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Characterization of Winds Through the Rotor Plane Using a Phased Array SODAR and Recommendations for Future Work

Regina Anne Deola
Sandia National Laboratories

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Abstract

Portable remote sensing devices are increasingly needed to cost effectively characterize the meteorology at a potential wind energy site as the size of modern wind turbines increase. A short term project co-locating a Sound Detection and Ranging System (SODAR) with a 200 meter instrumented meteorological tower at the Texas Tech Wind Technology Field Site was performed to collect and summarize wind information through an atmospheric layer typical of utility scale rotor plane depths. Data collected identified large speed shears and directional shears that may lead to unbalanced loads on the rotors. This report identifies suggestions for incorporation of additional data in wind resource assessments and a few thoughts on the potential for using a SODAR or SODAR data to quantify or investigate other parameters that may be significant to the wind industry.

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1 SUMMARY

A short-term field project co-locating a Sound Detection and Ranging System (SODAR) and 200 meter instrumented meteorological tower commenced at Texas Tech University in the fall of 2008. Data were gathered for approximately 3 months at the Wind Technology Field Site. The scope of the study was to collect and summarize wind information through an entire rotor plane, doubling the information over the present technique of collecting data through potential hub heights in wind resource assessments. The team members from the Texas Tech University included: Patrick Skinner, Jeff Livingston, Andy Swift, and Jamie Chapman. Team members from Sandia National Laboratories included: Bruce Reavis, Gina Deola, and Jose Zayas.

The specific goals of the study included:

- A tower-SODAR comparison to identify the quality and viability of the SODAR measurements
- The identification of SODAR data that may add value to wind resource assessments
- The identification of recommendations for future work using SODARs in the wind power industry.

The data collected identified that a controlled comparison of the tower and SODAR data generally yielded well correlated data. The summarized data showed large shears in wind speed and direction at a frequency of 5 to 10 percent, producing concern over the actual electrical power produced verses that calculated during a wind resource assessment. It is advised that future work be pursued in using a SODAR to collect data through the entire rotor plane, and use this data to refine wind resource assessment calculations. Direct modeling of power generation may be pursued with SODAR data since the information for the rotor plane, in three-dimensions, is available.

2 BACKGROUND

The standard size of wind turbines has increased above 80 to 100 meters high so that construction and installation of meteorological towers to measure actual hub height winds can be problematic and add additional cost and time to wind assessment projects. In addition to these challenges, wind measurements for only ½ of the profile that turbines operate within increases the uncertainty of the actual operating environment. Measuring winds throughout the swept area of the turbine rotor will reduce the uncertainty in the operating environment and the additional information may assist with developing increased turbine reliability. There are increasing disparities between the actual and calculated power yields for wind farms, and wind assessments are an important factor in the calculated yields. Actual characterization of the site specific wind resource through the whole operating profile of the turbines may provide the additional details needed to fine tune calculated economic yields.

Past practices in the wind industry have generally included one to several point scalar speed measurements at or below hub height, and do not always include wind direction at all levels in the sampling scheme. Wind directional shear through the whole turbine profile has not been well characterized, so the net effect on power production is not well established. Another important aspect for the wind industry is how to most effectively measure wind characteristics in/of a volume since wind turbines sweep through a volume of air, and not just a few points in the volume. Point measurement systems can be used to estimate the characteristics of the volume, but not really measure them.

A mobile and remote sensing platform to measure winds may prove to be a beneficial and flexible method for developing wind assessments as the heights of turbines increase. The ability to remotely sense the wind potential of any site, with the enhanced potential of mobility for micro-siting (technique requires fixed tower or resource for comparison) may prove to be a cost-effective method of gathering data and decreasing the subjectivity of selecting each particular turbine site in a farm, especially in complex terrain settings. A SODAR is a remote sensing instrument that can be configured to be mobile and self contained to operate in many environments. Another benefit of a SODAR use in wind resource assessments is the ability to characterize the wind profile above and below the hub height, from turbine tip through turbine tip.

2.1 Texas Tech University Meteorological Tower

The Texas Tech University 200 meter tower is of steel triangular cross section construction with the three faces approximately 1.2 meters wide [1]. General information on this tower may be found at: http://www.depts.ttu.edu/weweb/WindEnergy/Research%20Facilities/200mTower.php. It is instrumented at 10 levels and includes the full suite of meteorological variables useful in characterizing the lower boundary layer. Instruments include R.M. Young sensors such as sonic anemometers, UVW Gill sensors, shielded temperature and humidity probes, and two barometric sensors. The measurement levels above the ground (in meters) are: 0.91, 2.44, 3.96, 10.06, 16.76, 47.24, 74.68, 116.43, 158.19, and 199.95. Details may be found in the reference report noted above.

