Characterizing Wind Speed and Direction Shear with SoDAR Data

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ABSTRACT

SoDAR data from three sites were analyzed to identify frequency of occurrence of atypical wind conditions sufficient to impact resource suitability or turbine performance. Wind speed and direction measurements were obtained for a set of heights spanning a typical wind turbine rotor. For each site, 10-minute wind averages were collected for a three-month period. A power-law shear coefficient was then fit to each 10-minute set of wind speed measurements, yielding an accurate short-term measure of wind speed shear. Similar analysis was performed for wind direction shear (also called veer) by fitting a straight line to each set of 10-minute wind direction measurements. The wind direction change from lower to upper blade tip was then used as a short-term measure of veer.

To highlight the effect of speed and direction shear on turbine operation, data samples with hub height wind speed below 6 m/s were removed from the data set. Histogram representation is used to show the frequency-of-occurrence of speed and direction shear values, and the heavy-tailed distributions suggest that extreme shear and veer, while somewhat rare, occur surprisingly often and usually at night, when atmospheric stability reduces coupling between upper and lower level air. A reverse cumulative distribution, or frequency of exceedance plot, is shown to be useful in comparing the frequency of occurrence of degrees of shear at the three example sites.

OBJECTIVES

The primary objective of wind resource assessment is to identify sites with sufficient winds for power generation. When a candidate site is identified, the wind data for the site are further analyzed to ensure suitability of the local wind conditions for wind turbine operation. One aspect of suitability that is often neglected is the occurrence of extreme wind shear. Often, only a single, seasonal, average shear coefficient is obtained for a site, even though such long averages mask the presence of wind shear extremes that occur infrequently.

A common reason for over-averaging wind shear is the lack of accurate data. When the only available data are from below-hub-height met masts, wind shear values must be extrapolated from a small set of readings. As tower shadow and anemometer over-speeding can cause small errors in those readings, the extrapolated shear values will have uncertainty when averaged over short time intervals. Also, it is common to ignore wind direction shear altogether, because many met towers are instrumented with wind direction vanes at only a single height.

The development of inexpensive remote sensing technology, such as Sonic Detection and Ranging, or SoDAR, has made it practical to obtain accurate measurements of wind speed and direction at several heights across the swept area of a typical wind turbine rotor. Because modern SoDAR equipment is robust, is easy to deploy, and can run continuously, it is an ideal choice for studying the variety of local shear conditions present at any potential windfarm site.

For this research, we used measurements from a Second Wind Triton Sonic Wind Profiler, which measures 10-minute average wind speed and direction at six different heights spanning a typical rotor swept area, as shown in Figure 1.

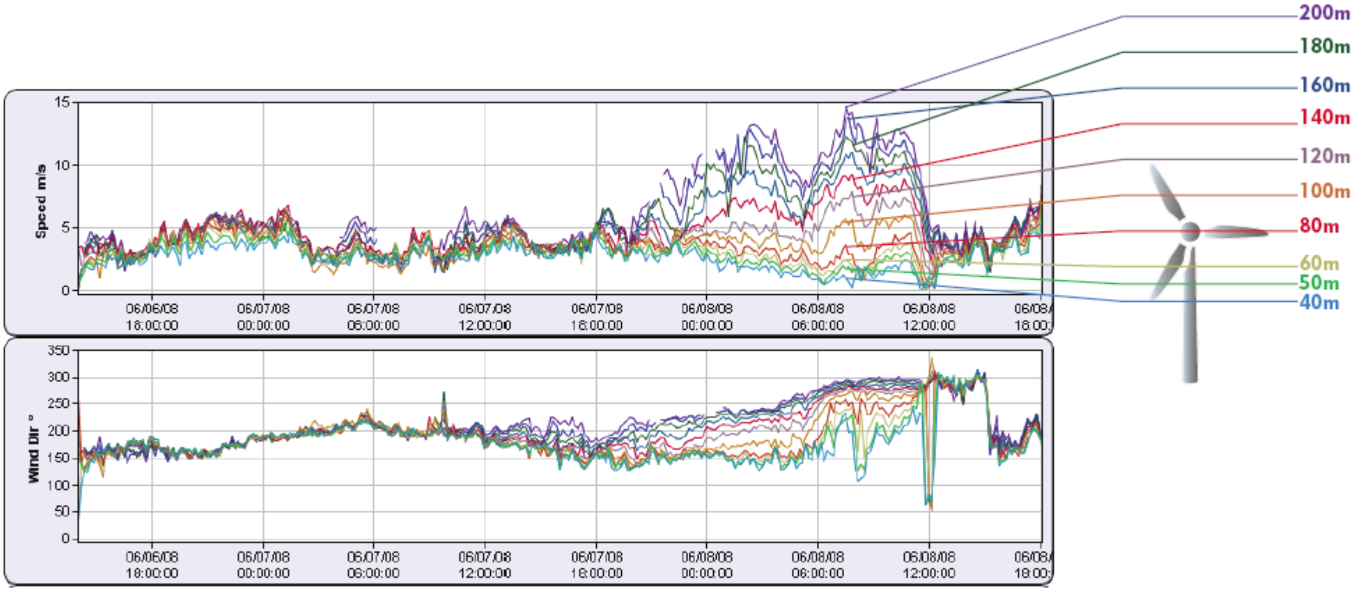

Figure 1: Example Triton Wind Speed and Direction Measurements with Extreme Shear.

The SoDAR measurements are easily analyzed to compute 10-minute values for both speed and direction shear over an entire measurement campaign. However, without a standard practice for incorporating short-term shear measurements, it is not clear what to do with such a large quantity of shear data. This paper develops a simple technique for plotting shear frequency of occurrence in order to highlight site-to-site differences that would affect wind turbine performance and reliability.

