Observed rotor-plane wind profiles derived from sodar measurements:

Potential impact on turbine power performance

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Abstract

The rotor plane of modern utility-scale wind turbines extends above the average height of the meteorological surface layer, and well above the top measurement height of typical masts used for resource assessment. Sodar measurements of wind profiles at 10 m intervals from 30 to 200 m have been made at more than 60 sites across North America and in Hawaii. While sodar can be used to provide accurate hub-height wind speeds, sodar wind profiles are also a rich source of additional information on variation in the wind profile across the entire rotor plane. Shear values at a given site in the range of typical turbine rotor discs have been found to vary according to stability, surface roughness, terrain steepness, and heterogeneity of upwind fetch. Furthermore, the wind profile often deviates significantly from a simple logarithmic law in this height range, and as a result shear can decrease or increase above hub height. Diurnal stability effects can produce shear parameters that vary by a factor of 2 above hub height, as compared to that from bottom of the sweep to the hub.

The spatial and temporal variability of the rotor-plane wind profile has implications for turbine power performance. IEC standards call for wind speed in a performance test to be measured within 2.5% of the turbine hub height. Under some circumstances, the wind speed can be assumed to be the same throughout the rotor plane (i.e., zero shear) but under many circumstances it is not. Thus the actual conditions for wind turbine operation can vary significantly from those under which the power test is done.

Introduction

IEC standards call for turbine power curves to be determined based on measurements at a single height that is within 2.5% of hub height. Modern utility-scale wind turbines have rotors that extend above the typical meteorological surface layer, and the entire rotor extends through a layer of the atmosphere where the shear can vary with height—typically from 40 to 120 m above ground level. Because it is possible to measure whole wind profiles at 5- or 10-m height increments with sodar, sodar measurements could provide insight into turbine performance variability at locations other than those at which power curves are developed.

The authors have been using sodar in wind resource assessment for several years and have analyzed wind profiles at more than 95 locations in NA and Hawaii. A substantial archive of wind profiles exists from which a great deal has been learned about how variable the rotor-plane wind profile can be. That variability—due to terrain, roughness, and stability, points to the questions being examined here:

- How well does the hub height wind power density represent the integrated rotor plane power density?
- If a power curve is developed in a location with one type of rotor-plane wind profile, while the turbine is operated in another, how might this affect turbine power performance?

The aim of this paper is to illustrate the ways in which the hub height wind power density is not necessarily representative of the integrated rotor-plane power density, and to suggest that sodar can play a role in addressing the variability in power curves and power performance.

Methodology

Sodar is a ground-based remote-sensing technology in which acoustic pulses or chirps are issued by the instrument, and the Doppler shift in the backscattered sound is determined at various delays, corresponding to different heights above the ground (Figure 1). In this way, sodar provides measurements of the wind profile throughout the rotor plane.

For the purposes of this paper, average wind profiles by hour of day were computed for 15 sites that vary in roughness and terrain. Only wind profiles with mean wind speed at 50 m of 4 m/s or greater were included, in order to get statistics that tended toward neutral stability. What follows is an empirical study of what has been observed at a wide range of sites, but it is not a random sample in any sense. Each of the sites' data discussed in this paper was collected from one of 8 ART model VT-1 sodars.

There are two general mathematical models that are commonly used to describe the surface layer wind profile: The first is the logarithmic profile:

$$U(z) = \frac{u_*}{k} \ln\left(\frac{z}{z_0}\right) \quad (1)$$

This form is derived from physics, and is defined by two scale factors, the friction velocity (u_*) and the roughness length (z_0); k is the von Karman constant, taken here to be 0.4, while U is the mean wind speed and z is the height. In the formulation here, variation due to stability and any displacement height is ignored. The friction velocity can be found from the slope of the best-fit line of wind speed versus $ln(z)$, and z_0 can be derived from the intercept.

The second mathematical model, the power law, is an approximation, based on empirical data. It is more commonly used in the wind industry because only two measurement heights are needed to describe the whole profile:

$$U(z_2) = U(z_1)\left(\frac{z_2}{z_1}\right)^{\alpha} \quad (2)$$

The shear parameter α is commonly derived from measurements at two heights (z_1, z_2) on a meteorological tower. If measurements at more than two heights are available some important parameters can be derived by examining the fit of the data to the logarithmic profile equation.

