# Classifying Rotor Span Shear Profile Variability
# and Improving Wind Turbine Production Prediction

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## Abstract

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.

This paper discusses how sodar-based wind profiles fluctuate in real-time in response to various atmospheric and surface influences. These include atmospheric stratification and varying depth of the surface layer, low-level jet formation above an inversion layer, and roughness- and terrain-induced effects that change with wind direction. Examples will be drawn from an extensive inventory of sodar field measurements sampled from over 100 sites across North America. A classification scheme for defining temporal wind shear variability will be proposed. Furthermore, the opportunities for improving the prediction energy production using rotor span wind profiles will be discussed.

## Introduction

Sodar (sound detection and ranging) is a useful addition to a meteorological monitoring program because it measures the wind profile up to and above the hub height of modern utility-scale wind turbines, which ranges from 65 to 100 m, whereas meteorological towers are typically only 50 to 60 m tall. By taking sodar measurements for a period of time near an existing met. tower, the wind shear up to hub height can be characterized as a function of wind direction, wind speed, and time of day. By combining these wind shear values with long term met. tower wind speed measurements, it is possible to calculate a more accurate annual-average wind speed at hub height than can be obtained from the met. tower alone.

Beyond the measurement of hub height wind speeds, sodar also provides a wealth of data about the lower atmospheric winds including the wind speed and direction through the entire layer of air occupied by wind turbines.

AWS Truewind has been using sodar in the wind resource assessment process since 2001. Since that time sodar data from more than 126 sites in North American and Hawaii have been analyzed (Figure 1). The absolute accuracy of sodar is comparable to that of anemometry in the field (Moore and Bailey, 2005), once adequate data quality measures have been taken, and once the differing physics between the two types of measurements have been addressed.

Previously (Moore et al. 2006) we worked with integrated wind power profiles to demonstrate that the hub height power in the wind is not representative of the power in the entire rotor disk, given the wide range of shear conditions that are encountered in actual practice. In this paper we further explore the types of temporal variation in wind profiles and the potential impact on power performance, with the aim of classifying sites and profiles according to the characteristics that produce the variation.

## Methodology:

In the course of using sodar for wind resource assessment, an archive of sodar wind profiles has been built representing more than 126 short- (1-2 month) and long-term (6 months to 1 year) assessments done since 2001 (Figure 1). Routine analysis includes plotting mean profiles by wind direction sector and by hour of day with both linear and logarithmic height axes (Figure 2) to assess the degree of conformity to power law and/or logarithmic wind profiles.

Routine analysis of each sodar study's data also includes screening of 10-minute average wind profile sequences for transient events such as frontal passages, low-level jets, strong downslope flow, etc. Factors affecting either the mean profile at a location or the time-varying profile are shown in Table 1. Although the factors in the table are divided into "meteorological" and "site" categories, it is clear that these are not exclusive categories, as one may influence the other; for instance, the vegetation on a site will affect the stability through the surface energy partitioning.

**Table 1 Factors affecting the shape of the wind profile.**

| **Meteorological:** | **Site:** |
|---|---|
| Stability (hour, season) | Slope steepness, aspect |
| Low-level jets | Upslope vs. downslope |
| Frontal passage | Vegetation (roughness, stability) |
| Local circulations (mountain/valley, sea breeze, etc.) | |

The wind profile response to the influences outlined in Table 1 can be detected or assessed by a variety of measures:

- Shear—change in horizontal wind speed with height
- Friction velocity (u*), roughness length (z0), displacement height
- Directional shear (degrees of rotation)
- Directional shear (along- and cross-wind component shear)
- Flow inclination– vertical/horizontal
- Turbulence Intensity

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 (Pederson). 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:

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

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.

It is important to recognize that the mean wind profile is composed of a sequence of time-varying profiles that exhibit very different properties in horizontal wind shear and directional shear. Below we present examples of how these properties have been found to vary.

