Doppler Lidar Measurements of Turbulent Structure Function over an Urban Area

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ABSTRACT

Analysis of radial wind velocity data from the Salford pulsed Doppler infrared lidar is used to calculate turbulent spectral statistics over the city of Salford in the United Kingdom. The results presented here, first, outline the error estimation procedure used to correct the radial wind velocity measurements from the Salford lidar system; second, they correct the data for the spatial averaging effects of the Salford lidar pulse; and finally, they use the corrected data to calculate turbulent spectral statistics. Using lidar data collected from the Salford Urban Meteorological Experiment (SALFEX), carried out in May 2002, kinetic energy dissipation rates, radial velocity variance, and integral length scales are calculated for the boundary layer above an urban canopy. The estimates of the kinetic energy dissipation rate from this method are compared to calculations using more traditional spectral methods. The estimates of the kinetic energy dissipation rate for the two methods are correlated and both show an increase in dissipation rate through the day. The procedure followed for the correction of the spatial averaging effects of the lidar pulse shape actually uses the Salford lidar pulse shape profile.

1. Introduction

Given current worries over the dispersion of pollutants in urban regions there is a great deal of interest in the structure of the boundary layer in and above these metropolitan areas. The effects of wind and turbulence are critical in dispersing or maintaining the high levels of pollutants produced in our inner city areas. However, traditional methods of measuring these parameters are extremely difficult due to both the practical difficulties associated with the deployment of instruments in urban areas and also due to the large- and small-scale heterogeneity found within these areas. This heterogeneity causes problems with generalizing results taken over limited areas.

The eyesafe nature of the Salford Doppler lidar system enables the use of the system in a region of the boundary layer that would otherwise be difficult to monitor. Also, the range and scanning capabilities of the system can be used to probe the atmosphere over very large areas and throughout the depth of the boundary layer. The scanning capability enables the laser beam to be directed, and the system can be altered to examine either the temporal nature of the turbulence by using a fixed beam over a time period or the spatial nature of the turbulence by scanning over a large volume.

Measurements of wind velocity taken using a Doppler lidar system differ from traditional point measurements in that they are a spatial average over the volume of the laser pulse, which is a pencil-shaped region with a length of 10s to 100s of meters and a diameter of approximately 0.5 m. Procedures must therefore be carried out to correct the wind velocity data for this spatial averaging. Further corrections must also be made to correct for system noise and systematic biases, as is done with any measurement system. This paper aims to provide measurements for the noise and bias for the Salford lidar system, correct for the inherent spatial averaging of the system (following well-documented procedures), and finally produce turbulence measurements over an urban boundary layer.

2. The Salford lidar system

The first development of the Salford Doppler lidar is discussed in Pearson and Collier (1999). In 2002, the
TABLE 1. Characteristics of the Salford lidar system.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmitter</td>
<td>CO₂ laser</td>
</tr>
<tr>
<td>Operating wavelength</td>
<td>10.6 μm</td>
</tr>
<tr>
<td>Energy per pulse</td>
<td>70 mJ</td>
</tr>
<tr>
<td>Pulse repetition frequency</td>
<td>Up to 50 Hz</td>
</tr>
<tr>
<td>Range resolution</td>
<td>112 m</td>
</tr>
<tr>
<td>Min range</td>
<td>700 m</td>
</tr>
<tr>
<td>Max range</td>
<td>9000 m</td>
</tr>
</tbody>
</table>

The signal processing, which is discussed fully in Pearson and Collier (1999), used an offline scheme based on correlogram accumulation. Using this procedure the autocorrelation function (ACF) for the return signal for each range gate is calculated. The ACFs are accumulated over the appropriate number of records, and the spectrum is then calculated. The peak of the spectrum is then assigned a velocity. The performance of this type of simple discrete spectral peak estimator is discussed in detail in Rye and Hardesty (1993). In the original system the processing integrated the return signal over 120 shots to obtain atmospheric data at a rate of 1 Hz. The transmitted pulse shape in the old system, as shown in Pearson and Collier (1999, their Fig. 4), was close to Gaussian (having very little of its power in the tail of the pulse). The pulse did not exhibit chirp (Dabas et al. 1998), and the system consequently did not produce a systematic velocity bias.

