radiative properties of cirrus to complement satellite-based observations. Lidar observations of cirrus by Platt et al\(^6\), Sassen\(^7\) and Thomas et al\(^8\) have made use of backscatter and depolarization at vertical and near-vertical incidence. The optical arrangement of the two channel receiver system employed in the latter measurements at Aberystwyth (52°N, 4°W) incorporates a Casse-grain receiving telescope with a 0.6 m diameter parabolic primary mirror, a secondary hyperbolic mirror, and a Ramsden eyepiece (Fig. 2). The two photomultipliers are fitted with dichroic polarizers for recording the two orthogonal components in the backscatter of the plane-polarized transmitted beam provided by the frequency-doubled output of a Neodymium-Yag laser at 532 nm. The laser output is expanded by a telescope which reduces the beam divergence to 0.1 m rad, the size of the field-stop aperture controlling the receiver field of view to 0.3-0.8 m rad, and the neutral density filter \( F_1 \) the light level to be counted. The combination of the small field of view and the 1 nm bandwidth interference filter \( F_2 \) reduces the background light to permit daytime operation. The system is capable of scanning in one azimuth, the tracking of receiver and a receiver being ensured by having the transmitter telescope built into the hollow shaft about which the receiver mirror is rotated.

A particularly interesting feature of lidar observations of cirrus, first noted by Platt\(^9\) and Gibson et al\(^10\), is the presence of non-spherical ice crystals having near horizontal orientations. The identification of such orientated crystals is illustrated in Fig. 3. This shows for a short period of observations at Aberystwyth on 11 Apr. 1987 the backscatter of the components polarized parallel and perpendicular to the incident radiation when the beam direction has been switched sequentially at 10s intervals between the vertical and 10 m rad from the vertical, with the signal being used to modulate a cathode ray display. It is seen that the results for the parallel component show white and dark regions corresponding to vertical and off-vertical beam directions, respectively. The perpendicular component shows no such varia-
Fig. 3—Observations of cirrus clouds at Aberystwyth for 1645-1705 GMT on 11 Apr. 1987 showing the backscattered components polarized (a) parallel and (b) perpendicular to the incident radiation, when the beam direction was switched sequentially at 10s intervals between the vertical and 10 m rad from the vertical.
The overall results deduced from 20 min samples using this approach for the majority of days free of low-lying clouds in the period July 1986 to September 1989 are summarized in Fig. 4. This shows the total number of times cirrus cloud was observed in different height ranges and also the number of times crystals having a preferred horizontal orientation were detected in different height ranges, represented by the full and broken lines, respectively. It is seen that the height of maximum occurrence of cirrus was near 9 km and there was about a 50% chance that orientated crystals were present at any height. The presence of such orientated crystals has a significant effect on the reflection and transmission properties of cirrus clouds, and, hence, on the calculation of atmospheric heating rates involving such clouds.

An important feature of stratospheric heights in both polar regions at low temperatures, below about 200 K, are the polar stratospheric clouds observed repeatedly from space. Lidar measurements of backscatter and depolarization from the ground in Antarctica and from a NASA research aircraft over the Arctic have provided information on the characteristics of these polar clouds. Subsequent measurements with an airborne system over the Arctic showed the presence of two types of cloud particles: at temperatures just above the frost point, the backscatter ratio (aerosol + molecular/molecular backscatter ratio) showed values less than 5 and depolarization ratios (perpendicular/parallel components ratio) less than 0.1; below the frost point, much larger scattering ratios (up to 80) and depolarization ratios of 0.3-0.5 were observed. The first type was consistent with a nitric acid trihydrate particle composition and the second with large ice crystals, both predicted theoretically. Subsequent aircraft measurements in the Arctic have confirmed these results and have, in fact, identified a sub-division of the Type 1 particles, some with low backscattering ratios and high depolarization ratios and others with higher backscattering ratios and lower depolarization ratios. Apart from the possible radiative impact of polar stratospheric clouds on the polar stratosphere, it has been realized that they play a crucial role in the depletion of stratospheric ozone. Specifically, the formation of Type 1 particles from nitric acid vapour serves to remove NOX and this provides a link between the particles and the springtime depletion of ozone most clearly apparent in Antarctica. In addition, it appears that heterogeneous reactions can serve to release reactive chlorine from reservoirs of HCl and ClONO2 on Type 1 polar stratospheric clouds.