VALIDATION

Before examining the wind shear distribution, a correlation study was conducted for each three-month data set in order to confirm its validity. To ensure that noisy or erroneous data were not included in the analysis, the Triton data were filtered based on a minimum quality factor of 90% and a maximum vertical wind speed of +/- 1.5 m/s. The quality factor is a parameter calculated at every height and is a function of the signal-to-noise ratio (SNR) and the number of valid data points collected over the 10-

minute interval. Implementing a minumum quality factor of 90% removes any noisy or invalid data that may have been recorded. The vertical wind speed filter removes erroneous data or data affected by precipitation.

The wind speeds as measured by the Triton were compared to adjacent tower wind speed data and correlation coefficients were determined. Figure 2 shows scatterplots of Triton and anemometer wind speeds measured at 50, 100, and 150 m at the Boulder Atmospheric Observatory from September 1st, 2008 to November 30th, 2008. The correlation coefficients were found to be very high at 0.985, 0.985, and 0.973 at 50, 100, and 150 m, respectively.

In Figure 2, the solid red line represents a 1:1 relationship between the Triton and tower wind speeds. As shown, at all three heights, the wind speed data have a narrow distribution and are scattered around the 1:1 line. The average wind speeds as measured by the Triton and tower were also compared. For this comparison, the tower data were directionally filtered to reduce tower shadow or tower speed-up effects. At 50, 100 and 150 m, the difference in average wind speed (Triton wind speed – Tower wind speed) was found to be 1.7 %, 0.8 % and 0.0 %, respectively. Upon successful completion of each validation study, the wind shear and veer distributions were analyzed.

METHODS

In order to compute short-term average shear values from SoDAR data, we use a set of 10-minute average wind speed and direction measurements from heights spanning a typical wind turbine rotor. For this paper, a representative wind turbine was assumed to have an 80 m hub height and an 80 m blade diameter. From lower tip height to upper tip height, the set of measurements from the Second Wind Triton included heights 40m, 50m, 60m, 80m, 100m, and 120m.

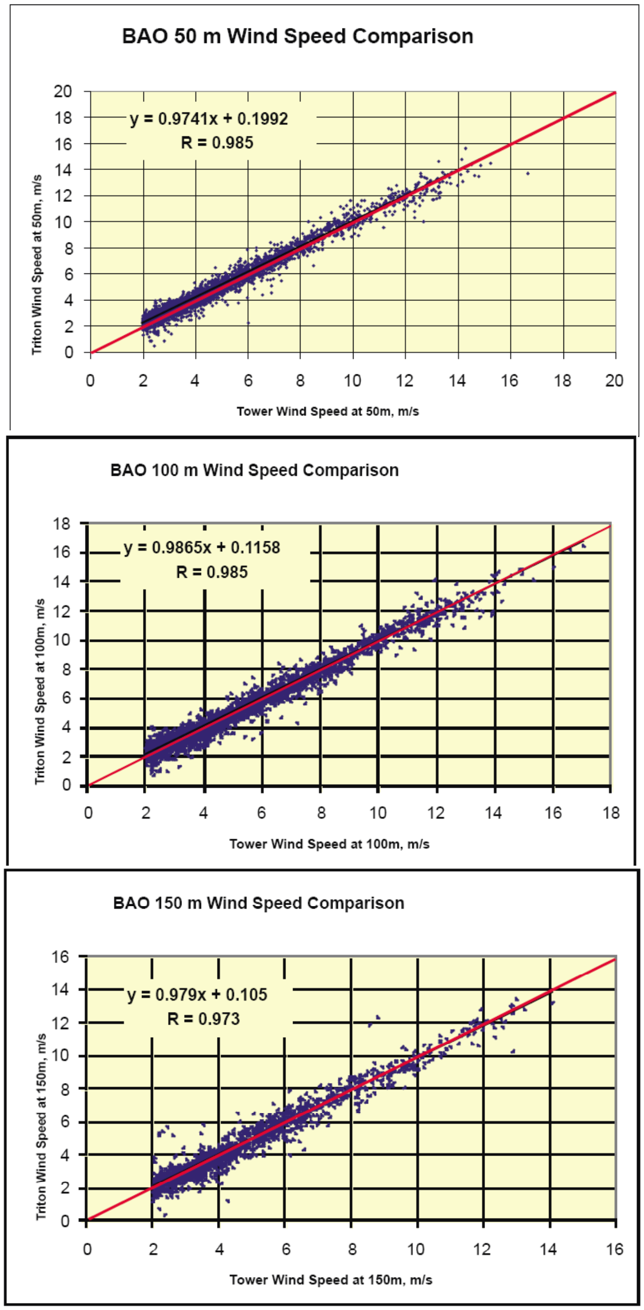

Figure 2: Scatterplots Showing Correlations between Tower and Triton Measurements.

In computing the wind speed shear value for each 10-minute interval, the set of measurements is fit to a power law curve, where measured wind speeds at different heights are assumed to be ratio-metrically related by the height ratio raised to the power *alpha* (α), where α is the shear exponent used here as wind speed shear value. The following derivation shows how to find a best-fit shear exponent, given a set of measurements from many heights.

The following power-law formula shows how the wind speed ratio is equated to the height ratio raised to the power α.

$$\left(\frac{U_1}{U_2}\right) = \left(\frac{H_1}{H_2}\right)^{\alpha}$$

where U_1 and U_2 are wind speed measurements at heights H_1 and H_2.