The new system uses the same processing procedure, but now carries out the calculations in real time. The number of pulses over which the return signal is accumulated can be set as a system input. The pulse shape is no longer Gaussian and has a significant amount of power in its tail, as is shown in Fig. 1. The Gaussian model fit, also shown in Fig. 1, contains 85% of the energy of the laser pulse. The pulse exhibits chirp and therefore this has to be considered in the signal processing.

3. Chirp and measurement bias

Dabas et al. (1998) showed that a 10-μm heterodyne Doppler lidar can produce a biased velocity measurement even when operating under stationary atmospheric conditions. The velocity bias is due to the combination of the atmospheric speckle effect and the asymmetry of the periodogram of the transmitted laser pulse. Dabas et al. (2000) showed that the velocity bias can therefore be considered to be due to a combination of a “speckle” effect and a “constant” effect.

The constant effect is due to the asymmetry in the pulse spectrum. For the Salford lidar pulse the frequency chirp in Fig. 1b shows a slight downsweep followed by an upsweep. The total magnitude of this frequency sweep is 1.5 MHz. The signal-processing procedure involves the range gating of the returned atmospheric signal. Calculating the convolution of the range gating (i.e., a rectangular window function) with the asymmetric pulse spectrum gives a constant bias due to the frequency chirp of 0.25 m s⁻¹. In addition, bias can be caused by imperfect compensation of pulse-to-pulse variations in the offset frequency. This effect is, however, monitored and corrected for on a shot-to-shot basis. All data considered in this analysis are corrected for the constant bias effect.

The atmospheric speckle over the pulse volume causes the return signal to also exhibit a velocity speckle bias, which, in the system described by Dabas et al. (1998), can reach ~0.5 m s⁻¹ for a single shot measurement. Dabas et al. (2000) note that using a shot accumulation procedure of n shots can divide the speckle bias by a factor of n, when the pulses over the integration are identical. Since the return signal of the Salford lidar system is always integrated over 10s of shots, the speckle bias is only of the order of ~0.01 m s⁻¹ under normal atmospheric conditions. This bias is therefore very small compared to the velocity estimation error, which is approximately 0.4 m s⁻¹ as discussed in section 5. The speckle bias is therefore not considered further.

Rye and Hardesty (1993) did show, however, that the amount of accumulation for the correlogram accumulation procedure is an important parameter in producing
4. Characteristics of the trial data

For the initial error analysis, reported upon later in this paper, a series of three sets of data were taken at a fixed elevation angle over the center of Salford, Greater Manchester, in northwest England. The data were taken over a 45-min period starting at 1300 UTC and from an elevated position 20 m above the surface. The elevation angle used, 4.7°, was the minimum possible given the local morphology. The data used were therefore in the height range 110–390 m above ground level, and over a horizontal distance of 3400 m. The ground level in this region, which includes both the city center and the River Irwell flood plane, varies in height by only ±3 m. The city morphology is a mixture of low-rise (2 stories) and high-rise (up to 20 stories) buildings with an industrial area to the south. The cross section shown in Fig. 2 outlines the main characteristics of the site, but details of the average building height were not included since the minimum measurement of the lidar was well above the roughness sublayer, that is, above the effects of the individual buildings (Roth 2000). The lidar beam was pointed into the direction of the city center, and the mean wind direction was perpendicular to the beam direction. The turbulence was found to be well mixed within the height range analyzed and the urban boundary layer was considered to have sufficient fetch (several kilometers) to be adapted to the surface conditions on the large scale. The data were taken with different system inputs as detailed in Table 2. The system SNR was in the range 12 to −6 dB for the measurements used in this analysis.

