Maximizing the Accuracy of Sodar Measurements for Wind Resource Assessment

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Introduction

Acoustic sounding or sodar (sonic detection and ranging) offers a wealth of information for wind resource assessment, especially when combined with conventional anemometry. The sodar provides not only complete vertical profiles of the horizontal wind speed and direction to a height of 200 m with 10 m vertical resolution, it also provides information on the vertical component of the wind.

We have worked with sodar data from more than 50 sites in North America and Hawaii, since 2001. In this paper we will focus on results aggregated from 7 sites with homogeneous, low cover—an example is shown in Figure 1; at each site NRG Max-40 cup anemometers were in use on 50 or 60 m NRG towers. The sodar model used has been an ART, LLC model VT-1. The low roughness and the homogenous fetch at these sites allow us to analyze in detail the factors that contribute to bias between sodar and anemometry. When these factors are accounted for, the bias becomes very small, and confidence in the absolute accuracy of the sodar wind speeds is increased.

Sodar Measurements

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:

$$\begin{aligned} W &= -\frac{fc}{2F} \\ V &= \frac{-fc}{2F\sin\Theta} - \frac{W}{\tan\Theta} \\ U &= \frac{-fc}{2F\sin\Theta} - \frac{W}{\tan\Theta} \end{aligned} \tag{1}$$

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.

Quality Assurance Methodology for Sodar Measurements

There are two general steps to the quality assurance process for the sodar measurements. The first is to determine that the sodar is functioning properly, and the second is to ensure that the sodar is sited properly.

A series of test and calibration procedures is routinely carried out, in which the output frequency, waveform and pulse length are verified, the sodar's ability to respond to changes in incoming frequency is checked, and the beam steering is verified by measuring the output phase angle of each speaker on each pulse. Last, a transponder test is applied in which the sodar is challenged with incoming pulses of fixed frequency and delay, representing programmed wind speed and direction at specified heights.

For most sodars data quality is compromised during periods of precipitation because sound can be scattered from snowflakes or raindrops, giving spurious velocity data. Therefore periods of precipitation must be removed from the dataset. This can be accomplished by having an onsite rain gauge, or by using a precipitation sensor to shut off sodar transmissions during periods of active precipitation.

Proper siting of sodar requires that fixed echoes be avoided if at all possible. Echoes from non-moving objects ("ground clutter") such as towers, trees, buildings, etc., will have a zero Doppler shift, and will therefore contribute a low bias to the derived wind speeds.

The sodar must be level. For a three-beam sodar, an off-level error will contribute to a low bias in the wind speed.

Accounting for the Differences between Sodar and Anemometry

Even given the proper functioning and siting of sodar, there are several potential sources of bias between sodar and mechanical anemometry simply based on the differing physics between the two. In order to effectively integrate the two types of measurements, each of these sources of bias should be understood and quantified so that adjustments or conversions can be made. Each of the major differences between sodar and anemometry is discussed below.

1. Sodar beam tilt

   In equations (1) above, the sodar beam tilt from the vertical is assumed to be constant. However, the actual beam tilt varies slightly with the speed of sound, which is a function of temperature. Therefore, some bias between the sodar measured speed and co-located anemometry can be expected, depending on how much the actual ambient temperature varies from the mean value entered in the sodar software. This variation can be accounted for in post-processing by using an on-site temperature measurement, such as is routinely available from meteorological monitoring masts. Alternatively, the sodar software can be configured to use a temperature that is logged with the sodar data—in this case, no post-processing adjustment is necessary. An example time series of post-processing beam tilt adjustment is shown in Figure 3.

2. Vector versus scalar wind speed

   Sodars compute a vector-average horizontal wind speed at the end of each averaging period:

$$Uhoriz = \sqrt{U^2 + V^2}$$

In a turbulent wind field, the varying wind direction causes the vector speed to be less than the scalar speed (the usual output from cup anemometers) for the same time period. Therefore a conversion between the vector and scalar wind speeds can be sought if the standard deviation of the wind direction is known (Figure 4).
If the standard deviation of the wind direction is not known, or if it is desirable to use the sodar data themselves to make the vector/scalar conversion, the sodar standard deviation of the vertical wind speed (σ_w) can be used to accomplish this. It is important to note that neither a wind vane nor the sodar is a turbulence instrument; however, both contain sufficient information about turbulence to be useful. For instance, both are correlated to the solar radiation (Figures 5 and 6).

