Derivation of cup-equivalent turbulence from Doppler Spectra obtained by scanning Continuous Wave (CW) lidar

ZephIR Lidar

Mark Pitter, Michael Harris, John Medley, Scott Wylie, Chris Slinger, Muhammad Mangat and CarloAlberto Ratti ZephIR Lidar, Ledbury, UK. (email: michael.harris@zephirlidar.com)

Introduction

The accurate derivation of wind turbulence parameters from remote sensing systems is a topic of active current research. With the increased use of lidar in the wind industry, it becomes crucial to provide turbulence intensity (TI) data that can be related to measurements obtained from cups and other devices. Different lidar scanning patterns and signal processing approaches have previously been investigated as a means to overcome some challenges that result from two issues: spatial averaging over the probe and scan volume, and contamination of the horizontal Doppler measurements by vertical flow components. Here we adopt a radically different approach to those previously used by scanning lidars to derive a measure of TI that corresponds closely with measurements from a cup anemometer. In fact the method is potentially superior to a cup in that it allows measurement of TI at different points in space, thus providing a better representation of the turbulence characteristics over a particular site.

Approach

Independent Doppler spectra are obtained as standard at 50Hz in a circular scan ensuring that measurements are made close to the same height as the reference cup twice every second. These parts of the scan are identified, and the corresponding raw data obtained at the cup height are amalgamated to provide averaged spectra. The left and right parts of the scan are separately analysed to give an indication of spatial variability of turbulence, which may additionally be a promising approach for detection of turbine wakes or flow complexity due to variation in terrain or land coverage. The 10-minute averaged spectra provide much information on the wind statistics, but here we simply calculate the standard deviation of the distribution, and divide by the mean speed to derive values for TI. Detailed investigation is ongoing to understand fully any impact of other experimental parameters such as scan angle (both 15 and 30 degree half cone angles were used), yaw misalignment, range and signal-to-noise ratio. Preliminary results indicate that the approach is robust to variation in these parameters.

Turbulence from CW Lidar

### TI from ground-based vertically-scanning lidar
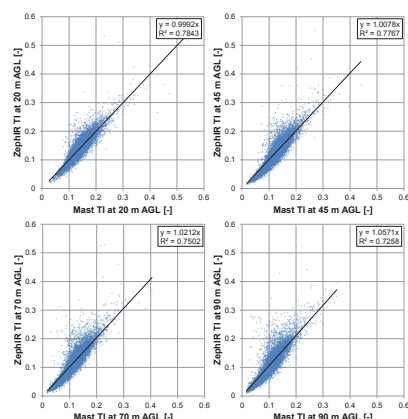
The results shown in figure 1 are obtained as standard output from a ground-based ZephIR 300, scanning in a cone of 30-degree half angle, deployed next to a high-quality tall mast at The UK Remote Sensing test site (UK RSTS). The data spans a period of 6-months, during which a wide range of conditions and speeds were experienced.

The shape of the correlation plots is characteristic of this type of measurement, as described in [1], and is a consequence of the effects due to measurement volume and vertical flow mentioned above. Although this results in some sensitivity of the measured TI to stability conditions, the overall average values of TI show a close agreement with those from the mast at all heights.

Figure 1: Measurement of TI from ground-based ZephIR 300 at four heights above ground level (20 m, 45 m, 70 m and 91 m).

Turbulence from turbine-mounted horizontally scanning lidar
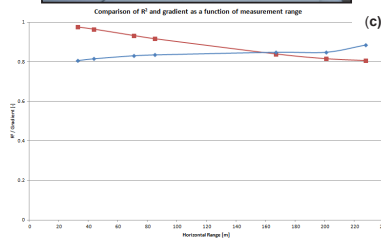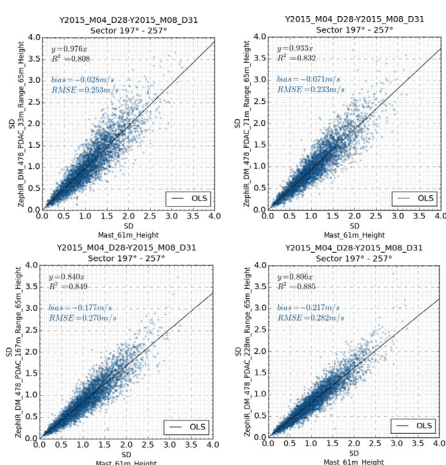
The next set of results in figure 2 have been obtained with a ZephIR Dual-Mode (DM) unit, mounted on the nacelle of a large wind turbine in moderately complex terrain. The scan axis is close to horizontal, and the cone half angle is 15 degrees; the turbine (and hence the lidar) is assumed to be correctly yawed to point closely into the wind. The data was processed for comparison with a cup mounted at the top of a 61 m met mast; hub height was 65 m, and data were obtained at different ranges for concurrent periods. The examples shown were obtained at ranges from ~0.5D (33 m) to ~3D (228 m).

Note that in this case the characteristic shape seen in the ground-based case is no longer present: the correlation plots form a straight line with some scatter. However, the effects of volume averaging are still present, as can be seen from the values of the gradients in the 4 plots at different ranges in front of the turbine.

Figure 2: (a) Correlation of Mast and ZephIR Std. Dev. at 61 m AGL as a function of measurement range; (b) Picture of a ZephIR DM installed on top of wind turbine in the North Sea; and (c) Graph to show how the gradient and R2 values of a forced linear regression vary as a function of measurement range.

