Introduction

This collection of papers attempts to gather in one volume a number of the key papers in the history of lidar used for atmospheric studies. The emphasis in this volume is on papers that made a significant contribution at the time of publication as well as a lasting contribution to the field of lidar and/or atmospheric remote sensing. An attempt was also made to include papers by many of the past and present leaders in the development and application of atmospheric lidar. It was, however, impossible to include many of the fine papers in the field. Some of those not included are mentioned in the introduction, in the reference sections of each paper, or in the reviews of lidar. The interested reader is referred to the numerous lidar reviews on general or specific topics [e.g., Collis and Uthe, 1972; Byer, 1975; Hinkley, 1976; Carswell, 1983; Killinger and Mooradian, 1983; Measures, 1984, 1987, and in preparation; Grant, 1987, 1991, 1995; Menzies and Hardesty, 1989; Reagan et al., 1989; She, 1990; Zanzottera, 1990] as well as to the proceedings of the biennial International Laser Radar Conference.

In general terms, lidar began with searchlights to study stratospheric aerosols and molecular density (see, e.g., Elterman [p. 3 and 1966] for a review of the use of searchlights for aerosols). The invention of the ruby laser [Maiman, 1960] provided a better source since it had a short pulse length, produced a low-divergence beam, was monochromatic, and had high pulse energy. These properties permitted lidar systems to be constructed which had many advantages over the use of searchlights. It is notable that the ruby laser was incorporated into the first lidar systems in at least three areas: aerosol lidar [Fiocco and Grams, p. 35], differential absorption lidar [Schotland, p. 423], and Raman lidar [Melfi et al., p. 296].

The field of lidar for atmospheric studies has had several general phases in its history: innovation, development, and application. The innovation phase was particularly pronounced in the 1960s and 1970s, with many pioneering demonstration experiments in this period. The development phase started in the 1970s and continues today. This phase includes improved laser sources and other hardware as well as an improved understanding of the theory of lidar. The applications phase began in the 1970s, accelerated in the 1980s, and continues unabated today. Many lidar systems have been developed and accepted as providing very important and often unique data for atmospheric studies. The systems have often undergone rigorous correlative measurement programs with the standard instruments of the day to gain acceptance.

In the sections that follow, brief sketches of the history of the branches of atmospheric lidar covered by this volume are presented, with references to some of the papers reprinted in this volume as well as other important papers presented in the reference section.

Aerosol Lidar

Stratospheric aerosols were the first atmospheric constituents studied using lidar. Fiocco and Grams [p. 35] used a ruby laser lidar system in this endeavor. At about the same time, scientists at Stanford Research Institute were doing similar work [e.g., Collis and Ligda, p. 37]. Such lidar systems afforded an excellent technique for studying volcanic aerosols, which was exploited early on both the east coast [McCormick et al., p. 53] and the west coast [Russell and Hake, 1977] of the United States.

Another topic of interest for aerosol lidar studies is plume behavior. The Stanford Research Institute (now SRI International) was a pioneer in this field, with a number of papers on this approach reviewed by Uthe [1983]. Uthe et al. [p. 108] also demonstrated the usefulness of using fluorescent particles for plume studies. Related to this work is the study of the boundary layer, exemplified by work such as that by McElroy and Smith [p. 121].

The interest in measuring wind fields from a space-based platform [Huffaker et al., p. 590, and references therein] was the motivating factor behind an interest in long-term measurements of upper-tropospheric aerosols, such as those being made by Post et al. [p. 86] and Menzies et al. [p. 100].

Interest in aerosol measurements has also led to the development of specialized lidar systems, such as the high-spectral-resolution lidar [Shipley et al., p. 91] and the micropulse lidar [Spinhirne, p. 246].

