Sodar Measurements to Reduce Shear Extrapolation Uncertainty

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Abstract

Remote sensing has several key roles to play in assessing both the wind resource and project performance. One such role is to reduce uncertainty in shear extrapolation, providing measurements from 30 m to 200 m in the transition layer between the atmospheric surface layer and the deeper boundary layer. Uncertainty is compounded by the fact that turbines operate in a layer of air and in site conditions where theoretical profiles don't necessarily apply. Past presentations have shown that the logarithmic wind profile extends on average to at least 80 m. However, significant deviations from both logarithmic and power law profiles occur as stability changes over the diurnal cycle and throughout the year; such deviations can lead to overestimation or underestimation of the wind speed. In addition, certain phenomena, such as directional shear across the rotor plane, are best addressed with remote sensing methodologies. Reducing uncertainty about the wind resource enhances energy security by facilitating project development.

Introduction

Sodar (Sound Detection And Ranging, or acoustic sounding) is a ground-based remote-sensing technique that uses backscattered sound from acoustic pulses (chirps) to measure the wind speed at multiple heights to a height of 200 m or more.

In the wind industry sodar campaigns are often conducted with the goal of understanding how the shear parameter above the top of typical meteorological towers changes relative to that below. The shear parameter is commonly used in a power-law expression to extrapolate the wind speed above tower top. Among the various factors that influence the shape of the wind profile is the static stability, i.e. the relative influence of surface heating (or cooling) compared to mechanical transfer of momentum. The static stability influences the amount and character of turbulence in the atmosphere; thus measures of turbulence are useful measures of stability. The objective of this study is to relate stability to the variation in measured versus extrapolated wind speeds.

Methods

Sodar studies have been conducted at close to 200 locations in North America and Hawaii (Figure 1). The sodar campaigns range in length from 4 weeks to more than 1 year.

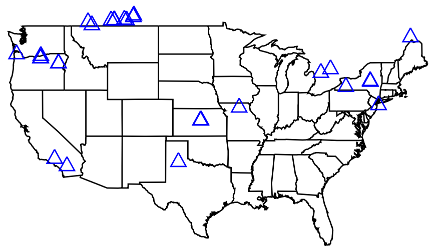

Figure 1. Locations of some of the sodar campaigns conducted to date.

The sodar emits a series of chirps or beeps at a frequency of 4500 Hz. There are 3 acoustic beams created in sequence: one vertical and two nominally 18 degrees off-vertical, at right angles to one another (Figure 2). The radial velocity along each beam is determined from the Doppler shift in frequency in the returned echo, and the wind speed components are determined from the following equations:

$$W = -\frac{fc}{2F}$$
$$V = \frac{-fc}{2F\sin\Theta} - \frac{W}{\tan\Theta} \qquad \textbf{(1)}$$
$$U = \frac{-fc}{2F\sin\Theta} - \frac{W}{\tan\Theta}$$

where Θ is the tilt angle from the vertical, W is the vertical component, U and V are the two horizontal components, F is the transmit frequency, f is the Doppler shift in frequency, and c is the speed of sound. The beams are steered by varying the phase among the speaker elements in the phased array.

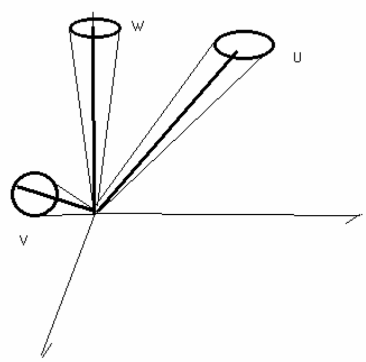

Figure 2. Schematic diagram of the 3 sodar acoustic beams.

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. It is important to note that although the horizontal component (U, V) standard deviations are calculated, this calculation is done for each component at the end of each averaging period. As such, the horizontal component standard deviations do not represent *u* and *v* turbulence components (along-wind and cross-wind) in the traditional sense of boundary-layer meteorology. Nonetheless the sodar components bear a strong relationship to the horizontal turbulence as measured by anemometry, as shown below.

