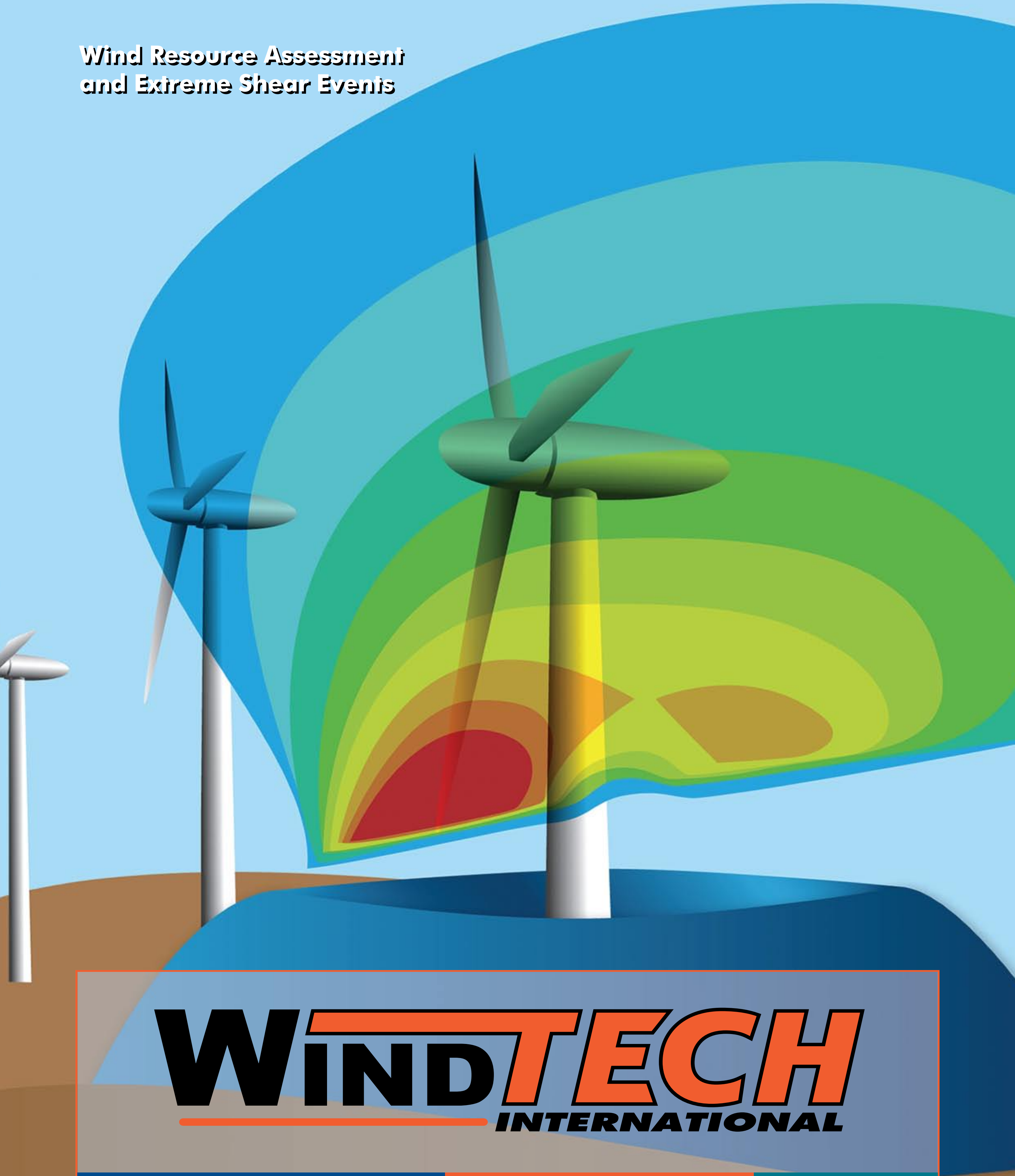
Wind Resource Assessment and Extreme Shear Events



WINDTECH INTERNATIONAL

July/August 2009 | Volume 5 | No. 5

Siteur Publications

Remote sensing technology, such as Sonic Detection and Ranging (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. However, obtaining a large number of values for wind speed and directional shear over an entire measurement campaign can result in an unwieldy amount of data and make it difficult to draw conclusions. This article describes a simple technique for plotting the frequency of shear occurrence in order to highlight site-to-site differences that would affect wind turbine performance and reliability.

