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Quantification of the Impact of NRG Sensor Drag on Yield Assessments

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EXECUTIVE SUMMARY

Accurate monitoring of wind speed data is essential to reliable wind resource assessments. Anemometers manufactured by NRG Systems Incorporated (NRG) are widely used in the wind power industry. On May 22, 2008, NRG released Technical Support Bulletin 008 acknowledging a manufacturing defect in NRG #40C and NRG #40 anemometers that causes the effected sensors to under-record wind speeds. GENIVAR identified the problem independently in early 2007 and termed the behavior "sensor drag".

GENIVAR compiled numerous sources of field data to characterize sensor drag and quantify its impact on yield estimates. Given that drag occurs intermittently; that drag frequency and magnitude of error varies; and that extrapolated wind speed errors depend on the heights of the affected sensors, a wide range of yield calculation errors are possible. GENIVAR has also determined that sensor drag impact on yield depends on site-specific wind speed distributions and data filtering methods. The impact of sensor drag, therefore, must be assessed for specific wind power project sites. In the case studies performed by GENIVAR, it was found that sensor drag can cause P50 yield values to be underestimated by as much as 7.5% and overestimated as much as 3.3%. It was also found that there is additional uncertainty due to sensor drag causing the P90 yield values to be underestimated by as much as 3.9% and overestimated by as much as 1.4% relative to the reference P90.

INTRODUCTION

Sensor Drag Background

GENIVAR Consultants LP (GENIVAR) performs wind resource assessments for wind power developers on a global scale. As part of its services, the company manages client wind monitoring data and performs regular quality assurance checks aided by its online data management software, WindServer™. GENIVAR, therefore, is in a unique position to analyze large amounts of field data. GENIVAR identified under-recorded wind speeds by the NRG #40C anemometers in early 2007; a behavior which GENIVAR termed "sensor drag".

Prompted by these findings, NRG launched an investigation and released Technical Support Bulletin 008 on May 22, 2008. In this bulletin, NRG initially associated sensor drag with regular wear and excess friction due to epoxy on the bearing of the sensor. Changes to the sensor design were made, but the problem persisted. More recent wind tunnel tests performed by NRG have linked the cause of the problem to sensor vibration. NRG observed that sensors are induced sporadically into a vibratory mode, typically causing them to under-read instantaneous wind speeds by 0.4 to 0.6 m/s. In addition, NRG observed higher occurrences of the vibratory mode between wind speeds of 4 and 10 m/s, and that the sensors were more likely to enter this mode during periods of decreasing wind speed.

Detection and Quantification

Under the premise that anemometers mounted at the same height will record similar wind speeds, redundant sensors are required for effective detection of sensor drag. Flow distortion around the met tower, nominal sensor error, and variability in wind speed and wind direction all contribute to discrepancies in normally-functioning redundant anemometers. GENIVAR, however, has observed that discrepancies due to sensor drag are larger in magnitude and different in character than the above mentioned sources of error.

GENIVAR primarily employs Tower Shadow plots generated by WindServer to detect sensor drag. This plot gives a polar representation of wind speed difference (ΔWS) vs. wind direction (WD), where divergence from zero ΔWS can indicate sensor drag. Figure 1 shows a sample Tower Shadow plot and the corresponding ΔWS histogram for a sample dataset. Both figures demonstrate a bimodal distribution of the wind speed difference typical of vibratory mode. In this example one sensor is recording correct wind speeds and the other is periodically in vibratory mode, resulting in a large concentration of points with a wind speed difference of -0.3 to -0.4 m/s.

The frequency of occurrence and mean wind speed error of drag vary greatly between individual sensors and over the life of a single sensor. It is common for vibratory mode to occur for a portion of a 10 minute averaging interval, resulting in a range in magnitude of wind speed errors. For these reasons, the error due to sensor drag will vary.