To provide a means of evaluating and comparing different wind profiles, a "power ratio" was constructed from:

$$PR = \frac{\overline{U_{80}^3}}{\overline{U^3(z)}} \qquad (3)$$

,or the ratio of the hub height (80 m) wind power density to the rotor-plane (heights 40 to 120 m) mean wind power density. Vertical variation in air density is neglected here. That is, the ratio of the 80 m speed cubed to the mean of the cubed speeds from 40 to 120 m. This ratio is greater than 1.0 and effectively it does not depend strongly on u_*, if a logarithmic profile throughout the rotor plane is assumed. Thus the PR for the logarithmic profile at a given u_* and z_0 can be used as a benchmark against which to compare "real-world" wind profiles measured with the sodar.

Once u_* is calculated from the best fit straight line of the logarithmic profile, a drag coefficient C_d also be constructed from

$$C_d = \frac{u_*^2}{U_{80}^2} \qquad (4)$$

, where U_{80} is the mean wind speed at 80 m. The drag coefficient is thus a non-dimensional measure of the efficiency of momentum transfer through the wind profile.

Results

The contrast between the wind profile plotted with a linear height axis and a logarithmic height axis is informative (Figure 2). The two plots in Figure 2 were made from the same average profile, representing the mean of 5,272 10-minute observations. In the linear profile, the power law extrapolation from the 50/30 m shear parameter is shown as a dashed line, and it is clear that on the average, the wind speed is less than the power-law would predict, above about 70 or 80 m. This tendency is also revealed in the logarithmic plot, for which the best-fit straight line is shown for the lower 80 m, and the break from the logarithmic profile is shown by points marked with an "X". The logarithmic profile appears to be a good fit below 80 m, with significant deviation occurring above that point.

For the profile shown in Figure 2, the PR as defined in equation (3) above is 1.0412. If the entire profile had conformed to the logarithmic profile as shown in the linear fit below 80 m, the PR would be 1.015. The difference between this and the actual PR of 1.0412 suggests that there is 2.6% less power in the average wind profile than would be in a logarithmic profile with the same u_* and z_0.

In Figure 3, the deviation from logarithmic profile is shown to vary with hour of day. For the hour 15 profile, the negative deviations from the logarithmic lead to a PR of 1.07627, compared to the benchmark PR of 1.0167, implying an energy loss of 5.95%, while the 0300 profile has a PR of 1.001796, compared to the benchmark of 1.01519, implying a *gain* of 1.3% over the logarithmic.

It should be noted that transient events can also be important in the variability of the wind profile, and under some conditions the logarithmic profile is not relevant to the real world. In Figure 4, a10 hour period of time with some sample wind profiles is shown, in which there appears to be a low-level jet that forms shortly after sunset and then decays, leaving the entire wind profile with negative shear. At this site, the frequency of such events depends on the season of the year, so that the average shear parameter can be negative for some wind directions in some months. The impact of this phenomenon on turbine performance is unknown.

When aggregated PR data are plotted against their computed drag coefficients (Figure 5), the results suggest that rougher sites have greater losses (higher PR relative their benchmark PR). That is, the ratio of the wind power density predicted by the hub height wind speeds to the rotor plane integrated wind power density increases. A summary of the median PR for sites grouped by drag coefficient is shown in Table 1. The table suggests that losses could be as high as 5.3% for the highest drag coefficient sites and conditions.

Given the non-random nature of the sites represented in this preliminary study, Table 1 probably presents an exaggeration of the implied losses due to wind profile variation, but it suggests a framework for evaluating measured wind profiles where the shear varies with height.

Table 1 Summary of median Power Ratios for 15 sites grouped by drag coefficient. The "Log Profile PR" is the benchmark PR that would be obtained if the logarithmic fit to the wind profile below 80 m pertained throughout the rotor plane.

	Low	**Medium**	**High**
Measured PR	1.014	1.048	1.071
Log Profile PR	1.018	1.018	1.018

Conclusions and Next Steps:

From this preliminary empirical study of sodar wind profiles we draw the following conclusions:

1. Based on measurements of whole wind profiles across a wide range of sites, there is variability in the actual relationship between the power density at hub height and the average for the whole rotor plane. If a turbine power curve is developed at a site with low roughness, a turbine in a location with higher roughness could produce 2-5 % less power, or 2-5% more, depending on the mean behavior of the upper wind profile. For these 15 sites, and for most hours of the day, there appears to be an increase in the PR (so a decrease in the integrated rotor plane power density relative to the hub height power density) with increasing drag coefficient, or surface roughness.