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).

Previous work has shown that variation in stability, as indicated or measured by the sodar vertical turbulence intensity (standard deviation of the vertical velocity divided by the horizontal wind speed = σ_w/U) is associated with variation in the shear parameter for a given site.

Results and Discussion

The adjusted wind speed measurements from the sodar are generally within 1% to 2% of co-located (within 100 m horizontal distance) anemometer measurements at the same height. Figure 3 shows a typical sodar wind profile along with anemometer measurements at multiple heights on an 80-m tower. Sodars also provide the standard deviations of the velocity components--two horizontal and the vertical. These quantities are correlated with the solar radiation and therefore also with stability (Figure 4). A sodar horizontal turbulence intensity (σ_U/U) can be constructed from the average of the two horizontal component standard deviations. This is found to be correlated with the horizontal turbulence intensity from anemometry (Figure 5). An advantage of using the horizontal component standard deviations is that they have a greater dynamic range than the vertical component (Figure 4).

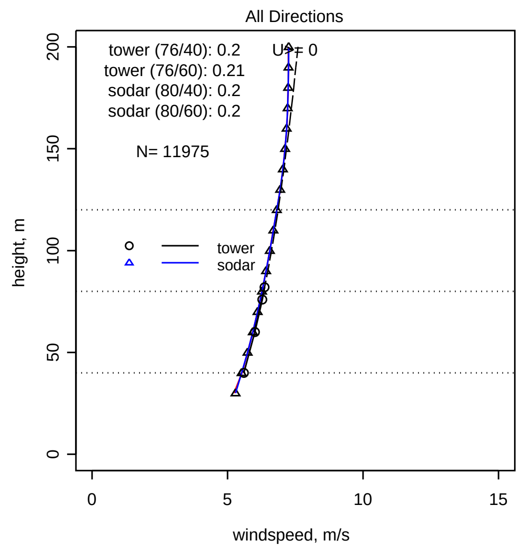

Figure 3. Average wind profile for sodar and 80-m tower.

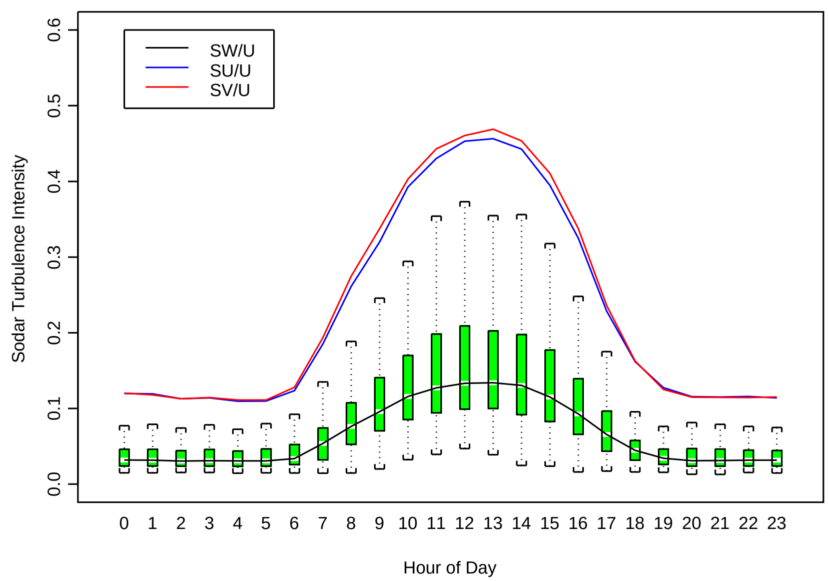

Figure 4. Boxplot of the vertical turbulence intensity (σ_W/U) by hour of day. Black line is through the median for each hour. Red and blue lines are the corresponding medians for the two horizontal component turbulence intensities.

