Laser Review

Wind Measurement Applications of Coherent Lidar

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Pulsed solid-state coherent laser radar (lidar) systems are rapidly evolving as useful sensors for a variety of ground-based and airborne measurement applications. This paper describes such measurement applications and sample demonstration measurement results associated with wake vortex detection and tracking, windshear and gust front detection, and wind field monitoring in support of Space Shuttle operations.

Key Words: Laser radar, Lidar, Doppler lidar, Solid-state, Wake vortex, Windshear

1. Introduction

Coherent lidar systems have proven to be useful sources for many remote sensing applications over the past several years. A predominance of coherent lidar application areas relates to the remote measurement of wind velocity using pulsed and continuous wave systems. Airborne wind measurement applications include microburst windshear detection aboard commercial airliners¹⁾, optical air data sensing²⁻⁴⁾, and clear air turbulence and gust front detection for military and commercial aircraft. Ground-based wind measurement applications include windshear, gust front, and turbulence monitoring in the vicinity of airport terminals⁵⁾, wake vortex detection and tracking along airport approach corridors⁶⁻⁸⁾, and general wind profiling in support of a variety of objectives such as improved Space Shuttle launch and landing operations^{9,10)}, improved ballistic trajectories, and planetary boundary layer modeling¹¹⁻¹³⁾.

Figure 1 is a block diagram of a typical pulsed coherent lidar system. The underlying principle of the pulsed lidar measurement of wind speed is the use of optical heterodyne (coherent) detection, in which laser pulses are transmitted into the atmosphere and scattered off of naturally-occurring small dust particles (aerosols) entrained in the ambient flow field. The transmitted pulse is frequency offset from the master and local oscillator (LO) by an

intermediate frequency (nIF) using an acoustooptic modulator (AOM) in the seed beam path. In many systems, the value of nIF can vary randomly from pulse to pulse (frequency jitter of a few MHz for our airborne 2 μ m systems). A small fraction of the transmitted pulse is often split off for the purpose of generating a pulse monitor signal at the output of a secondary photodetector (see below). The backscattered laser energy is Doppler-shifted in frequency by an amount D_n proportional to the velocity of the aerosols parallel to the direction of propagation of the illuminating laser (the radial velocity). This light is collected by the telescope and is combined with light from the LO on the surface of a photodetector. The light from the pulse sample is combined with light from the LO on the surface of a second photodetector to provide a pulse monitor signal useful for frequency offset and temporal jitter correction in the signal processor. The resultant IF photocurrent contains a heterodyne term consisting of the difference frequency between the backscattered light (or pulse monitor light in the case of the monitor photodetector) and the LO. With sufficient LO power (~ 1 mW for well-designed 2 μ m systems), the LO-induced shot noise dominates all other noise sources (e. g., detector dark current and johnson or thermal noise) and quantum-limited detection is achieved. We typically operate in a mode such that LO shot noise is 10 dB larger than all other noise sources combined over the entire IF passband. The Doppler

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Fig. 1 Block diagram of a coherent lidar system.

frequency shift is $\Delta \nu = -2v_r/\lambda$, where v_r is the radial velocity and λ is the operating wavelength. For $2 \mu\text{m}$ coherent lidar systems, the frequency shift is roughly 1 MHz per meter/second of particle velocity.

An excellent review of coherent lidar development over the years 1970-1988 has been compiled by Menzies and Hardesty¹⁴⁾. The majority of coherent laser radar remote sensing performed to date has utilized CO_2 gas laser technology at wavelengths of 9-11 μm . Recently, high-power, single-frequency laser sources in the solid-state wavelength region (0.7-3 μm) have spawned the development of near-infrared coherent lidar systems¹⁵⁻¹⁹⁾. These systems offer the advantages over the CO_2 systems of improved atmospheric transmission performance, less beam divergence for equivalent aperture sizes, and better range resolution for equivalent wind velocity resolution. This last fact is evident from the following equation relating range resolution and velocity resolution for conventional pulsed coherent lidar systems:

$$\Delta x \Delta \nu = c\lambda/3.4\pi, \quad (1)$$

where Δx is the range resolution measured to the full width at half maximum points, $\Delta \nu$ is the velocity resolution deemed to be twice the spectral width²⁰⁾ in meters per second, λ is the operating wavelength, and c is the speed of light. Short pulse systems can be designed to achieve high spatial resolution at the expense of velocity resolution, and vice versa. At 1 μm $\Delta x \Delta \nu = 28 \text{ m}^2/\text{s}$, at 2 μm $\Delta x \Delta \nu = 56 \text{ m}^2/\text{s}$, and at 10 μm $\Delta x \Delta \nu = 281 \text{ m}^2/\text{s}$. Thus, shorter wavelength systems are favored. Dis-

