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Coherent Lidar Design and Performance Verification

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Results of Year 1

The verification of beam alignment for coherent Doppler lidar in space can be achieved by a measurement of heterodyne efficiency using the surface return. Because the surface return is random, about 50 shots will be required for a good measure of alignement. This method does not require knowledge of the backscatter coefficient of the surface, the power transmitted, the atmospheric attenuation, or the detector gain. The crucial element is a direct detection signal that can be identified for each surface return.

The performance of algorithms for velocity estimation can be described with two basic parameters: the number of coherently detected photo-electrons per estimate and the number of independent signal samples per estimate. For low signal levels, the fraction of bad estimates is required to describe performance. The fraction of bad estimates is mainly a function of the number of effective photo-electrons per estimate and has a weak dependence on the estimator used and the velocity space searched.

The average error of spectral domain velocity estimation algorithms are bounded by a new periodogram Cramer-Rao Bound. Comparison of the periodogram CRB with the exact CRB indicates a factor of two improvement in velocity accuracy is possible using non-spectral domain estimators. This improvement has been demonstrated with a maximum-likelihood estimator.

For LAWS, the biggest science payoff would result from a short transmitted pulse, on the order of 0.5 microseconds instead of 3 microseconds. The advantages are better range resolution in the boundary layer, thus providing data of great interest to atmospheric scientists; more efficient designs for both CO2 and solid state lasers; an ideal design for a lower cost mission that will only measure the boundary layer and clouds; the 50 m range resolution will permit useful measurements of wind statistics that are essential for optimal design of velocity estimators; a short pulse will permit better velocity estimation algorithms because the statistics of the signal will be determined by the transmitted pulse (which is known) instead of the velocity fluctuations over the sensing volume of the pulse (which are unknown and difficult to estimate); and better measurements near clouds and the surface will be possible. The disadvantage are: the velocity accuracy in the regions of low backscatter with 1 km height resolution will be about 1.5-2 m/s and a design of a high-energy short pulse CO_2 laser would be difficult to verify with the breadboard laser.

The numerically errors for simulation of laser propagation in the atmosphere have been determined as a joint project with the University of California, San Diego. Useful scaling laws were obtained for Kolmogorov atmospheric refractive turbulence and a atmospheric refractive turbulence characterized with an inner scale. This permits verification of the simulation procedure which is essential for the evaluation of the effects of refractive turbulence on coherent Doppler lidar systems.

Publications

"Cramer Rao Bounds for Gaussian random processes and applications to radar processing of atmospheric signals", Rod Frehlich, IEEE Trans. Geoscience and Remote Sensing, Vol. 31, 1123-1131, (1993).

"Performance of mean-frequency estimators for Doppler radar and lidar", R. G. Frehlich and M. J. Yadlowski, J. Atmos. Ocean. Tech.,
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Results from Year 2

The use of heterodyne efficiency as an absolute measure of performance of coherent Doppler lidar was analyzed theoretically and with computer simulation. This produced a statistical description of the estimates of heterodyne efficiency as a function of beam misalignment for a typical ground based system and also space based systems where a new estimate was proposed to remove the random effects of the surface return.

The performance of a 2 micron coherent Doppler lidar was determined using data supplied by Coherent Technologies, Inc. The systematic error for measuring wind velocity was estimated as 3.6 cm/s from the signals from a non-moving target. A new method was proposed to determine the estimation error for wind measurements without the need for an independent wind measurement. The performance was within 20-30% of that from ideal simulations that assumed no wind turbulence over the pulse sensing volume. This is the first direct determination of the spatial statistics of the wind field with a Doppler lidar.

Coherent Doppler lidar signal covariance including wind shear and wind turbulence was derived and calculated for typical atmospheric conditions. For the measured wind statistics using the 2 micron lidar, the signal covariance was altered by the wind turbulence. This implies that the wind turbulence over the sensing volume of the pulse is an important effect. Simulation of lidar performance with wind turbulence included are presently underway and preliminary results are encouraging.

A comparison of 2 and 10 micron coherent Doppler lidar performance has determined the tradeoffs in performance for both boundary-layer and space-based measurements. It was assumed that all the system design parameters are fixed (range to target, telescope aperture, detector quantum efficiency, heterodyne efficiency, perfect beam alignment, optical element efficiency, laser pulse energy, atmospheric attenuation, range resolution, observation time per estimate, velocity search space) and the signal statistics are dominated by a 1 m/s rms wind fluctuation over the range gate. The performance was defined in terms of the quality of the velocity estimates which are only a function of the wavelength dependence of the backscatter coefficient β. For $\beta \propto \lambda^{-1}$ the number of photons collected per estimate is the same and a 10 micron system has better data quality because the fraction of bad estimates at low signal levels is less than for the 2 micron lidar. For $\beta \propto \lambda^{-2}$ the signal to noise ratio is the same and the 2 micron lidar has better data quality. The two systems have similar data quality when $\beta \propto \lambda^{-1.3}$. These results agree with the GE and TRW reports.