Lidar Cloud Research

Optical detection systems coupled with some of the first crop of "commercial" Q-switched ruby lasers by the mid-1960s were being pointed out of laboratory windows to investigate what could be learned about clouds using light detection and ranging (lidar). The post–World War II boom in research activity in the radar meteorology arena set the stage for this early lidar application, and both general principles and basic remote sensing techniques were borrowed and tested [see the reviews by Carswell, 1983, and Sassen, 1991].

One of the most promising for lidar cloud research was the polarization technique [Schotland et al., p. 178; Houston and Carswell, 1978], where, in its simplest form, a linearly polarized pulse is transmitted and the backscattered energy is divided into the orthogonal and parallel planes of polarization. (The ratio of these two signals is called the linear depolarization ratio, or delta value.) It was immediately apparent that, unlike the case for microwave radar, where the particles are typically much smaller than the incident wavelength, both the strength of the scattering interaction and the amount of depolarization generated were considerably stronger with lidar. This suggested that lidar probing displayed unique cloud research potential (as well as certain drawbacks such as limited depth of probing effects due to the strong nature of the scattering interaction).

We are still in the process of evaluating the role that lidar will play in the study of clouds, which is quite timely in view of the uncertainties in our comprehension of human-induced climate change effects, but the contributions to date are impressive.

Early polarization lidar results seemed to confirm a principle rooted in basic scattering theory: that lidar delta values could unambiguously discriminate between liquid and ice phase clouds [Schotland et al., p. 178], a capability that is still unique among remote sensing techniques. Although there were some experimental complications since spherical water droplets and crystalline ice particles generated backscattering by fundamentally different mechanisms, it was not long before approaches to remove the ambiguities were found.

First, droplets in clouds are packed so closely together with respect to the wavelength that the photon multiple scattering activity viewed by a lidar receiver can rapidly dominate the returned signal; this resulted in the production of increasing linear depolarization as the pulse penetrated into the cloud [Pal and Carswell, 1973]. However, the delta value increase (from near-zero values at cloud base) provided a clear signature of the multiple scattering process, which could be controlled by limiting the field of view of the receiver [Liou and Schotland, 1971] or by using special field stops [Allen and Platt, 1977] or innovative detector concepts [Sassen, p. 254; Bissonnette et al., p. 262].

Then it was noted that some high level clouds that were apparently composed of ice could produce near-zero delta values. This ambiguity initially led to the mischaracterization of some clouds [Platt and Bartusek, 1974], but since this behavior was soon shown to be elevation angle dependent [Platt, 1978], it was easily identified by tipping the lidar a few degrees off the zenith direction. This is a consequence of the ability of ice plate crystals to fall quite flat through the atmosphere, such that mirror-like reflections were returned to the monostatic receiver only at or near vertical incidence. Thus, rather than being a drawback, lidar provides information on the fall orientations, and hence shapes, of ice particles.

Note that although such depolarization applications are valid at any visible or near-infrared laser wavelength, mid-infrared CO_2 lidars do not measure much depolarization because of the strong energy absorption suffered during internal hydrometeor refraction and reflection [Eberhard, 1992].

As lidar systems began becoming more fieldworthy during the 1970s, opportunities to further test probing methods against other ground- or aircraft-based measurement systems increased. Attempts were made in the field to derive the rainfall rate from lidar [Shipley et al., 1974] and observe the "bright band" from melting snow [Sassen, 1977], which were previously the domain of radar studies. Initial "air-truth" comparisons with coordinated cloud research aircraft measurements [Sassen, 1978] left no doubt as to the ability of polarization lidar to distinguish ice from water clouds, even at unexpectantly cold supercooled temperatures approaching −40°C [Sassen et al., 1985].

By the mid-1980s, it was apparent that major cloud research studies like the 1986 Project FIRE (First ISCCP Regional Experiment) Intensive Field Observations program, designed to improve our understanding of the radiative effects of cirrus clouds, would benefit greatly from the incorporation of lidar sensing methods. As a matter of fact, the basic design of the experiment relied on a combination of one airborne and four ground-based lidar systems that could study cirrus clouds over a large geographical area (about one-half of the state of Wisconsin!). The lidar findings were highlighted in several cirrus cloud research papers published in the 1990 FIRE special issue of the *Monthly Weather Review* (Vol. 118, No. 11).

