7B.4 TURBULENCE, SHEAR AND STABILITY INFLUENCES ON LOWER BOUNDARY-LAYER PROFILES

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## [1]1. INTRODUCTION

Wind turbines generate power dynamically in response to fluctuating wind conditions encountered by the full rotor area. Wind turbine output simulations, however, are usually based on mean or binned wind data measured at two or three points from a meteorological mast at heights below or equal to hub height, but seldom above where the majority of the power is produced. With wider applications of sodar systems that sample vertical wind profiles at heights encompassing the full rotor plane, it is possible to simulate the output of wind turbines with greater accuracy. It is also possible to determine the degree to which production variability over the course of minutes and hours is due to fluctuations in the mean wind speed at hub-height versus fluctuations in the wind shear profile across the rotor span.

Using an extensive and growing database of sodar wind profiles at proposed wind project sites, we seek to understand how the rotor plane shear profile varies with stability as measured or indicated by the vertical turbulence intensity, $\sigma_w/U$, and to relate variation in the shear profile to the integrated rotor plane power in the wind.

## 2. METHODS

### *2.1 Sodar Data*

In the course of using sodar for wind resource assessment, an archive of sodar wind profiles has been built representing more than 150 short- (1-2 month) and long-term (6 months to 1 year) assessments done since 2001 across North America and Hawaii. Routine analysis includes plotting mean profiles by wind direction sector and by hour of day with both linear and logarithmic height axes to assess the degree of conformity to power law and/or logarithmic wind profiles.

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To achieve the highest possible accuracy in the wind speed measurements, the sodar beam tilt is calculated for each pulse from a temperature measurement which is part of the sodar data stream. In addition, when sodar is compared to anemometry, vector speeds are converted to scalar, and adjustments are made for anemometer overspeeding and response to off-horizontal flow (Moore and Bailey, 2005).

For this study, 32 of the more than 150 locations available were selected (Figure 1). The sites were selected for their geographic range, their diversity of cover types, diversity of climatological regimes and the absence of fixed echoes. There were 13 different sodars represented among the 32 campaigns; all were Model VT-1 monostatic single-frequency phased arrays from Atmospheric Research and Technology, LLC. Most of the sodars were mounted in a cargo trailer (Figure 2) but two were free-standing units. The sodars were operated with 10 minute averaging, with range gates configured either for 30 to 140 m at 5 m intervals, or from 30 to 200 m at 10 m intervals. Mean vector horizontal and vertical wind speeds at each range gate are provided, as well as the standard deviation of the velocity components (u,v, w) and signal amplitudes, signal-to-noise ratio, and other data quality parameters.

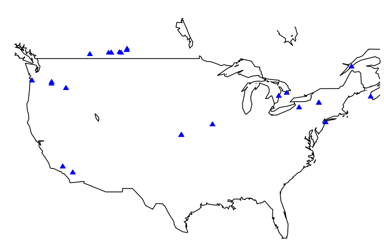

*Figure 1 Map of locations of 32 sites chosen for study of stability and shear parameters. Three sites in Hawaii are not shown.*

*Figure 2 ART model VT-1 sodar in a trailer-mounted configuration.*

A map of the CONUS sites included for analysis here is shown in Figure 1. Three sites in Hawaii were also included.

***2.2 Ancillary Measurements***

All the sodars from which data are included in this study have a measurement of temperature available, and some measure of precipitation, usually the state of a precipitation switch which is "on" if there if it is either snowing or raining. Many sodars have some combination of the following ancillary instrumentation: RM Young propeller-vane anemometer (giving horizontal U and direction), relative humidity, solar radiation, or rain gauge.

All sites had 50 or 60 m meteorological towers present, usually within 100 m of the sodar location. One site also had an 80 m lattice tower with a Csat 3-D sonic anemometer mounted at 79 m, as well as cup anemometry located every 10 m from 20 m to 80 m.

