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ROUGHNESS LENGTHS IN COMPLEX TERRAIN DERIVED FROM SODAR WIND PROFILES

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1. INTRODUCTION

Modern wind turbines have hub heights of 80 m, with rotor diameters of 60 m or more. Most towers for wind resource assessment are no more than 50 m tall. Monostatic, single-frequency sodars (ART, LLC model VT-1) have been in use by AWS Truewind since 2002 as part of wind energy resource assessment programs in the US and Canada. We have used sodars at more than 3 dozen sites in the US and Canada since April, 2002. Most sites have been in complex terrain, with heterogeneous surface roughness ranging from mature forest to a patchwork of forest and cropland.

Uncertainty in the effective surface roughness is an important factor in the uncertainty of wind model output for wind energy applications (Zack, et al., 2004). In this study we explore the potential for sodar wind profiles to provide information on local surface roughness.

2. METHODS

2.1 *Sodar Data Treatment*

A typical sodar measurement campaign lasts 3 to 4 weeks. Wind profiles are collected at 10 m intervals from 30 to 200 m with 10-minute averaging. A rain gauge or precipitation gauge is logged with the sodar data. This allows for the removal of periods of precipitation. Periods of low signal amplitude are also removed from the data set because this is indicative that snow has accumulated inside the sodar. The analyses here focus on periods when the 50 m wind speed was 5 ms^{-1} or more, representing conditions more relevant to wind turbine operation, and minimizing the influence of diabatic effects on the wind profile. In addition, for these analyses, solar irradiances obtained from GOES VIS satellite images (Perez et al., 2003) were used to restrict data to those observations with 400 Wm^{-2} solar irradiance or less.

The sodar provides the vector average horizontal wind speed and direction, mean u, v, and w component wind speeds, and the standard deviations of the components. Because the sodar program references nearby tower-based cup anemometry for temporal and spatial scaling, it is necessary to convert the sodar vector wind speed to an equivalent scalar speed for purposes of comparison. This conversion is based on the standard deviation of the sodar vertical velocity, which is a surrogate for the standard deviation of the wind direction.

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An adjustment is also made to the sodar horizontal wind speed to account for small variations in the effective beam tilt angle of the horizontal velocity component beams. This beam tilt angle varies slightly with temperature, and with the effective array spacing of each sodar unit.

Mechanical anemometers are also subject to overspeeding and to deviation from the desired cosine response to off-horizontal flow. Adjustments are also made for these effects based on the sodar vertical turbulence intensity and the sodar flow inclination.

Following these adjustments, agreement between the sodar and cup anemometer wind speeds in flat wind speeds, homogeneous, low-roughness terrain is quite good (Figures 1 and 2).

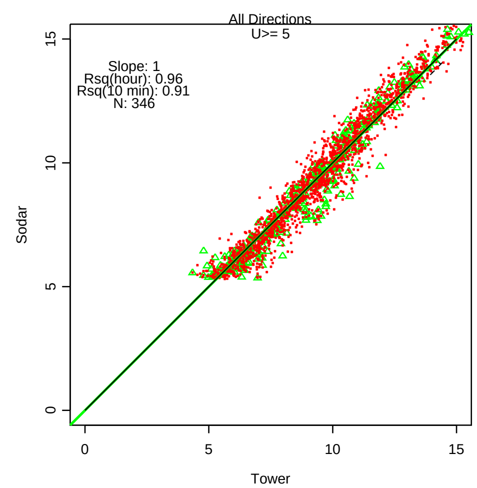

Figure 1. Relationship between 50 m wind speeds for sodar and cup anemometer at a site in southern Saskatchewan.

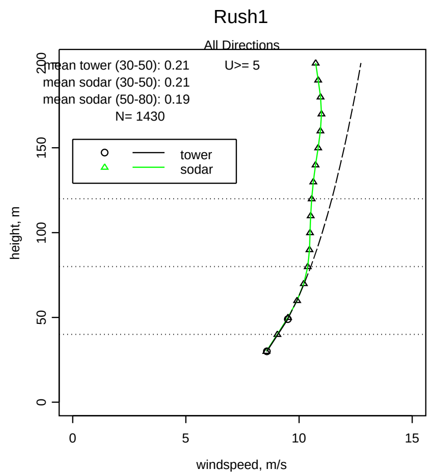

Figure 2. Average wind speed profiles for sodar (triangles) and tower (circles) at a site in southern Saskatchewan. The dashed line is the extrapolated power-law profile, using the power law exponent derived from the 50 and 30 m cup anemometer wind speeds.