The truly international spread of lidar systems for cloud and climate research has recently been illustrated by the success of the Experimental Cloud Lidar Pilot Study (ECLIPS) [see Platt et al., 1994]. Lidar investigators also turned their attention to the exotic clouds of the upper atmosphere, studying from the ground for the first time the rare noctilucent [Hansen et al., p. 242] and polar stratospheric [Stefanutti et al., 1992] clouds.

The next stage of lidar cloud research grew partly out of a recognition of the limitations inherent in lidar probing under many atmospheric conditions—the modern multiple remote sensor approach was born out of a need to understand cloud systems to an extent that no single instrument could reasonably be expected to provide. For example, in the study of the cloud seeding potential of winter mountain storm systems, it was found that a synergistic combination of polarization lidar (for locating supercooled water cloud layers), millimeter wave radar (for studying storm structure and estimated cloudtop height), and dual-channel microwave radiometer (for obtaining path-integrated liquid water amounts) were, along with balloon soundings, sufficient for providing the information necessary to determine if cloud seeding criteria were being met [Sassen, p. 207].

The multiple remote sensor technique was also shown to be highly appropriate for the study of high level cirrus clouds [Sassen et al., 1989, 1995], where in particular the combined lidar and mid-IR radiometer (LIRAD) approach has yielded important data on the optical properties of clouds in the visible and infrared spectral regions [Platt, p. 185; Platt et al., p. 223].

Finally, advancing lidar technologies have permitted the expansion of lidar cloud observing capabilities to outright hostile environments. A major development occurred beginning in the late 1970s, when a U2 spy-plane wing pod was equipped with a polarization lidar system capable of unattended operation at altitudes of up to ~25 km [Spinhirne et al., p. 199 and 1983]. The view from the stratosphere provided an unparalleled top-down image of atmospheric dynamics and cloud content, which undoubtedly contributed toward the extreme effort involved in the Earth-orbiting shuttle-based lidar observing system called LITE-the Laser In-space Technology Experiment [Winker et al., p. 270].

Back on Earth, although more sophisticated lidar sprectral techniques, such as high spectral resolution lidar [Grund and Eloranta, 1991] and Raman lidar [Ansmann et al., 1992 and p. 305], display the potential for obtaining intrinsically calibrated cloud extinction measurements, these methods also benefit from the addition of polarization diversity to improve cloud content analysis and for testing calibrations [Sassen, 1995].

Technological developments in terms of sufficiently high-energy but eye-safe lidars for continuous cloud observations (to replace the height-limited ceilometers currently in use) have recently come on-line [Spinhirne, p. 246]. Significantly, for the first time the operation of such a "micropulsed" lidar is in the process of accumulating a continuous multiyear climatology of cloud properties at the DOE Southern Great Plains Clouds and Radiation Testbed (CART) site, a heavily instrumented facility dedicated to climate-related research. Mobile lidar systems also regularly participate in special aircraft-supported cloud studies at the CART site to refine the cloud content data retrieval algorithms currently under development, a major remote sensing application that will no doubt be increasingly relied on in the future in cloud and climate research.

Raman Lidar

The first demonstrations of the use of the Raman technique for remote measurement of molecular constituents (nitrogen and oxygen) were made by Leonard [p. 289] and Cooney [p. 291]. Melfi et al. [p. 296] made the first water vapor measurements. Inaba and Kobayasi [p. 294] did a systematic study of the use of Raman lidar for the remote measurement of a number of pollutant molecular species. While the Raman lidar approach has the advantages of simplicity in that one laser line, preferably in the near-UV spectral region, where the Raman cross-section is greater, can be used for a number of molecular species, it suffers in general from reduced sensitivity and difficulty in daytime operation due to the low Raman cross sections.