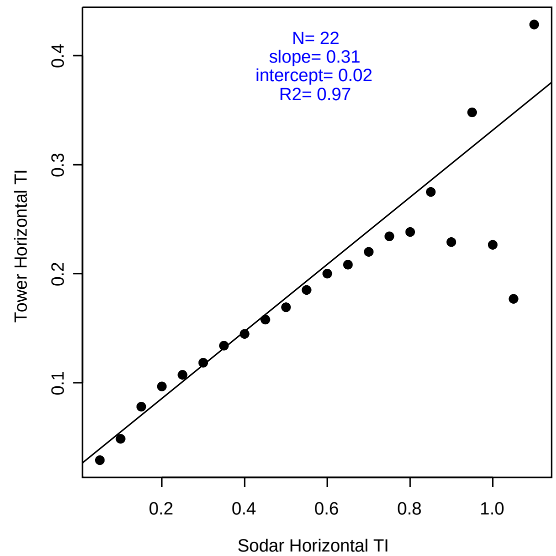

Figure 5. Tower horizontal turbulence intensity (TI) at 60 m versus sodar horizontal TI at 60 m calculated from the average of the two horizontal component standard deviations divided by the horizontal wind speed.

The ratio between the horizontal and vertical component standard deviations changes slightly with height above the surface (Figure 6). The change is most significant near the surface, where vertical motions are constrained by the presence of the ground. Boundary layer theory suggests that turbulence becomes more isotropic (equal scales in all spatial dimensions) as height above the surface increases, and as conditions become neutral (Garrett, 1992). The sodar results appear to confirm this theory, at least for the flat unobstructed sites included here.

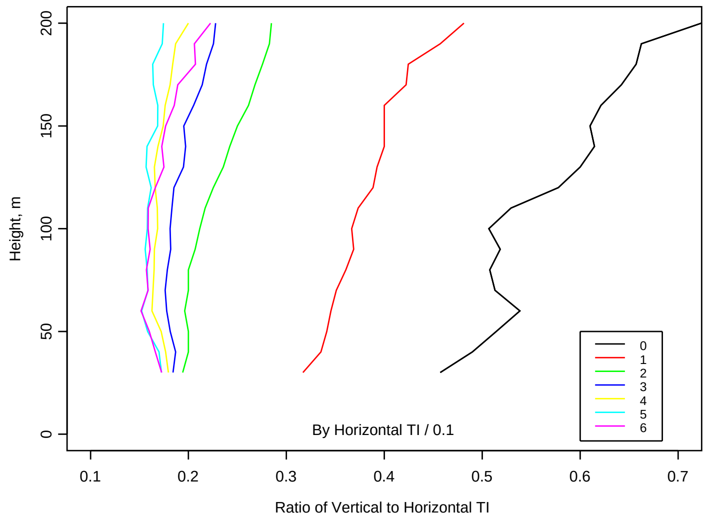

Figure 6. Vertical profiles of the median values of the ratio of sodar vertical TI (σ_W/U) to sodar horizontal TI ((σ_U+ σ_V)/2/U). Colors represent classes of the horizontal TI divided by 0.1, as shown in the legend. Only observations with 50-m wind speeds $\geq$ 4 m/s were included.

The shape of the wind profile (variation of wind speed with height above the ground) reflects several processes that are occurring in the lower boundary layer, specifically, the roughness of the surface which exerts drag on the wind, slope of the land which affects speedup and drainage flow, the surface heating or cooling which promotes or suppresses mixing, and the larger-scale atmospheric processes that determine the wind speed at upper levels. Figure 7 illustrates the changing shape of the wind profile in response to variation in stability as indicated by the vertical TI for two sites which are very different in surface roughness. One is a forested site in the northeast, and the other is in the desert southwest. As expected the forested site has higher shear overall, but it also has a greater degree of variation in wind profile shape with stability.