2.2 Terrain and Cover Analysis

In this paper we focus on results from 5 sites within a 20 km radius, in the Finger Lakes Region of New York State, with hilly terrain and partly or wholly forested cover. The studies were conducted in April through September, 2003.

Terrain features have been analyzed using Digital Elevation Model data available from USGS, and high resolution (1 m or less) aerial photographs available from the New York State GIS clearinghouse: (http://www.nysgis.state.ny.us/). PCI Geomatica software was used to extract DEM and DOQ profiles of the sodar site surroundings (Figure 3). For each 45-degree wind direction sector, the hill length, and hill half width at half-height were calculated from the DEM.

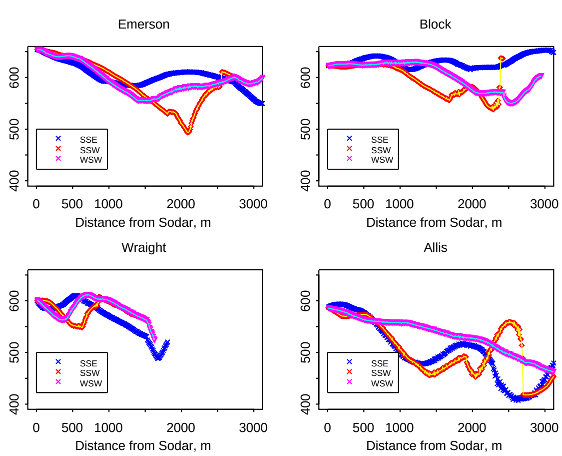

Figure 3. Example terrain profiles by direction sector at four of the sodar study sites. The y-axis represents elevation in meters.

2.3 Determination of the effective roughness length from sodar profiles.

Roughness length by wind direction sector for the 30-to-60 m and 30-to-80 m layers were determined using least squares fit to the neutral logarithmic wind profile (e.g. Hiyama, et al., 1996, and Beljaars, 1982) assuming a zero-plane displacement equal to zero (Figure 4):

$$U(z) = u_*/k \, [\ln (z/z_0)]$$

Shear parameters (α) for the 30-to-50 and 50-to-80 m layers were also determined from the power law (Irwin, 1979):

$$U_2/U_1=(z_2/z_1)^{\alpha}$$

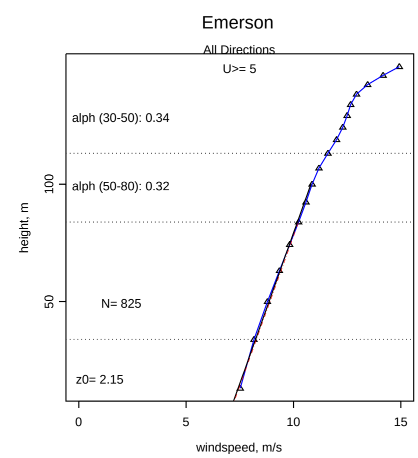

Figure 4. Mean wind profile for one site and all directions, plotted with ln(z). Least squares fits were done for the 30 to 60 and 30 to 80 m layers.

3.0 RESULTS

Hill steepness differentiates the profile parameters z_0 and α among sites (Figure 5) but other factors clearly are influencing these parameters. For instance, the “W4” and “W6” sectors (WNW and SSW winds at Wraight, respectively) differ in the vegetation cover within the first 0.5 to 1 km of the sodar, but W6 is the sector with the taller, forested cover. The logarithmic profiles at Wraight also have a “break” in them at 50 m, indicating that the flow is not homogeneous throughout the layer in which the z_0 was determined (Figure 6). These two sectors also have distinctly different vertical velocity profiles (Figure 7).