advantages of shorter wavelength systems include tighter alignment and optical surface tolerances, increased signal loss due to atmospheric refractive turbulence, and substantial eye safety restrictions for wavelengths below 1.4 μm . Thulium (Tm) and Holmium (Ho) doped solid-state lasers operating near 2 μm are preferred for many of the applications because they represent a good compromise between shorter wavelengths, eyesafe operation and laser performance.

Coherent Technologies, Inc. (CTI) developed the first flashlamp-pumped 1.06 μm and 2.09 μm coherent lidar systems for remote range-resolved wind measurement^{16,17)}. The flashlamp-pumped systems produce large pulse energies (25-1000 mJ), but are limited in pulse repetition frequency (PRF) to values below 20 Hz because of degrading thermal loading effects in the laser gain medium. More recently, diode-pumped 2- μm coherent lidars have been developed which are designed for higher average power, more efficient operation and, in some cases, for long-term autonomous operation^{18,19)}. The existing flashlamp-pumped systems have been used in several programs, demonstrating the utility of coherent lidar to a variety of wind-measurement applications. This paper presents recent 2.09 μm system field measurement results related to wake vortex detection and tracking; windshear and gust front detection and tracking; and wind profiling in support of space shuttle operations. The status of diode-pumped coherent lidar development is also described.

2. 2.09 μm Coherent Lidar System Description

The flashlamp-pumped 2.09- μm solid-state coherent lidar transceiver is described in detail elsewhere^{17,21}. The lidar transceiver uses a diode-pumped single-frequency continuous wave (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 $\sim 30\text{-mJ}$, 200-nsec single-frequency pulses at a PRF of $\sim 5\text{ Hz}$. The output pulse from the lidar system is sent to a 10 cm 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 to 360° azimuth and -20 to 90° elevation). Backscattered radiation is collected by the same telescope and coherently mixed with the local oscillator radiation on a room-temperature InGaAs photodetector.

The 2.09 μm system beat signal is in the 41 MHz bandwidth between 9 and 50 MHz and is baseband-sampled at 100 MHz prior to processing by the real-time signal processor. The photocurrents from the two photodetectors (one for the return signal and the other for the pulse monitor) are generally multiplexed together into a single digitizer input channel. The first 128 to 256 data samples (1.3-2.6 μs) correspond to the pulse monitor data and the remaining 7936 to 8064 (79-81 μs) samples correspond to the return signal data. The pulse monitor data is used to correct pulse-to-pulse frequency and temporal jitter. Frehlich et al.¹³ have performed careful system characterization measurements to determine the magnitude of systematic errors and the inherent velocity precision capability of the 2.09 μm system. These results indicated that the systematic velocity precision error is on the order of 3 cm/s and that single-pulse wind velocity precisions of 0.5-1 m/s can be readily obtained with the system.

A 2.4m $\times$ 3.8m $\times$ 2m (W $\times$ L $\times$ H) truck-mounted compartment houses the entire lidar system. Over the past two years, this lidar system has proved quite durable, with no catastrophic failures. 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 $< 1\text{ m/s}$) are 10-20 km in the atmospheric

boundary layer and to heights of 3-6 km²¹). The system has also been used to demonstrate hard target returns from 145 km range under clear atmospheric conditions¹⁷.

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. This sensor is currently being modified and will be installed aboard a C130 transport to perform velocity azimuth display (VAD) wind profiling to predict and improve the accuracy of air cargo parachute trajectories.

3. Wake Vortex Detection and Tracking

A major science and technology thrust has been initiated by the Federal Aviation Administration (FAA) and the National Aeronautics and Space Administration (NASA) to develop reliable means of detecting, tracking, measuring, and predicting the time evolution of the trailing wake vortices of commercial airliners. The goal of the FAA/NASA effort is to develop the understanding of the aircraft wake hazard that will permit an increased airport capacity by relaxing landing corridor spacing standards during instrument flight rules (IFR) conditions. What is lacking from the current knowledge base (see Hallock²², for an excellent review) is a thorough understanding of the link between the local meteorology and topography and vortex transport and decay.

