Multiple-pulse coherent laser radar waveform

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Introduction

A pulsed CO_2 (10.6μm) coherent lidar was developed that has unprecedented combined spatial and Doppler resolution by coherently combining many pulses. The resulting system is capable of measuring the motion of aerosols, and hence the air, with a precision of better than 0.5mm/s and a range resolution of about 2m.

A typical CO_2 lidar (MACAWS)[1] has $\Delta V = 1$m/s velocity resolution with a range resolution of $\Delta R = 300$m. Measurement of wind in a single pulse is limited to a velocity-range product of

$$\Delta V \Delta R \geq \frac{c\lambda}{8\pi}$$

For $\lambda = 10.6$μm, this product is about 100m^2/s. However, by coherently combining many short laser pulses, it is possible to increase the coherent integration time, thereby improving the Doppler resolution while still retaining fine spatial resolution. This is not possible in a conventional system because each pulse is emitted with a random optical phase. The present system achieves 10^{-3}m^2/s, an improvement of about five orders of magnitude, enabling the remote sensing of wind and turbulence with unprecedented resolution. While this technique is well known in the field of microwave radar,[2] to our knowledge it has not been applied in the optical domain.

Experiment

Figure 1 is a schematic diagram of the optical layout. The transmitter is a single-frequency, RF excited CO_2 laser operating on the 10P20 line with a pulse width of 13ns (FWHM). It was repetitively pulsed at 130kHz, resulting in an average transmitted power of 10 W. The lidar returns were mixed with light from a discharge-pumped cw laser (the local oscillator, LO) on a cooled (77K) HgCdTe detector. A thin-film polarizer (TFP) and quarterwave plate (QWP) were used to separate the transmitted from the returned light in this monostatic system. The LO was frequency shifted by 200MHz with an acousto-optic modulator (AOM). The final mirror was 30cm in diameter, though only about 20cm were used. A small fraction of the transmit beam was diverted to a White cell, delayed, and redirected to the detector to measure the phase of each transmit pulse relative to the LO. This phase is subtracted from the phase of the lidar return, resulting in a pulse-to-pulse coherent waveform. This is equivalent to a coherent cw waveform sampled at the pulse repetition rate, with the consequence that the Doppler spectrum is aliased at that rate.

The electrical signal from the detector is amplified (47 dB) and fed into a I/Q baseband converter. The RF signal from the detector is mixed with in-phase and quadrature versions of the 200MHz signal used to drive the AOM. The mixer signals are amplified (17 dB) and bandpass filtered (BP, 100 MHz) to produce in-phase and quadrature baseband versions of the RF signal. These signals are digitized in two, 500 MSa/s, 8 bit digitizers on PCI cards with 2 GB of onboard memory in a Windows NT IBM-compatible computer. Every other sample is saved to file, resulting in 250 MSa/s data. This is reasonable since the analog data bandwidth is 100 MHz. The data are transferred over 100Base-T Ethernet to a dual-processor PowerMac G4 for analysis.

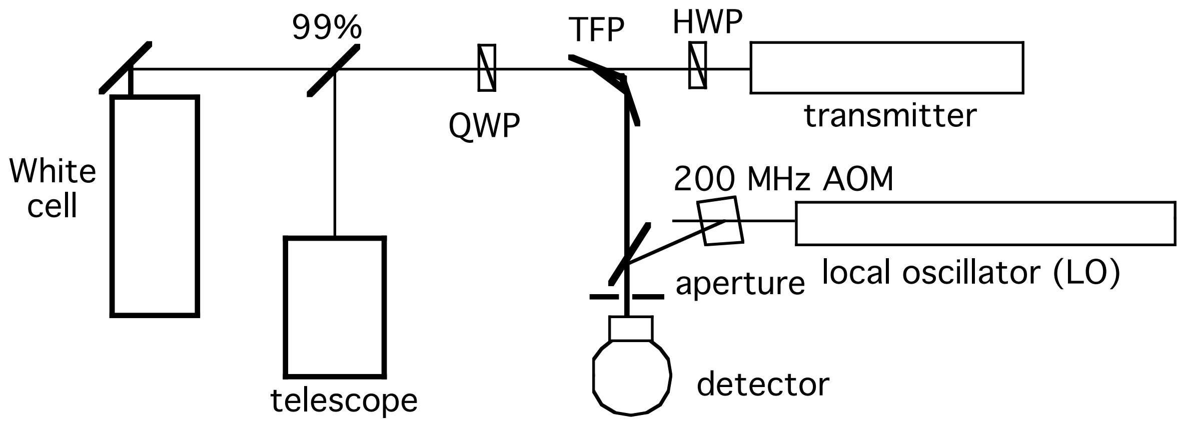


Fig. 1. Optical schematic diagram.

The transmit beam was focused to approximately a 2cm diameter waist at about 300m range. Figure 2 shows a typical plot of the returned heterodyne power as a function of range. For a diffraction-limited optical system and transmitter beam, the return signal is approximately Lorentzian function of range, proportional to[3]

$$\frac{1}{1+\left(\frac{z-z_f}{z_0}\right)^2}$$

where z is the range, z_f is the focus range of the lidar, and z_0 is the Rayleigh range.