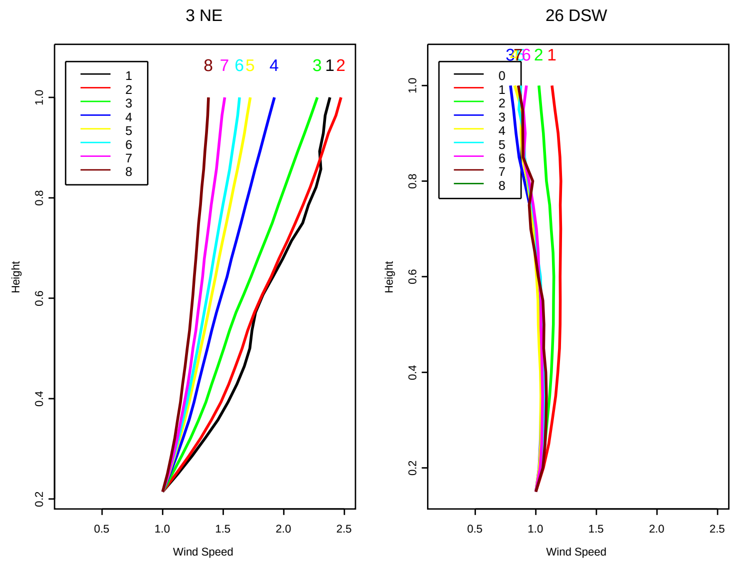

Figure 7. Normalized mean wind profiles by vertical TI category (=TI/0.05) for two sites (left) in the desert southwest and (right) in the northeast.

At flat sites with low roughness, at the lowest turbulence intensity categories, extrapolation with the lower-profile shear parameter tends not to produce a bias in the speed at 80 or 110 m. However, as the TI increases, there often is a decrease in the shear parameter with height, so that extrapolated values tend to overestimate the wind speed at hub height and above by a few percent. This bias increases with increasing turbulence intensity (Figures 8 and 9). There is also increasing absolute bias in extrapolated wind speed, as the wind speed increases (Figure 10).

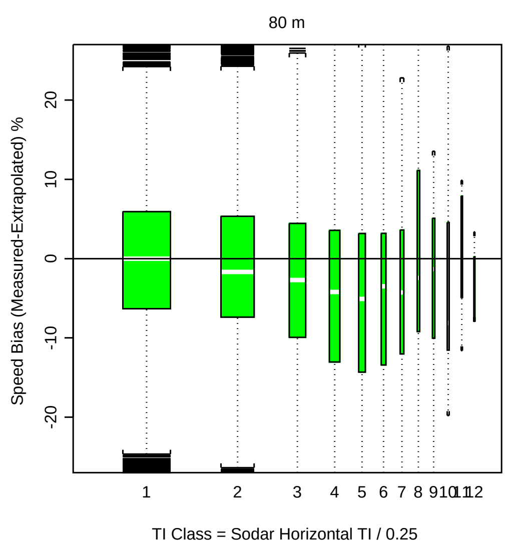

Figure 8. Boxplot of percent bias (sodar measured minus sodar-extrapolated) binned by sodar horizontal TI at 80 m divided by 0.25. Each box represents the central 50% of the distribution for the bin.

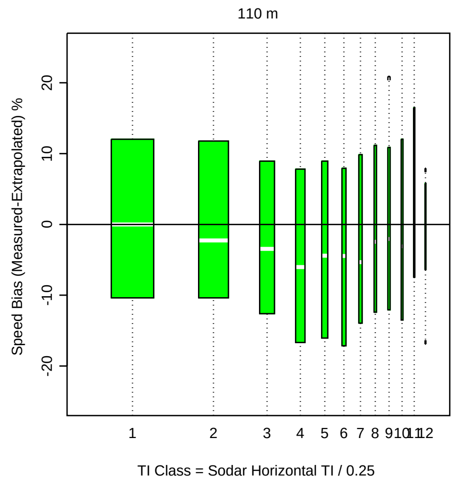

Figure 9. As in Figure 8, but for 110 m.