Since a certain amount of averaging has been done within the signal processing, we need to understand how much spatial averaging this entails. A coherent Doppler lidar measures the return signal from a pencil-shaped region of random scatterers (aerosol particles). The lidar beam is collimated, and the Salford pulsed Doppler lidar (PDL) has a transverse spatial dimension of only 1.0 m at a range of 4.5 km. For a fixed instant in time, the spatial extent of the lidar pulse along the transmit axis, $\Delta r$, given by the full-width half-maximum (FWHM) of the Gaussian profile in Fig. 1a, is 75 m. For a radial velocity estimate from one lidar pulse the illuminated aerosol region travels a distance, $\Delta p$, of 112 m. Therefore, the estimated velocity for a single pulse is a spatial average of the instantaneous radial velocity $v(r, \Delta r)$ over the sensing volume, where $r$ is the range along the transmit axis and $\Delta r$ is the time of measurement.

For multiple pulse measurements the total measurement time (dwell time), following Frehlich and Cornman (2002), is given by

$$T = \frac{N_p}{PRF},$$

where $N_p$ is the number of accumulated pulses and $PRF$ is the pulse repetition rate of the system.

If the mean wind velocity is moving through the beam in a transverse direction, then the lidar samples a parallelogram of the atmosphere in a plane defined by the fixed laser beam and the fixed mean velocity vector. The transverse distance sampled by the lidar for each velocity estimate will be $\Delta h = V_{\mu}T$, where $V_{\mu}$ is the mean transverse velocity. The velocity estimates should behave like the single-pulse estimates when the horizontal distance $\Delta h$ is much less than the range gate length $\Delta p$ (Frehlich and Cornman 2002). With the Salford lidar system this is the case, since as can be seen from Table 3, $\Delta h/\Delta p$ is at a maximum of 0.24. For the data in this analysis the transverse velocity, $V_{\mu}$, was 3 m s$^{-1}$ giving values for $\Delta h$ and $\Delta h/\Delta p$ as shown in Table 3.

Frehlich and Cornman (2002) used simulated PDL

![Fig. 2. Cross section showing the position of the Salford lidar system and lidar beam compared to the underlying average surface characteristics. The mean wind direction is going into the paper.](http://journals.ametsoc.org/doi/pdf/10.1175/1520-0426(2004)021<0753:DLMOTS>2.0.CO;2)
data to estimate the effects of spatial averaging on derived atmospheric quantities. Using calculations of the spatial structure function, they estimated the energy dissipation rate, $\epsilon$, and the integral length scale, $L_s$, for approximately 1000 independent realizations of a simulated wind field. This procedure will be followed to analyze data from the Salford pulsed Doppler lidar in the next section.

Probability density functions (PDFs) were plotted (Frehlich and Cornman 2002) to show the variability of the estimated $\epsilon$ and $L_s$ from the simulated data. These calculations were carried out for different values of the parameter $\Delta h/\Delta p$ to show the effects of different amounts of spatial averaging. The data simulation procedure was for data from a 2-\(\mu\)m PDL where the number of accumulated pulses, $N_p$, was 20.

Frehlich and Cornman found that for the calculations of $\epsilon$ the estimates were within 5% of the input value for situations where $\Delta h/\Delta p$ was in the range 0.1–0.25 (for the velocity differing error correcting procedure to be discussed in the following section). However, for the calculations of $L_s$, the PDFs were shown to be skewed to large values. For an input $L_s$ of 100 m they showed that for $\Delta h/\Delta p$ in the region 0.2–0.3 the $+1\sigma$ (calculated from the median of the PDF) was approximately 30 m. For lower values of $\Delta h/\Delta p$ in the region of 0.1, the standard deviation was much larger (100 m for $+1\sigma$).

To summarize, Frehlich and Cornman note that the spatial averaging of the velocity field in the horizontal direction of the lidar beam axis produces a negligible bias when $\Delta h/\Delta p \approx 0.2$. Using the Salford PDL data and following Frehlich and Cornman (2002), we can calculate the structure function for the 2 May 2002 data and subsequently produce estimates of $\epsilon$ and $L_s$.