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Wind Resource Assessment and Extreme Shear Events

Characterising Wind Speed and Directional Shear with sodar Data

The main objective of wind resource assessment is to identify sites with sufficient winds for power generation. When a candidate site is chosen, the wind data for the site are analysed further to see whether the wind conditions are suitable for wind turbine operation. When the only available data are from met masts that do not reach the hub height of a typical wind turbine, wind shear values must be extrapolated from a small set of readings. Often only a single, seasonal, average wind speed shear coefficient is obtained for a site. Wind directional shear is often ignored altogether because many met towers only have wind direction vanes at a single height. The seasonal averages mask the presence of wind shear 'events' – short periods of extreme wind speed and directional shear – that can have a large impact on both resource suitability and turbine performance.

Sonic Detection and Ranging (sodar) is a remote sensing technology that can be used to measure wind speed and direction at several heights across the swept area of a typical wind turbine rotor. For this research, we used Second Wind Inc.'s, Triton Sonic Wind Profiler, which measures 10-minute averages of wind speed and direction at six different heights spanning a typical rotor swept area. As illustrated in Figure 1, the 10-minute averages can show wind speed and directional shear 'events' that would not show up in the seasonal averages.

Over a wind measurement campaign, the large number of 10-minute values for wind speed and directional shear results in a large quantity of data. This article examines wind shear data collected over a period of time in three different sites and develops a simple technique for plotting shear events so that meaningful conclusions can be drawn about their presence and their effect on wind turbine performance and reliability.

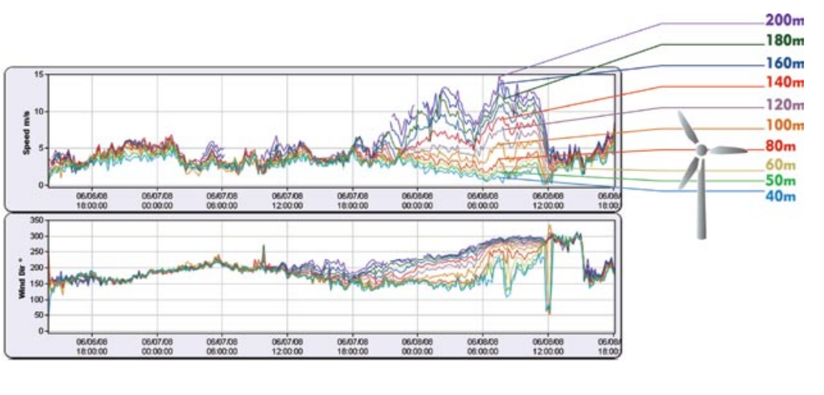

Figure 1. Example Triton wind speed and direction measurements showing extreme shear

Validating the Triton Data

To validate the Triton data, we conducted a three-month correlation study. The wind speeds as measured by the Triton were compared to wind speed data collected from an adjacent tower and correlation coefficients were determined.

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 ±1.5m/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 minimum 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.

Figure 2 shows scatterplots of Triton and anemometer wind speeds measured at 50, 100 and 150m at the Boulder Atmospheric Observatory from 1 September to 30 November 2008. The correlation coefficients were found to be very high at 0.985, 0.985 and 0.973 at 50, 100 and 150m 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

