

ATMOSPHERIC CORRELATION TIME MEASUREMENTS USING
COHERENT CO₂ LIDAR

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A pulsed TEA-CO₂ lidar with coherent detection has been used to measure the correlation time of backscatter from an ensemble of atmospheric aerosol particles which are illuminated by the pulsed radiation. The correlation time of the backscatter return signal is important in studies of atmospheric turbulence and its effects on optical propagation and backscatter. If the temporal coherence of the pulse is large enough (several microseconds), then the temporal coherence of the return signal is dominated by the turbulence and shear for a variety of interesting atmospheric conditions. Various techniques for correlation time measurement are discussed and evaluated.

The theoretical formulation of the spatio-temporal correlation function for the return signal field of a pulsed lidar, recently developed by Churnside and Yura [1] is used to provide correlation time estimates. (This formalism applies to turbulence scale sizes larger than the inner limit of the inertial sub-range.) In this study we have incorporated a laser pulse shape which is a better approximation of a TEA-CO₂ laser pulse than the Gaussian pulse shape used as an example by Churnside and Yura. The analytical results obtained are used to gain a better understanding of experimentally observed return signals using an injection-controlled TEA-CO₂ coherent lidar system described in an earlier publication [2].

The temporal autocovariance function of the pulsed lidar return signal amplitude $U(t)$ is defined as $\langle U(t)U(t+\tau) \rangle$ and can be written as in Ref. [1]:

$$\Gamma(\tau) = \frac{\beta(z)}{2z^2} \exp[-2k^2 \sigma_z^2 \tau^2] + \int_0^\infty dt' [P(t-t')P(t+\tau-t')]^{1/2} \quad (1)$$

where $P(t)$ = transmitted power at time t , $\beta(z)$ = aerosol backscatter coefficient at range z , $k = 2\pi/\lambda$. The aerosol velocity distributions $p(v_z), p(v_T)$ are assumed to be Gaussian within the volume of interest (100 m - 500 m) [3]:

$$p(v_z) = \frac{1}{\sqrt{2\pi} \sigma_z} \exp[-(v_z - \bar{v}_z)^2 / 2\sigma_z^2] \quad (2)$$

$$p(v_T) = \frac{1}{2\pi\sigma_T^2} \exp[-(v_T - \bar{v}_T)^2 / 2\sigma_T^2] \quad (3)$$

where v_z , v_t and σ_z^2 , σ_t^2 are the means and variances of the corresponding wind components. These two conditions and the expression for the equation (1) are only valid within the inertial subrange, considering that the outer scale of turbulence is approximately equal to the depth of the mixing layer, or to the spatial scale of organized convective motions.

Using Equation (1), we can calculate the temporal autocovariance function of the return signal field for modelled laser pulse shapes. A good approximation to the TEA-CO₂ laser pulse is a two-step function. Three different laser pulse shapes are considered in Figure 1, together with aerosol velocity fluctuation levels of $\sigma_z = 0$ and $\sigma_z = 1 \text{ ms}^{-1}$. The relationship between σ_z and ϵ , the viscous dissipation rate of turbulence, is obtained assuming the Kolmogoroff spectrum, where the spectral density of the average kinetic energy of the turbulence, $S(k) dk = A\epsilon^{2/3}k^{-5/3}dk$ [4], where $A \approx 0.5$ for longitudinal velocity fluctuations. By integrating the spectral density over the inertial subrange, assuming an outer scale length, $L_0 = 100 \text{ m}$ ($k_{\min} = 2\pi/L_0$), the value for ϵ which is determined for $\sigma_z = 1 \text{ ms}^{-1}$ is $\epsilon = 1.7 \times 10^{-2} \text{ m}^2\text{s}^{-3}$. This corresponds to "light to moderate" turbulence [5,6]. Characterization of clear air turbulence appears to be possible using the correlation measurements, however further developments of this study require, for the purpose of comparison, supporting information about atmospheric turbulence based on standard meteorological data.

Hardesty [7] recently reported observing typical velocity standard deviations of 2 ms^{-1} , based on pulsed CO₂ Doppler lidar spectral widths, corresponding to a correlation time of $0.7 \mu\text{s}$. Such a short correlation time, if representative of typical atmospheric conditions, places a significant limitation on the temporal coherence of a monochromatic laser pulse which is backscattered from a distant volume, and would have major implications on the performance characteristics of coherent Doppler lidars in the visible and infrared wavelengths. Further studies of this sort are important in assessing the effects of the atmosphere in various shear and stability regimes on the correlation time of aerosol backscatter.