3. Turbulence intensity and anemometer overspeeding

Mechanical anemometers overspeed in a turbulent wind field because they have inertia (Brock and Richardson, 2001), and they therefore tend to speed up in a gust more quickly than they slow down after the gust passes. Making an adjustment for this effect depends again on having a measure or indicator of the turbulence. The sodar vertical turbulence intensity (σ_w/U) can provide this measure (Figure 7), accounting for the bias between sodar and anemometer due to turbulence.

4. Flow Inclination

Certain cup anemometers respond to off-horizontal flow (Papadopoulos et al., 2002, Kaganov and Yaglom, 1976). Since the sodar yields a true horizontal wind speed, it is necessary to determine if off-horizontal components due to terrain-following flow are contributing to bias between the sodar and anemometry. The flow inclination can be determined from the ratio of the vertical to the horizontal speeds: W/U_h . If flow inclination accounts for part of the variance between the two, an adjustment can be made on this basis.

5. Volume Averaging

Sodar measures the speed in a volume. Each range gate or assigned height actually represents an integral of information in a depth of 20 m or more. In layers where there is high wind shear (large change of wind speed with height), the volume-averaging property will bias the speeds low, so that, if shear decreases with height, the shear calculated from the sodar will be greater than that from point measurements (mechanical anemometry) located at the same heights as the sodar range gate centers. Figure 8 provides an example of how volume averaging would affect the sodar wind speed profile for a model wind profile over forest.

Sodar σ_w as a Measure of Turbulence

In the discussion above we have shown that the sodar σ_w contains information about turbulence, in the same sense that the sigma-direction from a vane does. The σ_w can also be used to estimate the horizontal turbulence intensity. Examining data from many sites, there is always a relationship between the vertical turbulence intensity measured with the sodar, and the horizontal TI derived from cup anemometers. This relationship may vary with the site roughness, however (Figure 9). A conversion applicable for an individual site can be used to provide a vertical profile of the estimated horizontal TI above the top of typical meteorological mast.

Magnitudes of Various Factors

Each of the conversions or adjustments discussed above is generally less than 5% in magnitude. Once they are accounted for, confidence in the absolute accuracy of the sodar wind speed is increased. The following is a summary of the magnitudes of various factors:

1. Vector/scalar conversion: This is usually about 3% overall. Figure 10 illustrates the effect of the vector/scalar conversion on the wind profile.
2. Beam tilt: If the temperature adjustment to the beam tilt angle is done in post-processing, a 2%-3% adjustment often results, depending on the temperature setting in the sodar relative to the actual ambient temperature. No adjustment needs to be made of course if the temperature is logged with the sodar data and the speed of sound is updated in sodar software at each averaging period.
3. Turbulence intensity: The TI effect on anemometer overspeeding is generally about 2-3% overall, although it can be more if the site is very rough.
4. Flow inclination: In most cases this adjustment is less than 1%, but on an extreme slope (19%) it was found to be about -3% for downslope flow. The sign of the adjustment is opposite for upslope and downslope flow in the case of the NRG Max-40 anemometer.
5. Volume averaging: In the high shear layer above very rough surfaces, the sodar wind speeds can be biased low due to the volume averaging effect by as much as 3% (Figure 8). Since the bias will decrease as the shear decreases above the surface, the bias in the shear parameter will be greatest for the lower wind profile.

Each adjustment or conversion should be tested in each sodar/anemometer data set, to validate the appropriateness for that particular site and anemometer.

Conclusions

The following are the major conclusions of this work:

1. Sodar wind speeds are typically 5-7% lower than anemometer speeds on a nearby mast, if the differences in physics between the two are not accounted for.
2. The sodar beam tilt adjustment is ideally done with an on-site temperature sensor logged with the sodar data, but it can be accomplished in post-processing.
3. Anemometer overspeeding due to vertical turbulence and response to off-horizontal flow in steep terrain can each account for a small but measurable and significant bias in the wind speed between sodar and anemometer.
4. Sodar σ_w contains useful information about the mechanical and thermal turbulence at a site, and can be used to estimate the horizontal turbulence intensity.