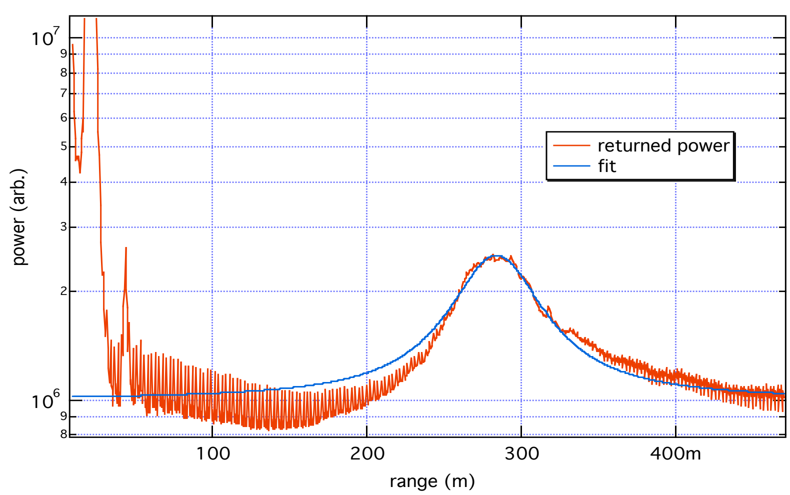


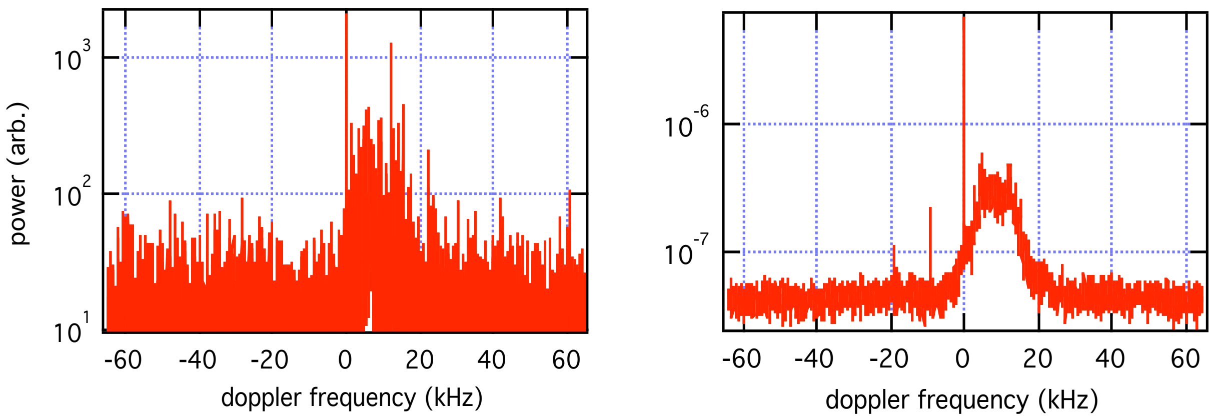
Fig. 2. Returned heterodyne power as a function of range.

The Lorentzian fit in Fig. 2 results in $z_0 = 32m$. This agrees well with the value calculated by assuming a gaussian transmit beam with a 0.1m $1/e^2$ power radius. At the time the data were taken (12:03am PDT, 0703 UTC, 4June2002), the weather was clear and the ground-level particulate measurement at the nearest monitoring station[4] was 30μg/m^3, roughly normal for this area and within a factor of two of typical values measured throughout the continental United States.

Applications

The coherent lidar described in the previous section provides full access to the amplitude and phase of the electric field of the aerosol scatter. The Fourier transform of the electric field is the Doppler spectrum of the aerosols, from which information may be deduced about their motion parallel to the laser beam.

Figure 3(a) is the instantaneous Doppler spectrum of a 2m range gate at 260m altitude, showing scattering by individual bright particles and a haze of smaller ones. The feature at zero frequency is an artifact. Figure 3(b) is the spectrum averaged over nearly one second, with a corresponding *rms* turbulent bandwidth of 5kHz or 2.5cm/s.



(a) single spectrum (0.03s) (b) time-averaged spectrum (0.8s)

Fig. 3. Doppler spectrum (30Hz resolution) of one 2m range gate at 260m altitude.

Doppler profiles such as the one plotted in Fig. 3 were used to calculate the turbulent dissipation rate, ε, from the expression

$$\varepsilon = 7\frac{u'^3}{L}$$

where u' is the *rms* turbulent velocity and L is the range gate length. The numerical factor in the equation is computed assuming a flat-topped range weighting. The vertical profile of turbulence in a 130m vertical interval is plotted in Fig. 4a as the beam was scanned conically at a 26^0 angle to the vertical. At the 1rpm rotation rate, the 0.8s horizontal axis corresponds to about 30m. The data were obtained at 4:50pm PDT (2350 UTC) 4Oct2002 with a 5.5m/s wind at about 300m altitude. Note the sharp boundary near 300m. Figure 4b shows a vertical profile of turbulence at night in calm wind (10:55pm PDT 3June2003, 0555 UTC). In this case, the profile shows stratification and higher levels of turbulence at higher altitudes.

