Suitability of Doppler Wind Lidars Measurement for Wind Climatology

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Introduction

To study the dispersion of pollutants in urban areas and to evaluate potential regulatory measures, both numerical and physical modelling tools at street scales are essential tools. The pollution dispersion in the complex urban canopy layer is challenging to predict because of the high level of turbulence in the driving wind field. To inform model setup and to assess simulation results, real-world profile observations are urgently needed. While a representative climatology of the mean wind profile is very valuable, also turbulence statistics such as variance in all three wind components, integral length scales, and spectral composition are required.

Traditionally, such information is derived from tall tower observations. The advantage of the mast measurements is a high sampling frequency of data acquisition. However, towers are usually insufficiently high and their deployment in urban settings is very rare as it is generally difficult to find a suitable location and they are expensive to build. Remote sensing profilers can be used to monitor the atmospheric boundary layer continuously. Wind climatology data at a site of interest would provide more accurate initial data for the microscale modellers (both the wind-tunnel and numerical simulations). Doppler wind lidars are powerful systems to obtain long-term observations of all three wind components at high temporal resolution along a vertical profile [1]. The first available measurement level, the range of the observations in the vertical and also the vertical resolution differ between instrument models and measurement setups [2].

The main objective of this report is to assess how Doppler Wind Lidar (DWL) profile measurements can be exploited to inform microscale flow modelling in urban settings.

Wind tunnel modelling – current state-of-the-art

Physical modelling is based on the analogy between the atmospheric boundary layer (ABL) and the aerodynamic boundary layer above a flat surface. The flow properties of a real site and its model are analogous if the ratios of all acting forces are identical. These ratios are called similarity numbers, e.g., Reynolds or Richardson numbers. Investigation of scaled atmospheric flows in laboratory conditions is advantageous since the conditions during measurements are under control, repeatable, and statistically stationary. Moreover, precise state-of–the-art experimental techniques (e.g. Laser Doppler Anemometry, Particle Image Velocimetry, Thermal Anemometry, and Flame Ionisation Detector with fast temporal response) can be employed at ease.

The wind engineering community sees the ABL as a special case of an aerodynamic boundary layer. To apply theoretical assumptions, certain criteria need to be fulfilled, such as a logarithmic vertical profile of the mean wind speed, a fully developed turbulence spectra with clearly pronounced inertial subrange, and temporal stationarity. However, such characteristics are very seldom present in real-world atmospheric measurements. The ABL measurements are very often subjected to spatial variations in surface roughness (inhomogeneous terrain) and a nonstationary forcing (changes in the synoptic flow and changes in the turbulent surface heat fluxes). Hence they do not fit into aerodynamicists' expectations.

Given real-world data for specific atmospheric conditions are rare, especially for specific sites of interest, best practice guidelines and tables with recommended values for the key parameters were developed, such as the frequently applied ESDU (originally the 'Engineering Sciences Data Unit') published in 2002 in UK [3] and VDI 3783 Blatt 12 from The Association of German Engineers originally published in 2000 with the major revision in 2022 [4]. Both guidance documents provide reference values for wind profiles in the atmospheric boundary layers as a function of surface roughness classes - from desert and ice flat plains to the cite centres. Tabled values consist of parameters that describe the logarithmic vertical profile of horizontal wind speed (roughness length, zero-plane displacement height), vertical profiles of turbulence intensity for each wind component, the spectral distribution of the turbulent kinetic energy (TKE) and the vertical profile of the integral length scales. These guidelines are tools for engineers to solve specific problems and to provide them with best practice recommendations without lengthy literature searches. They are part of a very complex system of recommendations for engineers, where the authority of a professional association guarantees the quality of the data. The associations sell these guidelines to sustain their activities. That's why they're not open source. This is one of our motivations to collect and process DWL data from the scientific community and make it freely available.