Taking the logarithm of both sides, the equation becomes:

$$\log\left(\frac{U_1}{U_2}\right) = \alpha \log\left(\frac{H_1}{H_2}\right)$$

To find an aggregate shear exponent, or best fit α, given a set of measured wind speeds, U_i, taken at heights H_i, the power law equation is reduced to the form of a straight line fit, by taking the logarithm of the U and H values to yield the points $\{ \log(H_i), \log(U_i) \}$. With a set of such points, a linear least-squares, or straight line fit is performed. The straight line corresponds to the equation:

$\log(U_i) = \alpha \log(H_i) + c$

While the constant offset term, c, is discarded, the slope of the fit line is α, the aggregate shear exponent that best fits the wind shear profile across the set of measured wind speeds. Figure 3 shows how a typical computed shear coefficient reflects the original 10-minute average wind speed data. The plot shows how the SoDAR data from heights spanning a turbine rotor nicely capture the 10-minute average shear characteristic without extrapolation.

Wind direction shear was calculated using a straight line fit to the wind direction measurements from the same set of heights. In this case, the wind direction is assumed to change linearly with height, not as a power-law function of height. Thus a straight line is fit to the points $\{ H_i, D_i \}$, where D_i is the measured wind direction from heights H_i, *unwrapped* to avoid jumps of 360 degrees. Figure 3 shows a typical line fit to a set of 10-minute wind direction measurements.

The slope of the best-fit line is a measure of how much the wind direction changes per meter of elevation. Multiplying the slope by the rotor diameter then yields a total wind direction change from lower blade tip to upper blade tip. For this paper, the total wind direction change, in degrees, over an 80m rotor, is used as a measure of wind direction shear, or veer.

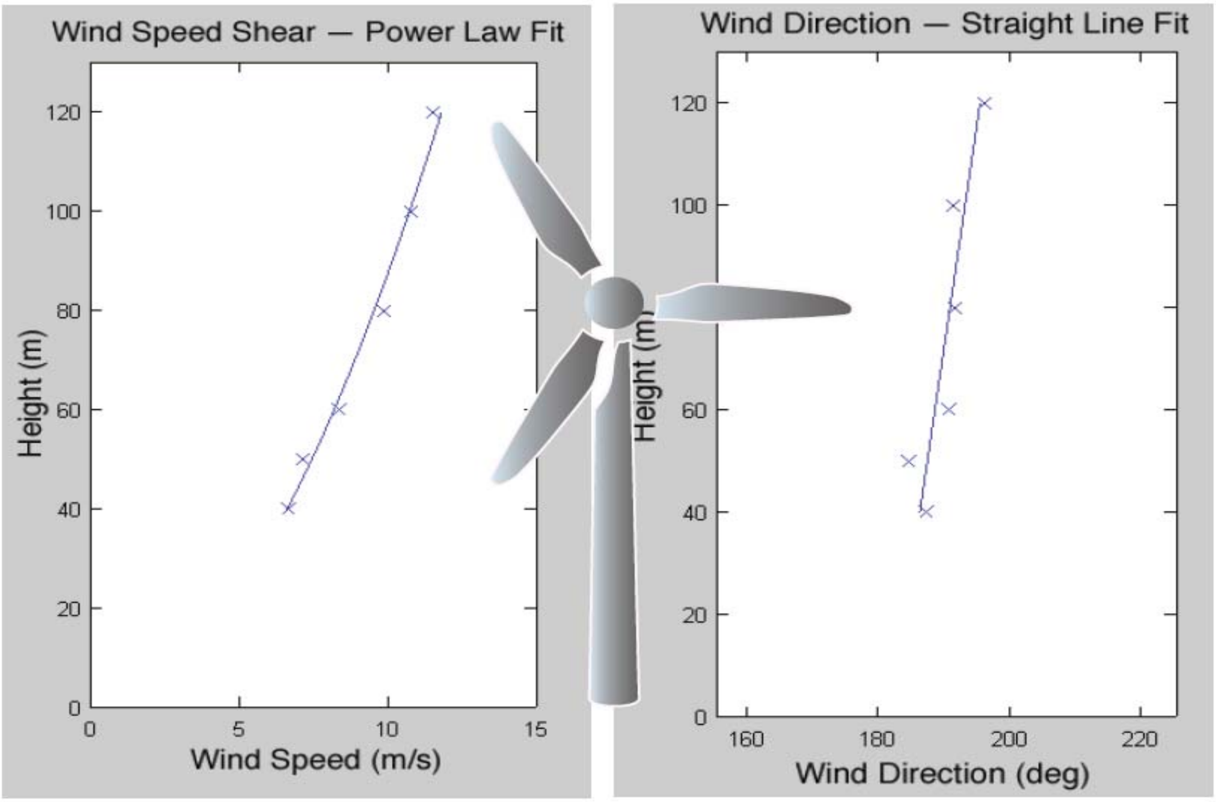

Figure 3: Sample Wind Measurements Showing Shear and Veer Fit.

As wind shear at low wind speeds has little or no consequence, all 10-minute data with hub height wind speed below 6 m/s were removed from the data set. In all likelihood, the remaining shear values occurred well within the operating range of most wind turbines. Histograms are shown for wind speed shear and wind direction shear in Figure 4. Also shown are the time-series SoDAR data from times of fairly extreme, yet frequently occurring shear and veer. The speed shear time-series example has a tip-to-tip wind speed ratio of 2:1 ($\alpha = 0.63$). The veer time-series example shows a tip-to-tip direction discrepancy of 15 degrees. The histograms show that, at least for short periods of time, far greater shear values occur. These shear extremes are most often masked in resource assessment, because shear coefficients are derived from long-term data averages.