### 5. Error analysis

The estimation of the retrieved radial velocities from the PDL are a function of the lidar parameters, the atmospheric conditions, and the velocity estimation procedure. It is therefore important to know what is the combined effect of the lidar parameters and the velocity estimation algorithm when attempting to measure the atmospheric conditions with a PDL system.

Following Drobinski et al. (2000) the wind velocity $V_r(r, t)$, at range $r$ and time $t$, measurement by a PDL can be written as the sum of an effective wind velocity, $V_n(r, t)$ and an error, $e(r, t)$:

$$V_r(r, t) = V_n(r, t) + e(r, t),$$

where, according to Frehlich et al. (1998), the effective wind velocity, $V_n(r)$, is a spatial average over the pulse duration and processing range gate of the true line-of-sight (LOS) wind velocity, $V_t(r)$. Drobinski et al. (2000) used a model that assumed the errors have a zero mean, which is not true in reality due to the asymmetry of the power of the transmitted pulse (Dabas et al. 1998) and low SNR (Frehlich and Yadlowsky 1994). Frehlich (2001) corrects the equation to take into account any bias due to the assumed errors having a nonzero mean as follows:

$$V_r(r, t) = V_n(r, t) + e(r, t) + \text{bias}(r, t).$$

A measurement of the bias of a PDL measurement requires an independent in situ measurement. The random error can be determined by 1) comparing with in situ measurements, 2) using the statistical properties of the velocity estimator and assuming ideal atmospheric conditions (Drobinski et al. 2000), or 3) using actual radial velocity data as outlined in Frehlich (2001).

Frehlich (2001) described three different techniques for deriving the error, $e(r, t)$, from actual PDL data. He estimates the error from the velocity spectrum from the velocity covariance and also from a velocity differencing procedure.

In this paper we follow the technique of velocity differencing that Frehlich (2001) shows to have the best performance and the smallest estimation error. From the radial velocity measurements from $N$ lidar data points, Frehlich (2001) produced two velocity estimates, $\hat{V}_r$ and $\hat{V}_s$, from the even- and odd-numbered data, respectively. Each estimate will have values from $N/2$ data points. For a fixed beam the estimates should have the same mean, $V_n(r, t)$, and the same bias (for well-behaved atmospheric conditions). Hence,

$$\Delta V_r\left(r, t, \frac{N}{2}\right) = \hat{V}_r\left(r, t, \frac{N}{2}\right) - \hat{V}_s\left(r, t, \frac{N}{2}\right).$$

From Eq. (3),

$$\Delta V(r, t, \frac{N}{2}) = e\left(r, t, \frac{N}{2}\right) + e_s\left(r, t, \frac{N}{2}\right).$$

and if $e$ and $e_s$ are statistically similar and uncorrelated, the variance is then given by

$$\sigma_{\Delta V}^2\left(r, \frac{N}{2}\right) = 2\sigma_e^2\left(r, \frac{N}{2}\right).$$

Therefore,

$$\sigma_r^2(r, N) = \frac{1}{2} \sigma_e^2\left(r, \frac{N}{2}\right) = \frac{\sigma_{\Delta V}^2}{4}. \tag{7}$$

Figure 3 shows the calculation for $\sigma_r^2$ for the three sets of data taken using the Salford PDL following the methodology of Frehlich and Cornman (2002). The fig-
ure shows that the error, $\sigma^2_e$, increases with range, as would be expected, due to decreasing SNR with range. Above 4480 m (range gate 40), the error, $\sigma^2_e$, is affected by bad estimates of radial velocity and data beyond this point are not used in the analysis. Frehlich (2001) notes that the velocity differencing algorithm can be modified for data in the weak signal regime, which is not carried out here.

A comparison of the curves in Fig. 3 shows that the error, $\sigma^2_e$, is increased when the number of pulse accumulations decreases since May02-02 displays larger errors than May02-01. The May02-2 data and May02-3 data are on average similar in magnitude.