## Results:

### *Inflow angle by Hour of Day (Diurnal/Mt. Valley)*

One type of temporal variation is due to mountain-valley circulations, where there is a diurnal upslope/downslope pattern to the wind; a detailed analysis of such circulations is provided in Stewart et al., 2002. Figure 3 illustrates this phenomenon at a dry western montaine site. The plot on the left is a hodograph, with the arrows showing the direction of the wind, the length of the arrows showing the magnitude of the wind, and the numbers indicating the hour of the day. At this site, the afternoon and early evening hours see strong southwesterly winds; the vertical velocity rose on the right confirms that the strong southwesterly winds have a strong upward component, or positive flow inclination. In this case the flow inclination for the strong upslope winds is as much as 10 degrees, which could reduce turbine output by 3 to 4%, using a cosine-squared term in the power calculation.

### *Directional Shear By Hour of Day*

Directional shear also varies with the hour of day. In most cases examined so far, the direction turns clockwise by 0.2 to 0.5 degrees per meter in the rotor plane, in the early morning hours. The turning is usually more pronounced at lower wind speeds, but even at wind speeds above 5 m/s it can be substantial. In the early morning hours stable conditions tend to prevail, and conditions are not well-mixed, even if the winds are significant. Mid-day, conditions are more well-mixed and the directional shear is close to zero. Figures 4 and 5 illustrate the typical pattern, as observed at two very different sites.

What is the impact on power production? As a first order answer to that, we used a cosine-squared relationship to express how flow that is off-normal to the rotor plane would affect turbine output. In this case we would expect a loss of 2% to 3% for the cases with rotor plane directional shear of 10° and 18° respectively. But note that the distribution of directional shear includes some values that are quite a bit larger, up to 30° or more.

### *Time-varying Horizontal wind shear*

Although it is common to use the mean wind profile to describe conditions at a site, in reality the wind profile is changing constantly, and these temporal variations may have significance for the power performance of a wind turbine. Figure 6 shows a sequence of 10-minute average wind profiles over the course of a 1.5 hour period at night. The flow was downslope at this time, and a speed maximum formed in the wind profile. Calculating the integrated power in each profile and comparing it to a model wind profile with the same hub height speed and positive shear throughout, a loss of as much as 5% is observed when the lower profile shear is very strong, at the time of the most pronounced speed maximum. On the other hand, an overall gain relative to the model profile is observed when there is less shear in the lower profile. Using this measure of integrated rotor plane power, even negative shear, which is not uncommon at certain sites, can produce a gain over what would be expected for the same hub height wind speed and positive shear.

### *Directional Shear—I*

An extreme case of directional shear is represented by the time/height depiction in Figure 7; the data come from a high mountain (~3000 m) in the western United States, where a thermal circulation commonly dominates. In this case there is a 180° direction shift that develops in the morning each day, between two layers of air within the rotor plane depth. The direction shift appears to move down the profile as mid-day approaches, and the wind speeds increase, so that by noon there are 8-10 m/s winds on either side of the shift, with opposite directions. This pattern was repeated every day for a sequence of about 10 days during this period. Obviously this site would present some difficulties for wind turbines under these conditions.

### *Directional Shear—II*

Another way to analyze directional shear is to decompose the wind vector at each height into a component that is parallel to the hub-height wind, and a component that is at right angles to it (Figure 8). The example shown is from a relatively flat open site with mixed forest and pasture surrounding it. The overall 80/50 m shear parameter was 0.28. For the period depicted in Figure 8, there was an average directional shear from 40 to 120 m of 14°, clockwise, and an 80 m wind speed of 10.1 m/s. This type of decomposition may prove useful going forward as we model in greater detail the response of the turbine rotor to varying angles of attack.

## **Elements of a Classification System:**

Just as wind forecasting for hour-ahead or day-ahead wind plant production requires an understanding of how different types of temporal transitions affect output, it would be advantageous to be able to have an *a priori* understanding of what to expect from a given site for resource assessment purposes. The aim of a classification system for wind profiles would be to link certain features of the surface, season, and local meteorology with the power performance characteristics of the wind. In this way we could anticipate or predict what the power performance impact might be from a given set of objective criteria. Eventually it might even be possible to create a GIS overlay of wind profile types or phenomena that would be expected under a given set of circumstances.

