9B.2 Lidar measurements of wind flow characteristics for inland and offshore wind energy

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Abstract

Wind-flow characteristics at the heights of modern wind turbines were obtained from High Resolution Doppler lidar measurements during two past-year experiments. One was conducted in the flat terrain of the US Great Plains, and the other off the New England coast, when HRDL was deployed on the research vessel Ronald Brown. These datasets were chosen because the Great Plains is a region of high wind resources on land, and waters off the New England coast are a region planned for development of wind farms in the near future. Analysis of wind and turbulence characteristics over a wide range of heights, variations of wind shear in time during strong and calm wind nights, along with examples of error in the actual and predicted wind resources will be given.

Keywords: Lidar, Wind Energy, wind speed profiles, wind shear, turbulence

Introduction

Doppler lidars, developed in the NOAA Earth System Research Laboratory, can provide much crucial information relevant to Wind Energy with high temporal and spatial resolution. Measurements of line-of-site (LOS) velocities, acquired twice per second with 30-m range resolution either in fixed elevation (conical), or fixed azimuth (vertical-slice) mode, allow profiles of wind speed, wind direction, horizontal wind component, and turbulence from ~surface up to several hundred meters AGL to be obtained with a vertical resolution of 5-15 m, and time resolution from 1min to 1 hour.

Studies on land using the High Resolution Doppler Lidar (HRDL) have demonstrated the ability of this instrument to reveal the structure and evolution of the boundary-layer during nocturnal stable and Low-Level Jet (LLJ) conditions, among the most difficult to characterize, understand, and model (Banta et al. 2002, 2003, 2006; Pichugina et al. 2008, 2010). These high-quality measurements are in precisely the layer of the atmosphere where information is most needed by wind energy (Emeis et al. 2007).

For offshore wind energy research obtaining high-quality, trustworthy measurements of wind-speed profiles through the lowest several hundred meters of the atmosphere over the ocean are an important but difficult task. In addition to the engineering challenges of wind farm deployment in the coastal zone and farther offshore (Misial and Ram, 2010), the meteorological challenge is that marine winds also are driven by many different scales of forcing. Synoptic-scale midlatitude storms often produce strong winds and often intensify as they move offshore. Tropical storms and hurricanes are also a factor that can produce wind-speed extremes. As a result of roughness or thermal contrasts between land and water, offshore flow generates transitional or “internal” boundary layer structure that is not well understood. The diurnal heating cycle produces sea-breeze circulations that change

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over periods of a few hours, and diurnally varying LLJ structure has often been observed in available offshore wind profiles. The interaction of these processes with onshore topography or irregular coastlines adds further complexity to the horizontal and vertical structure of the flows offshore. All these factors can produce strong spatial and temporal variability to the offshore wind field.

The high-resolution Doppler-lidar-based wind measurement system has been used in several ship-borne measurement campaigns over the past decade, providing unique profiles of marine wind speed, wind direction, and turbulence. The significant technological obstacles associated with the removal of ocean-wave-induced and other platform accelerations from the desired measurements of the air flow, were overcome by developing motion stabilized techniques to provide pointing-angle accuracy less than 1º in very rough sea conditions and produce reliable estimates of wind speed and direction over ocean. For such marine operations, the lidar was installed in a seatainer, together with a GPS-based inertial navigation unit (INU) capable of determining platform motion and orientation. A hemispheric (azimuth-elevation) scanner, mounted to the roof of the seatainer, was controlled to compensate for pointing errors introduced by platform motion, including those induced by ocean waves.

The paper presents wind flow characteristics at the heights of modern wind turbines obtained from HRDL measurements during two past year-experiments. One was conducted in the flat terrain of the US Great Plains, during the Lamar Low-Level jet Program in September 2003, and the other off the New England coast, during New England Air Quality Study in July-August 2004, when HRDL was deployed on the research vessel Ronald Brown. These datasets were chosen because the Great Plains is a region of high wind resources on land, and the waters off the New England coast are a region planned for development of wind farms in the near future.