6. Data analysis

The spectral statistics of the velocity field can be described by use of the spatial structure function. The spatial structure function is primarily described by two parameters: the energy dissipation rate, $\epsilon$ and the integral length scale, $L_i$. Frehlich and Cornman (2002) showed how calculations of the structure function of simulated PDL radial velocity data for different values of the parameter $\Delta h/\Delta p$, which had been corrected for the random error due of the lidar data, $\sigma^2_v$, can be fit to the von Kármán turbulence model for isotropic turbulence in the inertial subrange (Hinze 1959; Frehlich 2000) to derive values for the energy dissipation rate, $\epsilon$, and integral length scale, $L_i$.

Following Frehlich and Cornman (2002), for stationary conditions the structure function of $V(r, t)$ is independent of $t$ and is defined as

$$D_s(s) = \langle [V(r_0) - V(r_0 + s)]^2 \rangle,$$

where $s$ is the spatial separation between radial velocity measurements, $V$, and $\langle \rangle$ denotes an ensemble mean.

A simple model for the structure function is

$$D_s(s) = 2\sigma^2_v \Lambda \left( \frac{s}{L_o} \right),$$

where $\sigma^2_v$ is the variance of the radial velocity and $L_o$ is the outer scale of the turbulence. For the von Kármán model (Hinze 1959; Frehlich 2000),

$$\Lambda(x) = 1.0 - 0.592 \ 548 \ 5 x^{1/3} K_{1/3}(x),$$

where $K_{1/3}(x)$ is the modified Bessel function of order 1/3, and

$$L_i = 0.746 \ 834 \ 3L_o \ \text{and} \ \epsilon = 0.933 \ 668 \ \frac{\sigma^3_v}{L_o},$$

where $\epsilon$ is the energy dissipation rate.

The structure function from the PDL data is denoted by $\hat{D}_{\text{wgt}}$, and is calculated from

$$\hat{D}_{\text{wgt}}(r_1, r_2) = \langle [V_m(r_1, t) - V_m(r_2, t)]^2 \rangle.$$  

For a stationary and homogeneous wind field,

$$\hat{D}_{\text{wgt}}(r_1, r_2) = \hat{D}_{\text{raw}}(r_1 - r_2),$$

and when the estimation error $\epsilon(r, t)$ is uncorrelated with the wind velocity $V_m(r, t)$, then

$$\hat{D}_{\text{wgt}}(r_1 - r_2) = \hat{D}_{\text{raw}}(r_1 - r_2) - \hat{\sigma}^2_v(r_1 - r_2),$$

where $\hat{D}_{\text{raw}}$ is the uncorrected velocity structure function [from Frehlich and Cornman (2002), their Eq. (27)], and $\hat{\sigma}^2_v(r_1 - r_2)$ is the unbiased correction for the estimation error $\epsilon(r, t)$ of the velocity estimate using the velocity differencing error procedure described previously.

Frehlich et al. (1998) showed that the simple model for the structure function given in Eq. (9) can be altered to correct for the effect of spatial averaging of the lidar pulse volume. The corrected model is given by

$$\tilde{D}_{\text{wgt}}(s, \sigma_v, L_o) = 2\sigma^2_v G \left( \frac{s}{\Delta p}, \frac{\Delta p}{L_o}, \frac{\sqrt{2 \ln 2} \Delta p}{\Delta r} \right),$$

where

$$G(m, \mu, \chi) = \int_{-\infty}^{\infty} F(x, \mu) [\Lambda(\chi|m - x|) - \Lambda(\chi|x|)] \, dx$$

and $F(x, \mu)$, given by Frehlich (1998), is the transfer function describing the Gaussian lidar pulse. Using the normalized pulse shape from Fig. 1a, the transfer function describing the spatial averaging produced from the Salford lidar can be calculated. Then, $G(m, \mu, \chi)$ and $\tilde{D}_{\text{wgt}}(s, \sigma_v, L_o)$ can be calculated numerically for the simple von Kármán model.