The atmospheric feature which has attracted the greatest attention in lidar observations of Mie scattering is probably the stratospheric aerosol layer; the technique employed at a number of sites has served to monitor the enhancement of the layer following a number of volcanic eruptions. Information is generally provided on the macrophysical properties of the aerosol layer, including the height and thickness, with the integrated backscatter providing an indication of the aerosol loading. Lidar measurements have also been used to help validate satellite-borne photometer measurements of aerosol extinction of solar radiations at 1 μm (Ref. 36) and to identify small features in the aerosol layer which serve as monitors of dynamical influences.

4 Observations of composition

Increased attention has been drawn in recent years to the need for a global observational network designed specifically for the detection and monitoring of stratospheric composition changes associated with human activities. Early detection of depletion of the stratospheric ozone layer is a specific requirement. It has been realized that although satellite measurements provide global coverage, drifts in instrument calibration could complicate the accurate determination of trends. Complementary ground-based experiments are, therefore, required in any global observational system, and the lidar technique is recognized as being capable of providing the most accurate measurements of the ozone distribution at heights up to the upper stratosphere. The development of a ground-based technique for measuring the height distribution of water vapour with a good...
height resolution has also been of considerable interest because of the importance of this constituent in climate and weather, photochemistry and radio-wave propagation.

The Raman technique has the greatest potential for measuring atmospheric gases but suffers from relatively small values of cross-section. The basic requirement on the transmitter is that the wavelength should take advantage of the inverse fourth power dependance of cross-section, and a high energy and pulse repetition rate should also be available. The receiver needs to incorporate a spectrometer or interference filter matched to the Raman-shifted wavelength. The recent resurgence of activity in Raman scattering measurements of water vapour in the troposphere, after the earlier work in the late 1960s and early 1970s, can be attributed to advances in laser technology and the availability of interference filters which are capable of rejecting the strong Rayleigh and Mie backscatter returns. With two channel receiving systems, as shown in Fig. 2, simultaneous measurements of nitrogen and water vapour have been made using the frequency-tripled output of a Neodymium-Yag laser at 355 nm and interference filters centred at 387 nm and 408 nm to record vibrational bands of nitrogen and water vapour, respectively. The use of the ratio of the water vapour and nitrogen Raman signals to derive the mixing ratio of water vapour eliminates the need for the difficult estimation of extinction due to aerosol scattering and for a knowledge of the parameters of the system. With this type of system, measurements up to the tropopause required integration times of several hours. The incorporation of a XeF excimer laser operating at 351 nm would yield an average power larger by almost two orders of magnitude and, hence, a reduction in sampling time by a factor of about ten.

The differential absorption technique has been the most widely used lidar approach to composition studies in the troposphere and stratosphere. The first measurement of a molecular species, water vapour, was carried out using a temperature-tuned Ruby laser operating from 693.7 to 694.5 nm (Ref. 41). This approach provided measurements of water vapour up to 10 km (Ref. 42) but continuously tunable systems based on Ruby-pumped dye lasers and Neodymium-Yag-pumped dye lasers have provided access to the spectral region 720-730 nm where water vapour has line strengths more appropriate to tropospheric measurements. However, it is in the measurement of the vertical distribution of ozone that the technique has attracted the greatest attention, and this application is playing a significant role in monitoring the ozone layer. The approach depends on absorption in the Hartley-Huggins band between 280-320 nm. The choice of operating wavelength depends on the range of ozone concentrations to be measured, the vertical resolution required, the presence of interfering gases such as sulphur dioxide and nitrogen dioxide, and the scattering characteristics of aerosols. The earliest measurements were carried out with flashlamp-pumped, frequency-doubled dye lasers but subsequently the second-harmonic output of a Neodymium-Yag laser was used as the dye laser pump. However, greater reliability and ease of operation has been found with the use of Neodymium-Yag or excimer lasers for producing probing wavelengths directly and by stimulated Raman scattering in high pressure gas cells. Thus for measurements in the troposphere and lower stratosphere the quadrupled output of a Neodymium-Yag laser at 266 nm has been used to generate radiation at 289 and 294 nm by Raman shifting in high-pressure D₂ and HD, respectively, whereas an alternative second wavelength of 299 nm has also been generated by stimulated Raman scattering in H₂. To reach greater heights, the more weakly absorbed radiation at 308 nm produced by a Xe Cl excimer laser has been used with the reference wavelength being provided by stimulated Raman scattering in H₂ at 353 nm (Ref. 49) or by the third harmonic output of a Neodymium-Yag laser at 355 nm (Ref. 50). The results obtained at Haute Provence (44°N, 5°E) with the 289/299 nm and 308/355 nm wavelength combinations on 13 Sep. 1989 are shown in Fig. 5 (Ref. 51).