***2.3 Power calculation***

Understanding the potential impact of wind profile variability on turbine power performance can be approached by examining the integrated rotor-plane wind power density, such as was done by Moore et al. (2006). In the present work we incorporate a weighting that reflects the rotor swept area in each 10-m layer of air. As a first-order approximation the effect of wind that is either off-normal to the rotor disk or off-horizontal is modeled as the cosine-squared of the angle from normal or horizontal. Then the integrated power in the rotor plane wind profile ($P_T$) is calculated as the sum over all the 10-m layers from 40 to 120 m:

$$P_T = \sum_i P_i = \sum_i A_i \cos^2(\Delta\varphi) U_i^{\,3} \rho \qquad \textbf{(1)}$$

Where the $Pi$ is the power calculated for the $i$th layer, $A_i$ is the area of the rotor disk in the layer, $\Delta\varphi$ is the difference in wind direction for the layer relative to the hub height wind direction and $\rho$ is the air density.

***2.4 Stability Measurements***

Given that high speed sonic anemometry is not routinely used in the wind industry, a surrogate measure of stability was sought among the various measurements that are routinely made. The best of these surrogate measures was determined to be the sodar vertical turbulence intensity, or $\sigma_w/U$. This was compared to the Monin-Obukhov stability determined from the sonic anemometry at the one site where it was available.

***2.5 Shear parameters***

In the wind industry it is common to use a power law exponent or shear parameter as a kind of shorthand for the shape of the wind profile. The reason for this is that such shear parameters are used to extrapolate from the commonly-used 50 or 60 m tower top measurements to turbine hub height. Here, the shear parameters for the layer from heights $Z_1$ to $Z_2$ given wind speeds $U_1$ and $U_2$ at these heights calculated as:

$$\alpha = \frac{\log \frac{U_2}{U_1}}{\log \frac{Z_2}{Z_1}} \qquad (\mathbf{2})$$

**3. RESULTS AND DISCUSSION**

Sodar and cup anemometry wind speeds agree well, to within 1% to 2%, once the factors described in the data quality section are accounted for (Figure 3).

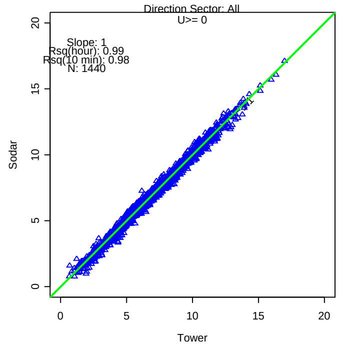


*Figure 3 Scatter plot of hourly-averaged sodar 50 m wind speeds against tower 50 m wind speeds.*

The sodar vertical TI ($\sigma_w$/U) is found to be the best surrogate measure of stability. This quantity is available at every range gate, for every sodar and for every averaging period. It has a strong diurnal signal indicating it is well-coupled to the surface solar heating (Figure 11, Appendix), and it is related to the Monin-Obukhov stability (Figure 4). Because vertical TI is a measure of stability, in that it indicates the intensity of vertical mixing, the shape of the wind profile depends on the TI (Figure 5).

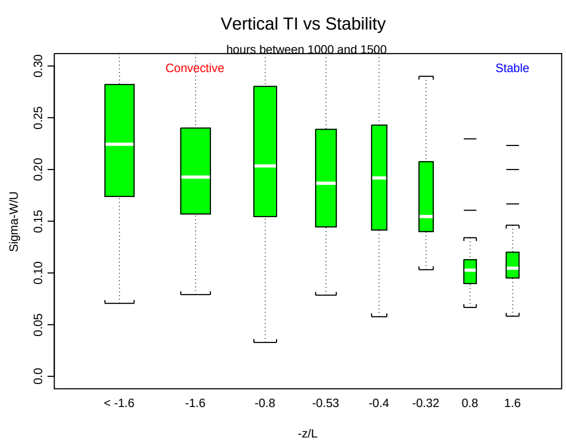


*Figure 4 Boxplot of mid-day vertical TI by Monin-Obukhov stability.*

The change in shear parameter throughout the profile is important for two reasons: first, a shear parameter calculated between 30 and 50 m or between 40 and 60 m is commonly used to extrapolate to hub height, for power output predictions, and second, because changing shear parameters within a wind profile affect the integrated rotor plane power. That is, the power in the wind profile can be more or less than that indicated by the hub height wind speed alone. Results for shear parameters for three layers in the boundary layer—30 to 50 m, 50 to 80 m and 80 m to 120 m are shown for 16 sites in Figure 12, Appendix. The shear parameters are binned by vertical TI class (i.e. TI divided by 0.05). The results indicate the strong influence of surface roughness on the shear parameters in general, going from the more vegetated northeast (NE) to the more barren desert southwest (DSW). In addition, there are two other generalizations that can be made from this grouping of data:

1. At higher shear sites there is a more dramatic decrease in shear with increasing TI, since roughness is playing a more significant role. This has already been illustrated in the mean wind profiles in Figure 5.
2. At higher shear sites there is a more regular decrease in shear with height, and this is particularly true at low vertical TI (or stable conditions).

The two Pacific northwest (PNW) sites that have negative shear in them (numbers 23 and 24) have downslope flow in the predominant wind sector. Negative shear is commonly observed on downslope flow. Two Great Plains sites (15 and 16) show increasing shear with height, a phenomenon that may arise from a low-level jet, or it may be terrain-driven.

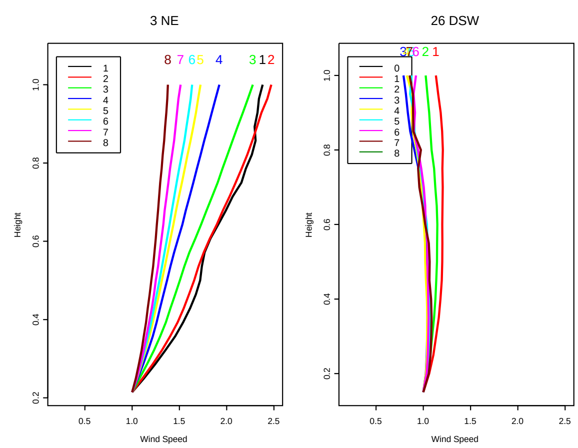


*Figure 5 Normalized mean wind profiles by vertical TI category (=TI/0.05) for two sites (left) in the desert southwest and (right) in the northeast.*

Sodar vertical TI also can be used to provide an estimate of the horizontal TI at turbine hub height (Figure 6), a quantity that is of some interest in site suitability analyses for particular turbines. It is found that horizontal TI decreases with height, and increases with increasing vertical TI. At higher heights, the relationship of horizontal to vertical TI is asymptotic; indicating the more constrained horizontal scale of turbulent eddies relative to the vertical scale.

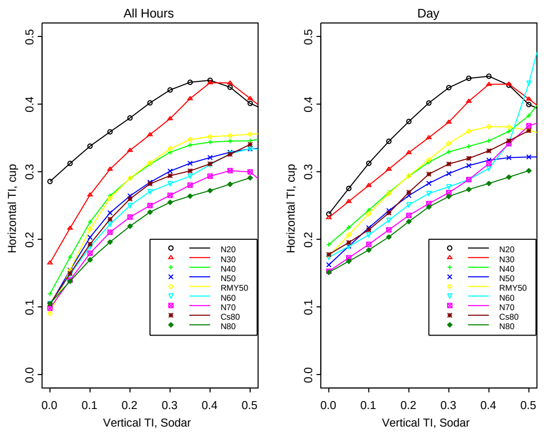


*Figure 6 Horizontal TI from cup anemometers as a function of vertical TI from sodar for various heights from 20 m to 80 m.*

Seasonal changes in the vertical TI and the 50 to 80 m shear parameter are illustrated for four sites in Figure 7 Here the spring transition is accompanied by a increase in the mid-day vertical TI as wind speeds decrease and conditions become more convective. There is a corresponding decrease in the 50 m to 80 m shear parameter.