Our experimental observations of correlation time are deduced from the statistical distribution properties of the return signal intensity from shot to shot, using the Inverse Relative Root Variance (IRRV) concept. The statistics of monochromatic, fully developed speckle patterns correspond to those of Rayleigh phasers with a Rayleigh distributed amplitude and uniformly distributed phase, and probability density functions (PDFs) of the intensity obey to an exponential distribution. This is applicable to atmospheric aerosol backscatter signals detected using a coherent receiver. The PDF of the atmospheric return intensity changes from an exponential distribution to a Gamma distribution as the turbulence level increases and as a temporal averaging of the signal is performed (long laser pulse or low-pass filtering at the output of the receiver) [8]. The first and the second moments of the statistical distribution of

the received power P_r , $\langle P_r \rangle$ and $\text{var}(P_r)$ are from their ratio $\langle P_r \rangle / [\text{var}(P_r)]^{1/2}$ a measure of the relative amplitude accuracy. This ratio is referred to as the inverse relative root variance (IRRV) and is related to the carrier-to-noise ratio (CNR) and to the IRRV_0 of the atmospheric signal.

$$\text{IRRV} = \left[\frac{\text{CNR}/2}{1 + \text{CNR}/2\text{IRRV}_0^2 + (2 \text{CNR})^{-1}} \right]^{1/2} \quad (7)$$

In the limit of large signal ($\text{CNR} > 5$), the IRRV is reduced to IRRV_0 . When this is the case, and when the received signal is subsequently smoothed by a RC filter, the IRRV is given as [9].

$$\text{IRRV} = [1 + 4\pi T/\tau_c]^{1/2} \quad (8)$$

where $T = RC$ and $\tau_c =$ correlation time of the atmospheric backscatter signal. Consequently a measure of IRRV leads to a measure of the correlation time.

Measurements were conducted at a given range, along a horizontal path and a slant path in order to investigate the effect of the turbulent eddies encountered within or near the top of the boundary layer. In order to reduce the spectral broadening induced by the laser pulse length, the CO_2 TEA laser was operated using a long pulse similar to the case (c) in Fig. 1. Measurements of the temporal coherence of the aerosol backscatter signal have resulted in a range between 2-2.5 μs for the correlation time under small to moderate turbulence conditions, which were the conditions observed most often. Much lower values ($< 1 \mu\text{s}$) were found for higher turbulence as encountered at the interface between the boundary layer and the free troposphere. Thus the use of coherent integration times much longer than 2.5 μs in feasibility studies of Doppler lidar performance may lead to overly optimistic conclusions.

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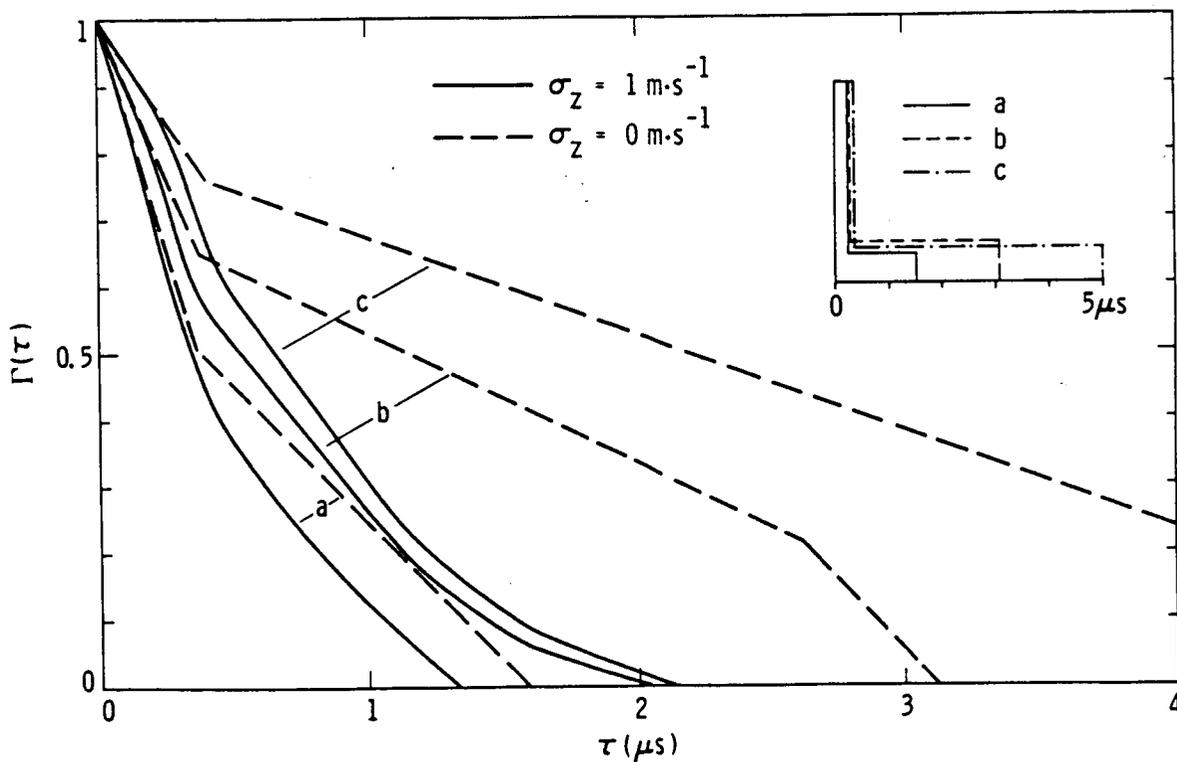


Fig. 1. Normalized temporal autocovariance function of aerosol returns versus time for three laser pulse shapes a, b, c.