2. The logarithmic profile appears to be a valid model for the wind profile up to at least about 80 m at most sites, although it can be higher than that at some very uniform sites and at mid-day.

3. Because it is possible to measure whole wind profiles with sodar, such measurements would provide insight into turbine performance variability at locations other than those at which power curves are developed. The results of this study strongly suggest that power performance testing at a variety of sites using sodar could be very productive.

Ongoing studies of this type will examine more sites and more elaborate models for the wind profile, including incorporating a displacement height. For instance, a simple model for the surface energy balance could be used to estimate the buoyancy flux in order to incorporate stability corrections to the logarithmic profile. Another view of the wind profile could be provided by making estimates of the profiles of the Weibull parameters, as done by Emeis (2001).

References

Emeis, S., 2001. Vertical variation of frequency distributions of wind speed in and above the surface layer observed by sodar. Meteorologische Zeitschrift 10: 141-149.

Moore, K. E. and B. H. Bailey. 2005. Maximizing the Accuracy of Sodar Measurements for Wind Resource Assessment. Proceedings of the American Wind Energy Association, Denver, CO, May, 2005.

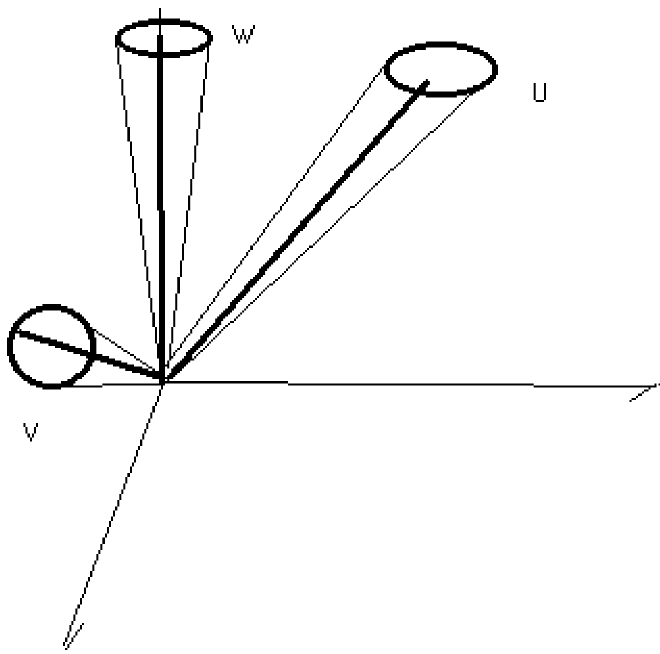
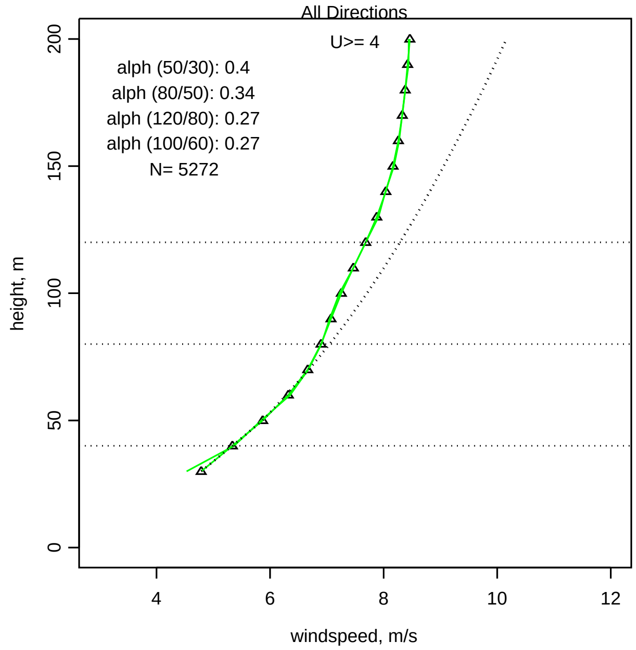


Figure 1 Idealized acoustic beam pattern from a 3-beam sodar.