5. Once the differences between sodar and anemometer are accounted for, mean sodar speeds should be within 2% of anemometry. The mean bias differences can be 0.2 m/s in flat homogenous terrain.

References

Brock, F. V. and S. J. Richardson, 2001. Meteorological Measurement Systems. Oxford University Press, 290 pp.

Kaganov, E. I. And A. M. Yaglom, 1976. Errors in wind speed measurements by rotation anemometers. Boundary-Layer Meteorology, 10: 15-34.

Papadopoulos, K. H., N. C. Stefanatos, U. S. Paulsen, and E. Morfiadakis, 2002. Effects of turbulence and flow inclination on the performance of cup anemometers in the field. Boundary-Layer Meteorology 101: 77-107.

Figures

Figure 1Installation of an ART, LLC model VT-1 sodar at a site in southern Saskatchewan, Canada.

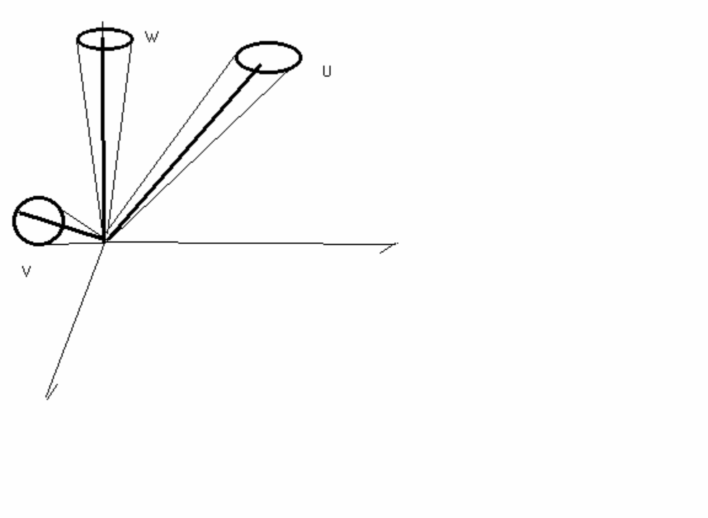

Figure 2 Idealized acoustic beam pattern from a 3-beam sodar.

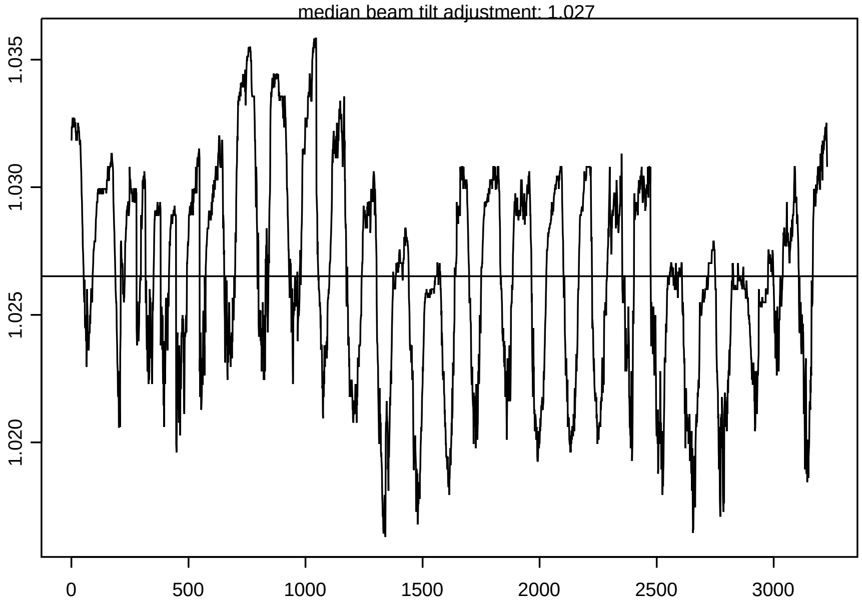

Figure 3Time series of the beam tilt adjustment factor (post-processing) due to temperature, from a single site.