Melfi and Whiteman [p. 300], however, reinvigorated the Raman lidar field by their brute-force demonstration of water vapor measurements to an altitude of 5 km. They used a frequency-tripled Nd:YAG laser (355 nm) and a 1.5 m diameter searchlight mirror for the receiver. While Raman lidar measurement of pollutant species did not develop far due to short measurement range and competition from the DIAL technique, the Raman lidar technique has become a standard procedure for nighttime ground-based measurement of water vapor to 8 km and daytime measurement to about 3 km [Whiteman et al., p. 316].

Resonance Fluorescence Lidar

Since quenching is not a problem in the upper atmosphere, fluorescence from its naturally occurring atoms and molecules may be detected easily by lidar. This technology, now matured, permits the detection of metal species (Na, K, Fe, Ca, etc.) as well as measurement of winds and temperature in the mesopause region, between 80 and 110 km, where fascinating phenomena (e.g., auroral arcs, noctilucent clouds) exist along with a counter-intuitive thermal structure of cooler summer than winter. Investigating this region of Earth's atmosphere with fluorescence lidar has been motivated by scientific curiosity from the start. In addition to dynamics, the atmosphere lidar has been used to probe notable events, such as noctilucent clouds [Hansen et al., p. 242] in cool polar summer nights.

After the first observation of mesopause Na atoms, measurements of Na density profile and column abundance were made by several groups in the 1970s [Sandford and Gibson, 1970; Hake et al., 1972; Blamont et al., 1972; Kirchhoff and Clemesha, 1973; Mégie and Blamont, 1977]. Seasonal variations in Na density were reported quite early [Gibson and Sandford, 1971].

Lidar measurements of atmospheric potassium [Felix et al., 1973], lithium [Jegou et al., p. 350], Ca and Ca^+ [Granier et al., p. 368], and the much more abundant iron atoms [Granier et al., 1989] followed. Such observations permit assessment of meteoric origin of these atoms and ions by comparing their relative abundance to that in the meteorites. To substantiate the meteoric origin, lidar has been used to observe sporadic Na [Clemesha et al., p. 344; von Zahn et al., p. 372; Kwon et al., 1988] and Fe layers [Bills and Gardner, p. 376; Alpers et al., 1990].

Recent works have revealed the correlation between sporadic E, Ca^+, and metal species (Na and Fe) [Gardner et al., p. 400] and between low geomagnetic latitude and the frequency of sporadic Na layer formation [Nagasawa and Abo, 1995]. In addition, meteoric trails [Kane and Gardner, 1993] were observed and mesopause sodium and potassium layers were simultaneously measured, suggesting a varied Na/K abundance ratio between a low summer (~ 10) to a high winter (~ 50) value over southern France [Mégie et al., p. 335].

Lidar observation of atmospheric Na density profiles was continued on a regular and/or campaign basis in the 1980s and 1990s, mostly by Gardner's group in Illinois (40°N, 88°W) and by Clemesha's group at the Instituto de Pesquisas Espaciais, Brazil (23°S, 46°W). Analysis of 15 years of Na density profiles revealed a long-term decreasing trend in centroid height, a possible evidence for global change [Clemesha et al., p. 380]. Gravity and tidal wave parameters have been intensively investigated since 1985 [Batista et al., 1985; Gardner and Voelz, 1985]. Both fluorescence and Rayleigh lidar data are being used increasingly by different groups for this purpose [Senft and Gardner, 1991; Whiteway and Carswell, 1994].

By reducing receiver bandwidth, daytime observation of the atmospheric Na layer was first reported by Gibson and Sandford [p. 333] and later by three different groups [Clemesha et al., 1982; Granier and Mégie, 1982; Kwon et al., 1987]. These investigations negated the notion of daytime abundance enhancement deduced from dayglow measurements and provided data for tidal investigations.