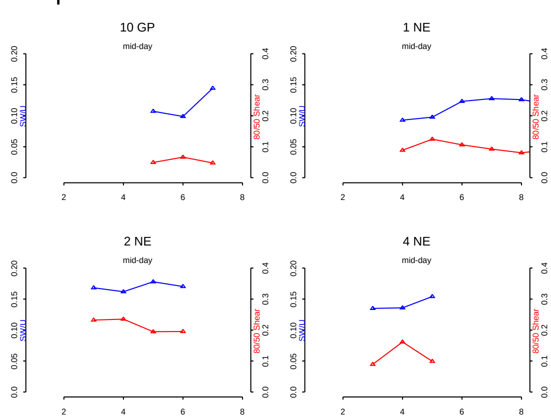


*Figure 7 Vertical TI (blue lines) and 80/50 m shear parameter (red) for 4 sites during the spring transition. Numbers on the horizontal axis are month of the year.*

The wind profile can take on a variety of shapes over relatively short periods of time. The varying shapes of the wind profile could have an impact on the power output of a wind turbine. Figure 8 illustrates a sequence of wind profiles over a 1.5 hour period at a site where downslope flow was common. The ratio of power in the rotor-plane wind profile (Equation 1) to that predicted by the hub height wind speed varies from -4.8% to +12.7% during this 1.5 hour period. Models of wind turbine power output may have to account for such time-varying, non-uniform wind profiles, in order to achieve accurate prediction of power production.

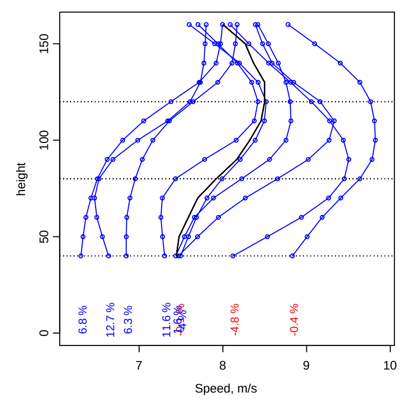


*Figure 8 Sequence of wind profiles measured during a 1.5 hour period of downslope flow. Numbers on the bottom are percent deviation of the integrated rotor plane power from the power determined by the hub height wind speed. Red numbers depict a deficit of power, blue a surplus.*

Sodar affords an opportunity to examine directional shear as well. Although at most sites, at the higher wind speeds that wind turbines operate, conditions tend to be fairly well-mixed, there is always some directional shear. At night, this shear can be substantial (up to 30° or more) even when there is wind greater than 5 or 6 m/s. At one mountaintop site in California, we observed a 180° wind direction shift that propagated down through the depth of a typical wind turbine rotor plane each day for several hours from 1000 to about 1400 for about 10 days (Figure 9). During some periods the wind speed across this direction shift was 7 to 8 m/s even while the directional shear was 180°. Clearly remote sensing has a role to play in detecting such phenomena in order to prevent or mitigate losses.

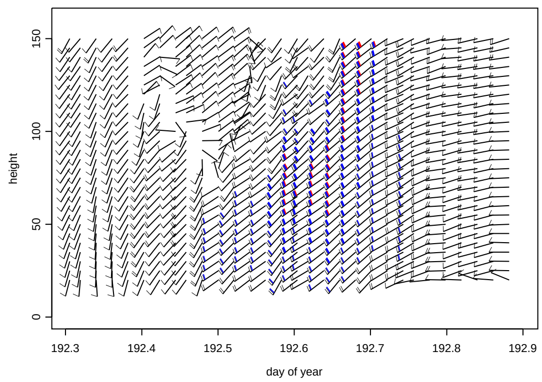


*Figure 9 Time-height sequence of wind vectors at a mountaintop site.*

Directional shear has also been analyzed through the decomposition of the wind vector at each height into its along-wind and cross-wind components (Walcek, 2004) (Figure 10), where the reference wind vector is defined as that at 80 m. The example in Figure 10 is at a flat, mid-latitude site; during the period depicted in the figure, the directional shear from 40 m to 120 m was 14°, and the wind speed at 80 m was 10.1 m/s. The information from this type of wind vector decomposition could be used in a model of turbine response to wind shear.