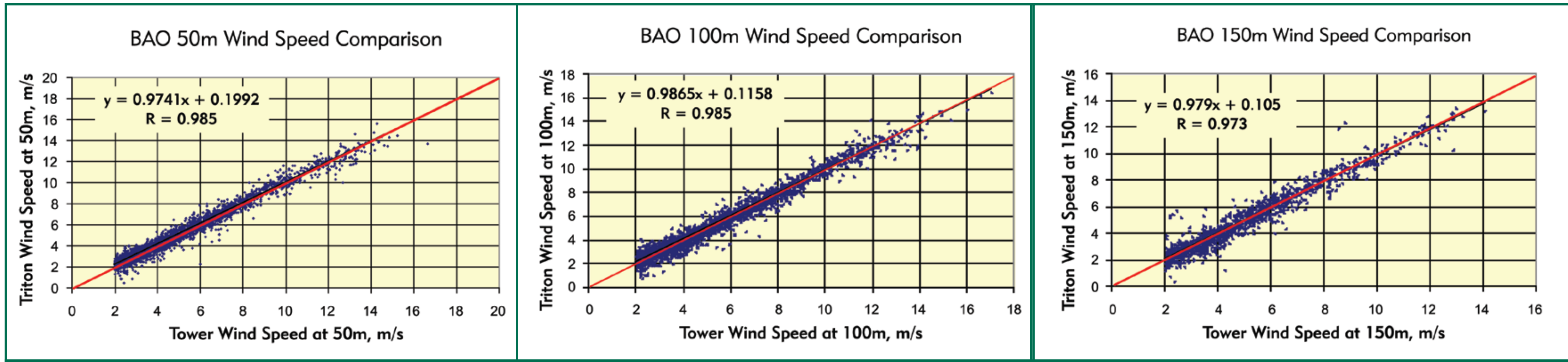

Figure 2. Scatterplots showing correlations between tower and Triton measurements

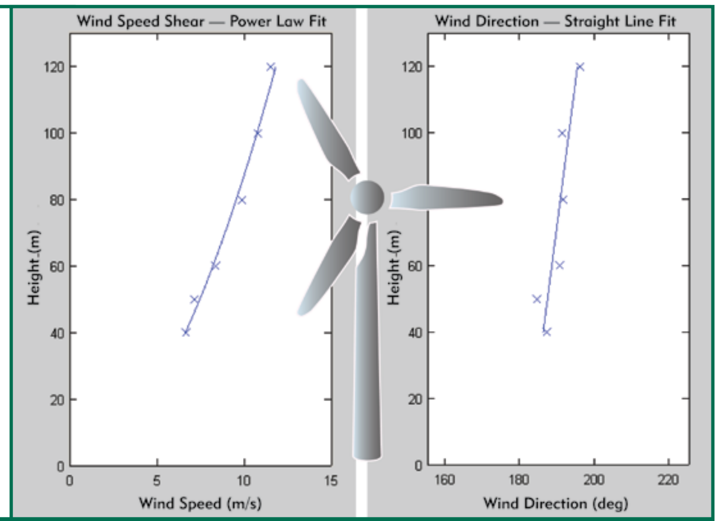

Figure 3. Sample wind measurements showing power-law exponent fit (left) and change of direction with height (right)

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 150m, the difference in average wind speed (Triton wind speed – tower wind speed) was found to be 1.7, 0.8 and 0.0% respectively.

Computing Short-Term Average Shear Values

To compute short-term average shear values, we used a set of 10-minute average wind speed and direction measurements from heights spanning a typical, 80-metre hub height wind turbine rotor: 40, 50, 60, 80, 100 and 120m.

In computing the wind speed shear value for each 10-minute interval, the set of measurements is fitted 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:

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

Finding an Aggregate Shear Exponent

To find an aggregate shear exponent, or best fit α, given a set of measured wind speeds, Ui, taken at heights Hi, 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:

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

When 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 directional 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 fitted to the points { H_i, D_i }, where Di is the measured wind direction from heights Hi, 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 metre 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 study, the total wind direction change, in degrees, over an 80m rotor, is used as a measure of wind directional shear.

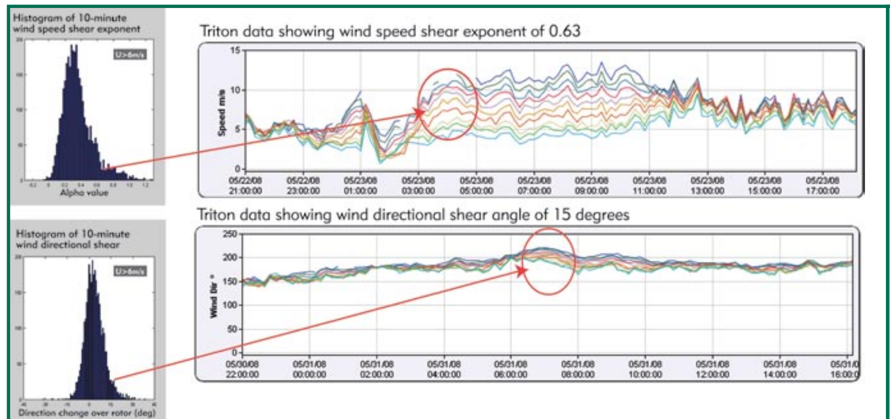

Figure 4. Histograms for wind speed shear exponent (top) and wind directional shear (bottom) with matching time-series data