The first observation of the atmospheric Na ground-state hyperfine structure population was reported, establishing the possibility of mesopause temperature (and wind) measurements with a fluorescence lidar [Gibson et al., p. 348]. To investigate thermal and dynamical structures of the mesopause region, lidar techniques for routine measurements of temperature and wind profiles have been of major interest since the mid-1980s. To determine Doppler broadening (and thus temperature) and Doppler shift (and thus wind) of laser induced fluorescence from atmospheric metal atoms, a narrowband (~ 100 MHz) tunable laser system is required. The Bonn University group [Fricke and von Zahn, p. 354] developed an excimer-pumped dye laser system and were able to measure mesopause temperature profiles by tuning and monitoring the frequency of each laser pulse. Their measurements in Andøya, Norway, resulted in several significant publications, leading to an understanding of the temperature structure of a polar mesopause [Lubken and von Zahn, 1991].

A narrowband lidar transmitter using a pulsed dye amplifier seeded by a cw ring dye laser and tuned to the Doppler-free features at the D_{2a} peak and crossover frequencies to take the advantage of the temperature sensitivities was developed by She's group at Colorado State. The first lidar observation of midlatitude mesopause temperature profiles [She et al., 1990] was carried out at Fort Collins, Colorado (41°N, 105°W), in collaboration with Gardner's group using this narrowband lidar transmitter and a transportable receiver along with data collection and analysis software from the University of Illinois. The possibility of measuring Doppler wind velocities with this lidar was mentioned in this first paper. The initial error budget for mesopause temperature and wind measurements [Bills et al., 1991a] and the laser tuning technique and associated spectroscopy for characterizing and controlling the narrowband transmitter [She et al., p. 384] were discussed.

Soon afterward, two more lidar systems of this type were in operation, one at Urbana, Illinois (40°N, 88°W), and the other at London, Ontario, Canada (43°N, 81°W). Initial horizontal wind measurements have been made by tuning the lidar to four frequencies with a stabilized Fabry-Perot etalon [Bills et al., 1991b] and to three frequencies with an acousto-optic modulator [She and Yu, 1994]. A concise summary on the principle as well as measurement potential of the Na wind/temperature lidar was then published [Gardner and Papen, 1995].

Considerable new geophysical results have been reported by the Illinois and Colorado State groups. Their initial lidar observations revealed the midlatitude thermal structure [Bills and Gardner, 1993], and contrary to COSPAR International Reference Atmosphere (CIRA 1986), two prevailing temperature minima in the mesopause region were observed [She et al., p. 396]. Gravity wave parameters including the Brunt-Vaisala frequency can be determined directly from the measured temperature profiles [She et al., 1991]. Regular nighttime temperature observations at Urbana, Illinois, and Fort Collins, Colorado, led to the first description of seasonal temperature variations in the mesopause region [Senft et al., p. 409]. An improved midlatitude temperature climatology followed [Yu and She, 1995].

Atmospheric winds in the mesopause region, which may be probed by measuring Doppler shift with a fluorescence lidar, are also very important. Since the vertical wind speed is typically a few centimeters per second, lidar measurements of the vertical component of wind velocity is a challenge. With both measured vertical wind and temperature profiles, the profile of the heat flux of the middle atmosphere can be determined [Tao and Gardner, 1995]. Using dual beams pointing symmetrically away from the zenith, the momentum fluxes of gravity waves may be determined from the measured variances of radial winds [Vincent and Reid, 1983].

Since most lidar measurements presently can only be conducted at night, daytime geophysical information is badly needed. The capability to reject sky background effectively, allowing routine daytime lidar operation, is another challenge. As mentioned, early efforts using a Fabry-Perot interferometer in the receiver have demonstrated the feasibility of daytime Na density measurement. However, no long data set on daytime measurements exists at this point. Recent use of a robust Na-vapor Faraday filter has rekindled hopes for regular 24 hour continuous observations with narrowband fluorescence lidar. The demonstrated high detected signal to background at high noon [Chen et al., p. 417] has made daytime measurements of temperature, winds, and Na density a real possibility.