The following is a list of elements that might be part of a wind profile classification system aimed at better characterizing power performance characteristics of the wind:

- Frequency and persistence of transition events
- Site type and climatic regime
- Terrain: steep vs. flat vs. rolling
- Roughness: smooth vs. rough
- Thermal influences: fronts, LLJ, stable/convective, energy partition

## Conclusions:

Better understanding of the time-varying output from individual turbines depends on a solid understanding of the entire wind profile, how turbines respond to the entire profile, and the factors that produce a given shape or sequence of profiles. Sites will be better characterized if the types of temporal transitions that take place can be anticipated or modeled. Given that some types of transitions or events are infrequent yet potentially very important, longer measurement campaigns with remote sensing techniques such as sodar may be required to capture these. It might also be important to adjust estimates of energy production for projects to account for the types of phenomena we have presented here.

Finally, we would like to make a case for conducting sodar/turbine performance studies at a variety of sites under varying circumstances. Such measurements would be very fruitful for the industry as we seek to better predict turbine performance under varying atmospheric conditions.

## References

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, June, 2005, Denver, CO.

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.

Pedersen, T. F., 2002. Power curve measurements under influence of skew airflow and turbulence.

Stewart, J.Q., C. D. Whiteman, W. J. Steenburgh, and X. Bian. 2002. A climatological study of thermally driven wind systems of the U.S. intermountain west. Bull. Am. Met. Soc. May 2002 699-708.

