S4-1 Development and Application of Coherent Doppler Lidar

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I. Introduction

For nearly two decades the Environmental Technology Laboratory has investigated the technology and applications of coherent lidar for atmospheric remote sensing. During this period, many new technological gains and insights into atmospheric processes have been gained, particularly in the area of atmospheric dynamics. Coherent lidar offers a means of measuring wind fields with high temporal and spatial resolution in the highly variable, non precipitating boundary layer and lower troposphere. Such an observational capability occupies an important niche in the arsenal of techniques that can be brought to bear to improve fundamental understanding and develop better models for characterizing the atmospheric state.

II. Coherent Lidar Technology

Coherent Doppler lidars typically operate in the middle infrared at wavelengths between 1 and 10 micrometers. At these wavelengths, because available detectors are characterized by high noise figures, coherent detection enables higher signal to noise ratio than can be obtained with direct detection of weak, atmospheric backscatter signals. A prime attribute of coherent detection is the capability to measure the relative phase of the backscattered signal, and hence its frequency. This attribute led researchers in the 1970's to suggest the use of coherent lidar for measuring atmospheric winds by computing the Doppler shift of radiation backscattered from small atmospheric aerosols.

Most early work utilizing coherent detection involved carbon dioxide laser sources operating in the 9-11 μm spectral region. In the late 1970's, NOAA Wave Propagation Laboratory (now the Environmental Technology Laboratory, ETL) initiated a study aimed at examining the feasibility of deploying a CO_2 coherent lidar on an earth orbiting satellite to measure wind fields over the entire globe. This concept has proven to be an elusive goal over the past two decades. However, the study led to development at ETL of a demonstration 1-J per pulse CO_2 lidar for measuring winds(Post and Cupp, 1990). This lidar has been extensively utilitized over the past decade in a wide variety of investigations of dynamical phenomena in the atmosphere.

Although CO_2 technology is relatively efficient and has been well established over the years, it has some disadvantages for spacebased applications. Detectors in the 10 μm spectral region require cooling, adding weight and power to the payload. A multi-joule CO_2 lidar would be relatively large and heavy, a disadvantage at a time when money is tight such that compact, lightweight instruments are preferred. Consequently, despite the overall capability for CO_2 lidar technology to meet the spacebased challenge, significant effort has been put forth over the past decade to develop solid state lidar technology for coherent lidar systems. Solid state lidar sources operating in the 2 μm spectral region, in addition to their potential for small size and reliability, also enable the development of lidar systems with high spatial resolution and measurement accuracy..

At ETL, we have investigated the use of end-pumped Tm,Lu:YAG transmitters operating in the low water vapor absorption window at 2.022 μm. We have developed a low energy (3 mJ), high spatial resolution (30 m), high pulse rate(500Hz) Doppler lidar for applications in boundary layer turbulence and flux studies (Grund et al, 1997). The instrument has been applied in several field studies to provide high resolution characterization of atmospheric winds and turbulence fields (see Section IV).

For spacebased applications, instruments with two to three orders of magnitude more pulse energy are required. The transmitter for the now-canceled- SPARCLE space shuttle demonstration Doppler lidar was designed to produce 100 mJ pulse energies at a pulse rate of 6 Hz.

III. Measurement of Mesoscale Flows

The 1-J CO_2 ETL lidar retains its position as a unique instrument for investigations of mesoscale flows in clear air. Its extended range (to 30 km) enables probing of a variety of atmospheric phenomena. Examples of applications of the lidar include structure of downslope windstorms, mountain wave induced rotors and their effect on commercial aircraft, mountain and valley flows as transporters of air pollutants, characterization of radial wind shear encountered by the space shuttle, and convective initiation by thunderstorm outflows. During the fall of 1999 the lidar will be deployed in the Brenner Pass in Austria as part of the Mesoscale Alpine Programme intensive field study to investigate the initiation and development of severe gap flows.

In 1995, the ETL 1-J lidar was modified for deployment on the NASA DC-8 research aircraft as the Multi-Agency Coherent Atmospheric Wind Sensor (MACAWS, Rothermel et al, 1998). The MACAWS instrument employs sideward looking fore and aft scanning to provide measures of horizontal wind structure over a 3-dimensional volume extending to 25 km from and about 8 km above and below the aircraft. During 3 airborne lidar field campaigns, the MACAWS lidar has been applied for observations of 3-dimensional flow around a coastal headland, flow through a mountain barrier, and measurement of hurricane eyewall winds.