New lidars are continuously being proposed and developed. A tunable solid-state alexandrite laser has been explored as a versatile source for measuring metal atoms and ions in the mesopause region. After a decade of development, the first report on mesopause temperature measurements using a narrowband alexandrite laser probing atmospheric potassium atoms was recently published [von Zahn and Höffner, p. 413]. Although potassium abundance is an order of magnitude lower than sodium, this shortcoming could be offset by using an Alexandrite laser with higher power and much longer pulse width, making it competitive to the Na system.

On the other hand, using the sum-frequency technique to generate a beam at 589 nm with sufficient cw power can simplify the present Na pulsed dye system for future operation [Moosmüller and Vance, 1997]. By taking advantage of the population difference in two iron ground states separated by 2 nm, Gelbwachs [1994] has proposed an iron Boltzmann factor lidar using a broadband tunable laser for mesopause temperature measurements. Schemes for ultraviolet fluorescence lidars for remote sensing of the auroral ionosphere have recently been proposed [Garner and Dao, 1995].

Differential Absorption Lidar (DIAL)

The DIAL approach was conceived by Richard Schotland ca. 1964, shortly after the invention of the ruby laser. Schotland had been thinking about using searchlights to measure stratospheric ozone, but when he became aware of the ruby laser, he determined that the ruby laser line near 694.3 nm could be temperature tuned through some water vapor lines. His conference paper [Schotland, p. 423] was the first demonstration of the ability of a lidar system to measure the concentration of molecular species in the atmosphere. He named the technique DASE for differential absorption and scattering of energy, sometimes called DAS for differential absorption and scattering. However, this term had the connotation of daze or confuse, so M. Lattimer Wright of Stanford Research Institute, who was working on a study project for NASA Langley about space-based lidar systems, came up with the acronym DIAL, which was first published in Grant and Hake [1975].

The DIAL technique did not receive much attention between 1966 and 1973, primarily because it did not seem to hold out as much promise as the Raman scattering technique [e.g., Inaba and Kobayasi, p. 294]. This changed with the publication of Byer and Garbuny [p. 431], which presented systems calculations showing that the DIAL technique would have significant long-range advantages over the Raman scattering technique. Rothe et al. [p. 448], who had set up a rooftop experiment in Cologne to measure NO_2 using the fluorescence technique, quickly converted to the DIAL technique after reading Byer and Garbuny's paper. Grant et al. [p. 456] followed soon thereafter with a calibrated remote measurement, using a known concentration of NO_2, and the pace rapidly accelerated. Murray et al. [p. 461] demonstrated the first CO_2 laser DIAL measurements of water vapor. The 1970s and early 1980s saw a number of races to demonstrate the DIAL measurements of many new species in the UV, visible, and IR spectral regions.

In the 1980s, attention started to turn to more careful considerations of the error sources in DIAL measurements; one of the early papers was that by Schotland [p. 441]. Killinger and Menyuk [p. 476] reported on turbulence-induced correlation on pulsed lidar systems using topographic targets, and Menyuk and Killinger [1983] extended the analysis to include a number of error sources for the mid-IR spectral region using CO_2 lasers and topographic targets. Browell et al. [p. 501] discussed how to process ozone DIAL measurements in the presence of spatially inhomogeneous aerosols. Ismail and Browell [1989] and Grant [1991] discuss error sources for water vapor measurements in the near-IR spectral region.

By the early 1980s, DIAL systems had been well enough developed that they could be used in field campaigns to study such molecular species. Semitrailer or van-mounted systems were used in a number of countries to measure sulfur dioxide [Hawley et al., 1983], nitrogen dioxide [Fredriksson et al., p. 479], and ozone. That period also saw the development of the first airborne DIAL system, used to measure ozone [Browell et al., p. 488]. It has gone on to be used in over 17 international field campaigns to study both tropospheric and stratospheric ozone [Browell, 1989; Browell et al., 1996]. Ground-based excimer laser lidar systems are being used routinely to study stratospheric ozone [McDermid et al., p. 511; McGee et al., p. 521]. The Lidar Atmospheric Sensing Experiment (LASE) was developed as an autonomous water vapor DIAL system as a precursor to a space-based DIAL system [Browell et al., 1997].