Following the calculation of the correction for the estimation error, $\sigma^2_v$, from Eq. (7) and using the Salford lidar data taken on 2 May 2002, the corrected structure function was calculated from Eq. (15). Figure 4 shows...
the calculation of the structure function $D_{raw}(s)$, and the corrected data $D_{wgt}(s)$. Using Eq. (9) the structure function $D_{wgt}(s)$, for the von Kármán model was calculated. Following this the corrected structure function $D_{wgt}(s)$, from the von Kármán model was calculated from Eq. (16). This curve corrects for the spatial averaging of the Salford lidar pulse. The best-fit curve from the corrected von Kármán model to the corrected structure function from the Salford lidar is also shown in Fig. 4. From the fit to the corrected von Kármán model structure function, $D_{wgt}(s)$, we can derive values for $\sigma^2_{s}$ and $L_{o}$. Then using Eqs. (11) and (12) we can calculate values for $L_{i}$ and $e$, respectively.

To fit the model structure function curve to the lidar data structure function, a weighted least squares procedure was followed. The parameters of the wind field, $\sigma_{s}$ and $L_{o}$, were determined by minimizing the weighted error $J^2$ as shown below:

$$J^2(\sigma_{s}, L_{o}) = \sum_{k=1}^{N_{i}} N_{s}(k\Delta s)[D_{wgt}(k\Delta s) - \hat{D}_{wgt}(k\Delta s, \sigma_{s}, L_{o})]^2, \quad (18)$$

where $\Delta s$ is the range separation between adjacent velocity estimates, $N_{i}$ is the maximum number of lags, and $N_{s}$ is the number of independent samples of the velocity difference at separation $k\Delta s$. The function was minimized for $\sigma_{s}$ and $L_{o}$ separately in an iterative process.

7. Results

The new Salford University pulsed Doppler lidar system was first deployed in an urban field experiment in Salford city center in the United Kingdom from 2 to 7 May 2002. The first day of the experiment was intended to establish the system performance capabilities and take measurements to calculate the system errors. This paper is intended to address the question of the size of the system biases and the measurement accuracy. Three sets of data from 2 May 2002 were analyzed.

The weather on 2 May 2002 was convective with cumulus clouds developing through the day. Figure 5 shows the virtual potential temperature from a series of radiosonde ascents showing the boundary layer to be unstable through its depth. The top of the mixed layer at 1242 UTC can be seen at a height of 1800 m.

The three sets of data discussed in this report were taken for three different system configurations, as detailed in Table 2. The three datasets were taken in a 45-
min period starting from 1300 UTC. The aim was to calculate the system sensitivity for the three different setups. Following Frehlich (2001) a technique of velocity differencing was used to calculate the size of the estimation error. Figure 3 shows the standard deviation of the estimation error as a function of range. Table 4 shows the average estimation error variance, \( \sigma_e^2 \), for ranges 10–40. It is seen that the error is increased for the May02-2 and May02-3 datasets where the amount of accumulation of shots is decreased. The difference in \( \sigma_e^2 \) between May02-2 and May02-3 is not significant. Each dataset comprises approximately 10 min of data, and the mean and trend were removed before the data were analyzed. The lidar beam was pointed to be perpendicular to the mean wind direction at the start of the experiment, as measured using an azimuth scan from the lidar (not shown). The lidar beam was inclined at an angle of 4.7° from the horizontal, which provides data in the height range 110–390 m. Table 4 gives the mean radial velocity and velocity variance through the profile. The increase in the mean radial velocity seen in May02-3 is possibly due to a slight change in the mean wind direction. The increase in velocity variance is due to the increasing turbulence apparent on the day.

Following the procedure outlined in section 6, calculations were carried out to measure the kinetic energy dissipation rate from the calculation of the structure function. The calculation of the structure function accounted for the non-Gaussian shape of the Salford lidar pulse. This is a modification of the method outlined in Frehlich et al. (1998), which assumed a Gaussian pulse shape. Curves for the structure function for the three sets of data are shown in Fig. 4. The points in Figs. 4a–c are from calculations from the lidar data while the lines are from the von Kármán model. It can be seen from the figure that the corrected lidar data and corrected von Kármán model data are a good fit for separations of between 300 and 1500 m. The difference between the uncorrected von Kármán model, \( \tilde{D}_e(s) \), and the corrected model, \( \tilde{D}_{cor}(s) \), shows the importance of spatially correcting the data for both size and shape of the pulse length. Table 5 shows the kinetic energy dissipation rate, integral length scale, and velocity variance from the fitted model curves.