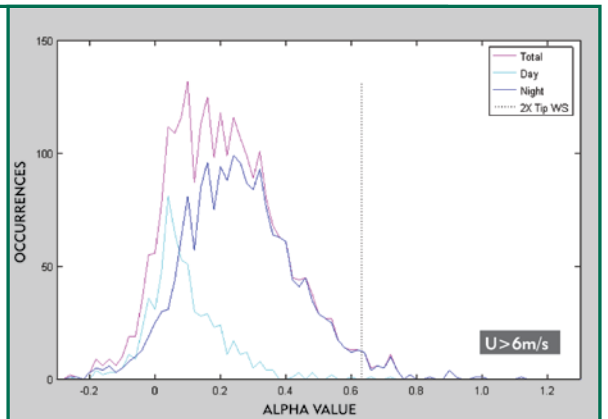

Figure 5. Histogram of BAO shear exponent with day/night decomposition

Showing the Shear Extremes, or Wind Shear Events

As wind shear at low wind speeds has little or no effect on turbine performance or resource suitability, all 10-minute data with hub height wind speed below 6m/s were removed from the dataset. In all likelihood, the remaining wind speed shear values occurred well within the operating range of most wind turbines. Histograms are shown for wind speed shear and wind directional shear in Figure 4. Also shown are the time-series sodar data from times of fairly extreme, yet frequently occurring, wind speed and directional shear. The speed shear time-series example has a tip-to-tip wind speed ratio of 2:1 (α = 0.63). The wind directional shear 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 the ones most often masked in resource assessment, because shear coefficients are derived from long-term data averages.

Most Extreme Shear Events Occur at Night

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 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 night-time histogram is approximately equal to the daytime histogram.

Site	Period	Location	Description
BAO	Sept–Nov 2008	Boulder Atmospheric Observatory	Nearby 300m tower
Cape Cod	May–July 2008	Massachusetts	Coastal cranberry bog
Wind farm	Nov–Jan 2008/09	Texas	Operating wind farm

