Doppler Lidar Observations of Hydrometeors

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ABSTRACT

Significant Doppler lidar returns have been observed from snow and rain. This demonstrates the feasibility of measuring velocity and range of hydrometeors with 10.6-μm wavelength CO_2 laser lidar.

1. Introduction

The application of visible wavelength lidar to meteorological aerosol distribution problems has been reviewed by Collis (1970) and others. An extension of the lidar concept to include Doppler-shift information from aerosol particles allows remote measurement of mean wind velocity (Lawrence *et al.*, 1972). This work, based on homodyne detection (in the radar sense) of the Doppler-shifted backscatter from the aerosols, requires a CO_2 laser for ranges of 30 m or more in the turbulent atmosphere.

Our work extends the concept of lidar detection of aerosols to the detection of hydrometeors in the atmosphere. The advantages of the 10.6-μm CO_2 laser wavelength for hydrometeor lidar, compared to visible wavelengths, include such factors as: 1) lower sky background noise power, 2) eye safety, 3) much smaller refractive effects from the turbulent atmosphere, 4) larger backscatter-to-forward-scatter ratio, 5) superior haze and precipitation penetration, and 6) greater laser power conversion efficiency and frequency stability. However, water is much more strongly absorbing at a 10.6 μm wavelength than at visible wavelengths, and it was not clear from previous work that hydrometeors would yield a detectable lidar signal.

Detecting the fall velocity and particle density of hydrometeors has such applications as objectively classifying precipitation type, remotely detecting precipitation above a region of sea spray, and estimating precipitation rate.

2. Apparatus

A frequency-stable, single-longitudinal-mode CO_2 laser served as transmitter and local oscillator for the system. This unit operated at an average power of 1 W, cw. The backscattered signal was mixed with the local oscillator on a cooled Hg:Cd:Te infrared detector, which has a flat frequency response to at least 10 MHz. This detector was illuminated by using a NaCl beamsplitter set to deflect some of the laser energy through a NaCl lens to the detector element.

A 30-cm modified Gregorian telescope could be optionally used as both a transmitter and receiver element. When the telescope was used, the probed volume of the atmosphere was the small focus volume of the system, $\sim$5 cm^3. When no telescope was used, returns came from a much larger region of the precipitation, estimated to be 2 cm diameter by 15 m long. The angle of view of the horizontal optical system was directed upward at 45° elevation through an open laboratory window. Fig. 1 indicates schematically the layout.

The detector signal, after amplification by a broadband preamplifier, passed to a swept-filter spectrum analyzer. Data consisted of observed or photographed

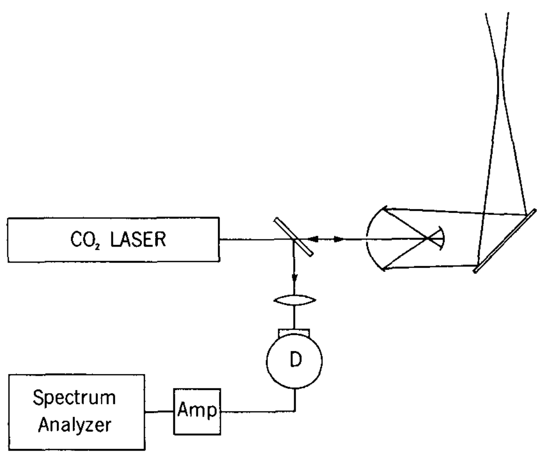

FIG. 1. Schematic of experimental apparatus. The CO_2 laser emission is transmitted either directly or through a focusing telescope. Colinear backscattered radiation is reflected from the laser output mirror and/or is nonresonantly amplified in a double pass through the laser discharge. The beamsplitter samples the return together with the laser main beam as local oscillator.

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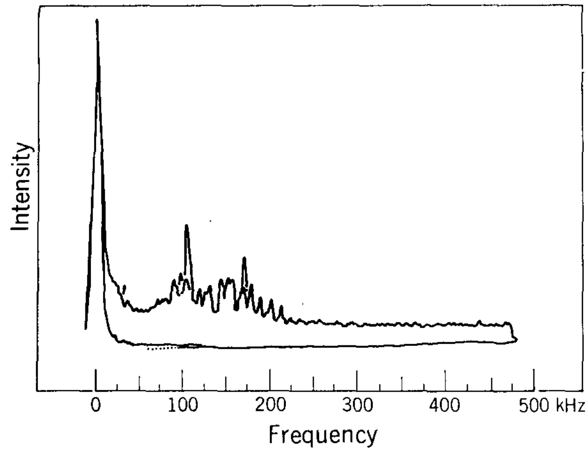

FIG. 2. Typical Doppler lidar return from snowfall for a Doppler calibration of 188.9 kHz per m sec^{-1} of radial velocity component. Analyzer scan time 20 msec, 1 kHz filter width, 500 kHz scan width.

calibrated spectrum-analyzer oscilloscope displays. Intensity peaks as a function of frequency identify the velocities of the scattering particles in the beam as well as giving more qualitative information on particle velocity and number density distributions.