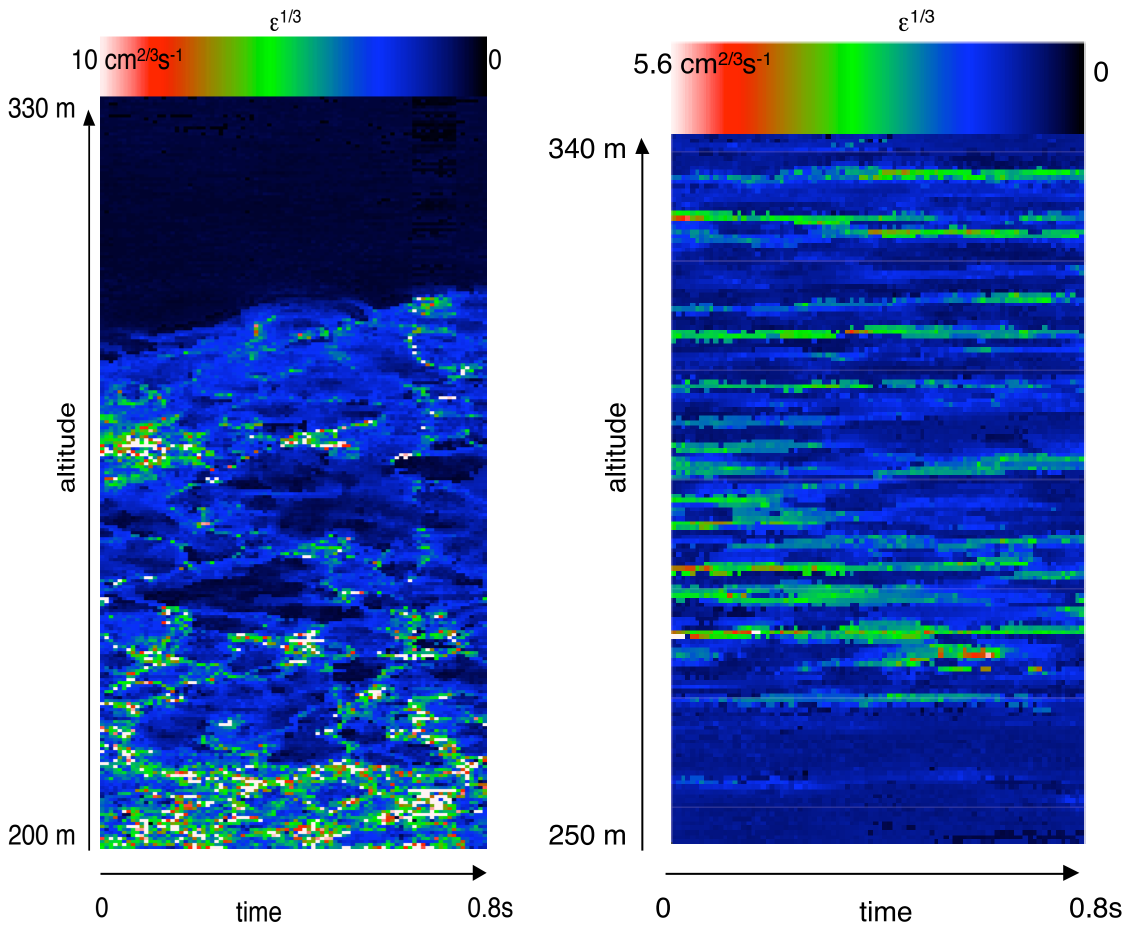


Fig. 4. Vertical turbulence profile (eddy dissipation rate).

Acknowledgments

The authors gratefully acknowledge the fast and user-friendly software written by Joon Choi and Reed Morrison, as well as the expert mechanical design of David Windisch. We are indebted to Christopher Bracikowski for helpful discussions and assistance with data analysis. This work was supported by the Defense Advanced Research Projects Agency under the supervision of Edward Carapezza and David Law, who provided many valuable suggestions over the course of the project.

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[1] Rothermel, J., L.D. Olivier, R.M. Banta, R.M. Hardesty, J.N. Howell, D.R. Cutten, S.C. Johnson, R.T. Menzies, and D.M. Tratt, 1998: "Remote sensing of multi-level wind fields with high-energy airborne scanning coherent Doppler lidar." *Optics Express* ,240-50 (1998).

[2] Nathanson, F.E., *Radar Design Principles*, Ch. 11(McGraw-Hill, New York, 1969).

[3] assuming gaussian transmit and BPLO beams, using the equations in R.G. Frehlich and M.J. Kavaya, "Coherent laser radar performance for general atmospheric refractive turbulence," Appl. Opt. **30**, 5325-5352 (1991).

[4] Southern California Air Quality Management District (SCAQMD) Alpha Telemetry System, Long Beach station. Concentrations at the location of the laboratory in Torrance, CA (about 15 km away from the station) are normally somewhat lower.