While ozone and water vapor are the species most commonly measured using the DIAL technique, significant progress has been made in measuring other species as well. The reviews by Zanzottera [1990], Svanberg [1994], and Grant [1995] are the most recent reviews of DIAL. Some of the more interesting recent papers on DIAL topics include measurement of hydrocarbons [Milton, 1995], mercury [Ferrara et al., 1997], NO [Kölsch et al., 1992], and chemical warfare agents [Quagliano et al., 1997].

Rayleigh Lidar

The first determination of an atmospheric temperature profile from Rayleigh-lidar-measured atmospheric density was made in 1967 and credited to Sandford and collaborators in England, according to an early review article by Kent and Wright [1970]. Modern Rayleigh lidar based on a frequency-doubled Nd:YAG laser at 532 nm that can be used for routine atmospheric temperature and density profiling (between 35 to 70 km) was implemented at the French Observatory of Haute-Provence (OHP) by Chanin and collaborators [Hauchecorne and Chanin, p. 527]. Using the data collected, this group has reported the early lidar observations of gravity and tidal waves [Chanin and Hauchecorne, p. 531], planetary waves [Hauchecorne and Chanin, 1983], as well as mesospheric temperature inversion around 70 km [Hauchecorne et al., 1987]. The midlatitude temperature climatology and trends between 33 and 87 km were established by 11 years of Rayleigh lidar data [Hauchecorne et al., p. 538].

Depending on the receiver aperture used, temperature measurements beyond 90 km could be made by Rayleigh scattering [Meriwether et al., 1994; Sica et al., 1995]. Rayleigh lidar based on a frequency-doubled Nd:YAG laser is indeed a robust system and has been widely adopted. At the time of this writing, Rayleigh lidar stations for routine operation (often automated) have covered different longitudes from pole to pole.

Since the main application for Rayleigh lidar is the measurement of atmospheric state parameters, aerosol interference cannot be tolerated. Thus, much of the ongoing Rayleigh lidars are for the measurement of density, pressure, and temperature above 30 km, where aerosol is negligible. As the interest increases in problems involving different atmospheric layers, such as stratosphere-troposphere exchange, one needs to extend the measurement range of Rayleigh lidar to below 30 km. An effective method to reject aerosol interference is thus needed. By comparing the received rotational Raman scattering signal in two different frequency bands, temperature measurements down to 10 km has been demonstrated [Nedeljkovic et al., 1993]. Using an atomic vapor filter to reject aerosol scattering, a narrowband Rayleigh lidar, which has ~50 times more signal than the corresponding rotational Raman lidar, has been used to demonstrate the feasibility of atmospheric temperature and aerosol measurements using a dye-based transmitter system down to 1 km [She et al., 1992].

In addition to density and temperature, atmospheric winds in the middle atmosphere are of great interest. The frequency (Doppler) shift of Rayleigh scattered light from a narrowband laser may be measured with a Fabry-Perot interferometer to determine the line-of-sight wind. The first horizontal wind measurement between 25 and 60 km using a dual Fabry-Perot interferometer was again performed at the OHP [Chanin et al., p. 639]. Similar lidars are now in operation at Arecibo [Tepley et al., 1991] and ALOMAR [von Zahn et al., 1995]. Although the radar-blind altitude range between 25 and 60 km is important, with a larger receiving telescope, the measurement range can be extended beyond 60 km to 80 km. Advances in Doppler wind measurements in the troposphere, especially in the planetary boundary layer (below ~2 km) are discussed in the Doppler lidar section.

