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RECENT DEVELOPMENTS IN SOLID-STATE 2-μm COHERENT LIDAR

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Introduction

Coherent lidar systems using solid-state lasers have proven to be useful sources for many remote sensing applications over the past several years. Because of their relative eye safety, Thulium (Tm) and Holmium (Ho) doped solid-state lasers operating near 2 μm have been and continue to be favored for many of the applications. A 30-mJ pulse energy, 5-Hz pulse repetition frequency (PRF), flashlamp-pumped 2-μm lidar has been utilized in several measurement programs, demonstrating the utility of 2-μm coherent lidar. More recently, diode-pumped 2-μm coherent lidars have been developed which are designed for higher average power, more efficient operation, and in a some cases for long-term autonomous operation. Below we provide a few examples of the measurement capability demonstrated by 2-μm coherent lidar and describe the status of the diode-pumped coherent lidar systems.

Flashlamp-Pumped 2-μm Lidar System Description

An earlier version of the flashlamp-pumped 2.09-μm solid-state coherent lidar transceiver is described in detail elsewhere.[1] The lidar transceiver uses a diode-pumped single-frequency cw Tm,Ho:YAG laser for the local oscillator source and to seed a flashlamp-pumped Q-switched Cr,Tm,Ho: YAG laser. The Q-switched laser is typically used in a configuration which produces ~ 30-mJ, 200-ns single-frequency pulses at a PRF of ~ 5 Hz. The pulsed output is expanded using a 10-cm-diameter off-axis telescope and directed into the atmosphere or toward the target using a two-mirror computer-controlled scanner. The scanner provides coverage over the entire "super-hemisphere" (0 - 360 degrees azimuth and - 25 - 90 degrees elevation). Backscattered radiation is collected by the same telescope and coherently mixed with the local oscillator radiation on a room-temperature extended-wavelength InGaAs photodetector. The resultant beat signal is amplified and digitized at 100 MHz prior to processing by a real-time digital signal processor (DSP) and display system. A 2.4m x 3.8m x 2m (W x L x H) truck-mounted compartment houses the entire lidar system.

Measurement Capability

This flashlamp-pumped lidar has been utilized in several measurement programs over the past 3 years. Here we provide a few examples of recent measurements.

The 30-mJ pulse energy system has demonstrated long range wind and atmospheric aerosol backscatter measurement capability. The maximum range at which accurate radial velocity measurements can be made depends on several factors, including the atmospheric backscatter, transmission, and refractive turbulence, and the number of pulses averaged. With 10 pulse averaging under clear atmospheric conditions, typical wind measurement ranges (accuracy < 1 m/s) are 10-20 km in the atmospheric boundary layer and to heights of 3-6 km.[1] The system has also been used to demonstrate hard target (mountainside) returns from 145 km range under clear atmospheric conditions.

Demonstrated velocity measurement accuracy with the 200-ns pulses from this system is described in detail elsewhere.[2] Single-shot measurement accuracy of <5 cm/s has been demonstrated against hard targets under high signal-to-noise ratio (SNR) conditions — SNR ~30 dB. Because of intra-pulse speckle effects induced by the pulse propagation, the measurement accuracy obtainable against distributed aerosol targets in high SNR is reduced compared to that against hard targets. Even so, we have demonstrated *single-shot* velocity measurement precision of ~0.6 m/s with simultaneous range resolution of ~55 m against atmospheric aerosol targets. With pulse averaging the velocity measurement precision is improved as $(N)^{-1/2}$, assuming pulse-to-pulse decorrelation and a stationary target during the time required to transmit the N pulses.

The shorter 2-μm wavelength, compared to CO_2 lidar systems, allows improved range resolution for a given velocity resolution, or improved velocity resolution for a given range resolution. The measurement of an aircraft wake vortex, shown in Figure 1, illustrates the simultaneous velocity and range measurement capability of the system. The measurements were made at Stapleton airport (Denver, CO) on June 17, 1993.[3] The figure shows the range height indicator (RHI) display of the radial velocity measured by the 2-μm lidar at two different times following the passage of a DC10 through the vertical measurement plane. The mean ambient radial velocity was ~2.7 m/s away from the lidar when the measurements were taken. The shaded regions indicate radial velocities below this mean value and the unshaded regions indicate radial velocities above this mean value. The radial velocity contours are separated by 0.5 m/s. The upper and lower traces show the radial velocity measurements ~20 seconds and ~40 seconds after the DC10 passed through the measurement plane in a landing configuration. The RHI scan plane was perpendicular to the aircraft flight path. The radial velocity signature of the aircraft wake vortex is the four-lobed pattern of alternating radial velocity located ~0.85 km from the lidar. Note that the vortex has drifted to a lower height and down wind during the 20 second time period between the upper and lower frames of the figure.