The value of the differential absorption technique for monitoring ozone variations has been recognized by its incorporation in the ground-based Network for the Detection of Stratospheric Change (NDSC) under consideration within the NASA Upper Atmosphere Research Programme, and in the Tropospheric Environmental Studies by Laser Sounding (TESLAS) project of the European Scientific EUROTAR Programme for Environmental Research. At the same time, individual systems, both ground-based and airborne, are already contributing to our knowledge and understanding of the sudden changes in ozone concentration which occur during spring in polar regions.

Some of the earliest measurements of composition were based on flashlamp-pumped dye lasers which could be tuned to correspond to a characteristic transition of the constituent for resonance scattering measurements. As indicated in Fig. 1(b), this approach has provided information on meteoric atoms and ions at mesospheric and low thermospheric heights. In view of the difficulties associated with the derivation of absolute concentrations from the
5 Observations of density and temperature structure

Over the past two decades satellite-borne sensors have provided information on the density or temperature structure at middle-atmospheric heights on a global scale. The height resolution available operationally has been limited to 10-15 km, but some instruments have provided a 3 km resolution. Studies requiring better height resolution have depended on information provided by the world-wide network of meteorological balloons and rockets sounding stations. However, ground-based lidar observations of Raman scattering, differential absorption, Rayleigh scattering and resonance scattering are together capable of providing measurements of density and temperature over the whole height range up to about 100 km, with a resolution depending on the approach adopted.

Observations of elastic scattering from heights where aerosols make no significant contribution have long been used to derive the relative total molecular density as a function of height. The early observations use Ruby lasers as sources but the subsequent use of the frequency-doubled output of a Neodymium-Yag laser at 532 nm (Ref. 65) provided a higher pulse repetition rate, and further advantages of higher mean power, increased Rayleigh scattering, and larger quantum efficiencies of photomultipliers at ultraviolet wavelengths are offered by excimer lasers. This approach to the measurement of molecular density is based on the assumption that the atmospheric returns are caused solely by Rayleigh scattering and is, consequently, restricted to heights above about 30 km. A downward extension of the density data is possible with the use of vibrational-rotational Raman backscatter from nitrogen, described in Section 4. However, allowance then needs to be made for extinction by aerosols and Rayleigh scattering, particularly at tropospheric heights. In a recent study by Melfi et al., the third-harmonic radiation from a Neodymium-Yag laser at 355 nm was used to observe the nitrogen Raman signal at 387 nm and also Rayleigh and Mie scattering to apply a correction for extinction.

The differential absorption technique has also been applied in measurements of atmospheric pressure with tunable Alexandrite lasers in the oxygen A band near 760 nm (Ref. 5). In this approach, the absorbed line is tuned to an absorption trough, a broad region of nearly uniform absorption between two strong oxygen lines; since the measurement is in the far wing of collision-broadened lines, the absorption is very pressure dependent. A second wavelength is chosen to have minimum absorption but similar backscatter to the first. To date, measurements from radar equation, it has been customary to normalize the backscatter from the meteoric atoms or ions to the Rayleigh backscatter from heights free of aerosols, normally chosen to be above 30 km. The estimation of the metal atom or ion concentrations then involves a knowledge of the molecular concentration at this height and the appropriate resonance and Rayleigh backscatter cross-sections. The approach was first used by Bowman et al. to measure the distribution of sodium atoms by observing resonance scattering of the D2 (2S1/2-2P3/2) line at 589.0 nm, and various aspects of the sodium layer have since been examined. The difficulties of generating radiations at certain required wavelengths led to the replacement of flashlamps as dye laser pumps by Ruby lasers or the harmonics of Neodymium-Yag lasers. This development led to the measurement of potassium atoms at 769.9 nm (Refs 57 and 58), lithium at 670.8 nm (Ref. 59) and neutral and ionized calcium at 423 and 393 nm, respectively.

Relatively little use has been made of fluorescence for studies of molecular constituents because of the restriction imposed by collisional quenching, even at stratospheric heights. The measurement of OH, indicated in Fig. 1(b), refers to a balloon measurement by Heaps and McGee in which excitation was by radiation at 282 nm, generated by frequency doubling the output of a dye laser.
the ground and from an aircraft have yielded pressure measurements up to about 1.5-2 km.