2.2 SODAR

The SODAR used in this report is an Atmospheric Research and Technology (ART) Virtual Tower (VT-1). General information on this SODAR may be found at: http://www.sodar.com. SODARs utilize sound to remote sense the wind in the atmospheric boundary layer. The VT-1 is capable of operating in the lower atmospheric boundary layer, and can generally obtain measurements between 30 and 200 meters above ground. It transmits pulses of sound and listens for a returned signal. The amplitude and frequency of the returned signal is used to calculate vertical profiles of winds [2]. The VT-1 includes a user interface to select certain parameters such as the transmit frequency and pulse duration of the outgoing sound, and averaging interval of the returned signal. Details may be found in the reference manual noted above.

3 METHODOLOGY

Many previous and detailed SODAR-tower comparisons can be found in the literature [3, 4, 5, 6]. These works detail the results of the physical differences in measurements, techniques for minimizing differences, calibrations, and importance to the wind industry. Some suggest including a standardization of the SODAR measurements to tower measurements, and some do not. The tower was not used to standardize the SODAR measurements in this study since the focus of this effort is not another highly controlled tower-SODAR comparison, but to identify the potential of SODAR data uses in wind assessments. In addition, standardizing the SODAR to the tower then includes errors from the standard. Spatial separation between the two measuring platforms, the difference in measurement heights, and the different frequency of measurements will basically ensure that there will be a difference in the resolved measurements when 5 minute average data is discretely compared. The objective of presenting a comparison in this report is to give reasonable assurance that the SODAR as a measurement tool is an effective method to collect data for use in wind assessments.

3.1 Potential Influences on Measurement Uncertainty

There are uncertainties associated with every field measurement. Uncertainty includes both bias and precision, or systematic and random errors that are propagated through the measuring system. Most wind instruments are manufactured to have accuracies within 1 or 2 percent of a full scale known value in wind tunnel tests, and this would be the very best expected accuracy in the field. For any single tower system with installed wind instruments, there are additional potential uncertainties [7]. Potential measurements errors, or uncertainties, associated with the total tower measuring system include:

- errors associated with the tower structure (distortion of wind blowing through the tower),
- tower boom arm alignment and level (out of level errors),
- sensors configuration on instrument arm (distortion and/or out of level errors),
- the actual turbulent wind field,
- and the data logger collection device.

Careful installation can minimize many, but not all of the additional uncertainties, so the total uncertainty in the measurement still has the potential to be larger than the 1 or 2 percent identified for any wind instrument.

For SODARs, the measurement uncertainties include:

- spatial and temporal separation of sampling volumes,
- loss of signal in noise,
- bias due to beam spreading,
- height estimate uncertainties,
- and out of level errors.

As with the uncertainties for tower measurements, careful site selection and installation can minimize many, but not all of the uncertainties associated with SODAR measurements. The stated accuracy of the VT-1 SODAR is $\pm$ 0.25 m/s, or 1% at full scale.

For matching independent measurements from two measuring platforms, there are additional uncertainties that may cause variation between the two measurements. The uncertainties are associated with potential temporal and spatial differences. There is a spatial separation of approximately 400 meters between the tower and SODAR. In addition, there were periods of time when the tower's 5-minute averages varied for a minute later off the even minute, for up to ½ day. At the very best, only 80 percent of the observations making up the averages for each platform fell within the actual averaging interval during these times. Due to the potential temporal differences and the spatial separation, residuals of the discrete pairs are expected to be large at times.

3.2 Tower and SODAR Configuration

The configuration of the self contained mobile SODAR platform included south facing solar panels and batteries for electrical power. Due to this off the shelf configuration and the area available for locating the SODAR up wind of the tower, the tower structure had the potential to produce backscatter of the SODAR pulses. To allow for ample spacing to minimize these tower effects and potential effects from the large guy wires, the suggested standoff distance of 200 meters was doubled. The tower-SODAR separation was approximately 400 meters for this effort due to the available land and SODAR configurations. Figure 1 shows the field study configuration.

Several items were synchronized at the beginning of the data collection period to minimize errors in data reduction. The clock times were synchronized using the http://tycho.usno.navy.mil/ website to ensure minimal temporal differences in data. The data were recorded in Coordinated Universal Time (UTC), also known as Greenwich Mean Time (GMT). Time stamps were checked approximately monthly to ensure minimal drift of the time stamps. Verification of magnetic declination input in both platforms was done to resolve wind direction data differences to within 1 degree based on true north. Measurement units were coordinated to minimize unit conversions during the comparison period.