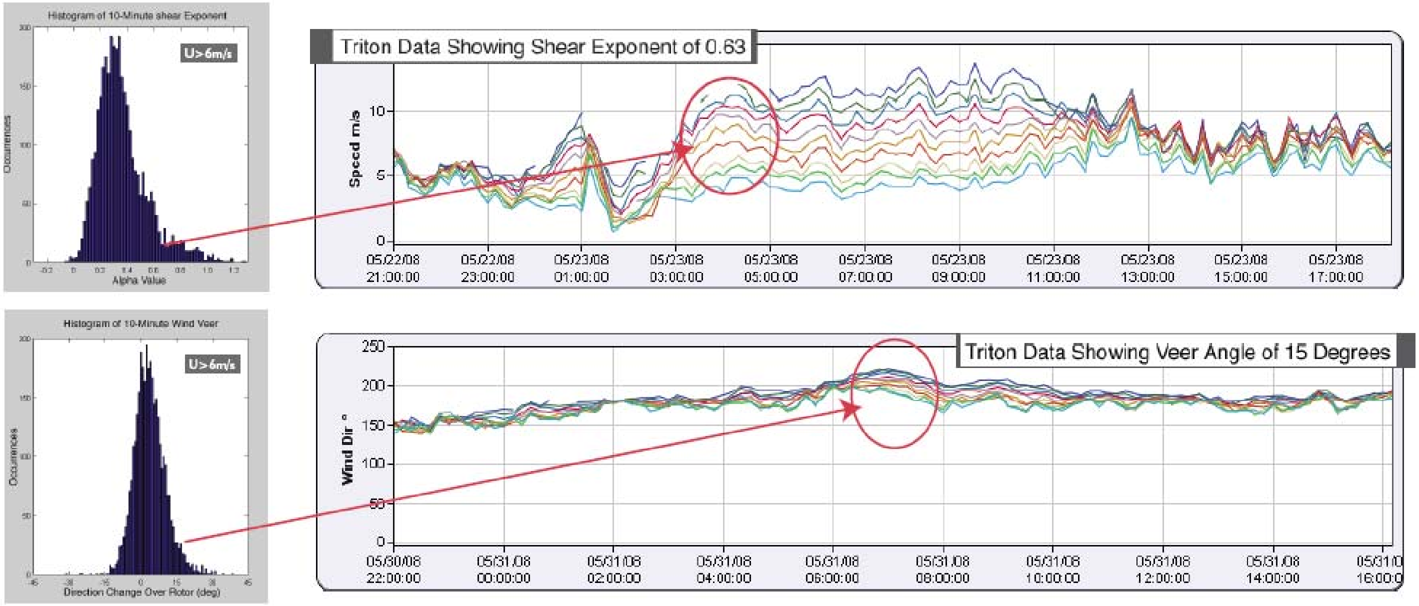

Figure 4: Histograms for Wind Speed Shear Exponent and Directional Shear with Matching Time Series Data.

RESULTS

A three-month data set was obtained for each of three example sites:

SITE	*PERIOD*	*LOCATION*	*DESCRIPTION*
BAO	Sept–Nov 2008	Boulder Atmospheric Observatory	Nearby 300 m Tower
Cape Cod	May–July 2008	Massachusetts	Coastal Cranberry Bog
Windfarm	Nov–Jan 2008/9	Texas	Operating Windfarm

Wind shear is reduced by coupling between layers of air during periods of atmospheric instability, such as when solar heating causes convective mixing of the air. For this reason, most extreme shear events occur during periods of high atmospheric stability, usually at night. Even on overcast days, atmospheric stability is usually somewhat reduced, providing a degree of protection against extreme shear.

The diurnal trend is demonstrated by segregating the shear and veer histograms by time of day. To do this, we plot the histogram using a line chart instead of a bar chart. Three lines are plotted: the total histogram, including all data with hub height wind speed >6 m/s, the daytime histogram, including only data between one hour after sunrise and one hour before sunset, and the nighttime histogram, including data from other times. The hour bias is introduced because the sun must reach a sufficient angle in the sky before convection begins to overcome atmospheric stability.

Figure 5 shows the wind speed shear histograms for the BAO test site. The vertical dotted line corresponds to a fairly extreme shear value of 0.63, where the upper blade-tip wind speed is twice that of the lower blade tip. For this dataset, shear in excess of 0.4 is shown to occur at night, because the daytime histogram is approximately zero, and nighttime histogram is approximately equal to the daytime histogram.