Heretofore, the only reliable means of remotely measuring the velocity field associated with wake vortices has been with continuous wave (CW) CO₂ Doppler lidar systems^{6,7} and sodar systems²³. The maximum stand-off range of such sensors is typically less than 300 m. Detailed performance analyses of pulsed coherent lidar systems have indicated the potential for wake vortex detection and tracking utilizing a short wavelength system to ranges of several kilometers²⁴. As illustrated in Fig. 1, the shorter solid-state wavelengths allow improved range resolution for a given velocity resolution, which is key to the detection and tracking of aircraft wakes whose characteristic dimensions are of the order of the aircraft wingspan. The first detection and tracking of wake vortices with a pulsed coherent lidar was achieved in 1992 using the short-pulse (180 nsec) 1.06 μm system⁸.

In 1993, a wake vortex database was compiled with the 2.09 μm coherent lidar system at Denver Stapleton International Airport. A more detailed

Fig. 2 RHI display of lidar-measured radial velocity 20 seconds (upper) and 40 seconds (lower) after passage of a DC10 through the vertical measurement plane. The aircraft initially pierced the measurement plane at a height of 85 m and a ground range of 810 m. The shaded regions correspond to velocity values below 2.7 m/s and the unshaded regions correspond to velocities above 2.7 m/s.

description of those measurements can be found elsewhere⁸). Figure 2 shows a range-height indicator (RHI) display of radial velocity measured by the 2- μ m lidar at two different times (~ 20 s and ~ 40 s, respectively) following the passage of a DC10 through the vertical measurement plane on the morning of June 17, 1993. The RHI scan plane was perpendicular to the aircraft flight path. The lidar is located at Range = 0 and Height = 0. The mean ambient radial velocity was ~ 2.7 m/s away from the lidar when the measurements were taken. Periodograms are accumulated over two pulses in each of 128 overlapping range gates (32 samples each) and a Gaussian matched filter is applied to the estimate spectrum. The Doppler frequency corresponding to the peak matched filter output bin is then converted to a radial velocity estimate. Positive radial velocities are away from the lidar and negative radial velocities are toward the lidar. The shaded regions indicate radial velocities below the $+2.7$ m/s 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 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 downwind during the 20 second time period between the upper and lower frames of the figure.

The lidar-measured mean radial velocity can provide a strong vortex signature provided sufficient

pulse averaging is employed to reduce laser speckle effects. For low PRF systems, such as the 2.09 μ m flashlamp-pumped system, we have found that optimum vortex detection and tracking performance requires a maximum-likelihood matched filter analysis that utilizes the entire Doppler spectrum over the search grid⁸). This type of optimal signal processing has demonstrated that reliable vortex tracks can be achieved with pulsed solid-state systems.

4. Windshear and Gust Front Detection and Tracking

In support of the Federal Aviation Administration (FAA) Terminal Area Surveillance System (TASS) Program effort to evaluate pulsed solid-state coherent lidar's utility to wind state characterization in the airport terminal area, the 2.09 μ m system has been used during windshear and gust front measurements at CTI's Table Mountain test facilities north of Boulder, Colorado and at Denver Stapleton International Airport.

Figure 3 shows color RHI plots of measured radial wind velocity. These measurements were made on March 9, 1993 near Boulder, Colorado. The lidar scanned vertically at a rate of 1.8°/sec along the 40° azimuthal direction (in a northeasterly direction, away from the front range foothills and mountains) and averaged five pulses per wind velocity estimate. Figure 3a was produced over a 40 second period ending at 8:37 P.M. local time and Figure 3b was produced over the subsequent 40 second period. The RHI displays have been expanded to better display the observed velocity structure within 2.5 km from the lidar. The radial velocity estimates are plotted in a false-color display with the scale bar shown at the bottom of the RHI display. A significant amount of structure is apparent in both figures. In particular, a 12 m/s shear layer is present at a height of 1-2 km. The winds at this altitude are blowing away from the lidar and are due to outflow from the front range mountains. For heights nearer the ground, the radial wind velocity is toward the lidar. In Fig. 3a a 10 m/s ground-level wind gust is located approximately 1.4 km from the lidar and is blowing toward the lidar. In Fig. 3b, this same wind gust is detected at a range of 1.1 km. This capability to monitor wind gusts, their locations and movements, is one of the TASS objectives for coherent lidar.