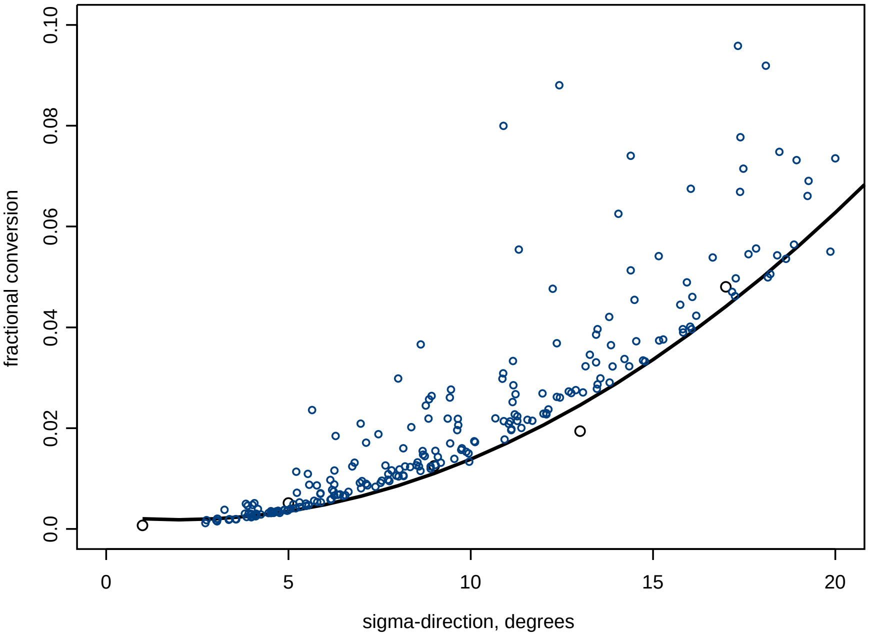

Figure 4 Fractional conversion between vector and scalar wind speeds as a function of the standard deviation of the wind direction ("sigma-direction"). The black line is a numerical model based on many random time series with varying sigma-direction. The blue circles represent actual data from a surface anemometer for which both vector and scalar speeds were logged.

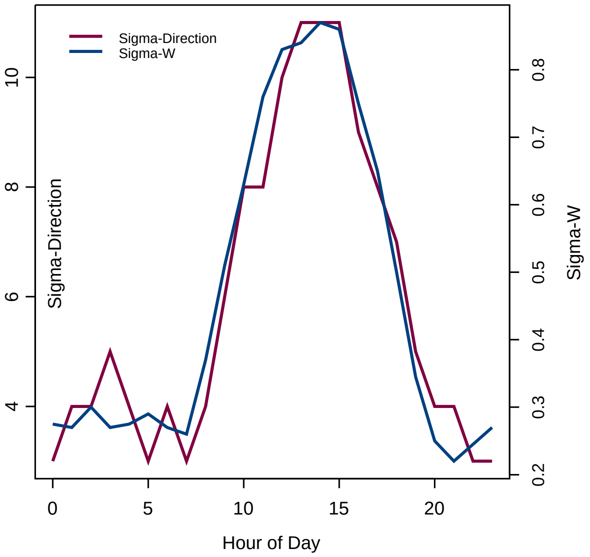

Figure 5 Median standard deviation of wind direction (sigma-direction) and standard deviation of sodar vertical velocity (sigma-W) as a function of hour of day.