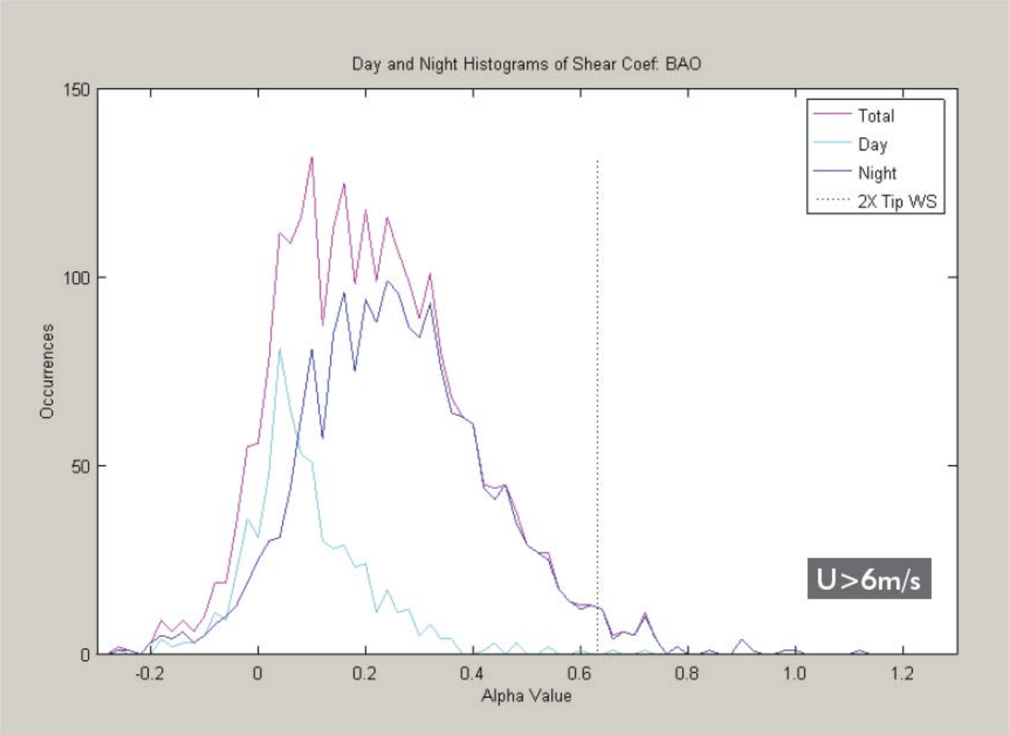

Figure 5: Histogram of BAO Shear Exponent with Day/Night Decomposition.

The wind veer histogram of the BAO site is shown in Figure 6. Here again, extreme shear is seen to occur mostly at night, as the daytime histogram is approximately zero for veer values in excess of +/- 15 degrees. It is interesting to note that the veer histogram tails are right sided, with veer more often having increasing angle with increasing height. This phenomenon is related to the Ekman spiral, where friction and the Coriolis force vector in the Northern Hemisphere more often cause a positive shift of wind direction with increasing height.

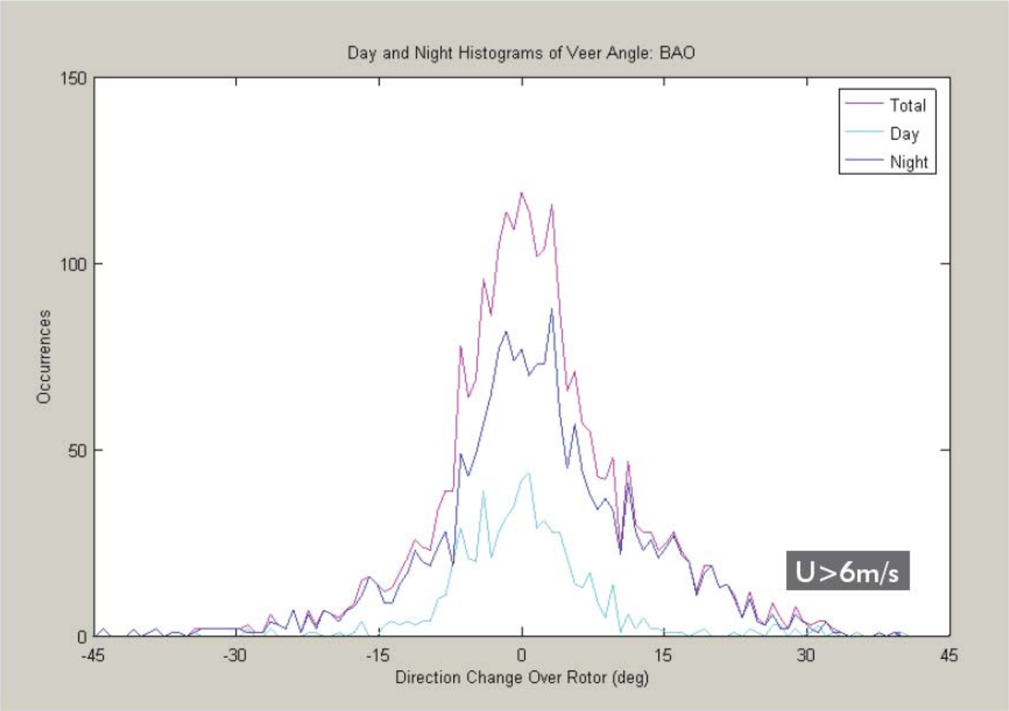

Figure 6: Histogram of BAO Veer with Day/Night Decomposition.

Figures 7 and 8 show the shear and veer histograms for the Cape Cod site, which is a cranberry bog about a mile downwind of an open ocean bay. The wind speed shear at this site is often very extreme at night, with values exceeding 1.0, where the upper blade-tip wind speed is three times that of the lower blade tip. Veer at this site is less severe than at the other sites, but the histograms are quite noticeably right-sided. The extreme values on the right side of the distribution show equal daytime/nighttime occurrence, while those on the left are daytime only. Presumably this is because the summer daytime storm activity can cause strong veer during the day, while the nighttime atmospheric forces follow the positive direction predicted by the Ekman spiral.