The eddy kinetic energy dissipation rate is seen to increase throughout the duration of the experiment. This is typical behavior for a convective boundary layer where \( \epsilon \) normally increases through the morning and early afternoon before slowly decreasing in the late afternoon (Stull 1988). The values are also typical for a convective boundary layer (Stull 1988). Frehlich and Cormans (2002) show that \( \epsilon \)’s error for this method for \( \Delta h/\Delta p \) in the range 0.1–0.2 is approximately 12%. Table 5 also shows kinetic energy dissipation rates obtained from the amplitude of the power spectra of the radial velocity correlations. The methodology, outlined by Gal-Chen et al. (1992), is used to filter and spectrally analyze the data. Data for range gates 10–40 are used. The spectra for the three datasets are shown in Fig. 6. The values for the kinetic energy dissipation rate from the covariance spectrum correlate well with those from the structure function curves. However, the dissipation rate calculated from the covariance spectrum is slightly larger. This is due to the fact that using the covariance spectral method means no correction is carried out to remove the variance due to the system estimation error, \( \sigma_e^2 \).

The deviation of the corrected model fit, \( \tilde{D}_{cor}(s) \), to

### Table 4. Mean radial velocity, mean radial velocity variance, and estimation error, \( \sigma_e^2 \), averaged over the line of sight of the lidar beam.

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Mean velocity (m/s)</th>
<th>Velocity variance (m²/s²)</th>
<th>( \sigma_e^2 ) (m²/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 02-1</td>
<td>0.14</td>
<td>1.09</td>
<td>0.16</td>
</tr>
<tr>
<td>May 02-2</td>
<td>0.14</td>
<td>1.41</td>
<td>0.23</td>
</tr>
<tr>
<td>May 02-3</td>
<td>0.94</td>
<td>1.66</td>
<td>0.25</td>
</tr>
</tbody>
</table>

### Table 5. Eddy kinetic energy dissipation rates calculated from the covariance spectrum and from the structure function. Also given are the integral length scale and \( \sigma_e^2 \) from the fitted von Kármán model curve.

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Kinetic energy dissipation rate from covariance spectrum (m²/s³)</th>
<th>Kinetic energy dissipation rate from structure function (m²/s³)</th>
<th>Integral length scale from structure function (m)</th>
<th>Corrected velocity variance, ( \sigma_e^2 ) (m²/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 02-1</td>
<td>1.1 \times 10^{-3}</td>
<td>0.9 \times 10^{-3}</td>
<td>375</td>
<td>0.63</td>
</tr>
<tr>
<td>May 02-2</td>
<td>2.3 \times 10^{-3}</td>
<td>2.2 \times 10^{-3}</td>
<td>290</td>
<td>0.94</td>
</tr>
<tr>
<td>May 02-3</td>
<td>4.3 \times 10^{-3}</td>
<td>3.2 \times 10^{-3}</td>
<td>355</td>
<td>1.45</td>
</tr>
</tbody>
</table>
the Salford lidar data, $\dot{D}_{\text{oss}}(s)$, at very small ($\Delta s = 100–200$ m) and very large separations ($\Delta s = 2000–3000$ m) is possibly due to the pulse-to-pulse variability in the pulse shape, duration, and chirp that is present in CO$_2$ lidars (Dabas et al. 2000). From Fig. 4 it can be seen that at the smallest separations, the corrected model curve is below that for the lidar data, suggesting that there is more coherence to the lidar data at these separations than is calculated from the corrected von Kármán model.

Values for the integral length scale can also be obtained from the fit of the von Kármán model. Frehlich and Cornman (2002) note however that for $\Delta h/\Delta p$ in the range 0.1–0.2 the estimate can be from 25% smaller to 100% larger than the actual value.