Lidar data validation

A critical issue for WE applications is the question of measurement accuracy of the instruments employed, yet few careful studies have documented the accuracy of remote-sensing and other methods used to determine winds aloft. In this section we review some studies that have compared Doppler-lidar measurements on land and at sea with more familiar sensors, including tower-mounted anemometer, sodar, and rawinsonde. One approach to assessing HRDL performance vs. tower-mounted anemometer data is to operate the lidar in staring mode aimed at a sonic anemometer and comparing the 2-Hz individual-beam velocity estimates for the appropriate lidar range gate with ‘instantaneous’ tower values. Kelley et al. (2007) found good agreement between HRDL and sonic measurements on a 120-m tower, but also noted a systematic tendency for sonic winds to be weaker than lidar winds at slow wind speeds and higher than lidar wind speeds at stronger winds speeds, which they attributed to Reynolds-number dependent tower flow-distortion effects in the sonic winds. Pichugina et al. (2008) showed that HRDL wind-speed data averaged over 5- to 15-min intervals were highly correlated with sonic-anemometer means for the same vertical level and averaging period, as indicated by correlation coefficients r > 0.95 for the entire sample, and r > 0.98 for many individual nights. Banakh et al. (2010) have also shown that estimates of the wind velocity and wind direction could be obtained with acceptable accuracy even at low signal-to-noise ratio down to values of -20 dB. HRDL and sodar velocities were mostly in good agreement within the turbulent nocturnal BL, where the sodar signal was generally strong enough to obtain good velocity estimates (Pichugina et al 2008). Overall these comparisons demonstrate HRDL’s ability to provide accurate estimates of mean wind speed in regions of sufficiently high aerosol backscatter signal, which was routinely observed in at least the lowest 500 m of the atmosphere during fog- and cloud-free conditions. These studies have also documented the ability of HRDL to measure turbulence variables, including stream-wise (along-wind) variance profiles (Pichugina et al. 2008; Drobinski et al. 2004) and turbulence kinetic-energy dissipation (Banakh et al. 2010).

Although capable of high-precision measurements over land, the important question for offshore wind measurements is how well the lidar/motion-compensation system can measure mean-wind components over water. At present this question cannot be addressed as well over the ocean as over land because of the absence of offshore tower or other solid-platform measurements, but the stationary hard-target tests indicated a precision of <10 cm s^{-1} for the motion-compensation calculation. Some comparisons have been made with shipborne sonic-anemometer measurements made from a boom in front of the bow of the RHB at a height of 17 m above the ocean surface. These measurements have also been effectively compensated for ship motions as described by Fairall et al. (2006). The results of the comparisons show that HRDL winds at low elevation angles, evaluated at 17 m, agree well with the sonic anemometer winds.

Other comparisons with rawinsonde and radar wind profiler at sea have been reported by Wolfe et al. (2007). HRDL and the rawinsonde winds agreed well for all vertical levels compared. HRDL winds were also in reasonable agreement with profiler wind speeds above ~500 m above the sea surface. Below this level profiler winds often deviated significantly from HRDL and rawinsonde, which was attributed to radar sidelobe signal reflecting from moving ocean waves, sometimes referred to as “sea clutter” (Wolfe et al. 2007). Over land rawinsonde winds have an uncertainty of ~1 m s^{-1} or more (a factor of at least 5-10 greater than HRDL), which should not be affected by operating this instrument from a ship, once the balloon rises above the ship’s atmospheric wake (which may extend up to 60-80 m). The agreement between HRDL and rawinsonde thus indicates that the uncertainty in the HRDL shipboard winds is at least this good. Although WE applications require better precision, this demonstrated level of precision in the mean HRDL winds is at least sufficient to explore spatial and temporal variability of the offshore winds and the vertical structure of offshore wind profiles. A preliminary error-propagation analysis of the random instrumental errors and those due to the motion-compensation system indicate a precision of < 10 cm s^{-1} for averaging over 15 min. Further work is needed to establish how closely the shipboard HRDL system approximates the high precision obtainable during land-based operations.