3. Observations

With the telescope in the system, the Doppler signal from hydrometeors was very intermittent. At a range of $\sim$15 m with the 5 cm^3 focal volume, only individual particles were observed during a sampling period $\leqslant$1 sec. Integration of the spectrum analyzer output for 10^3 sec or more in a digital averager is required to make useful observations on particle distributions with close-focus optics. A detected Doppler burst occurred when a hydrometeor passed through the sampling region at the instant the spectrum analyzer was sweeping the frequency appropriate to the particle velocity. For a spectrum analyzer duty cycle (filter bandwidth$\div$frequency sweep) of 2%, the signal observation rate with the telescope was approximately 0.05 sec^{-1}, for cases similar to the snow observations discussed later.

Removing the telescope sacrifices range information for an enlarged (indefinite) spatial sampling volume. With such a sampling volume in snowfall, for example, an essentially continuous Doppler signal was observed. A significant feature was the adequate homodyne signal level, even with small collection optics of less than 5 mrad receiver aperture.

Fig. 2 is redrawn from a typical snowfall observation. Signal peaks occur at 100 and 170 kHz, although it is obvious that a wide range of frequencies from approximately 75 to 200 kHz were generated by the hydrometeor scatter. Applying the Doppler calibration factor (Lawrence *et al.*, 1972) of 188.9 kHz per m sec^{-1} for 10.59-μm radiation to the intensity peaks, radial hydrometeor velocities of approximately 0.53 to 0.90 m sec^{-1} are indicated. If we assume vertical fall with a measured 45° lidar elevation angle, hydrometeor fall velocities of 0.75 to 1.27 m sec^{-1} are suggested, which is reasonable for snowfall (Langleben, 1954).

Interpreting Fig. 2 requires some care since the data represent neither a time average nor an instantaneous average over a large number of particles in a distribution. Significant changes in the Doppler spectrum occurred over intervals of a few seconds. The two signal peaks represent aggregates of a few particles or ranges where different radial velocities occurred. Some of the substructure may have been due to orientational motion of the snow or to microscale turbulent fluctuations. The spread in observed fall velocities is larger than expected for the free atmosphere. Flow perturbations near the building affected the velocity distribution, particularly the spread.

Data similar to those in Fig. 2 were observed from rain. Of course, the signal peaks occurred at higher frequencies. Qualitatively, the rain return was less intense and more intermittent then the snow backscatter, but the rain data showed less spread in velocity space. Generally, one expects a larger percentage velocity spread for rain than for snow, in contrast to these observations. The anomalously large spread in snow data, due to flow perturbations, explains the relative differences. Rain fall velocities were in the range expected from Gunn and Kinzer (1949).

The apparatus is not yet suited to a meaningful quantitative measurement of backscattered intensity or comparison of snow and rain signal magnitudes. Mie theory is likewise not developed sufficiently to calculate snow backscatter at the large size parameters involved in the 10.6 μm lidar. The principal objective of the experiment, to test the observability of hydrometeors by means of 10.6-μm Doppler lidar, is supported by the spectrum-analyzer data.

4. Extensions and conclusions

An expansion of the sampling volume for the telescope-based system, by extending the useful range or reducing the primary mirror diameter, would reduce the intermittency problem. Even more improvement in signal rate, while still retaining the range information that is lost with the unfocused setup, would accrue from substituting a frequency-tracking heterodyne filter for the low-duty-cycle, scanning spectrum analyzer. A tracking filter operates with essentially 100% duty factor for the peak-intensity component in the frequency spectrum.

Sophistication of the optical system, including increased laser power, is an obvious possibility for increasing signal level and effective range. Our reported experiment was not signal-level limited for the

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close ranges studied, even in the unfocused case where the effective signal-collection optics were very small. We plan quantitative measurements of backscatter intensity from hydrometeors to clarify the signal-level question.

The addition of fall velocity information to transmissometer data on snowfall rate (Robertson, 1973) should serve to refine or possibly supplant such rate data, for example.

Hydrometeor velocities, velocity distributions, and information on number density are accessible to 10.6-μm Doppler lidar sensing techniques. Such lidar measurements have specific advantages (and limitations) with respect to visible lidar and radar probes of similar variables. Studies related to hydrometeor identification, classification, and motion in an automated, unmanned observing station as well as to severe storm investigations may well utilize the interaction of hydrometeors with CO_2 laser Doppler probes.

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