Other very old reference used in both guidelines in work of J. Counihan [5]. He collected a wide range of ABL tower measurements from years 1880 to 1972 and summarized them in the graphs and tables giving typical values of the aerodynamic parameters as the power-law exponent, roughness length, integral length scales, and power spectra. Experimental equipment has undergone a fundamental enhancement since then.

Stationary time series of all three wind velocity components are needed at high temporal frequency to estimate all turbulence properties reliably, as they are calculated from the time series of the fluctuations around a stationary mean value. Any biases or temporal trends can affect the accuracy of the mean and may hence alter the resulting turbulence estimates. Therefore, is essential to choose appropriate averaging periods. The classical wind-speed spectrum from Van der Hoven (1957) [6] shows that the dominant temporal scales of turbulence have a duration of about 1 to 5 minutes, and the dominant synoptic variations have frequency of several days. These two spectral peaks are separated by "the spectral gap" at approximately 30 to 60 minutes which conveniently separates synoptic and turbulent motions. Turbulence estimations from classical Eddy Covariance systems hence often work with an averaging period of 30-60 min. To account for variations in atmospheric stability, the optimal averaging period can be chosen inversely proportional to the mean wind speed from the aerodynamical point of view. Note that the presence of the spectral gap has been questioned lately [7].

Obtaining Wind Climatology information from urban Doppler Wind Lidar (DWL) measurements

To demonstrate what type of information can be extracted from continuous DWL observations in urban settings that have not been specifically designed for this application, we utilise profile measurements obtained using a Vaisala WindCube 400s that is operated in the centre of Paris on top of a tall building at the QUALAIR-SU supersite in the framework of the PANAME multi-project initiative. All details are described in [8].

The DWL data were vertically ranging from 150 m to 6000 m, however, here we focus on the lowest 1000 m for the analysis of the near-surface turbulent flow over the urban terrain. Instantaneous data with averaged sampling frequency of 2.9 s are averaged to 15-minutes to produce a vertical profile with 35 levels for an initial sorting of the data.

The 15-minutes variations were analysed to identify long time intervals with steady weather – steady wind speed and wind direction. We preferred dates with strong winds which presumably creates a neutral thermal stratification. Two types of wind behaviours were observed:
1] "normal" profiles with increasing wind speed with height and very mild wind tilt up to 1000 m,
2] "mixed" profiles with almost constant wind speed and wind direction up to 1000 m.

For the "normal" profile types, the one representative profile was calculated from the longer interval for steady weather (mean time interval of averaging was typically 8 hours) at days April 10, 11, 18, 22, 23. Averaged normal profiles were then fitted by the logarithmic profile (the wind-tunnel guideline VDI (2000). The essential turbulent parameters such as roughness length z_0, a power law exponent α and zero-plane displacement d_0 were determined. The parameters successfully classified the profiles into a rough class (e.g., April 10 (wind direction 300°) and April 23 (270°)) and a very rough class (e.g., April 22 (285°)). This procedure appeared to be successful for categorising the mean wind profiles for different wind directions, as the roughness length of the urban terrain changes with the wind direction.

The instantaneous horizontal wind speed data were analysed for the selected days. The measurement consists of five-laser-beam setup (LOS) – one beam for 90° elevation angle and four beams for 75° elevation angle to each direction – north, east, south and west, respectively. All the LOSs were consecutively recorded for seven minutes. One measurement run contains approximately 150 values covering these five LOSs. The time steps between the beams were not equidistant but it had been ranging from 1.8 to 4.6 s, with averaged time step 2.9 s. The data directly from one laser beam location provide only 30 samples in one run, with time step of approximately 15 s in average. The electrical noise adds other small irregularities to the sampling frequency that can be successfully solved by an interpolation. The horizontal data however includes gaps which could not be - due to their nature of measuring – filled with the interpolation.