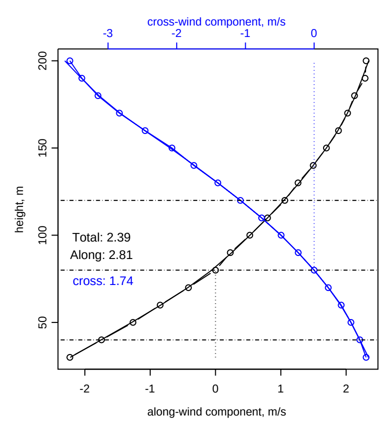


*Figure 10 Along-wind and cross wind shear for a site in Great Plains. The "mean" horizontal wind vector is defined as the vector at 80 m.*

## 4. CONCLUSIONS

Sodar wind speeds and directions are comparable to anemometry in the field, and sodar has sufficient accuracy to provide critical information concerning the wind profile under varying conditions. The sodar vertical TI can be used as a stability indicator which relates the shear parameters for various layers to the stability. The vertical TI is also a useful tool for the estimation of hub height horizontal TI, a quantity of interest for turbine site suitability determination.

Time varying wind profiles have widely varying integrated rotor plane power. Remote sensing devices such as sodar can be used to assess how the varying power in the wind will affect power output.

## 5. REFERENCES


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Moore, K. E., B. H. Bailey, and D. Bernadett, 2006. Observed rotor-plane wind profiles derived from sodar measurements: Potential impact on turbine power performance. Proceedings of the American Wind Energy Association, June 2006, Pittsburgh, PA.

Walcek, C. 2004. Diurnal variations in the 2-dimensional nature of wind shear in the planetary boundary layer. Proceedings of the Am. Met. Soc., 18th Boundary Layers and Turbulence

# A. APPENDIX

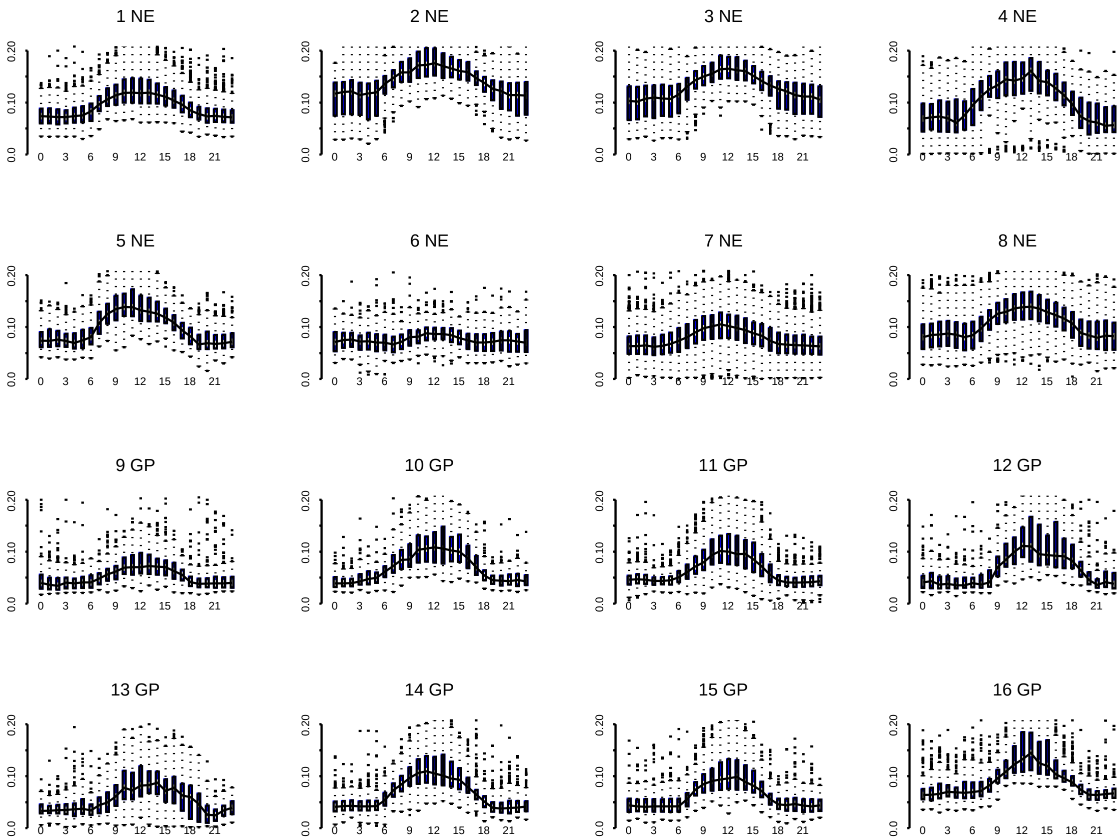


*Figure 11 Diurnal pattern of sodar vertical TI for 16 sites in the continental US. Site 6 represents a sodar campaign during a windy, overcast November period.*