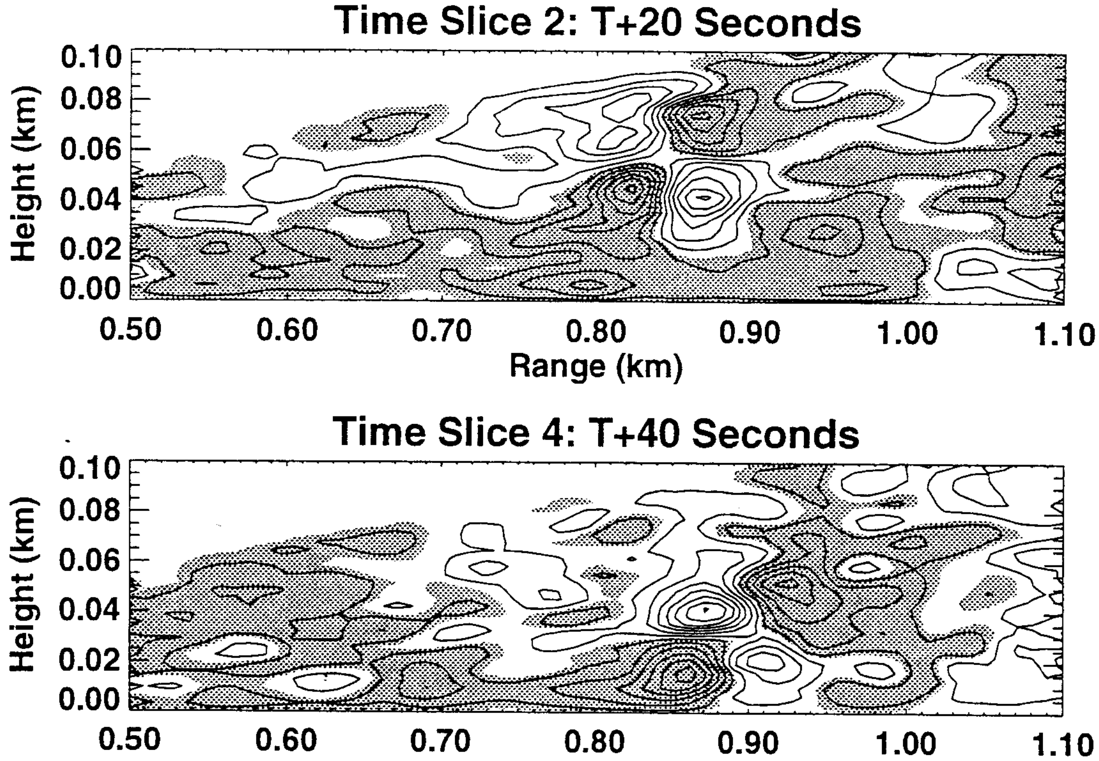

Fig. 1. Radial velocity contours measured by the 2-μm coherent lidar 20 seconds (upper) and 40 seconds (lower) following the flight of a DC10 through the vertical measurement plane.

A limited sample of calibrated atmospheric aerosol backscatter measurements have been made using the flashlamp-pumped system. Figure 2 shows median backscatter profiles measured with the system at the Kennedy Space Center (KSC), Florida and at Stapleton airport, Denver, CO. The data used to calculate the Denver mean profile consists of 12 profiles taken during the day between April 14 and June 28, 1993. The KSC data consists of only four profiles taken between January 12 and January 19, 1993. Even though the data sets are limited, the mean profiles provide examples of backscatter conditions and illustrate the measurement capability of the system.

Profiles were also obtained from altitudes greater than 7 km, but the backscatter returns dropped below the sensitivity limit of the system more frequently. The Denver profile begins at 1.8 km due to the ~1.6 km ground height. Each of the individual profiles that are used to calculate the mean profiles was obtained by averaging the returns from 400 - 1000 pulses. A target which has a known backscatter at 2 µm is used to calibrate the lidar before each measurement. Estimation of the effects of atmospheric attenuation and refractive turbulence are used in calculating the individual backscatter profiles from the raw data.

We have recently developed a more compact flashlamp-pumped coherent lidar transceiver using Tm:YAG lasers. This system produces up to 100 mJ pulse energies at ~2.02 µm and operates at a PRF of 6 Hz. The increased pulse energy will allow accurate measurements at greater ranges and/or under lower backscatter conditions. Near-diffraction-limited performance from the flashlamp-pumped laser at similar energies should be possible at ~10 Hz PRF with laser design improvements.