Table 1. Sites and time periods studied

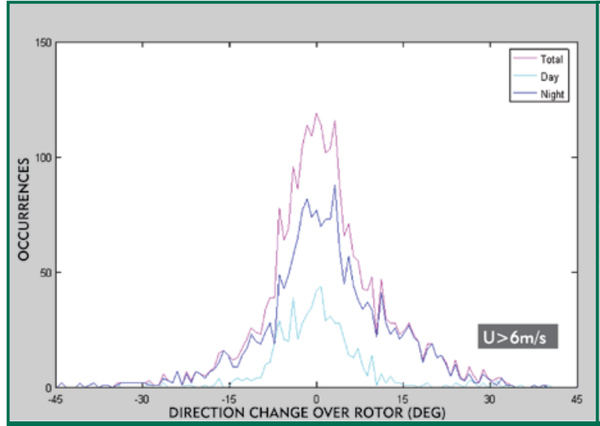

Figure 6. Histogram of BAO wind directional shear with day/night decomposition

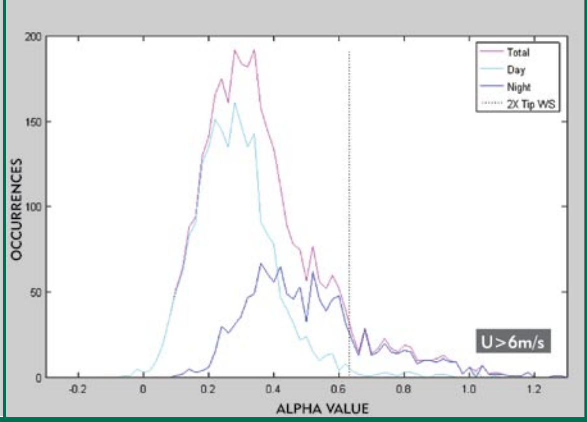

Figure 7. Histogram of Cape Cod shear exponent with day/night decomposition

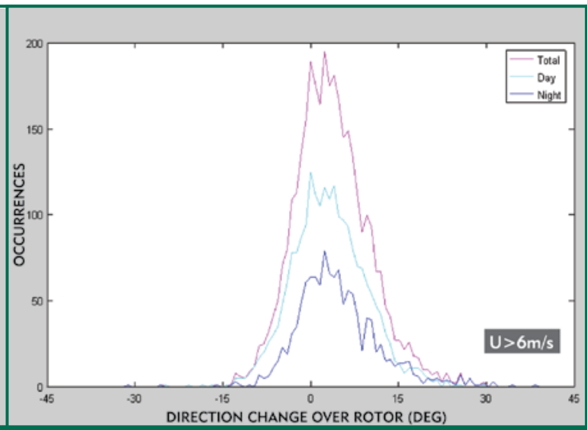

Figure 8. Histogram of Cape Cod wind directional shear with day/night decomposition

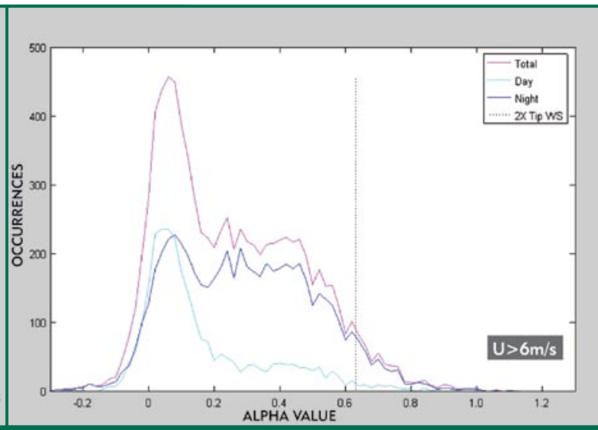

Figure 9. Histogram of wind farm shear exponent with day/night decomposition

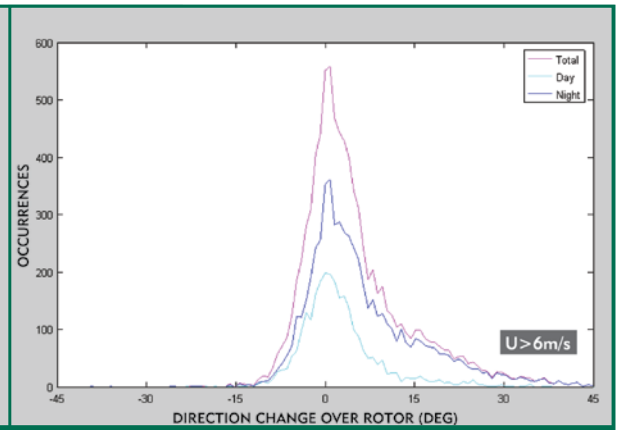

Figure 10. Histogram of wind farm wind directional shear with day/night decomposition

The wind directional shear histogram of the BAO site is shown in Figure 6. Here again, extreme wind speed shear happens mostly at night, as the daytime histogram is approximately zero for wind directional shear values in excess of ±15 degrees. It is interesting to note that the wind directional shear histogram tails are right sided, with directional shear 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.

Figures 7 and 8 show the shear 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. Wind directional shear 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/night-time occurrence, while those on the left are daytime only. Presumably this is because the summer daytime storm activity can cause strong directional shear during the day, while the night-time atmospheric forces follow the positive direction predicted by the Ekman spiral.

The last example site is an operating wind farm 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 night-time samples than daytime samples. The wind directional shear data for this site, shown in Figure 10, are quite extreme, almost entirely at night, and right-sided.