IV. Studies of vertical motion and turbulence

Smaller scale turbulent processes within the planetary boundary layer are important in characterizing the vertical transport of atmospheric constituents, latent and specific heat, and momentum between the surface and the free atmosphere. Measurement of turbulence quantities requires lidar instruments with good spatial resolution, high accuracy, and small minimum range to provide the necessary observations within the boundary layer. To address boundary layer issues, two compact boundary layer lidars have been developed at ETL. The 3 mJ solid lidar (known as the High Resolution Doppler Lidar, HRDL), introduced in section II, provides high spatial resolution measurements to ranges of 4 km and heights of 2-3 km. Observations from this instrument have been used to estimate momentum and turbulence kinetic energy profiles in a daytime mixed boundary layer, to estimate heat flux between the surface and the free atmosphere, and to identify shallow nocturnal low level jet flows that exist within a few tens of meters above the surface. During the 1999 Nauru 99 experiment, this instrument was deployed with large suite of microwave and optical remote sensors on a NOAA research ship in the tropical western Pacific ocean to study cloud and radiative transfer processes in that region. The ship-based investigation also was aimed at characterizing the representativeness of the the Department of Energy Atmospheric Radiation Measurements (ARM) site on Nauru island as a mid ocean site. During this cruise the lidar performed exceeding well despite the rather difficult shipboard operating environment.

ETL has also developed a second Doppler lidar for boundary layer and cloud studies. The mini-MOPA Doppler lidar (Brewer et al, 1997) is a CO_2 lidar with high pulse rate (400 Hz), high accuracy (cm s^{-1}), reasonable spatial resolution (90 m) and reasonable sensitivity despite its low pulse energy (2 mJ). During June and July 1999 the mini-MOPAlidar was operated 24 hours per day for 3 and 4 days at a time as part of the Nashville Southern Oxidants Study air quality experiment. The instrument observed vertical transport and turbulence during the day and horizontal transport and low jets after sunset. Primary goal of the experiment was to investigate the relationship between surface *in situ* ozone and ozone precursor measurements, and the vertical and horizontal transport processes observed by the lidar.

The mini-MOPA lidar was designed as a dual wavelength instrument to enable simultaneous wind, aerosol and differential absorption lidar (DIAL) water vapor measurements. The lidar can be operated at alternating wavelengths on and off the 10R(20) water vapor absorption line when water vapor profile information is desired. Tests of path averaged water vapor measurements over a 3 km path have yielded accuracies of better than 10%.

Although the mini-MOPA and HRDL instruments are similar in many respects, performance and applicability can vary depending on the atmospheric condition and the specific measurement objective. For example, modeling verified by observational data indicates degradation of coherence along the propagation path due to atmospheric turbulence can significantly degrade the performance of the HRDL instrument at ranges as short as a few km.. This can significantly limit performance for horizontally pointing applications, such as characterization of the spatial variability of the wind field. On the other hand, the significantly better range resolution of the 2 μm lidar makes it well-suited to studies of vertical velocity, turbulence kinetic energy, and momentum flux. The presence of both HRDL and the mini-MOPA enables us to choose the most suitable system, or even combine instruments, to obtain the desired objective.

V. Spacebased Lidar measurements of winds

Coherent Doppler technology deployed on an earth-orbiting satellite has been proposed as a potential technique for providing valuable measurements of global wind fields. Modeling studies indicate that measurements of wind fields over the oceans and in other data sparse regions can significantly improve analysis and forecasting of the earth's atmospheric state. Current research is aimed at applying 2 μm solid state lidar technology to the problem of designing a suitable spacebased instrument.

Several critical measurement issues must be addressed and resolved to obtain good lidar wind measurements. These include eventual development of a reliable, stable, 2 μm solid state operating at 1-J levels or more, demonstration that the required short term pointing accuracy of on the order of 10 μr can be maintained, demonstration of long term pointing knowledge, and clear demonstration of signal estimation techniques at very low signal levels.

The SPARCLE coherent lidar space shuttle mission was designed to resolve many of these issues Scheduled for launch in early 2001, the mission would have employed a 100 mJ laser transceiver and 0.25 m diameter telescope to measure winds from clouds and boundary layer aerosols. Modeling studies and scaling of ground-based lidar returns indicated that such a mission would yield significant science and technological value. Recent cost problems, however, appear to have placed the mission in jeopardy, at least in its present form. If the SPARCLE mission is indeed canceled, additional experiments from ground-based and airborne platforms, in parallel with lidar technology development, likely will be the near-term path of progress for eventual spacebased wind measurements.

VI. References

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