## Figures

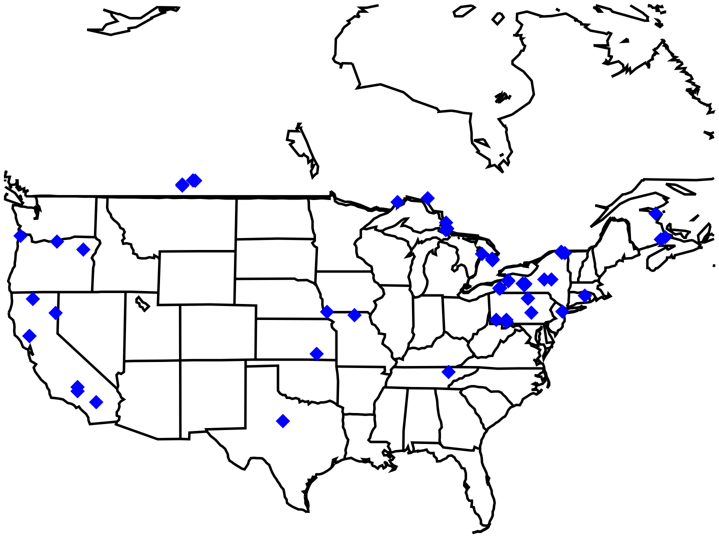

**Figure 1 A sample of the more than 126 sodar locations analyzed as of May, 2007.**

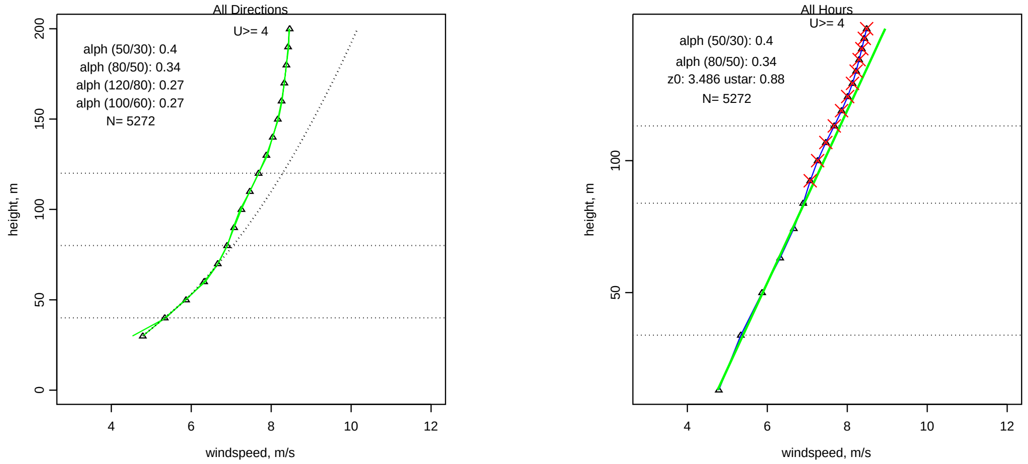

**Figure 2. Example mean wind profile for all directions and for speeds > 4 m/s plotted (left) with a linear height axis and (right) with a logarithmic height axis. The green line in the left plot is the least-squares fit to the data below 80 m.**

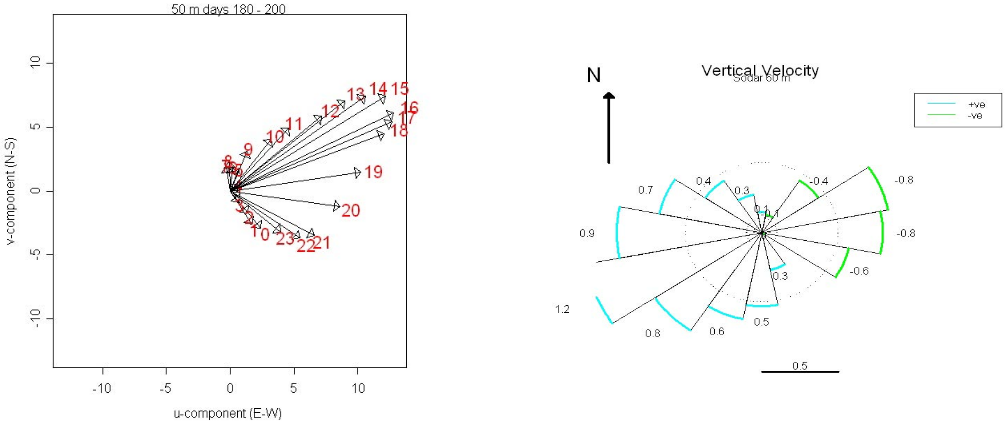

**Figure 2 Hodograph (left) and vertical velocity rose (right) for a site illustrating afternoon upslope flow (positive) and nocturnal downslope flow (negative). Numbers next to the hodograph arrows designate the hour of day. Numbers on the vertical velocity rose are in m/s.**

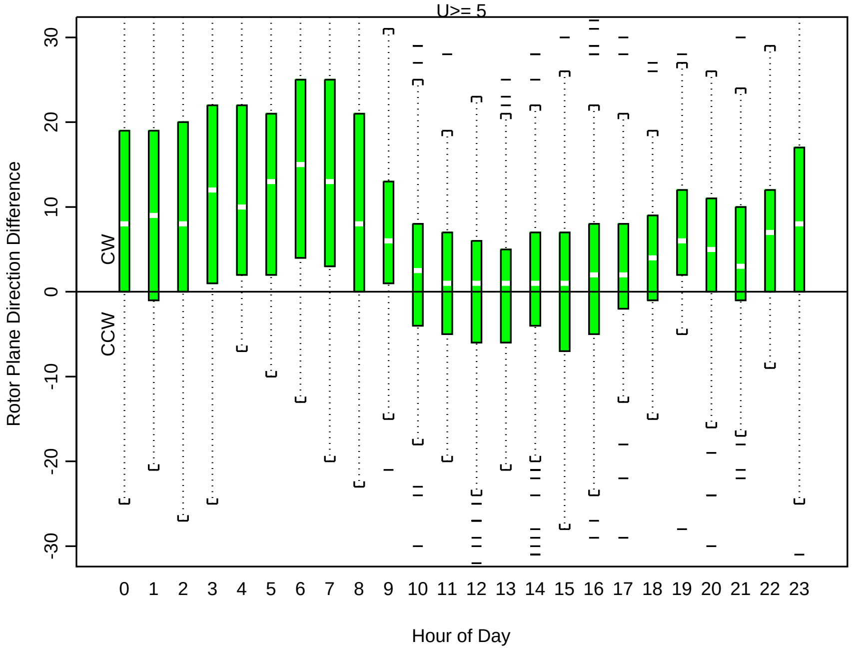

**Figure 4 Rotor plane directional difference (degrees) between 40 and 120 m, by hour of day at a site in the Northeastern US, with mixed forest and pasture surrounding it. Each green box represents 50% of the distribution, and the "whiskers" represent 95% of the distribution for each bin.**

