J7.6 LIDAR MEASUREMENTS AS AN ALTERNATIVE TO TRADITIONAL ANEMOMETRY IN WIND ENERGY RESEARCH

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A major issue in addressing wind energy projects is the lack of high-quality measurements, quantitatively characterizing the wind and turbulent structure of the atmospheric layer where modern wind turbines operate. As the capacity and size of modern wind turbines continue to grow, the uncertainty in vertical extrapolation of wind measurements from surface meteorological stations or small towers instrumented by sonic/cup anemometers, can increase significantly.

Conventional measurements from tall (120-200 m) meteorological towers provide better results on wind field characteristics (Kelley et al., 2004), but the number of such towers is very limited and these measurements are still representative only of a few points across the rotor heights.

In most of the studies, for example to estimate turbine wake effects for optimal wind farm layout, concurrent inflow/outflow measurements from two or more tall towers are required, which can dramatically increase project expenses. Furthermore, it is more difficult to build tall towers, especially in the complex terrain or offshore.

Remote sensing instruments (wind profilers, sodars, and lidars) have a great potential for filling these gaps by providing high-quality measurements of wind profiles up to several hundred meters above the ground.

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With the fast development of new technologies and more effective materials, these instruments are becoming less expensive and an affordable alternative to the traditional measurements in wind energy.

Having in mind all advantages and disadvantages of remote sensing instruments for WE researching needs, our paper intends to discuss the benefits of lidar measurements.

Scanning lidars can capture both inflow and outflow wind characteristics with spatial and temporal resolution needed for many tasks including wind resource assessment, power curve measurements, estimation of wind shear at rotor heights, or evaluation of the velocity deficit and wake parameters downwind of wind turbines (Harris and Hand, 2006).

Research lidars, designed and developed at the Earth System Research Laboratory (ERSL) of the National Oceanic and Atmospheric Administration (NOAA), have been used extensively during past two decades for meteorological applications such as air quality and boundary layer studies, including offshore ship-borne measurements.

Most of these studies included high resolution measurements of wind and turbulence profiles. Detailed analysis of these measurements for WE purposes can provide unique knowledge of wind resources and wind-flow characteristics in different parts of the US, under different atmospheric and terrain-roughness conditions, over land and over water, and be of great use for developing and evaluating wind-turbine and atmospheric models.

This paper presents some of the examples of wind flow characteristics measured by one of the ERSL/NOAA lidars - the High Resolution Doppler lidar (HRDL) which is well suited for wind energy research needs due to its high temporal and spatial resolution, narrow beam width, and capability to measure the component of the wind velocity parallel to the lidar beam with a precision approaching ~10 cm s^{-1} (Grund et al, 2001). Moving flexibility, ability to instantly change the scanning strategy to sweep the atmosphere in vertical or horizontal plane and provide continuous information about wind and turbulence conditions at elevated heights above the range of tower measurements, has made HRDL a good alternative to traditional sonic/cup anemometer measurements, which would need to be installed on very tall towers (Pichugina et al., 2004-2008, Banta, Pichugina, 2006).

Results presented here were obtained from HRDL measurements during two past experiments, one of which was conducted in the flat terrain of the US Great Plains, and the other during an off-shore experiment, where HRDL was deployed on the NOAA research vessel Ronald Brown.

The first experiment, the Lamar Low-Level Jet Program of September 2003 in southeastern Colorado (LLLJP03), was designed to study wind-flow characteristics important for wind turbine operations and wind farm siting (Banta et al. 2006, Banta 2008, Kelley et al. 2004, Pichugina et al. 2008). Another experiment, the New England Air Quality Study (NEAQS), was conducted in July-August 2004. The description of this experiment goals and data can be found at <http://www.esrl.noaa.gov/csd/ICARTT/>

This study is focused on deviations of observed wind profiles from logarithmic or power law profiles, understanding how variation in stability affects the difference between measured and extrapolated wind profiles across the entire layer of turbine operations, and the analysis of directional shear as a function of stability.

Wind characteristics

The HRDL measurements of the radial or line-of sight (LOS) velocity during both experiments were obtained in two scanning modes: by sweeping the atmosphere in the vertical (vertical-slice scans), to provide profiles of the mean-wind component U (z) and the variance component σ_u^2 (z) in the vertical plane which was often oriented along the mean wind direction, and by sweeping the atmosphere in azimuth plane (conical scans), to provide profiles of the mean wind speed and direction. Profiles were computed up to several hundred meters above the ground level by averaging LOS velocity measurements over time intervals ranging from 1 min to several hours depending on the analysis goals.