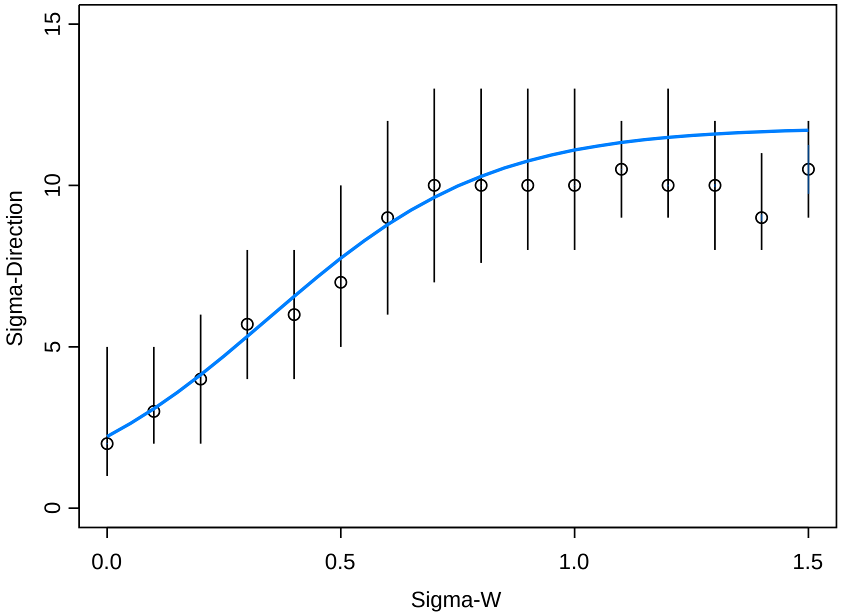

Figure 6 Standard deviation of the wind direction as a function of the sodar σ_w. The points are medians across 7 sites. The vertical bars are standard errors. The blue line is a logistic curve fit with non-linear least squares.

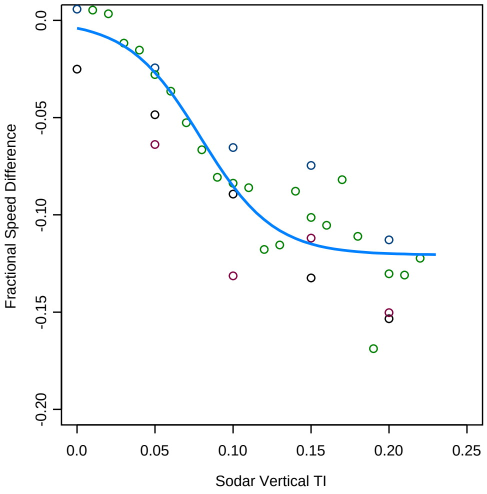

Figure 7 Effect of vertical turbulence intensity on the fractional speed difference between sodar and tower. Data from 3 sites were aggregated, representing 6000 observations. The blue line is a logistic curve fit to the 6000 points.