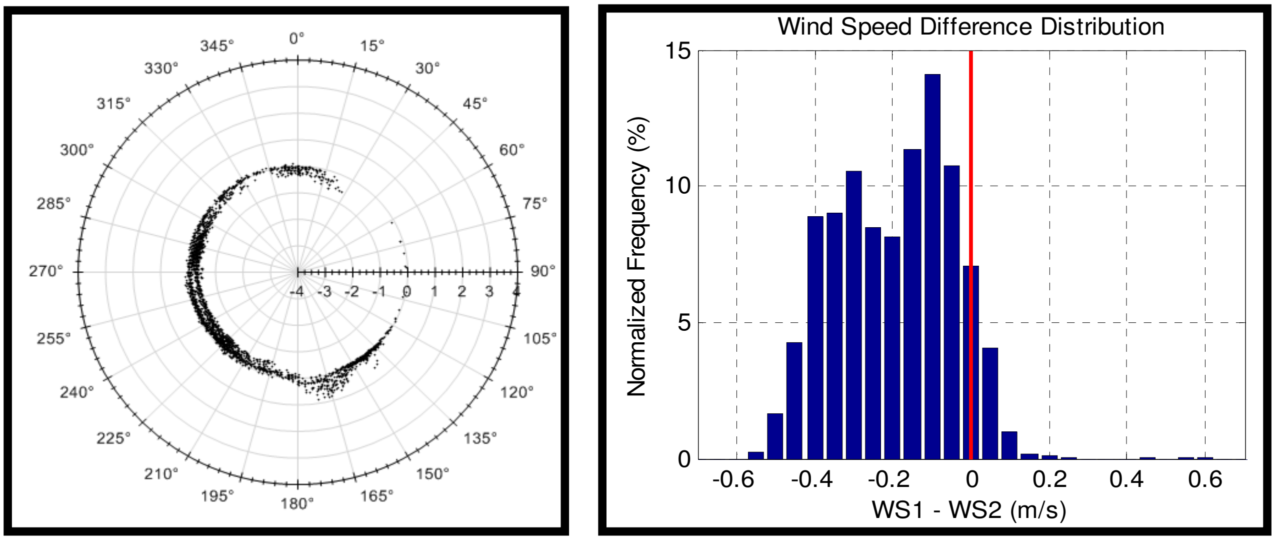

Figure 1: WindServer™ Tower Shadow Plot (left) and Corresponding ∆WS Histogram (right). Single Sensor Vibratory Mode is Present.

METHODS

Background

GENIVAR's approach to assessing the impact of drag involved characterizing drag and applying it to a reference dataset. The reference data set had one year of data from two measurement heights, each height with redundant NRG #40C anemometers that demonstrated no sensor drag over the whole year. Drag characteristics were then applied to the reference data to emulate several drag scenarios. A yield estimate was then performed for the reference dataset and the emulated drag datasets to assess the impact of drag.

Characterization of Sensor Drag

Sensor drag was characterized by analyzing data from 33 sample pairs of anemometers. In each case one sensor was functioning properly and one was dragging. All data was taken from sensor pairs mounted at the top of the monitoring tower to minimize biases caused by tower flow distortion. Each of the 33 samples had one-month data records.

A distribution of wind speed error representative of the average of the 33 cases was generated and is shown in Figure 3 of the *Results* section. To isolate sensor drag from typical sensor error, it was assumed that the distribution of wind speed differences recorded by properly functioning redundant anemometers is normally distributed and centered on zero. This symmetrical distribution was subtracted from the distribution generated from the dragging data.

This procedure was performed for the combined sample of sensor pairs and drag was then characterized by the relative frequency, mean, and standard deviation of the isolated drag error distributions. The data representative of sensor drag was binned by wind speed in order to quantify the frequency and severity of drag in the following wind speed ranges: 3.5 to 6 m/s, 6 to 8 m/s, 8 to 12 m/s, and 12 m/s to 25 m/s.

Emulation of Dragging Sensor Characteristics

A range of sensor drag characteristics was observed within the sample data set of 33 sensor pairs. Characteristics of the isolated drag error distributions were determined including relative frequency, mean, and standard deviation. To emulate typical drag severity, the average isolated drag error distribution was applied to the reference data set with the average relative frequency. In addition, maximum drag severity was emulated by applying the average isolated drag error distribution to the reference dataset with 100% relative frequency.

Given that the reference data set has two monitoring heights, each with two sensors, there are several combinations for individual sensors to be affected by drag. Shear characterization and extrapolated wind speeds are affected differently depending on which sensors exhibit drag characteristics. The combinations are summarized in Table 2 of the *Results* section.