Doppler Lidar

The development of the Doppler wind lidar field, as with other lidar techniques, has been largely dictated by the laser physics and technology developments. By the mid-1960s the new laser field had developed to the point where researchers who were interested in optical communication applications recognized a way to use heterodyne detection of single-mode laser radiation as a leading technique. The CO_2 laser was the favorite, and high-speed detectors, operating at cryogenic temperatures, offered the needed bandwidth.

The use of the same technology for Doppler measurements was quickly realized in early demonstration experiments, with a paper by Huffaker et al. [p. 561] demonstrating the measurement of aircraft vortices. Continued development of CO_2 laser technology and 10-μm-wavelength detectors which could operate well at or above the liquid nitrogen temperature took place in the early 1970s. The NASA Marshall Space Flight Center group, in collaboration with Raytheon, began developing an airborne Doppler lidar instrument for atmospheric wind field measurements, with test flights taking place in the late 1970s and early 1980s [Bilbro et al., 1984 and p. 627].

The NOAA Wave Propagation Laboratory group meanwhile demonstrated atmospheric measurements with a ground-based pulsed Doppler lidar in 1981 [Post et al., p. 566]. Both the NASA MSFC and NOAA lasers were MOPA (maser oscillator power amplifier) designs using low-pressure gas discharges, requiring large volumes for only a few millijoules of pulse energy. Notable examples of the applications of the more compact Doppler lidars using cw laser transmitters in the early 1980s were the airborne instrument developed by the Royal Signals and Radar Establishment in the UK for true air-speed measurements [Woodfield and Vaughan, p. 572] and the portable scanning ground-based instrument developed by the German DFVLR group for atmospheric boundary layer wind profiling and for aircraft wake vortex studies [Köpp et al., p. 604].

The development of the atmospheric pressure TEA-CO_2 laser in the early 1970s, principally by the Canadians at the Defence Research Establishment Valcartier [Beaulieu, 1971], and the initial demonstration of a joule-class injection-seeded TEA laser transmitter for coherent lidar application at JPL [Mégie and Menzies, 1979] quickly opened up the opportunity for Doppler lidar groups to develop more powerful lidars to probe the atmosphere at large ranges and to collect data in relatively short time periods [e.g., Hardesty et al., 1988]. Doppler processors developed for these lidars utilized the heritage of Doppler weather radar signal processing techniques, and real-time displays of wind fields were produced using scanning lidars.

Much thought was given to an Earth-orbiting system which could measure wind fields in the troposphere on a global scale [cf. Huffaker et al., p. 590, and references to earlier NOAA reports therein; Menzies, p. 619; NASA, 1987]. The ground-based NOAA lidar [Post and Neff, p. 611] was used for measurements of wind fields in complex terrain (lee winds from mountains, canyon and valley winds, etc.), applications for which the use of Doppler radars is problematic. Ground-based and airborne lidars were applied to aeronautics and air traffic safety issues, with studies of wind shears, microbursts, wing-tip vortices, and clear-air turbulence.

In the late 1980s and early 1990s solid-state laser technology was utilized in Doppler lidar, due largely to advances made in injection-seeding techniques and to the advent of arrays of diode lasers as pumps. The diode-array pumping resulted in transmitters with much higher overall electrical-to-optical efficiencies. This laser technology helped to stimulate Doppler lidar development using both direct detection and coherent detection approaches.

The French CNRS group began studying the middle atmospheric dynamics using a direct detection Rayleigh Doppler lidar [Chanin et al., p. 639]. Groups from the University of Michigan [Abreu et al., 1992] and the NASA Goddard Space Flight Center [Gentry and Korb, 1994] began demonstrating direct detection Doppler lidars for boundary layer wind profiling. In the coherent detection arena the issue of eye safety [Menzies, 1989] fueled the development and use of the 2 μm laser devices [Henderson et al., 1991]. Doppler lidars using solid-state lasers have been used to provide wind profile data for shuttle launch operations [Hawley et al., p. 646], and more recently for atmospheric boundary layer studies and in aircraft for demonstration measurements of wind profiles both ahead of and below the aircraft.

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