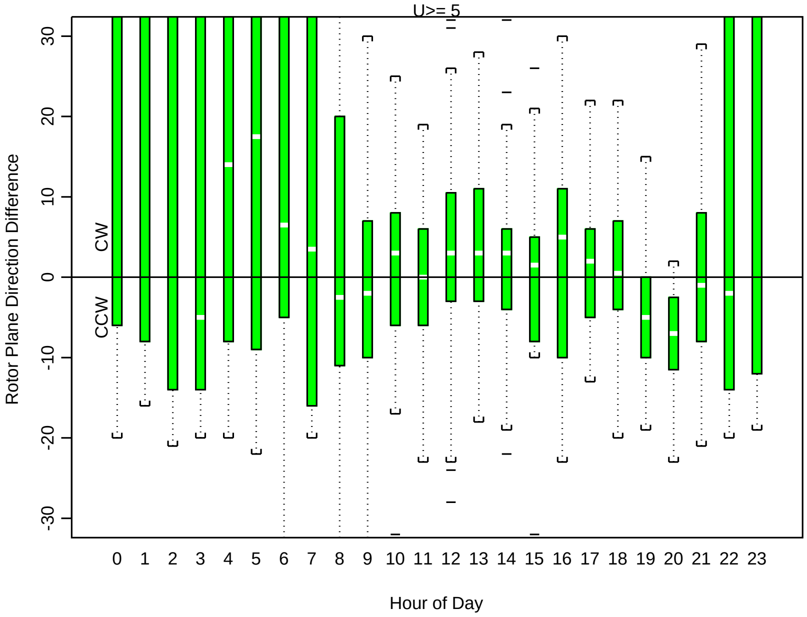

**Figure 5 Rotor plane directional difference (degrees) between 40 and 120 m, by hour of day at a steep, dry site in the Northwestern US. Each green box represents 50% of the distribution, and the "whiskers" represent 95% of the distribution for each bin.**

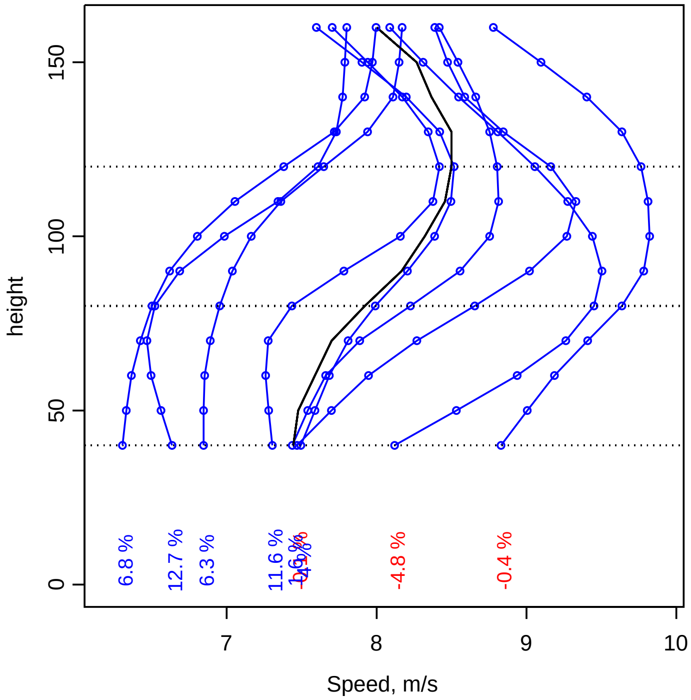

**Figure 6 Sequence of wind speed profiles over the course of about 1.5 hours at night. Flow was downslope. The numbers on the bottom reflect the integrated power loss (red) or gain (blue) relative to the power computed from a model wind profile with the same hub height wind speed and positive shear of 0.21 throughout the rotor plane. The black line is the mean profile for the period.**