Figure 1 shows 10-min averaged time-height cross sections of mean wind speed and wind direction, obtained from lidar conical scans performed at fixed shallow (2-16°) elevation angles during 2 nights in September 2003.

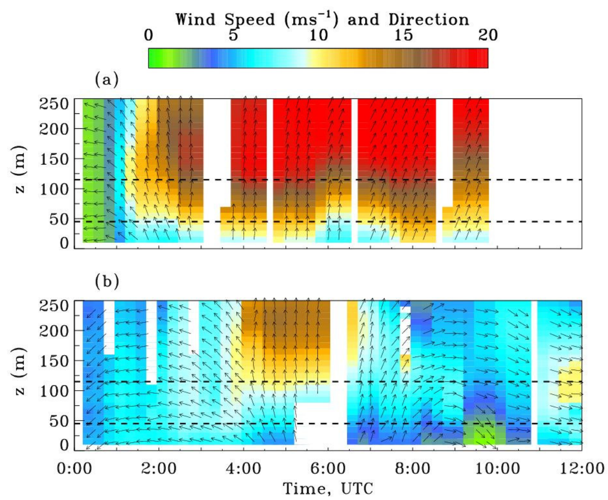

Figure 1. Mean wind speed (color) and direction (arrows), computed from HRDL conical scans during the night of September (a) 15th and (b) September 16th 2003. In both panels data averaged over 10-min time intervals and over 10 m vertical bins.

Data from all individual scans were processed with a technique described in Banta et al. (2002). The arrows in both panels indicate the direction of wind flow, and the color indicates wind speed magnitude from 0 (green) to 20 m s^{-1} (red). Dashed lines on both panels show the height (45-115 m) of GE 1.5 MW turbine rotors operated at the Green wind farm near Lamar, Colorado.

This figure illustrates considerable difference in the magnitude of wind speed between two consecutive nights. During the night of September 15 the winds were twice as strong as those on September 16. Wind directions in both plots show similar patterns: changing direction of winds during evening and morning transition times, and almost constant southerly direction at the middle of the local night (~4-8 UTC).

Both plots in the figure demonstrate the important ability of HRDL measurements to provide data on wind and directional shear across the entire layer occupied by turbine rotors. Knowledge of these parameters is very important for turbine operation, since modern turbine rotors are so large that wind conditions can differ above and below the turbine hub.

Wind shear

Wind shear at the turbine rotor heights was much stronger during the night of Sept 15, which was also characterized by frequent low-level jets (LLJ), with jet maxima of 15-25 m s^{-1} at heights of 150-200 m, and a very stable boundary layer (BL) most of the night (~200-1000 UTC). A dynamic stability ($d\theta / dz$) and Richardson number (*Ri*), computed from 1-min means of sonic anemometer measurements at the 54, 85, and 116 m tower levels, presented in Figure 2 (a) and (b) for both nights as in Fig. 1. During the night of Sept. 15, *Ri* remained in the critical range (0 < *Ri* < 0.25) and static stability oscillated between 0.025 and 0.040 K/m most of the time compare to only 2 hours (from ~430 to 630 UTC) of weaker LLJs during the other night.

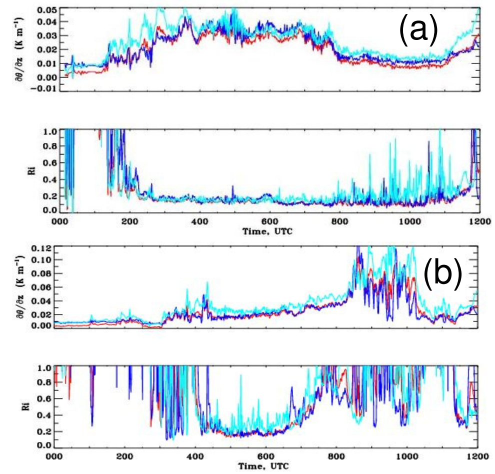

Figure 2. Dynamic stability (top panels) and gradient Richardson number (bottom panels), calculated from sonic anemometer measurements at 3 tower levels during the night of (a) September 15 and (b) September 16. Both variables were computed between 45-85, 85-116, and 45-116 m and shown on the figure by different colors. (The indication of layers is not important to the content of the text)

Distribution of 10-min wind shear in the layer of a 1.5 MW turbine rotor (45-115 m), computed for all strong wind nights from Lamar experiment, is indicated by a black line in Figure 3. Blue lines indicate mean (0.066) and median (0.07) values and red solid line is a cumulative histogram.

Figure shows that wind shear was > 4 m s^{-1} per 100 m more than 90% of time and > 8 m s^{-1} more than 50% of time as indicated by green dashed line.