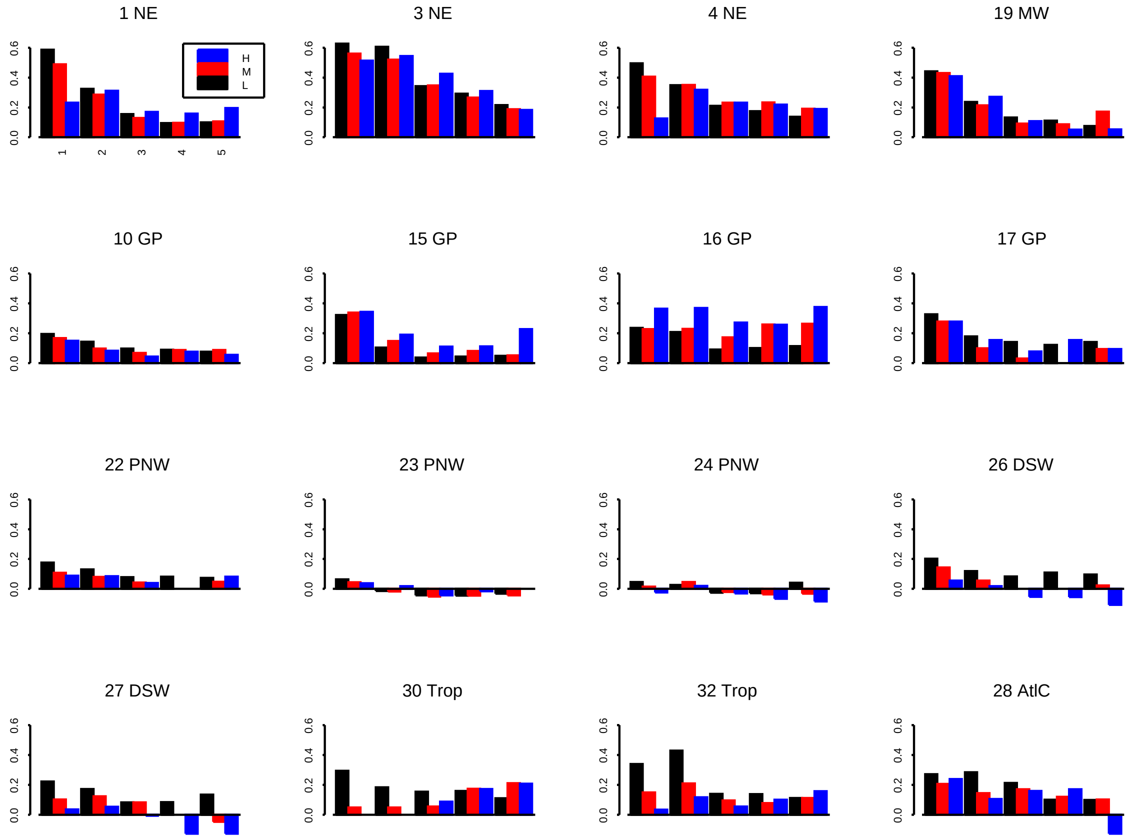


*Figure 12 Shear parameters for low (black, 30 to 50 m), middle (red, 50 m to 80 m) and upper (blue, 80 m to 120 m) layers, binned by vertical TI class (=TI/0.05) for 16 sites. "NE" is northeast, "MW" is Midwest, "GP" is Great Plains, "PNW" is Pacific Northwest, "DSW" is desert southwest, "Trop" is Tropical (Hawaii) and "AtlC" is Atlantic Coast.*