Measurement example of temporal variability

Figure 1 shows 10-min averaged time-height cross sections of mean wind speed and wind direction, obtained from lidar measurements inland on 15-16 September, 2003 (left panels), and offshore (right panels), when RHB was stationed in Boston Harbor during nighttime hours (0000-1200 UTC) on 13 and 16 July, 2004. These data were obtained from LOS measurements at fixed shallow (2-16°) elevation angles using modified VAD techniques (Banta et al, 2002). Wind speeds in all panels are color coded and color scales of 0-20 m s^{-1} (left) and 0-14 m s^{-1} (right) are shown. .The arrows in all panels indicate the direction of wind flow. Two dotted horizontal lines indicate the rotor-sweeping layer (45-115 m) of GE 1.5 MW turbines operated at the Green wind farm near Lamar, Colorado, and (50-150 m) for bigger turbines that would be installed offshore.

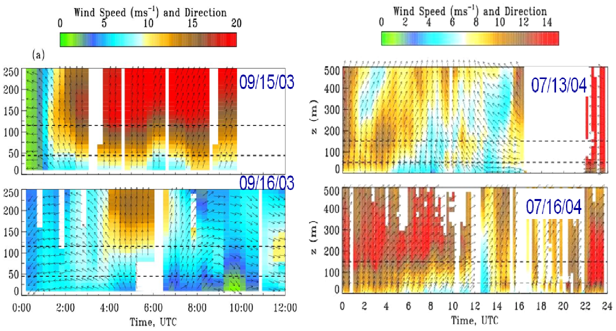

Figure 1. Mean wind speed (color) and direction (arrows), computed from HRDL conical scans during two nights: inland (left panels) and offshore (right panels). Vertical axis is height above surface/sea level (m), and horizontal axis is time in UTC (local Eastern Standard Time lags UTC by 5 h), and color scale at top is in m s^{-1}.

This figure illustrates considerable difference in the magnitude of wind speed between two nights both inland and offshore.

Inland: 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 in the middle of the local night (~400-800 UTC).

Offshore: The night of 13 July was characterized by transitional flow shifting from polluted continental to clean oceanic air: south-southwesterly winds shifted to southerly at ~0700 then to almost easterly during the morning transitional period (at ~1200 UTC). LLJs were observed during the period of 0300-0500 UTC with wind speed maxima of 10-11 m s^{-1} at 160-180 m. During the night of 16 July, winds were twice as strong as those on the night of 13 July with sustained west-southwesterly flow. Strong LLJs were observed in 71% of 15-min profiles throughout the night, from 00 to 10 UTC. The rest of the profiles showed more complex, layered structure (Type III profiles as in Pichugina and Banta 2010) with strong shear in the lowest 200 m.

During the strong-wind nights of 15 September and 16 July frequent LLJs were observed just above the rotor layer, generating strong turbulence at rotor heights. Vertical differences in wind speed (wind shear) and fast temporal changes (ramps) are evident on all panels, both inland and offshore.

Such information can then be used to provide an accurate estimate of wind and directional shear across the entire layer in which offshore turbine rotors operate. Knowledge of these parameters is important for turbine operation, since modern turbine rotors are so large that wind conditions can differ above and below the turbine hub.

Measurement example of spatial variability

Cross sections in Fig. 1 illustrate considerable temporal variability in wind speed and direction during each night and between nights both inland and offshore. The existence of spatial variability in the offshore wind field has important consequences for wind energy.

Strong spatial variability at inland sites due to topography are well documented, but recurrent spatial variability of the rotor-level flows is also an important issue offshore.

Regions of enhanced speeds, which may be tied to shoreline irregularities or coastal topography, would be favored for energy generation, whereas other regions of reduced winds may not. Obviously it is important to be able to identify the more favorable locations, but spatial variability also affects the ability to sample the flow field. Isolated in-situ or profiling instrumentation on a fixed mast or platform is incapable of detecting spatial variability, so the representativeness of such measurements is an issue. Arrays of fixed measurements can sample spatial variability, but the relevant spatial scales of variability must be known and factored into the array design.