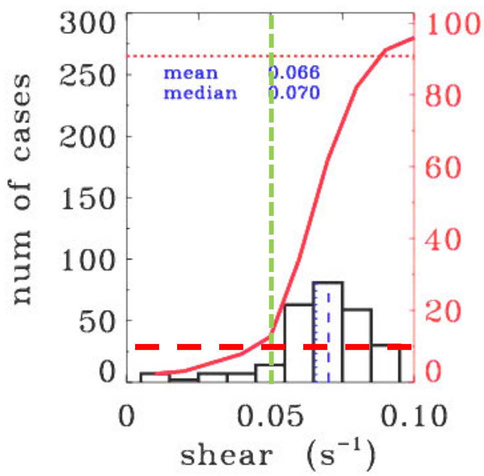

Figure 3. Distribution of wind shear in the layer of 45-115 m, computed from HRDL measurements during all strong (>15 ms^{-1}) wind nights from Lamar experiment, is indicated by a black line. Red solid line indicates a cumulative histogram.

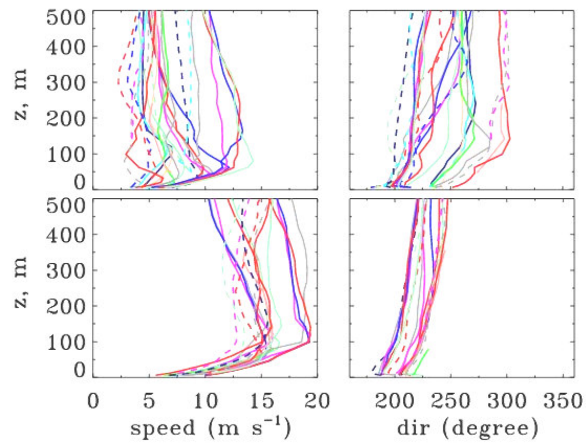

Figure 4. Hourly profiles of mean wind speed (left panels) and wind direction (right panels) from HRDL measurements during the NEAQS-04 experiment: (top) July 30 2004 and (bottom) July 31 2004. On all four panels, solid lines represent late afternoon and nighttime profiles (0000-1200, 2000-2400 UTC) indicated by different colors. Daytime profiles, from 7000 to 1400 local time, are shown by dashed lines.

Analysis of HRDL data obtained during all nights from the Lamar experiment in a flat terrain shows that a strong wind shear was observed in a majority of 10-min profiles, but the height of the maximum shear varies in time depending on BL stability, LLJ presence and strength.

Hourly-averaged nighttime profiles of mean wind speed over flat terrain often exhibit strong, almost linear wind shear that extend up to ~ 100-250 m for all study nights from Lamar experiment and up to ~ 100-150 m for all study nights from another experiment in the Great Plains, the Cooperative Atmosphere-Surface Exchange Study campaign of October 1999 in southeastern Kansas (CASES-99), which is well described in Poulos et al. 2002, Banta et al. 2002, 2003.

Strong linear shear was also often observed in hourly wind speed profiles measured by HRDL over water surfaces during the NEAQS-04. An example of wind speed (left panels) and wind direction (right panels) profiles for continuous measurements during 48 hours period in July 30-31 2004 are shown in Figure 4.

As shown in the Figure 4, winds were less intense (5-13 m s^{-1}) with broader range (200^o-300^o) of wind directions during the 24-hour period of July 30 (bottom panels) as compared to stronger winds (12-20 m s^{-1}) and narrow range of wind directions during July 31 (top panels).

Despite a difference in the magnitude of wind speeds and height of the wind speed maxima, most of wind profiles beneath the wind speed maxima were close to linear, rather than showing a "normal", "power law" profile. Similar results were observed for the majority of the nighttime hourly profiles from all experiments, both over flat terrain and over water.

Power law wind profiles

The assumption of a normal wind profile or the power law relation: $U=U_0(z/z_0)^\alpha$ is a common approach used in the wind energy industry to estimate the wind speed U at a higher elevation (z) using surface (usually at

10-20 m) or tower measurements of wind speeds U_0 at height z_0. The shear exponent (α) is typically assumed to be equal to 0.2 and rated wind speed for turbine operations near 12 m s^{-1} as specified by the International Electrotechnical Commission (IEC) for Normal Wind Profile.

The shear exponent calculated between 52 and 113 m using cup anemometer data during Lamar experiment (Kelley et al., 2004), also showed a diurnal and annual variations of the shear exponent, with a maximum peak at 0.2 and a slight secondary maximum at about 0.4 in the shear exponent histogram.