Based on the assumption of hydrostatic equilibrium and the perfect gas law, the profile of relative density provides the height variation of temperature. Lidar measurements of Rayleigh scattering at different sites have then provided information on changes of the temperature profile over the stratosphere-mesosphere height range with season and during planetary-wave disturbances. The good height resolution achievable with the technique provides information on the details of the height profile of temperature, especially at stratospheric heights where a resolution better than 100 m is commonly achieved. These lidar studies have also indicated the presence of gravity wave and tidal disturbances in density or temperature in the stratosphere and mesosphere. Considerable interest has been recently inspired in the presence of gravity waves in the middle atmosphere because of their role in determining the large-scale circulation and thermal structure of the middle atmosphere. Lidar observations in the 30-65 km height range then provide a useful compliment to the information provided by the MST radar technique which cannot operate in this region because of the lack of irregularities of suitable scale size to provide radar returns. The types of density perturbations observed are illustrated in Fig. 6 which relates to measurements at Aberystwyth on the night of 28 Mar. 1990 (Ref. 77). It shows contours of density perturbation from the background profile $\rho'(h)$ normalized to the appropriate background value at the same height $\rho(h)$, based on successive profiles measured with 17 min integration times using the second-harmonic output of a Neodymium-Yag laser operating with a pulse energy of 300 mJ and a repetition frequency of 10 Hz, and a receiving mirror of 1 m diameter. The contours show the presence of a wave-like structure with a vertical wavelength of about 4 km in the stratosphere and 10 km in the mesosphere, and displaying a downward phase propagation. Such a wave-

![Fig. 6](image-url)

Fig. 6—Contours of fractional density perturbation, based on profiles measured at Aberystwyth during successive 17 min intervals on the night of 28 Mar. 1990 (after Mitchell et al.)
like structure is commonly observed in Rayleigh backscatter observations of the stratosphere\textsuperscript{66,73}. The fractional density perturbations can themselves, be related to the potential energy \( E_p(h) \) per unit mass, given by 0.5 \((g/N)^2 \rho \dot{\rho} / \rho \dot{\rho} \) (Ref. 78), where \( g \) represents the acceleration due to gravity and \( N \) the Brunt-Väisälä frequency. The contour plot in Fig. 7 then shows the variation of \( \log_{10} E_p(h) \), where \( E_p(h) \) is in J kg\(^{-1}\), throughout the year\textsuperscript{77}. A strong annual cycle is apparent, with an increasing semi-annual component at greater heights. The ratios of maximum to minimum potential energy are about 2.5, 5 and 6 at heights of 55 km, 45 km and 35 km, respectively.

The study of atmospheric waves from observations of density perturbations is limited in that it relates only to vertical buoyancy oscillations and gives no information on horizontal motions. The commercial availability of single longitudinal mode operation with Neodymium-Yag lasers, effected by diode pumped injection seeding, makes the measurement of the Doppler shift of the Rayleigh scattered signal feasible. The use of this approach to the measurement of winds in the stratosphere has been demonstrated by Chanin et al.\textsuperscript{79}

For reasonable sampling times, the temperature data derived from measurements of Rayleigh backscatter are limited to lower mesospheric heights. For still greater heights, between 80 and 100 km, use has been made of dye lasers to exploit the Doppler width of radiation resonantly scattered from sodium atoms. Blamont et al.\textsuperscript{80} made use of a flashlamp-pumped dye laser to excite all the hyperfine components of the sodium D\(_2\) line and the backscattered radiation was partially absorbed in a cell containing sodium vapour at a known temperature. The reduction of the radiation in traversing the cell was a function only of the optical thickness of the sodium vapour and of the ratio of the temperature of the scattering layer to that of the cell. The disadvantage of this approach is the relatively large sampling period required. In a new approach introduced by Gibson et al.\textsuperscript{81} and first used by Thomas and Bhattacharyya\textsuperscript{82}, a laser with a linewidth of about 0.1 pm, about one thirteenth of the Doppler widths of the D\(_1\) or D\(_2\) complexes at temperatures in the 80-100 km height range, was used to observe the bimodal form of the D\(_2\) line arising from the two groups of hyperfine components. Since the relative strengths and frequencies of the components are known, the line profile for any temperature can be computed; the temperature giving the best fit to the observed profile can then be estimated. Frickle and von Zahn\textsuperscript{83} applied this approach by using a Neodymium-Yag laser pumped dye laser producing a 0.13 pm spectral width to measure the ratio of the maximum to minimum intensity within the D\(_2\) profile.