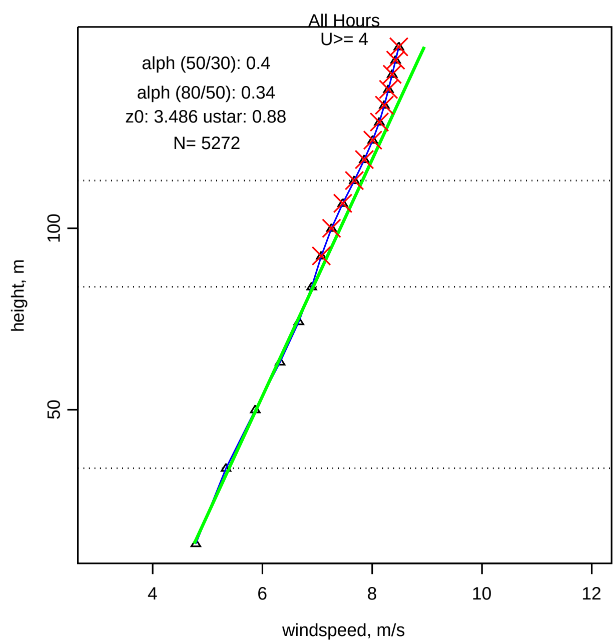
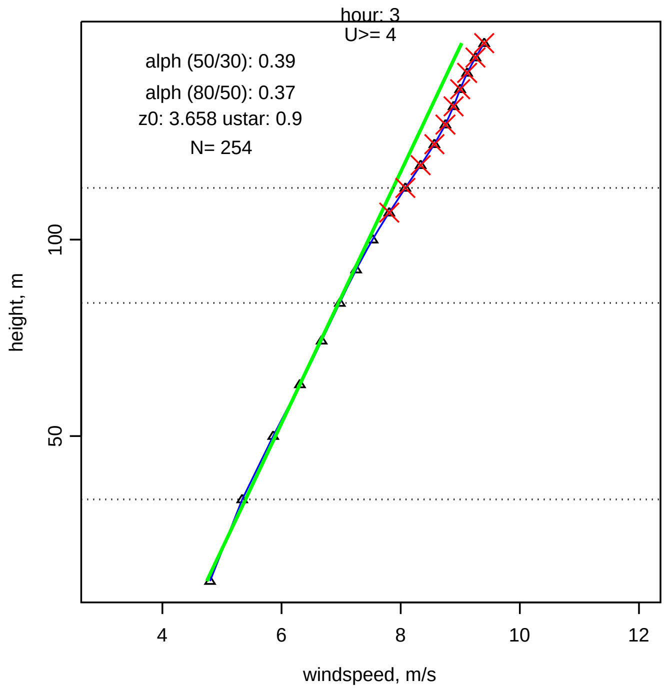


Figure 2 Two representations of the same average wind profile. (upper) with linear height axis and (lower) logarithmic height axis. Triangles are sodar measurements. Typical turbine rotor plane and hub height are denoted with horizontal dashed lines. The dashed line in the upper plot is the extrapolated power law profile using the 50/30 m shear parameter. In the lower plot, the logarithmic profile is defined by the best-fit straight line to the observations below 80 m. Observations that deviate from the logarithmic profile by more than 5% are denoted by red "X"s.



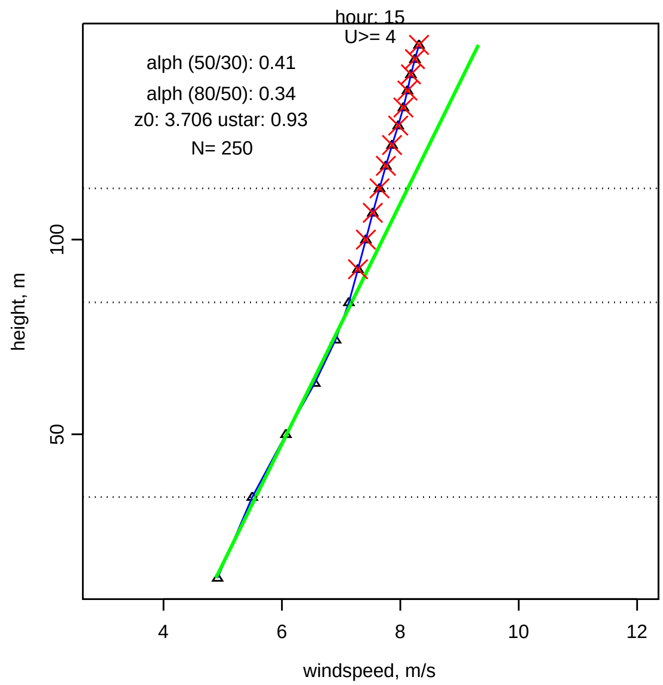


Figure 3 Mean wind profiles plotted with a logarithmic height axis for two different hours of the day. The straight line is the best straight-line fit for the profile below 80 m.