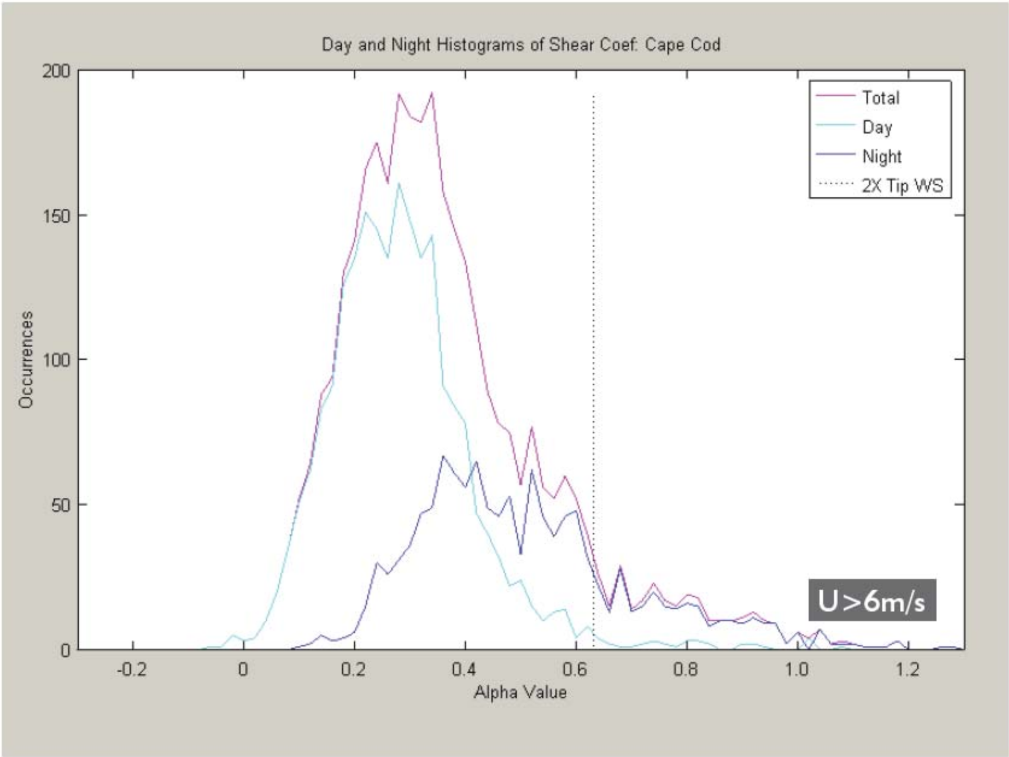

Figure 7: Histogram of Cape Cod Shear Exponent with Day/Night Decomposition.

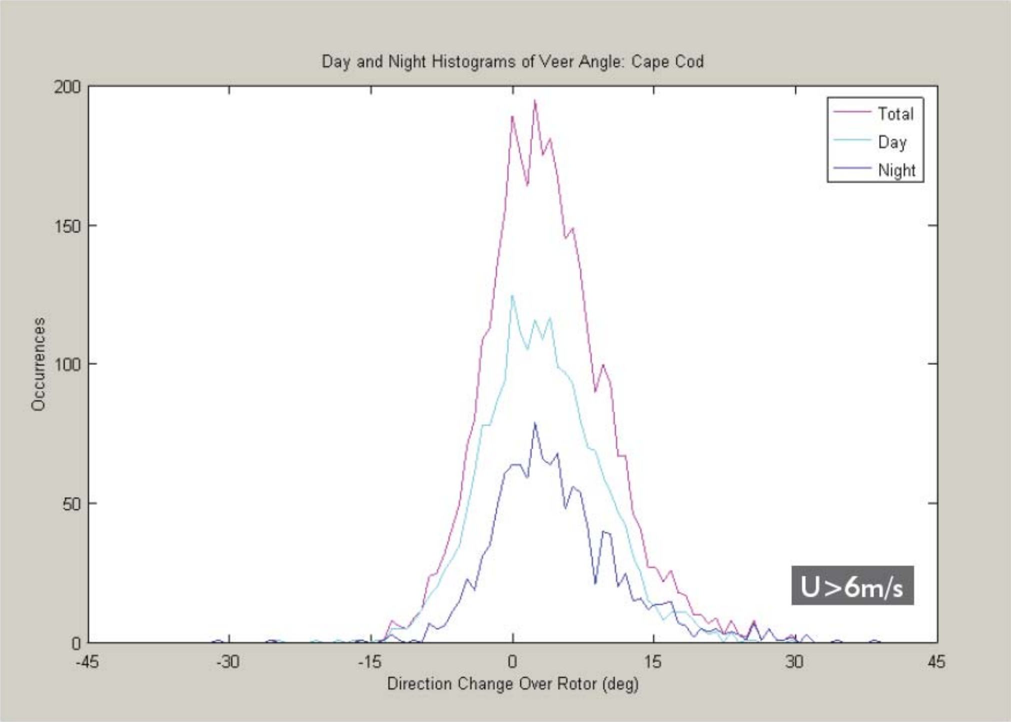

Figure 8: Histogram of Cape Cod Veer with Day/Night Decomposition.

The last example site is an operating windfarm in Texas. Figure 9 shows the wind speed shear, which is usually quite small during the day, but spans a large range at night. It is worth noting that this three-month dataset is from winter months, and thus contains more nighttime samples than daytime samples. The veer data for this site, shown in Figure 10, are quite extreme, almost entirely at night, and right-sided.