6 Future deployment of lidars in space

The applications of ground-based and airborne lidar systems, some of which have been outlined in Sections 3, 4 and 5, have demonstrated the measurement capabilities and reliability of the technique. The incorporation of such systems in spacecraft for providing global data on a number of atmospheric parameters is expected to make significant contributions to meteorology and climatology, and has consequently been the subject of considerable study by both ESA and NASA since 1974. However, developments in laser technology and the access to greater weight, volume and power facilities on large space platforms planned for the mid-1990s have inspired renewed attention to the concept of space-borne lidars\textsuperscript{11}, and specific missions are already planned in the USA (Ref. 6) and USSR (Ref. 84).

The particular advantage of lidar systems in space is the good resolution achievable vertically, already demonstrated in ground-based and airborne measurements, and horizontally; the minimum footprint will be determined by the diffraction limit of the transmitting telescope, which can be as small as a few metres. These capabilities will be particularly well suited to studies of the height of the planetary boundary layer, cloud-top heights, vertical profiles of aerosols, and sub-visible clouds. The NASA Lidar in Space Technology Experiment (LITE) (Ref.
to be carried on a manned, short-duration US Shuttle flight planned for 1993 is to be directed towards these types of measurements, and also of atmospheric temperatures, with modest height resolution. It will incorporate a Neodymium-Yag laser, with frequency-doubling and tripling crystals, and a 1 m diameter receiving mirror. It is intended to evaluate lidar techniques and operations in space, and will be followed by a series of subsequent flights leading to unmanned, long-duration missions. A corresponding development is in progress in the USSR where a system incorporating a frequency-doubled Neodymium-Yag laser and a 27 cm diameter receiving mirror is to be mounted on the manned orbital station MIR for measurements of the upper boundary of clouds and their optical properties. Differential absorption lidar systems will be developed from these simple backscatter systems, and the measurements of particular value to meteorological and climate studies will be profiles of water vapour and temperature, and also of pressure down to the Earth's surface. The traditional method of global wind measurements from space is based on the observation of cloud movements using geostationary imaging radiometers. The provision of improved cloud heights determined by lidar will assist in obtaining wind vectors at different atmospheric levels, provided the lidar measurements and the information from the satellite sensor images can be correlated. However, serious consideration is also being given to the measurement of the three-dimensional wind field throughout the troposphere and lower stratosphere using a Doppler lidar system. Systems based on a CO₂ laser source and coherent detection with a heterodyne receiver have attracted the greatest attention but some consideration has also been given to operations with a Neodymium-Yag laser and direct detection using a multiple Fabry-Perot interferometer. An added complication with these wind measurement systems is the need to scan the laser beam with a large nadir angle. Such a scanning facility could also provide a greater spatial coverage in the backscatter measurements.

A major consideration for each of the three types of application: backscatter, differential absorption and Doppler wind, is the choice of laser. The lifetime and reliability will be particularly relevant because of the need to ensure a minimum operational time of 2-3 years for meteorological-type applications. Fortunately, progress in new laser material and advances in diode-laser pumping arrangements promise improvements in performance and reliability of solid-state lasers, and improved lifetimes and stability have been achieved with CO₂ lasers. The Neodymium-Yag laser could find applications in all three types of measurement: as the source for backscatter and Doppler lidar measurements, and in the longer-term as a pump for a Ti-Sapphire laser producing radiation in the 710-950 nm wavelength range for differential absorption measurements of water vapour. The Neodymium-Yag laser itself would be pumped initially by a flashlamp but diode-laser pumping is expected to develop from the low-power performance already available. For the differential absorption measurements of molecular oxygen and water vapour, considerable attention has already been paid to the Alexandrite laser operating at 720-780 nm (Ref. 86) and it seems likely that this will find application in space-borne measurements of these constituents. Flashlamp pumping is possible but an all solid-state laser can be envisaged with a diode-pumped Neodymium-Yag laser which itself pumps an Alexandrite laser. In considering the choice of laser to be incorporated in the coherent Doppler wind experiment, an added consideration is the eye-safety requirements, in view of the large pulse energy and beam collimation requirements. This is a severe restriction on the use of 1 μm radiation, and measurements at 10 μm with a CO₂ laser are currently favoured. The alternative approach of incoherent Doppler lidar measurements, based on a frequency-doubled Neodymium-Yag laser, imposes less demands on pointing accuracy and matching of transmitter and receiver beams. However, great care needs to be taken to maximize the overall optical efficiency and quantum efficiency of the detector.

References