5. Wind Profiling in Support of Space Shuttle Operations

NASA/Marshall Space Flight Center has funded several coherent lidar system measurement programs in conjunction with space shuttle launch and

MEASURED RADIAL VELOCITY - TIME SLICE 1
(POSITIVE AWAY FROM LIDAR)

(a)

MEASURED RADIAL VELOCITY - TIME SLICE 2
(POSITIVE AWAY FROM LIDAR)

(b)

Fig. 3 RHI display of lidar-measured radial wind velocity for March 9, 1993 along the 40° azimuth and away from the Colorado Front Range. Velocity estimates are color-coded according to the color-lookup table shown at the bottom of the display. Panels (a) and (b) are separated in time by roughly 45 seconds.

Fig. 4 Comparison of Space Shuttle (solid line) and lidar-measured wind velocity component along the 19° glide slope. Lidar data corresponds to: data directly along the 19° glide slope during landing (dotted line) and data inferred from a VAD profile collected shortly before landing (dashed line).

landing operations. During September of 1991, an energy-augmented version of the CTI-developed $1.06 \mu\text{m}$ coherent lidar system provided vertical wind profile data to a record 26 km altitude during the launch of the STS-48 mission⁹⁾. Measurements have also been conducted using the National Oceanic and Atmospheric Administration (NOAA) CO_2 Doppler lidar. In January of 1993, the $2.09 \mu\text{m}$ coherent lidar was deployed at Kennedy Space Center, Florida during the STS-54 mission¹⁰⁾. NASA/MSFC is most interested in evaluating coherent lidar's ability to provide accurate wind data along the approach corridor in order to minimize the variance of shuttle touchdown points on the 15,000 ft runway at Kennedy Space Center.

Figure 4 compares velocity measurements made with the lidar and the space shuttle during its landing. The space shuttle velocity measurements are derived from flight performance and pitot static tube data. Figure 4 compares the velocity component along the shuttle glide slope (150° azimuth from true north and 19° elevation angle) as derived from: shuttle flight data; projections of a lidar velocity azimuth display (VAD) wind profile onto the glide slope; and lidar measurements performed during landing along a line-of-sight (LOS) parallel to the glide slope but offset by ~ 3 km. Note that the VAD projection agrees well with the more direct LOS lidar measurements and that both agree very well with the shuttle data. The 1 m/s fluctuations in the shuttle data are primarily due to measurement noise, although turbulent wind eddies also contribute.

The data of Fig. 4 indicate that the shuttle traversed through two boundary layer windshears. The first between an altitude of 2.5 km and 1.2 km (7 m/s headwind to 4 m/s tailwind) and the second between an altitude of 1.2 km and the ground (4 m/s tailwind to 3 m/s headwind). The ground-level shear (height of 50 m or line of sight range of 150 m) seen in the shuttle data is underrepresented in lidar data. This is because the scatter of the transmitted pulse off of the transmit/receive optics creates a "blind spot" that precludes accurate wind measurements within 150 m of the lidar. However, the ground-level wind shear was detected with the laser radar using a RHI scan in the vertical plane containing the glide slope.

6. Airborne Applications

Until recently, the primary airborne coherent lidar systems utilized for wind measurement have been based on CW CO_2 lasers^{2-4,25)}. Airborne CW CO_2 coherent lidars have been applied to measurement of true airspeed, clear air turbulence, and transverse wind velocity. In 1992, a pulsed CO_2 coherent lidar, the Coherent Lidar Airborne Shear Sensor (CLASS), was demonstrated for airborne microburst windshear detection aboard a Boeing 737 research aircraft^{1,26)}. A 2 mm version of this sensor, the CLASS-2, is presently being flight tested⁹⁾. We are now developing diode-pumped $2 \mu\text{m}$ coherent lidar systems for NASA and the U.S. Air Force which will produce 2-5 W of average power and will be utilized for airborne wind measurement applications such as air data, high-altitude turbulence detection, gust alleviation, and prediction of projectile ballistics²⁷⁾.

7. Summary

Existing flashlamp-pumped lidar systems have proven useful for demonstrating and evaluating the utility of solid-state coherent lidar to a variety of potential wind measurement applications. Emerging diode-pumped coherent lidar systems are being carefully engineered to maintain long-term autonomous operation aboard commercial and military aircraft as well as ground installations. Laser power levels of 2-5 W, with PRFs of a few hundred to a few kilohertz, are presently being developed. Windshear, turbulence, gust front, and wake vortex detection, tracking, and characterization greatly benefit from the ability of such solid-state systems to provide simultaneously high velocity and range resolution.

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