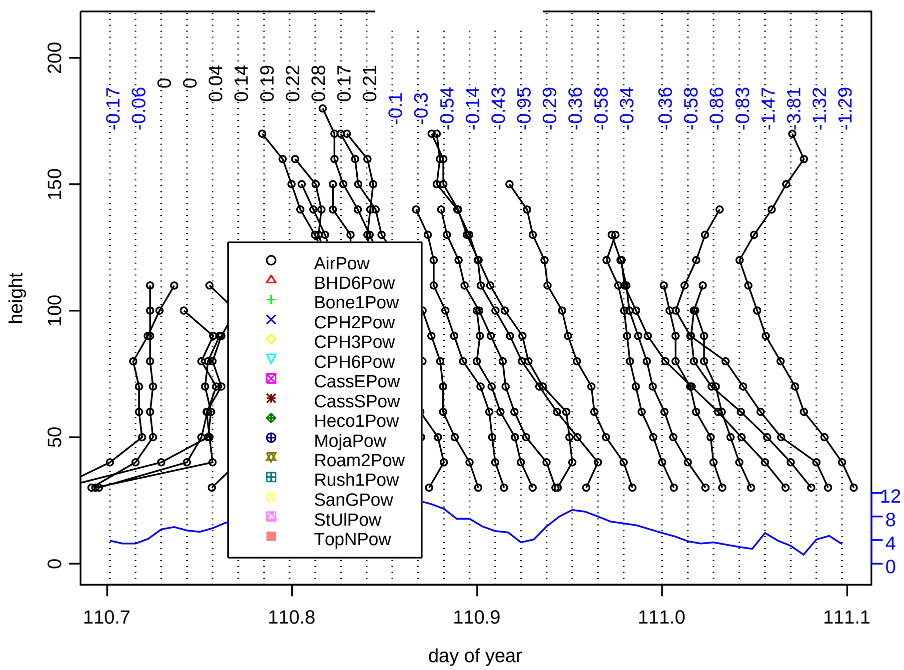


Figure 4 Time sequence of wind profiles during the night of April 20-21, 2005 at a site in the Great Plains. Numbers at the top represent the 80/60 shear for the 10 minute period represented. Negative shears are shown in blue. The blue line at the bottom depicts the mean wind speed at 50 m.

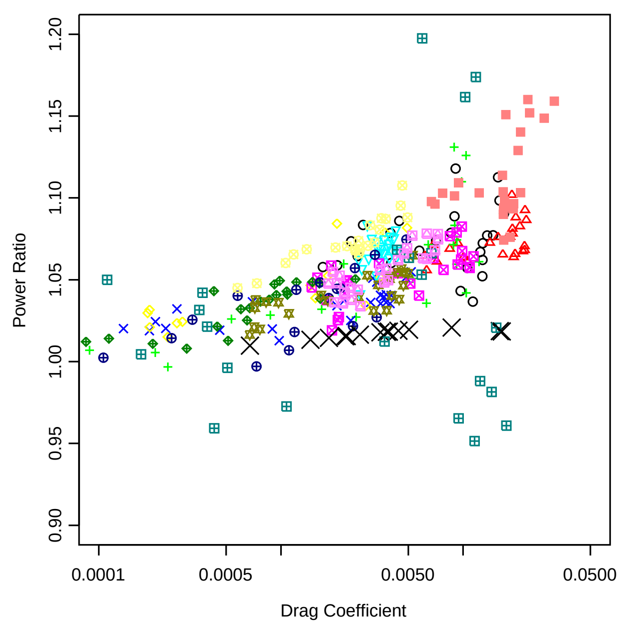


Figure 5 Power ratio for the 15 sites included in the study, plotted against the drag coefficient for each particular wind profile. Note that the drag coefficient is shown on a log scale. The black "X"s are the benchmark value of PR for each profile, assuming that a logarithmic profile applied throughout the rotor plane.