Work was completed on the error scaling of computer simulations of laser propagation in the atmosphere. This work was a collaboration with the UCSD radio astronomy group, that uses the same algorithm for radio propagation through the solar wind, ionosphere, and interstellar medium.

The effects of wind turbulence defined by Kolmogorov spatial statistics were investigated theoretically and with simulations. The results were compared with the analysis of CTI's data. The results for velocity estimation error were within 5% of the simulation results when the wind turbulence was included. For typical boundary layer experiments, a spatial array of in situ wind sensors would be required to produce a statistically reliable comparison of coherent Doppler lidar wind measurements. A new theoretical prediction of the effects of the pulse averaging of the wind field on estimates of the spatial structure function and the variance of the velocity field has excellent agreement with simulations and the measurements from CTI's data. The conditions under which corrections for the effects of pulse averaging can be performed were determined. This permits accurate estimates of the velocity variance, the velocity structure function, and the energy dissipation rate when Kolmogorov scaling is valid or when a valid model exists for the spatial statistics.

The effects of wind turbulence with Kolmogorov spatial statistics were determined for the benchmark LAWS parameters for both 2 and 10 micron lidars. The performance is sensitive to the wavelength dependence of the backscatter coefficient β. For $\beta \propto \lambda^{-1}$, both systems have similar performance, with the 10 micron system having fewer random outliers at low signal levels. For $\beta \propto \lambda^{-2}$, the 2 micron system has better performance. The increase in sensitive from pulse accumulation was investigated using simulations. The increase in sensitivity depends on the wind field statistics. For a 1 m/s rms fluctuation along the accumulation path, 8 t0 10 Db improvement is possible if the sensitivity threshold is defined as the signal level that produces 50% good estimates.

Publications

"Comparison of 2 and 10 Micron Coherent Doppler Lidar Performance", Rod Frehlich, J. Atmos. Ocean. Tech., Vol. 12, 415-420, (1995).

"Simulation of Wave Propagation in Three-Dimensional Random Media", W. A. Coles, J. P. Filice, R. G. Frehlich, and M. J. Yadlowsky, Applied Optics, Vol. 34, 2089-2101, (1995).

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"Coherent Doppler lidar signal covariance including wind shear and wind turbulence", R. G. Frehlich, Applied Optics, Vol. 33, 6472-6481, (1994).

"Performance of a 2 Micron Coherent Doppler Lidar for Wind Measurements", Rod Frehlich, Stephen Hannon, and Sammy Henderson, J. Atmos. Ocean. Tech. Vol. 11, 1517-1528, (1994).

Results for Year 3

The performance of coherent Doppler lidar in the weak signal regime was determined by computer simulations using the best velocity estimators. Threshold signal levels were defined for useful and good data based on the fraction of the estimates that were random outliers due to the fading in the return signal. The dependence on threshold signal level S with the number of lidar pulses N used for each estimate produced simple empirical curves of the form $S = KN^{-a}$ were $a \approx 0.75$ for small N and $a \approx 0.5$ for large N. The statistical accuracy of the good velocity estimates at the threshold signal level was approximately constant as a function of N. This simplifies system design analysis. For space based applications, performance was investigated using the Capon estimator with various levels of wind turbulence for a 2 and 10 micron lidar. Simple scaling laws for the threshold signal level with pulse accumulation were produced.

Analysis of 2 micron Doppler lidar data from a new experiment was completed. This data is from a diode-pumped solid-state lidar with low pulse energy which is ideal for investigating the low signal regime. Results indicate excellent agreement with simulations for the fraction of outliers. The estimation error of the good velocity estimates is more difficult to determine because of the large data set required for statistical reliability. The results are within 15% of ideal simulations. For a 10 km horizontal path, velocity accuracy of better than 0.2 m/sec was demonstrated using 100 pulses of data. The factor of 10 improvement in system sensitivity was verified for these boundary layer conditions.

Velocity statistics *from* data for a vertically pointing 2 micron Doppler lidar were extracted for both the boundary --layer and the troposphere. The boundary layer results agree with mixed-layer similarity theory and the results for the troposphere agree with gravity-wave spectra. These results provide a new description of the velocity fluctuations over the type of measurement cell proposed for space-based measurements. More data will provide ground-based information for predicting the quality of space-based measurements.

Improved algorithms for extracting the performance of velocity estimators with wind turbulence included were also produced. These algorithms permit robust parameter estimation for a wide variety of conditions. They were applied to many cases by Brian Lottman, the graduate student supported by NASA for the summer. Simulations of the effects of refractive turbulence on laser propagation were also conducted in collaboration with Reg Hill of NOAA. This work produced new techniques for estimating the parameters of the atmospheric refractive index spectrum, which is required for any optical remote sensing instrument. This is particularly important for ground-based testing of lidar performance.

Publications

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