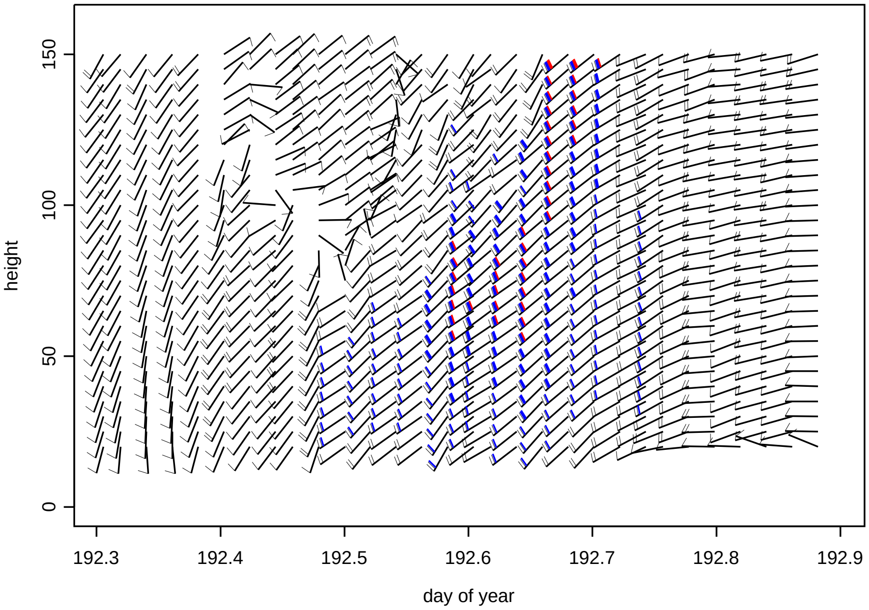

**Figure 7 Time-height depiction of the wind profile at a mountainous site in the western US. Southwesterly flow encounters northeasterly flow at about 100 m, and strong directional shear across the rotor plane layer ensues.**

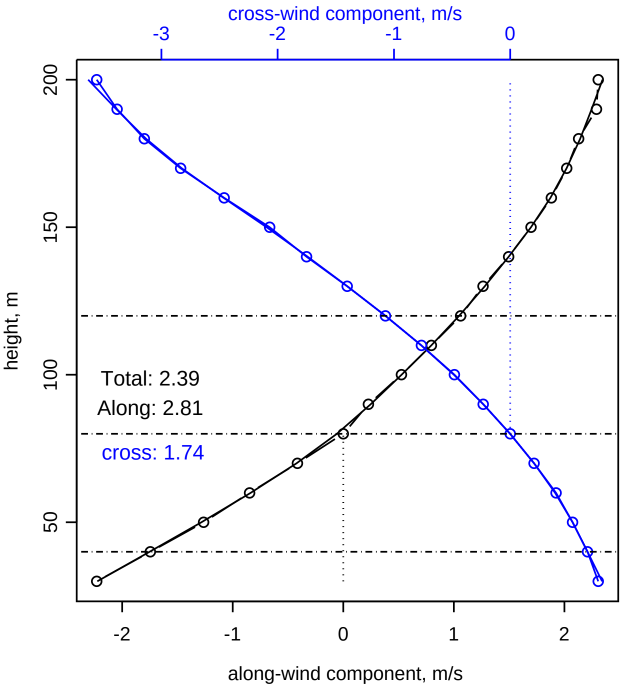

**Figure 8 Shear profile decomposition for a Great Plains site. The black line (curving upward from left to right) illustrates the along-wind component of the wind (relative to hub height), while the blue line shows the cross-wind component. The mean wind speed at 80 m was 10.1 m/s, and the total directional shear from 40 m to 120 m was 14° clockwise.**