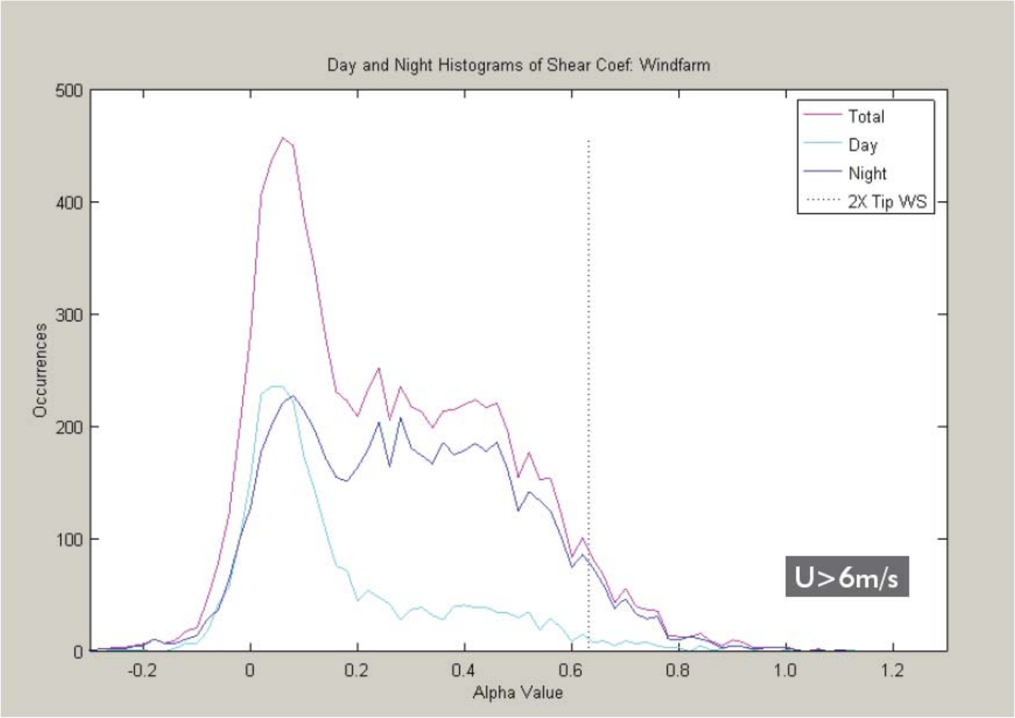

Figure 9: Histogram of Windfarm Shear Exponent with Day/Night Decomposition.

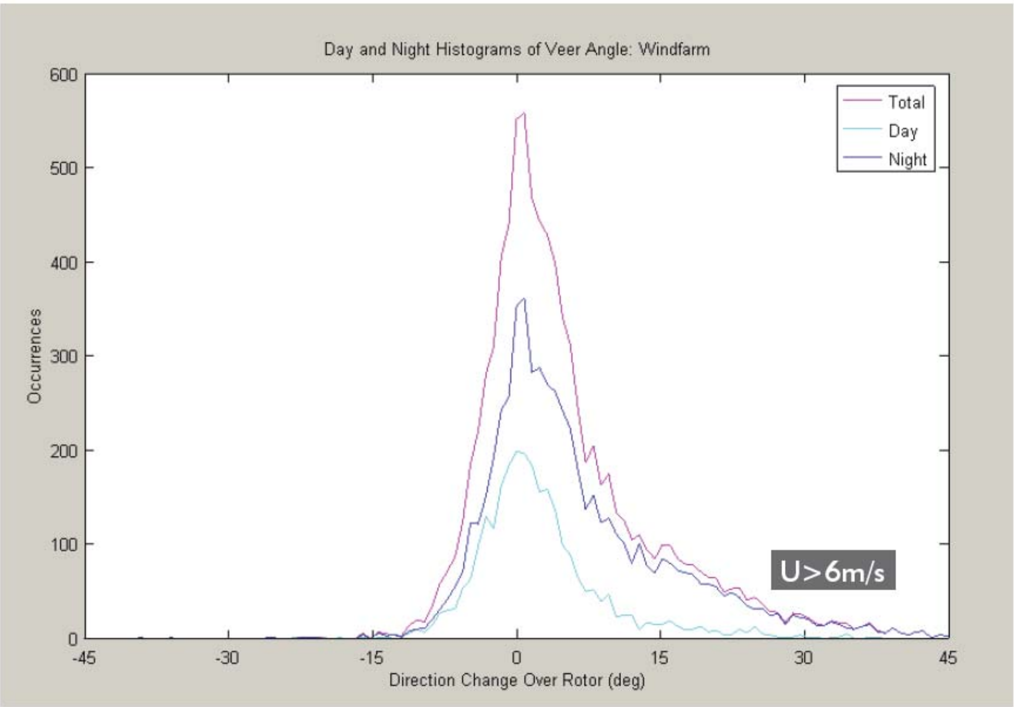

Figure 10: Histogram of Windfarm Veer with Day/Night Decomposition.

The day/night histograms from the three different sites shown in Figures 5-10 have similar character, but a detailed site comparison is difficult without plotting on a common axis. One very effective way to compare sites is to plot the frequency of exceedance distribution. Like an inverse cumulative distribution, the frequency of exceedance indicates the percentage of time that the sheer was in excess of a value. Because the data were filtered to remove periods with low wind speed, the percentages indicated are with respect to turbine operational time. By plotting the frequency of exceedance of wind speed and direction shear for all three sites, the site-to-site differences are quite apparent.

Figure 11 shows the frequency of exceedance of wind speed shear for the three example sites. From the chart, it is evident that swept area shear in excess of 2:1 ($\alpha = 0.63$) occurs almost 10% of turbine operational time at the Cape Cod site, while only 2% at the BAO site.

Figure 12 shows the frequency of exceedance of the absolute value of wind direction shear for the three example sites. From the chart, it is evident that swept area veer in excess of 20 degrees occurs almost 10% of turbine operational time at two of the sites, but only occurs 2% of the time at the Cape Cod site. Thus the site with the highest speed shear is seen to have the lowest directional shear.