Distributions of the shear exponent between heights of 45-115, 45-200, and 45-250 m, based on 10-min means of wind speed for the entire period of HRDL observations at the Lamar site, indicate that in most cases α>0.2, with a dominant mode of 0.3-0.36 (Pichugina et al., 2009).

Here we used the value of α=0.34, along with another value of the shear exponent routinely used in WE (α=1/7), to illustrate deviations in computed and measured profiles (Figure 5). HRDL- measured wind profiles for the night of Sept. 16, 2003 in this Figure are shown by solid black lines. Normal wind profiles computed with two different base velocities U_0=25m and U_0=45 m are shown by blue and red lines correspondently, where solid color lines are

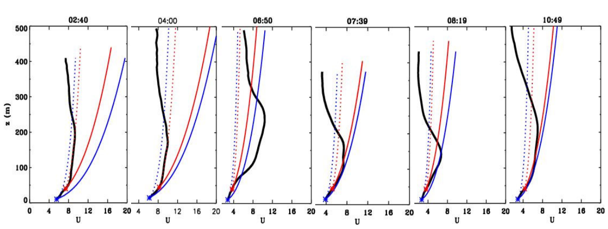

Figure 5. Examples of HRDL measured wind profiles during the night of Sept. 16, 2003 are shown by black lines. Color lines represent normal wind profiles computed with two different shear exponents (dotted with α=1/7, and solid with α=0.34), and base velocity estimated at two different heights (blue at z=25 m, red at z=45 m).

present profiles computed with shear exponent of 0.34 and dotted color lines are present profiles computed with shear exponent of 1/7.

Similar analysis of 10-min profiles for all study nights from Lamar experiments shows that greater deviations from logarithmic or power law profiles were observed under stable conditions and frequent presence of strong low level jets. The stronger deviations between observed and measured profiles appeared above 50-80 m.

The differences in calculated and measured wind speeds can be explained by the variability of the shear exponent over the time and by the presence of the LLJ in most of the HRDL-measured horizontal velocity profiles, having an almost linear shape of the profile below the LLJ maximum (Pichugina, Banta, 2010), in contrast to the Normal wind profile shape.

Wind profile shapes

Profiles of the 10 min averaged streamwise mean-wind component U(z) obtained from HRDL vertical-slice scan data during strong wind nights and stable boundary layer (SBL) conditions at the Lamar field projects show a variety in shapes that can be grouped in 3 common profile types as illustrated in left panel of Figure 6: Type I- the classic Low Level Let (LLJ) shape with a distinct maximum or “nose,” Type II- a uniform or “flat” profile, and Type III- a profile in which the shear in the subjet layer showed a layered structure (Pichugina, Banta, 2010).

Although Type II and III profiles may not be defined as a LLJ in some studies because of the lack of a distinct nose, wind shear in these profiles generated by the same mechanism (Blackadar, 1957) due to an acceleration of the wind over the late-afternoon well-mixed flow, a dynamic response in the lower boundary layer to surface cooling. Therefore the winds are stronger in this accelerated layer and can considerably contribute to the wind resource/wind power if this layer extended up to turbine rotor height. Shear generated turbulence kinetic energy in this layer, one component of which is σ_u^2

(Banta et al., 2006), can adversely affect turbine performance by producing vibrations in the rotor blades, limiting the lifetimes of turbine hardware (Kelley et al. 2004).]

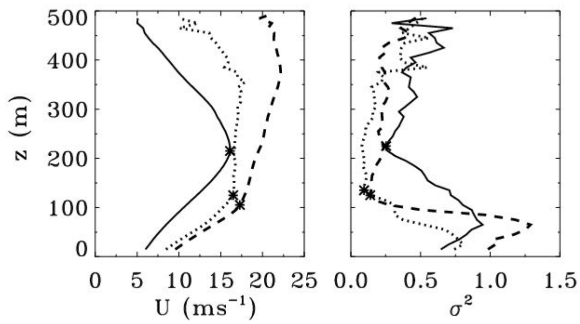

Figure 6. Three basic types of (left panel) the horizontal wind profile observed with HRDL measurements: Type I - solid, Type II - dotted, and Type III - dashed lines. Asterisks indicate points of the maximum wind shear. Corresponding variance profiles are shown in the right panel.

The acceleration of the LLJ and production of turbulence and turbulent fluxes in the shear zone below the jet, are not well represented in NWP and climate models, and thus are a source for error in surface-atmosphere interaction processes, lasting over approximately half of the diurnal cycle each day.

Profiles of high temporal and vertical resolution, provided by HRDL, are essential for estimate wind and directional shear at turbine rotor heights, verification of existing statistical and numerical models, and WE research.

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