Calculation of Impact on Yield

For the reference and emulated drag datasets, wind speeds at the measurement heights were extrapolated based on the power law. It is assumed that wind speed increases with height and that the ratio of wind speed varies exponentially with the ratio of their heights according to equation (1).

$$\frac{V_2}{V_1} = \left(\frac{H_2}{H_1}\right)^{\alpha} \qquad (1)$$

Where:

- H_1 is the first height
- H_2 is the second height
- V_1 is the wind speed at the first height
- V_2 is the wind speed at the second height
- α is the wind shear exponent

The average shear exponents are calculated from the wind speeds at the two measurement heights for a set of 6 wind direction bins, 12 time-of-day bins, and 6 season bins. The shear exponents are applied to top level wind speed measurements to obtain wind speeds at the extrapolation height. As shown in Figure 2, the extrapolated hub height wind speed will be overestimated if only lower level sensors are affected by drag, and underestimated if higher level sensors are affected. In this example, sensor heights of 45 m and 60 m and an extrapolation height of 80 m are used. The true wind speeds at the 45 and 60 m height were assumed to be 6.6 and 7.0 m/s respectively. When only the 45 m measurement under-speeds by 0.2 m/s, the 80 m wind speed is over-estimated by 0.3 m/s. When only the 60 m measurement under-speeds by 0.2 m/s, the 80 m wind speed is underestimated by 0.4 m/s.

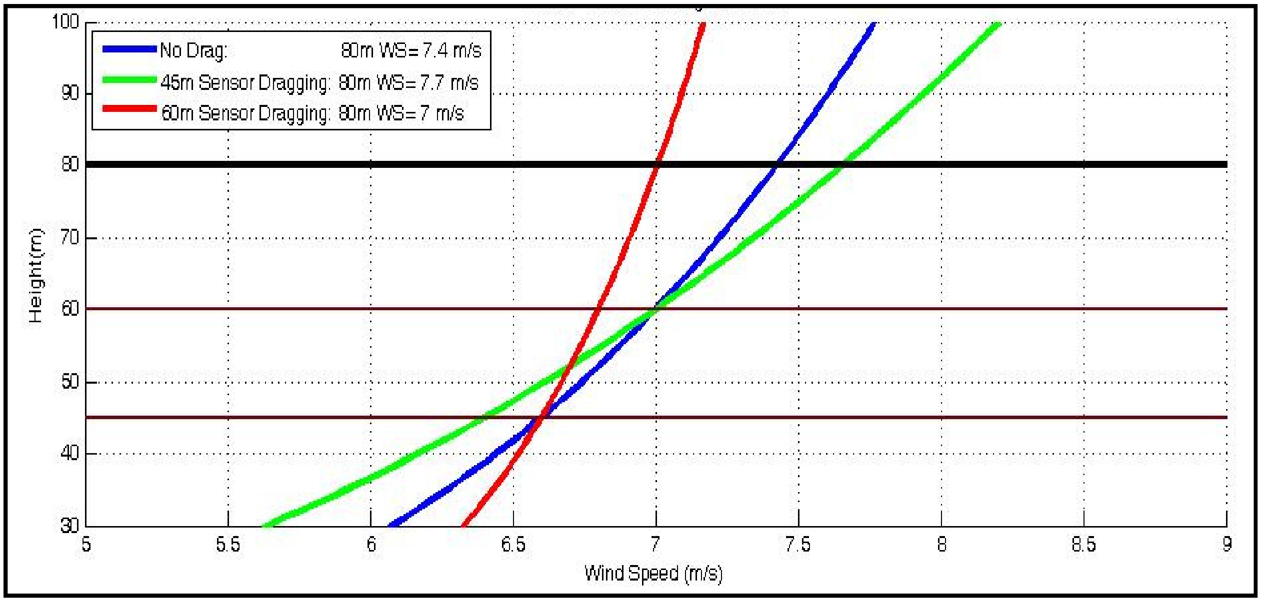

Figure 2: The Effects of Sensor Drag on Extrapolated Wind Speed Calculations

It was also assumed that the method of wind speed quality assurance would affect the impact of sensor drag on yield estimates. To assess this, emulated drag data was subjected to two different quality assurance methods. The first method averaged every record of the redundant wind speeds. The second method was based on WindServer quality assurance algorithms.

A normalized turbine performance curve was generated for this study based on the performance curves of four different turbine technologies. Hub height wind speeds were applied to this curve to calculate yield. A reference yield was generated using the non-dragging data. Yield was then calculated for each emulated drag scenario.