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Turbulence from Spectral Averaging

The operational nature of a CW lidar means that precise measurements of the Doppler spectrum can be obtained at a very high rate of 50 Hz. As a result, high frequency information about the distribution of wind speeds within the probe volume can be captured.

Rather than fitting to each second's data to determine the wind speed, and then calculating wind statistics from the fit results, the work in [2] averaged 10-minutes worth of spectral data, and then calculated the standard deviation of the resulting distribution. Figure 3 shows around 90-seconds worth of 'raw' spectral data recorded by a ZephIR DM. The high frequency spectra are then normalised and averaged over each 10-minute period to produce a plot like that in figure 3(b).
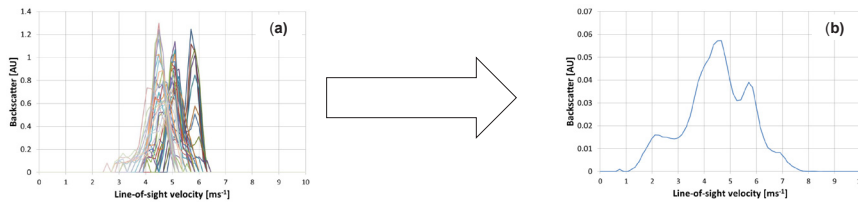

Figure 3: (a) Individual one second spectra from CW measurements; (b) Ten minute averaged spectrum calculated from the individual one second measurements.

It was shown mathematically in [2], and it can be seen in figure 3(b), that high frequency features are retained. These can be suppressed by the standard algorithms. Turbulence can then be found by calculating the statistics of this averaged distribution.

Results

Turbulence from spectral analysis, Denmark case study
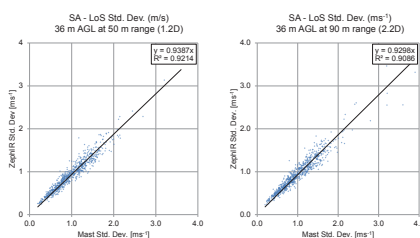
The first case study is from a ZephIR DM mounted on the nacelle of a test turbine of D= 40 m, with a hub-height mast located 2.2D from the tower in the typical upwind direction. In this case the scan cone half angle was 30 degrees. The comparison of turbulence data with the mast is encouraging with good correlation. The gradients are slightly below unity since the beam is misaligned with the wind by roughly 30 degrees.

Figure 4: Correlation of Std. Dev. between a mast and ZephIR DM at two different ranges. Spectral averaging was used to calculate ZephIR DM Std. Dev.

Turbulence from spectral analysis, UK case study
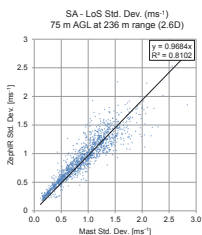
This second case involved a larger turbine (D = 90 m), and hence measurement at longer ranges for comparison with the mast, located at 2.6D. The ZephIR DM was configured here with a 15 degree cone half angle. Hence, the beam is aligned more closely with the wind direction than the previous case. Correspondingly, the gradient of the turbulence correlation plot against the mast is closer to unity. The results raise some questions about the fundamental nature of turbulence, and we have next investigated some aspects using data from the UK RSTS mast.

Figure 5: Correlation of Std. Dev. between a mast and ZephIR DM at 236 m. Spectral averaging was used to calculate ZephIR DM Std. Dev.

Mast-to-mast measurement variations
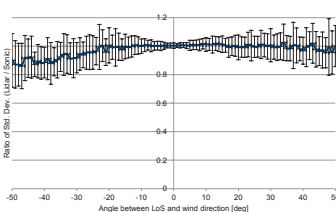
To further develop our understanding we have carried out a study on data from a 91 m sonic anemometer at the UK RSTS. To mimic the lidar, which measures the component of velocity resolved along its beam, data from the sonic were resolved along an arbitrary axis. Next we have looked at the ratio of 10-minute standard deviation between the resolved and unresolved sonic output. The error bars show the standard deviation of the 10-minutes ratios, which show a negligible bias within ±20 degrees.

Figure 6: Ratio of Std. Dev. for sonic (resolved) to sonic (unresolved) versus wind direction relative to arbitrary axis.

Summary and Conclusions

The results show a good level of agreement between turbulence statistics measured by the turbine-mounted lidar and cup anemometers. This is partly a consequence of the largely horizontal measurement geometry which excludes vertical components that normally contaminate ground-based lidar measurements. In addition the spectral analysis approach largely eliminates the effect of spatial averaging. Work is continuing to understand the range dependence of the method, and to use the results to investigate the statistical properties of turbulence as the flow enters the turbine's induction zone, right up to the rotor.

In addition, a better understanding of the variation between measurements from two different anemometers – a cup and a sonic – was undertaken as a means to better understand the impact of measuring turbulence projected along a given axis (as performed by a lidar), compared with a cup, which does not distinguish along which direction the speed fluctuations are aligned. This shows evidence that a small bias may result from the lidar spectral method, when the beam is significantly misaligned with the wind. With further work this bias can be accounted for as the misalignment between the wind and the beam will be known.

References

1. "Can lidars measure turbulence? Comparison between Z300 and IEC-compliant mast", W Barker et al, EWEA (2012)
2. "Retrieving wind statistics from average spectrum of continuous-wave lidar," E. Branlard et al, Atmos. Meas. Tech., 6, 1673-1683 (2013)