Making a Detailed Site Comparison

The day/night histograms from the three different sites shown in Figures 5–10 have similar characteristics, 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 shear 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 directional shear for all three sites, we can make the site-to-site differences 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 directional shear for the three example sites. From the chart, it is evident that swept area directional shear 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.

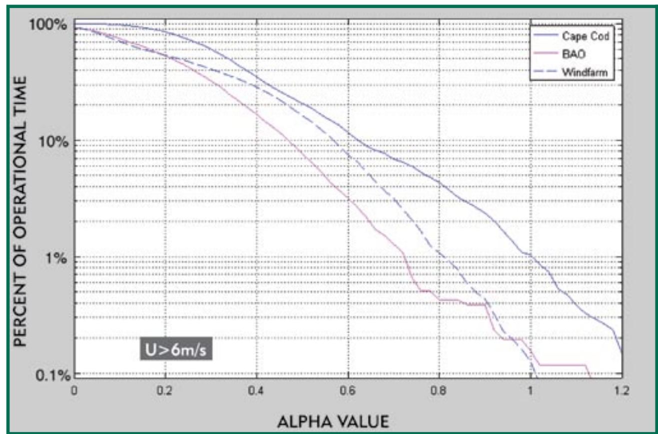

Figure 11. Frequency of exceedance of wind speed shear exponent at three example sites

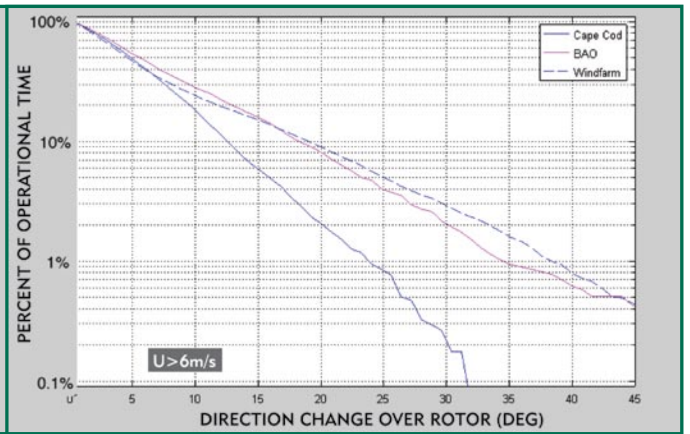

Figure 12. Frequency of exceedance of wind directional shear at three example sites

Conclusions

All the example sites were subject to extreme shear events, even though the data were filtered to remove light wind periods, when the hub height wind speed was below a conservative 6m/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. The distributions 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 downtime. Site statistics beyond simple, extrapolated, seasonal averages should be evaluated, and sodar measurement technology is well suited to provide the data. ■

Further Reading

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Biography of the Authors

Niels LaWhite received his B.S. degree in Electrical Engineering from the Massachusetts Institute of Technology in 1987 and returned for graduate work in 1992, where he specialised in signal processing and power systems. He has been working in the wind industry since 1987. LaWhite consulted in the wind industry for more than a decade, and designed several Second Wind products, including turbine controllers, data loggers, and wind SCADA systems. He joined Second Wind as a principal researcher on the Triton sodar project in 2005.

Liz Walls is a research scientist at Second Wind. She joined the company in September 2007 upon completion of her master's degree in mechanical engineering from the University of Massachusetts Amherst's Renewable Energy Research Laboratory. While at UMass-Amherst, she researched sodar technology and has brought this expertise to Second Wind's research and development team.

Kenneth E. Cohn received his B.S.M.S. in Metallurgy from the Carnegie Institute of Technology. In 1980 Cohn co-founded Second Wind Inc. Cohn co-developed the AL-2000 data logger series. From 1983 to 1985 Cohn worked as a wind industry consultant in several California-based wind energy companies. His responsibilities included evaluating wind turbines, designing and laying out wind farms, and supervising wind feasibility studies. In 1985 Cohn returned to Second Wind. He was a project leader in developing two SCADA systems, the Second Wind System and the Advanced Distributed Monitoring System. Cohn was also a lead designer of Second Wind's Nomad 2 data logger, C-3 anemometer and PV-1 wind vane. Cohn has participated on the American Wind Energy Association's siting standards and other industry committees and has presented many papers at AWEA conferences.

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