The instantaneous vertical velocity data were recorded for two minutes, containing around 140 points and usually were of high quality without gaps (see Figure 1). The low number of instantaneous values within one DWL LOS run is unfortunately too low for any spectral analysis (the Fourier spectral analysis or the wavelet analysis). Spectral diagnostics requires much more data to be able to detect any repetitive frequency patterns in the time series. This number of points can still provide some statistics such as variances, but correlations or time-lag correlations could be negatively affected. Therefore the longer continuous time series would be desirable for further statistical and spectral analyses.

For the climatologic purpose, longer averaged wind profiles is also needed to determine classes of the topographically structured terrain of the Paris city for various wind directions. Even so, this classification will be limited to solely neutral thermal conditions, which covers the minority of the meteorological events. Climatologically, as Paris is a geographical location with prevailing south-western and east-east-north winds, the suitable characteristics from less frequent directions will be possible to achieve only with data from longer period (several years). The spring, autumn, and winter terms with strong wind episodes have higher number of neutral thermal stratification situations.

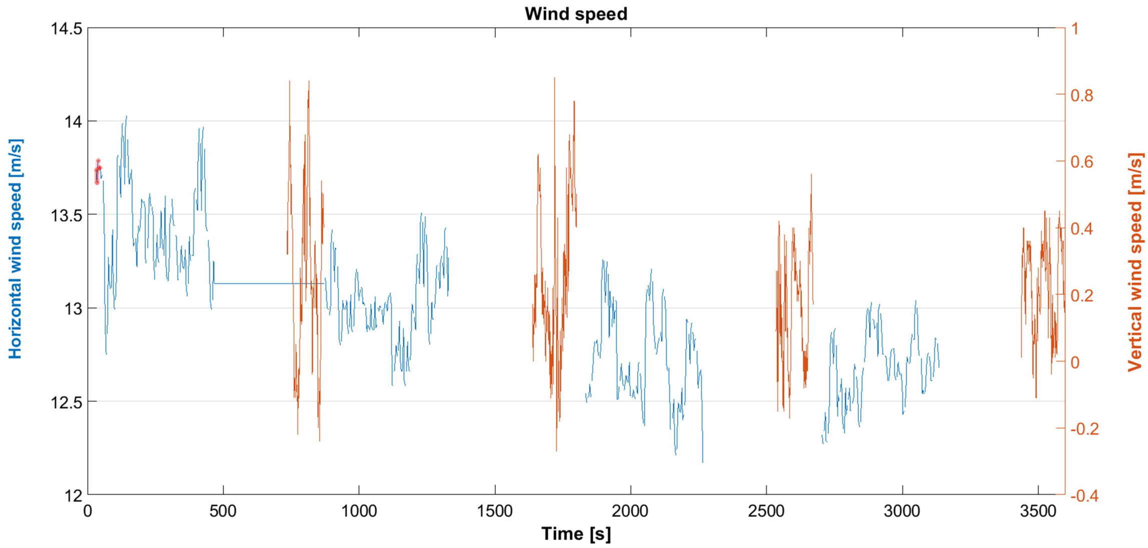

Fig. 1: Sample of horizontal wind speed data packets (blue) and vertical wind speed data packets (red). The first five red points at the very beginning of blue horizontal speed data denotes one run of LOSs.

Conclusion

Scanning strategies of DWL are driven by specific scientific questions, monitoring needs of the wind energy industry or e.g. by the needs of operational meteorology. The main idea is to measure more than one variable with a single device. Such strategies alternate the vertical stare and azimuthal or switching beams modes to capture all three wind components. The resulting timeseries of a particular wind component is nonequidistant with the long gaps. The gaps need to be filled and the whole timeseries equidistantly resampled to obtain higher-order statistics which are the basic tools to study turbulence characteristics. But usually the gaps are too long (sometimes even longer than the measurement period) and its artificial filling may introduce false signals to the statistics.

If the DWL data should serve to the wind and turbulence climatology then the scanning strategy should be set to produce uninterrupted timeseries of either horizontal or vertical wind components. The nonequidistant sampling can be resampled without major loss of information. The long gaps in the timeseries are the main problem for turbulence statistics.

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