The S, SE and SW trajectories (sectors 3, 4 and 5 in Figure 5) generally exhibit homogeneous profiles for the most part, and the low roughness parameters cluster together, despite the variability in surface cover within the first km of each sodar site.

The high z_0 values for sectors 1, 6 and 7 (Figure 5) may result from the fact that several sites are bounded on the N or NW by steep-sided valleys; flow from that direction may result in inhomogeneous wind profiles, and anomalously high z_0 values. More variable terrain profiles out to 2 km (Figure 3) appear to be associated with greater scatter in the derived z_0.

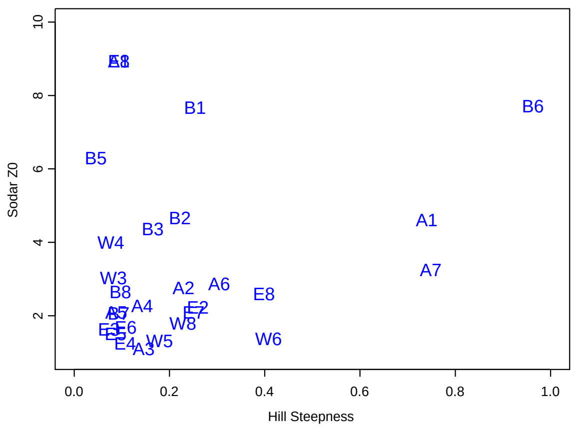

Figure 5. Roughness length derived from sodar profiles vs. hill steepness. Each point is identified by a letter indicating the site (E=Emerson, B=Block, A=Allis, W=Wraight), and a number giving the 45^{o} wind direction sector, clockwise from 0 degrees.

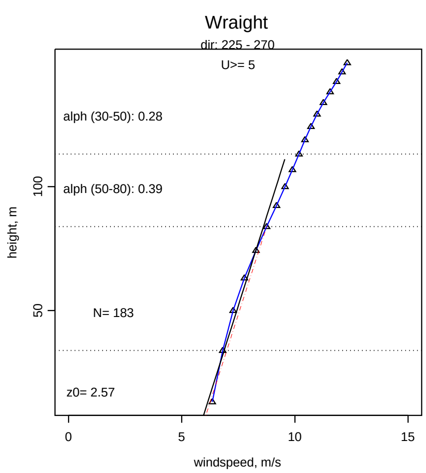

Figure 6. Wind profile for the WSW sector at Wraight.

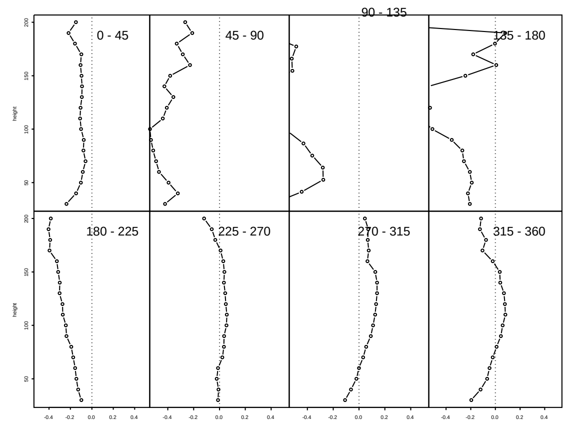

Figure 7. Vertical velocity profiles at Wraight Road, by wind direction sector.

4. CONCLUSIONS

Sodar is a useful tool in the wind resource assessment process, providing wind measurements at turbine hub heights where often only extrapolated values were available previously.

The 30 to 80 m layer of the wind profiles at the sites in this study often belong to the same logarithmic profile, with a break in the profile commonly occurring at 100 m or above. However, at some sites, a discontinuity occurred at heights as low as 50 m, suggesting that upwind terrain or roughness discontinuities are influencing the flow at those heights.

Even in flat, low-roughness terrain, the power law-extrapolated wind profile and the sodar-measured profile diverge at some height (Figure 2). The degree of under- or over-estimation of the wind resource at 80 m due to extrapolation from 50 m is likely a function of stability as well as terrain.

5. REFERENCES

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