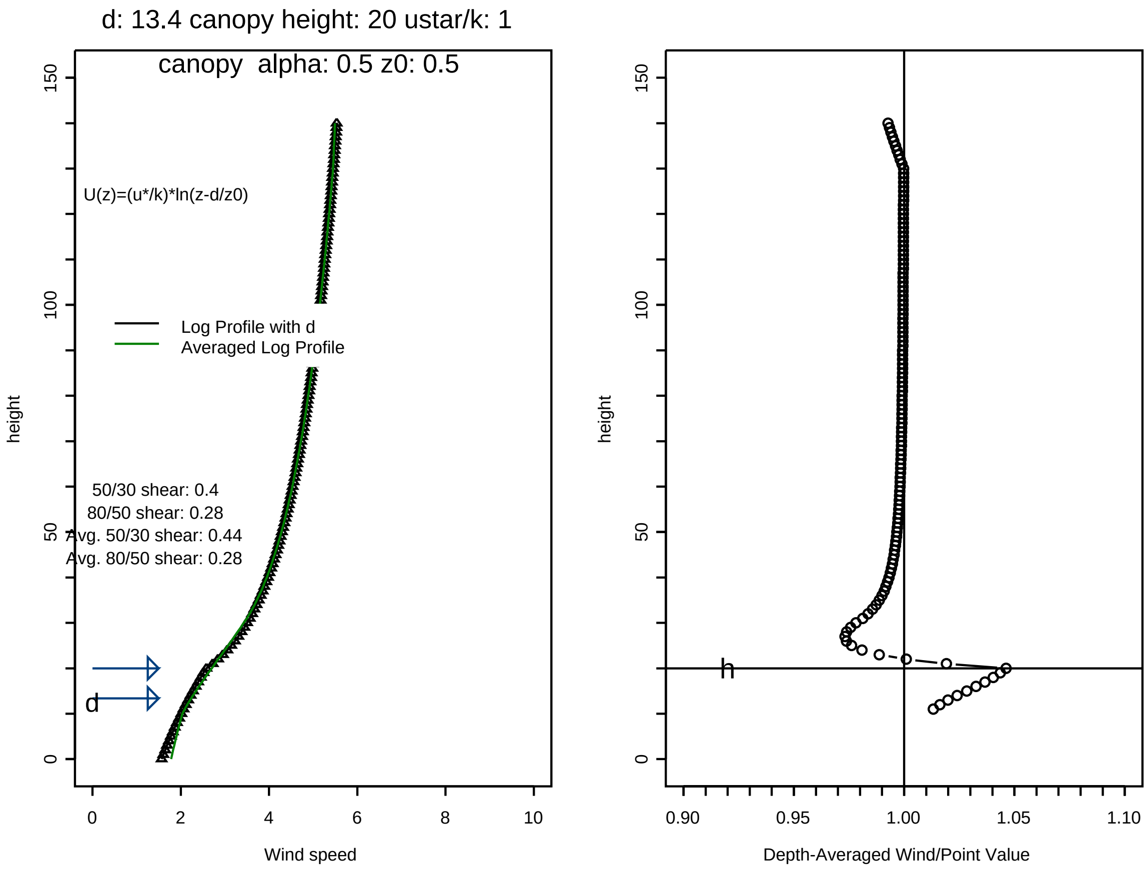

Figure 8 Model of volume averaging effect for sodar measurements in a forested site. (Left) A logarithmic wind profile with displacement height is shown. The green line is the volume-averaged wind speed over a depth of 20 m, while the black triangles represent point measurements at each height. "d" is the displacement height. An exponential profile is assumed below canopy top (Right) Ratio of the depth-averaged wind speed to the point value in the center of the considered depth, with height.

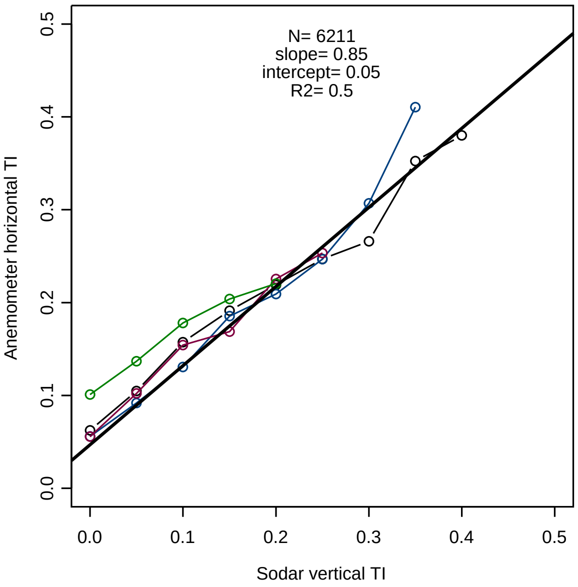

Figure 9 Horizontal turbulence intensity (σ_u/U) from an NRG Max-40 anemometer versus sodar vertical turbulence intensity (σ_w/U) for 3 sites. The black line represents the regression of the medians of the binned values across all 3 sites. The green points and line are from a site with high roughness, while the others are from flat sites with low roughness.

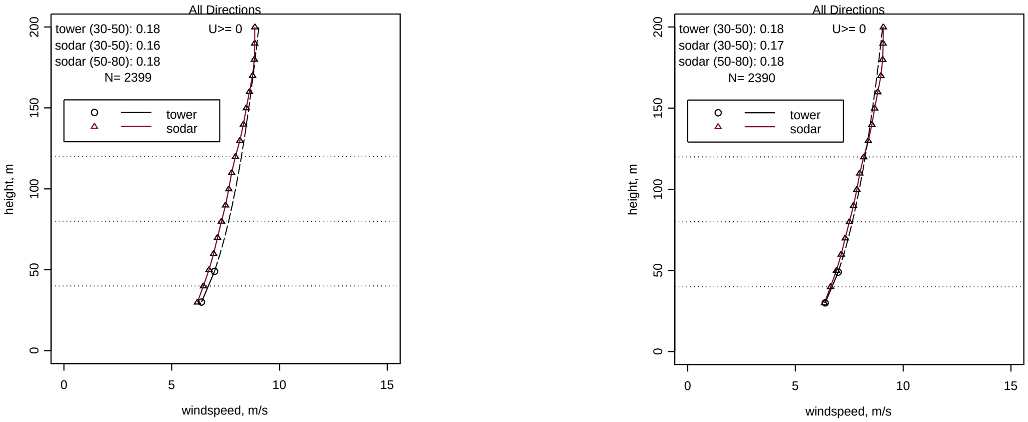

Figure 10 Average wind speed profiles without (left) and with (right) vector/scalar conversion. The red line with triangles represents the sodar wind speeds, while the black circles are the tower speeds. The dashed line is the power-law extrapolated wind speed using the tower 50/30 m shear parameter.