8. Conclusions

The aim of this initial data analysis was to address the questions regarding instrument bias and estimation error in the Salford lidar system. The Salford pulsed Doppler lidar system was designed and built by QinetiQ [formerly the Defence and Evaluation and Research Agency (DERA), in Malvern, United Kingdom], specifically to be used in urban areas. It is unique in its system setup and is one of only a handful of purpose-built atmospheric Doppler lidar systems around the world. It was therefore important to investigate and document the specific system biases and errors.

The Salford lidar system was successfully deployed in an urban area: city center Salford, as part of the Salford Urban Meteorological Experiment (SALFEX) in May 2002. It was used to profile the wind and turbulence above the urban canopy region. This paper outlines the calculation procedure used to estimate the system biases and estimation errors. A bias due to the constant effect of the frequency chirp has been calculated to be $-0.25$ m s$^{-1}$. This bias was removed from all data before further analysis was done. Because of the shot accumulation procedure used in the processing algorithm the bias due to the speckle effect of the frequency chirp is only of the order of 0.02 m s$^{-1}$ under normal atmospheric conditions. This is well within the region of the velocity estimation accuracy, shown in Fig. 4, which is of the order of 0.4 m s$^{-1}$. The effects of the speckle bias were therefore not considered further. The velocity estimation error is calculated using a method of velocity differencing discussed by Frehlich (2001).

Frehlich and Cornman (2002) used simulated lidar data to calculate the accuracy of fitting a simple von Kármán turbulence model to the structure function derived from the lidar data. They show that values for the kinetic energy dissipation rate, integral length scale, and velocity variance can be successfully obtained using their method. The methodology corrects for the estimation error and the spatial averaging inherent in the lidar data processing procedure and should therefore give more accurate values for the derived quantities. Frehlich and Cornman (2002) assumed a Gaussian profile to their lidar pulse, but the Salford lidar pulse is not Gaussian, so their procedure was modified to take into account the actual Salford lidar pulse profile. Following the procedure outlined by Fredlich and Cornman (2002), data from the SALFEX experiment was used to calculate the kinetic energy dissipation rate, integral length scale, and velocity variance above the urban canopy. The calculations were done for data taken over 10-min periods and spatially averaged, for heights in the range 110–390 m, and over a horizontal length of 3.5 km above a mixed urban canopy region.

For the three datasets analyzed the kinetic energy dissipation rate was found to increase through the day. This is normal behavior for a convective boundary layer where the dissipation rate is normally seen to increase through the morning and early afternoon (Stull 1988). Frehlich and Cornman (2002) show that the error on the kinetic energy dissipation rate, $\epsilon$, using this methodology is approximately 12%. The dissipation rate was also estimated from the correlation spectrum. These two results are very similar. The structure function estimation is lower, as would be expected due to the correction for lidar velocity estimation error and spatial averaging. The values for the velocity variance reflect those of the dissipation rate in that they increase during the day and are higher in the uncorrected data. Again the lower corrected values are due to the error estimation correction procedure. The values for the integral length scale are of the order of 250–400 m and are therefore only of the order 2 to 4 times the length of the lidar pulse. Frehlich and Cornman (2002) note that even with their simulated data the magnitude of the estimated integral length scale can be 100% larger than the input value.

However, despite these reservations, lidar systems are unique in that they do actually measure the spatial variability along the line of sight of the beam and therefore no assumptions of “frozen turbulence” need be applied. Furthermore, values of parameters such as the integral length scale, kinetic energy dissipation rate, as well as integral time scale are important inputs into standard dispersion models. It is therefore important to establish estimation procedures for the parameters described above: the kinetic energy dissipation rate, the velocity variance, and the integral length scale. In principle the Salford PDL can measure these parameters from the top of the urban canopy to the top of the urban boundary layer, but as with any field experiment, local morphology and atmospheric conditions normally dictate the actual range of the system. The vertical resolution of the measured and derived quantities is dependent on the elevation angle of the beam, and the spatial and temporal averaging required.

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