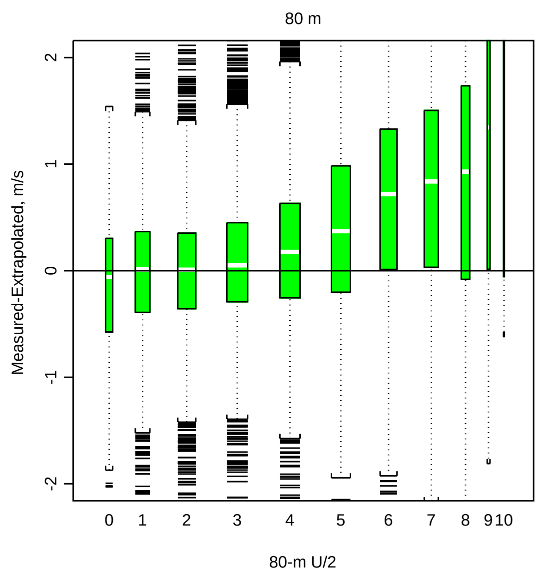

Figure 10. Boxplot of speed bias (measured-extrapolated) as a function of wind speed category (U/2).

Directional shear is another feature of the wind profile that can be resolved with remote sensing techniques. Figure 11 shows a boxplot of the directional shear across a typical turbine rotor plane as a function of the sodar horizontal turbulence intensity. As expected, conditions with low TI, which are more likely at night, have more directional shear due to the decoupling of flow under stable conditions. This plot illustrates a typical site in flat terrain with uncomplicated upstream roughness. Most sites examined thus far exhibit a 10-degree to 20- degree clockwise rotation of the wind vector under night-time conditions, with more extreme rotation occurring infrequently.

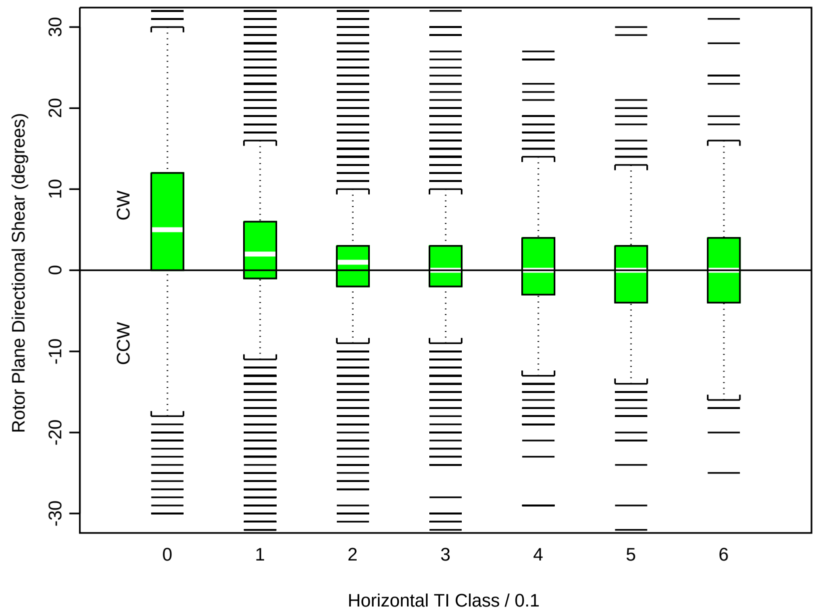

Figure 11. Rotor plane directional shear (top minus bottom) by horizontal TI class. Only observations with 50-m wind speeds ≥ 4 m/s were included.

Conclusions

- Remote sensing can provide accurate measurements of the wind speed throughout a typical turbine rotor plane. Detailed analysis of the measurements help illuminate possible sources of bias in power-law extrapolation from meteorological towers.

- The sodar component turbulence intensities offer simple and effective indicators of stability. The horizontal and vertical turbulence intensities are correlated.

- The wind profile shape (shear parameter or slope of the logarithmic profile) is sensitive to stability. It is necessary to be aware of the stability conditions under which a measurement campaign is done, in order to be sure of capturing a representative sample of stabilities.

- Rotation of the wind vector by 10 to 20 degrees from 40 m to 120 m under stable conditions (decreased turbulent mixing) is common.

- In order to use sodar to reduce shear extrapolation uncertainty, the relationship between shear above tower top to that below must be known. The difference between extrapolated wind speed and measured wind speed varies with stability.

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