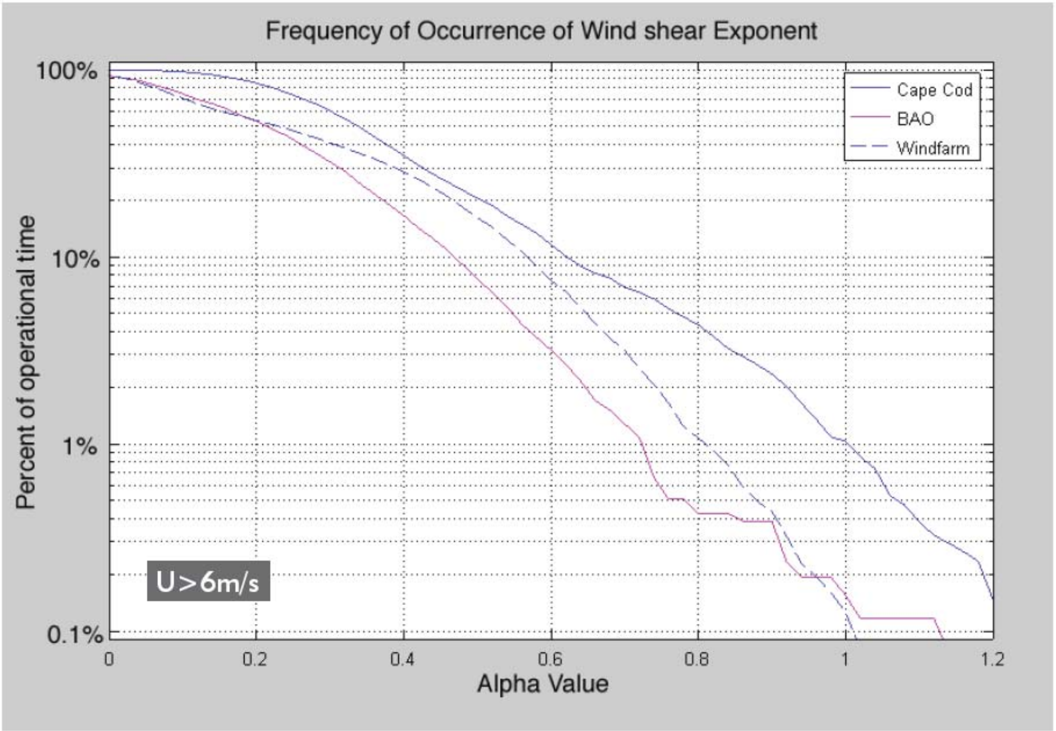

Figure 11: Frequency of Exceedance of Shear Exponent at Three Example Sites.

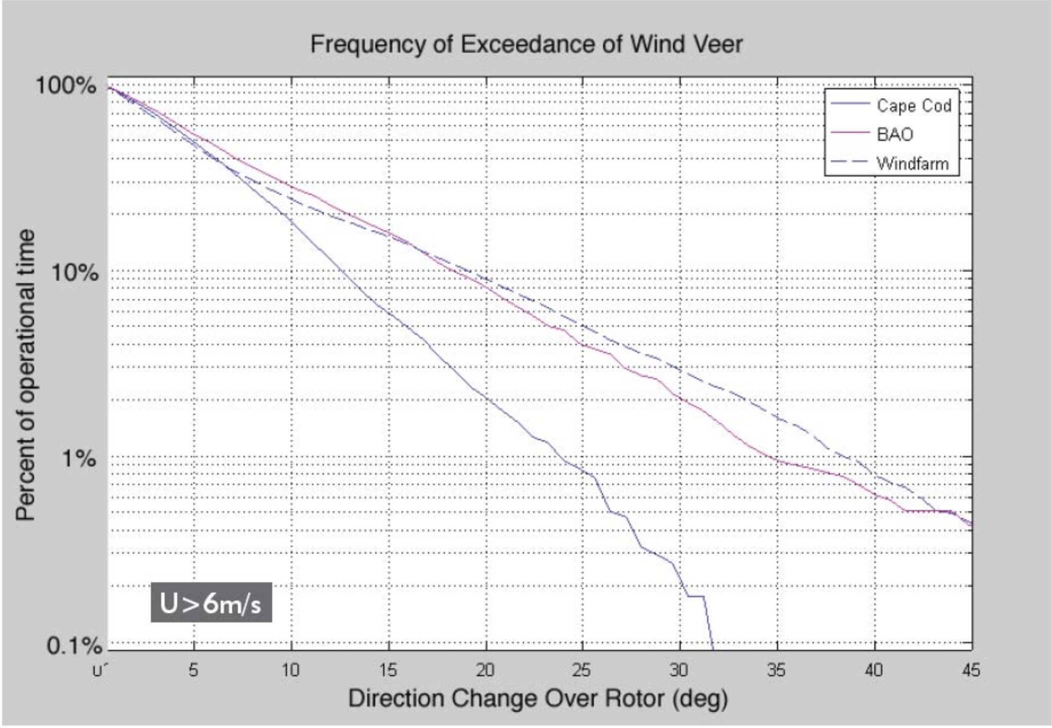

Figure 12: Frequency of Exceedance of Veer at Three Example Sites.

CONCLUSIONS

Short-term wind speed and direction shear values were computed based on 10-minute average SoDAR measurements. The results indicate the presence of extreme shear at all example sites, even though the data were filtered to remove light wind periods, when the hub height wind speed was below a conservative, 6 m/s cut-in threshold. Extreme shear is shown to occur mostly at night, presumably because the more stable atmosphere overnight does little to relieve the atmospheric force gradients that cause shear. Lastly, the frequency of occurrence of shear extremes is shown using a log-scale frequency of exceedance plot, and the distributions are observed to differ substantially from site to site.

More work is needed to assess the importance of measuring short-term wind shear values. As wind turbine technology advances to include individual blade pitch control, the extent to which differing winds across the rotor cause performance and reliability problems may change. At the current time, however, extreme wind shear is thought to contribute to performance degradation and operational down time, so site statistics beyond simple, extrapolated, seasonal averages should be evaluated, and SoDAR measurement technology is well suited to provide the data.

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