Calculation of Impact on P90

For each drag scenario, there is a range of possible yield errors attributed to the range of drag severity. This contributes to the overall uncertainty of a yield calculation. To assess the impact of drag on yield confidence levels, a reference P50 yield was assumed for the non-dragging reference data and 8% standard uncertainty from all other sources. For the additional source of uncertainty from the presence of drag, the P90 was calculated using equations (2) and (3). The probability of drag was assumed to have a rectangular distribution.

$$P90_{drag} = \left[P50_{reference} + \varepsilon_{average\ drag}\right] + Z_{P90} \cdot \sqrt{\sigma_{typical}^2 + \sigma_{drag}^2} \qquad (2)$$

and,

$$\sigma_{drag} = \frac{\varepsilon_{maximum\ drag} - \varepsilon_{average\ drag}}{\sqrt{3}} \qquad (3)$$

where:

- $P90_{drag}$ is the 90% probability of exceedence yield including additional uncertainty associated with drag
- $P50_{reference}$ is the 50% probability of exceedence yield of the reference data
- $\varepsilon_{average\ drag}$ is the error in yield due to average emulated drag
- Z_{P90} is the z-score for 90% probability of exceedence of a normal distribution (constant of -1.28)

- $\sigma_{typical}$ is the standard uncertainty for all sources other than drag (assumed 8%)
- σ_{drag} is the additional standard uncertainty associated with the range of errors due to drag, calculated based on uniform distribution of yield errors due to drag
- $\varepsilon_{maximum\ drag}$ is the error in yield due to maximum emulated drag

RESULTS

Characteristics of Sensor Drag

Table 1 summarizes the drag characteristics for each wind speed bin. It was found that drag occurred most frequently for the 6-8 m/s bin. The mean of the isolated drag error distribution was found to be consistent for all wind speed bins and the standard deviations decreased as wind speed increased.

Table 1: Relative frequency, Mean, and Standard Deviation of Isolated Drag Error Distributions for Each Wind Speed Bin

Wind Speed Bin:	3.5-6 m/s	6-8 m/s	8-12 m/s	12 m/s +
Relative Frequency of drag (%)	26.3	41.8	34.6	9.8
Mean of drag error distribution (m/s)	0.27	0.29	0.28	0.33
Standard deviation of drag error distribution (m/s)	0.14	0.14	0.12	0.10

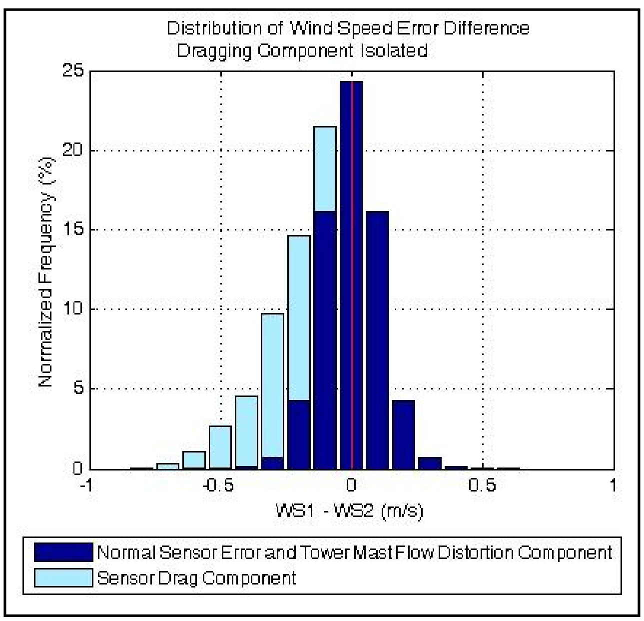

Figure 3: ΔWS Histogram for Average Sensor Drag Based on a Sample Size of 33 Anemometer Pairs

The wind speed difference histogram for the average sensor drag scenario and for all wind speeds is illustrated in Figure 3. Based on the assumptions stated in the *Methods* section, the typical wind speed errors are shown in dark blue and the sensor drag error is shown in light blue. There is a high frequency of wind speed differences of 0.2 and 0.3 m/s and a large overlap between error due to sensor drag and typical errors. For this reason sensor drag cannot categorically be identified. WindServer data filtering will mitigate the effects of sensor drag, but not eliminate them entirely.