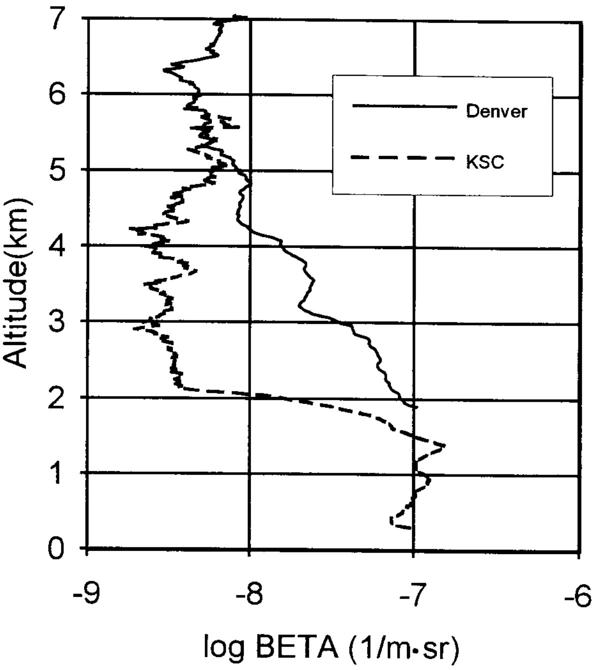

Fig. 2. Median atmospheric aerosol profiles measured at Kennedy Space Center, Florida and Denver, CO using the 2-µm coherent lidar.

Higher Average Power 2-µm Lidar Systems

Diode lasers can be used to replace flashlamps in pumping the pulsed 2-µm lidar transmitter, resulting in increased average power, PRF, and efficiency while maintaining near-diffraction-limited beam quality. Higher PRF systems are needed for many applications where the measurement volume is large or where the state of the atmosphere or target is rapidly changing. Diode pumped 2-µm lasers producing several watts average power and pulse energies of ~5 mJ at several hundred Hz have been demonstrated to date.[1] Very compact diode-pumped 2-µm coherent lidar transceivers at these average power levels and pulse energies have recently been demonstrated.[4,5] The diode pumped transceiver we have developed[4] produces 3.5 mJ pulse energies at a PRF of 200 Hz and is designed for autonomous operation onboard an aircraft for remote detection of microburst windshear.[6] We are currently developing higher power diode-pumped coherent transceivers capable of producing 10-30 mJ pulse energies at PRFs of several hundred Hz. The 30 mJ flashlamp-pumped lidar performance has shown that these pulse energies are useful for many ground-based and airborne applications. Compact and efficient diode-pumped systems with even higher energies at lower PRFs will be useful for very long range measurements. Lower PRF diode pumped 2-μm lasers producing higher pulse energies have also been demonstrated.[7-9] The status of the diode pumped technology will be summarized in the presentation.

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References

1. S.W. Henderson, P.J.M. Suni, C.P. Hale, S.M. Hannon, J.R. Magee, D.L. Bruns and E.H. Yuen, "Coherent Laser Radar at 2μm Using Solid-State Lasers," IEEE Trans. on Geoscience and Remote Sensing, 31, 4-15, (1993).

2. R. Frehlich, S.M. Hannon, and S.W. Henderson, "Performance of a 2-micron Coherent Lidar for Wind Measurements," submitted for publication in J. Atm. and Oceanic Tech., (January, 1994).

3. S.M. Hannon and J.A.L. Thomson, "Aircraft Wake Vortex Detection and Measurement with a Pulsed Solid-State Coherent Laser Radar," submitted for publication in the Journal of Modern Optics, Special Issue on Coherent Laser Radar (February, 1994).

4. P.J.M. Suni, G.H. Gates, E.H. Yuen, D.L. Bruns, S.R. Vetorino, and T.J. Valle, "A Diode-Pumped 2-μm Transceiver for Ground and Airborne Doppler Lidar Measurements," Paper WB5, Tech. Digest for 7th Conference on Coherent Laser Radar Applications and Technology, 206-209 (1993).

5. J. Kmetec, T. Kubo, D. Shannon, S. Re, F. Adams, and T. Kane, "Diode-Pumped 2 μm Coherent Laser Radar," Tech. Digest for Conf. on Lasers and Electro-Optics (CLEO), 46 (1993).

6. R. Targ, M.J. Kavaya, R.M. Huffaker, and R.L. Bowles, "Coherent lidar airborne windshear sensor: performance evaluation," Appl. Opt. 30, 2013 (1991).

7. S.R. Bowman, J.G. Lynn, S.K. Searles, B.J. Feldman, J. McMahon, W. Whitney, and D. Epp, "High-average-power operation of a Q-switched diode-pumped holmium laser," Opt. Lett. 18, 1724, (1993).

8. J.C. McCarthy, G.L. Labrie, and E.P. Chicklis, "High Efficiency, Pulsed Diode-Pumped Two Micron Lasers," paper AThB5, tech. digest of the topical meeting on Advanced Solid-State Lasers, Salt Lake City (Feb. 7-10, 1994).

9. M.G. Jani, N.P. Barnes, K.E. Murray, and G.E. Lochard, "Long-pulse-length 2-μm diode-pumped $YLiF_4$ laser," Opt. Lett. 18, 1636 (1993).