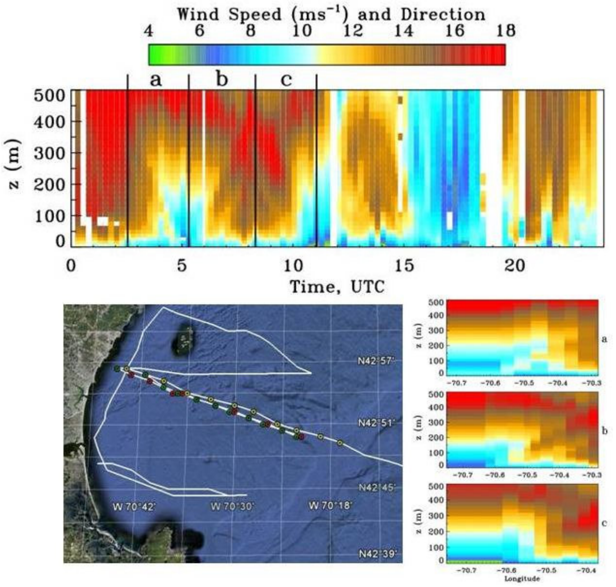

Figure 2. Top panel: Time-height cross section of mean wind speed, computed from HRDL conical scans during 11 August 2004 (axes and color scale as in Fig. 7). Black vertical lines on the top panel indicate 3 segments shown by circles in the ship track at the left bottom plot. Brief gaps were during periods when scans other than conical scans were being performed. Right bottom plots show mean wind speeds for these segments as a function of longitude.

The other way to sample spatial variability is using mobile platforms, such as the ship RHB. Unequivocal identification of spatial changes is possible by retracing the ship path back and forth over an area. Although such patterns were not performed often during NEAQS, Fig.2 (bottom, left) shows one example where the RHB retraced the same course three times on 11 August. These legs are marked a, b, and c on the time-height cross section for this day (Fig.2, top panel). Replotted on longitude plots in Fig.2 (bottom, right) with west to the left, these legs show persistence of the spatial patterns in time. This repeatability indicates genuine spatial patterns in the wind features, such as the LLJ at 300 m height on the east side of the cross sections, especially evident in legs b and c.

Conclusions

Sample results demonstrate the ability of the NOAA Doppler lidar to characterize atmospheric flow properties that are difficult to capture with other instrumentation. The availability of accurate, high-resolution profile data gives a number of advantages in determining quantities of interest to wind energy. For example, Pichugina et al. (2010) have shown that such profiles are necessary to provide accurate estimates of SBL depth, a traditionally difficult measurement, and Tucker et al. (2009) showed that shipboard lidar-measured turbulence profiles can be used to provide boundary-layer depth measurements over the ocean 24-h per day. Profile data can also be used to assess the errors associated with using standardized (e.g., power-law) profiles to extrapolate wind-speed values from near the surface to turbine hub height, and to provide measured values of the speed and directional shear across the blade layer, often significantly underestimated using the standardized profiles, especially during LLJ conditions. Presented examples show that near-surface winds often do not see many even significant changes in the flow aloft, so that near-surface measurements, or even low-resolution profile measurements, often produce misleading results when extrapolated to hub height. Such results can lead to significant error in estimates of the turbine power output.

An important issue for offshore WE is spatial variability, the existence of regions of higher mean wind speeds associated with coastal irregularities or onshore topography. Offshore arrays of measurements aloft must be designed to sample this variability, but factors such as typical distance scales of the variability are currently unknown, and it is therefore also unknown whether NWP models are characterizing this variability properly. Mobile platforms such as ships equipped with high-resolution profiling instrumentation are an important capability for investigating these types of variability, as illustrated in this study.

The existing datasets of HRDL offshore measurements represent a resource that can be used to better understand the range of atmospheric conditions, and their spatial and temporal variability, encountered by offshore wind turbines above the surface at the level of the rotor blades, to validate numerical models, to support satellite estimates of wind resources, and to supplement developing offshore wind-resource maps.

The HRDL/motion-compensation system can also be valuable asset operated from shipboard as a mobile measurement platform, to address spatial variability of the flow or to move from station to station to accumulate data on the temporal variability of flow properties at individual sites. Such datasets would also be valuable for furthering understanding of flow processes aloft and for NWP model initialization, verification, and improvement. Determining the true accuracy of the shipborne system would provide confidence in the use of the datasets for these applications.

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