Calculation of Impact on Yield

Using a normalized power curve, the yield was calculated for the reference dataset and several emulated drag scenarios. Each yield calculation was performed with simple wind speed averaging of redundant anemometers and WindServer quality assurance (QA). Table 2 summarizes the yield errors calculated based on these different sensor drag configurations. It can be seen that the maximum overestimate of yield for the average sensor drag scenario occurs when both lower level sensors are dragging, and the maximum underestimate occurs when both top level sensors are dragging.

It should be noted that for simple wind speed averaging of redundant anemometers, yield calculations tend to be lower than those based on WindServer quality assurance. This is evident when comparing the reference yield to the yield calculated for no sensor drag with the wind speed averaging technique. This underestimation is due to the lack of correction of tower shadow and other sensor errors. Table 2 illustrates that WindServer quality assurance reduces the yield errors in all drag scenarios. This is most apparent in the cases of single sensor drag at one or both levels, where WindServer quality assurance reduces the yield error by as much as 3.3%.

Table 2: Errors in Yield Estimates as a Percent Relative to the Reference Yield

		No Drag at Bottom		Single Drag at bottom		Dual Drag at Bottom	
		Wind Speed Averaging	WindServer QA	Wind Speed Averaging	WindServer QA	Wind Speed Averaging	WindServer QA
No Drag at Top	Max	-0.5%	REFERENCE	1.5%	0.1%	3.3%	2.8%
	Avg			0.7%	0.0%	1.4%	0.7%
	Min			-0.5%	0.0%	-0.5%	0.0%
Single Drag at Top	Max	-0.5%	0.0%	1.5%	0.1%	3.3%	2.8%
	Avg	-1.8%	-0.1%	-0.6%	-0.1%	0.1%	0.6%
	Min	-3.6%	-0.3%	-3.6%	-0.3%	-3.6%	-0.3%
Dual Drag at Top	Max	-0.5%	0.0%	1.5%	0.1%	3.3%	2.8%
	Avg	-3.3%	-1.2%	-2.2%	-1.2%	-1.4%	-0.5%
	Min	-7.5%	-5.9%	-7.5%	-5.9%	-7.5%	-5.9%

Calculation of Impact on P90

The range of yield error due to the presence of drag was identified as a source of uncertainty in yield estimates. The impact on 90% probability of exceedence yield estimates was assessed as described in the *Methods* section. The resulting P90 values for all drag scenarios are summarized in Table 3.

Table 3: 90% Probability of Exceedence Yield Estimates as a Percent of Reference P50 Yield Assuming 8% Standard Uncertainty from All Sources Other Than Drag

	No Drag at Bottom		Single Drag at bottom		Dual Drag at Bottom	
	Wind Speed Averaging	WindServer QA	Wind Speed Averaging	WindServer QA	Wind Speed Averaging	WindServer QA
No Drag at Top	89.3%	89.8% REFERENCE P90	90.4%	89.8%	91.1%	90.3%
Single Drag at Top	87.9%	89.7%	89.0%	89.7%	89.6%	90.2%
Dual Drag at Top	86.3%	88.5%	87.2%	88.5%	87.8%	89.0%

CONCLUSIONS

Sensor drag can be characterized using data from redundant anemometer pairs where one sensor is dragging. Although there are discrepancies between properly functioning redundant anemometers due to tower flow distortion, nominal sensor error, and temporal variability of wind speed and direction; these discrepancies can reasonably be isolated from those caused by sensor drag. Based on the methods detailed in this report, drag was found to occur most frequently between 6 and 8 m/s. The mean drag error did not vary greatly with wind speeds, but the range of errors decreased with increasing wind speed.

Yield calculations are most severely affected when both sensors at one height are dragging. The largest overestimate of yield occurs when both bottom level sensors are dragging and both top level sensors are functioning properly. The largest underestimate occurs when both top level sensors are dragging and both bottom level sensors are functioning properly. WindServer quality assurance can help mitigate the errors in yield calculations caused by sensor drag by up to 3.3%.

P50 and P90 yield values are similarly affected by sensor drag. The distribution of possible yields for a given site increases due to the uncertainty associated with sensor drag. P50 yield values can be underestimated by as much as 7.5% and overestimated as much as 3.3%. P90 yield values can be underestimated by as much as 3.9% and overestimated by as much as 1.4% relative to the reference P90.