3.2.1 Tower Calibrations

The tower instruments were calibrated within approximately 6 weeks of the start of the co-located data collection period. While the tower instruments performed well in the calibrations, the tower boom arms and instrument arms are not kept in situ during the calibration. The long six-inch square diameter tower booms are designed to rotate into and out of position due to the large structure of the tower. This has the potential to influence measurements due to level and orientation of the instrument after the calibration is complete. The tower data used is from Gill UVW anemometers in which the U and V components of the wind are measured with separate instruments.

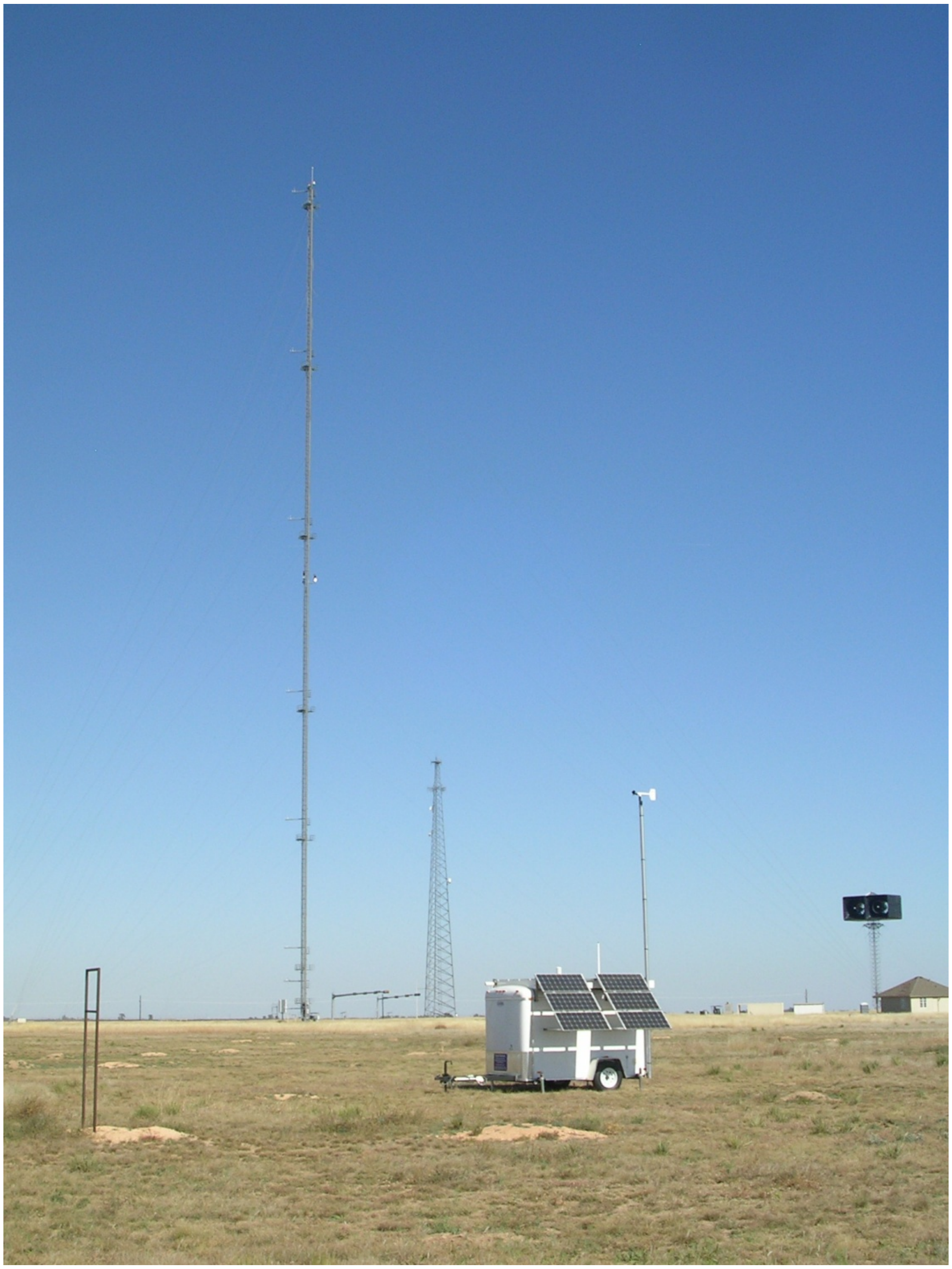

Figure 1. The SODAR and Tower field configuration.

A few weeks into the data collection period, the tower operator identified that the vertical wind speed should not be used due to a large positive bias found while developing the averaging routine. In addition, there was data that was identified as "noisy" by the tower operator, and mathematical smoothing of the data was completed prior to developing the 5 minute averages of the tower data.

3.2.2 SODAR System Checks

The SODAR was calibrated, or system checked, with tools specific to this SODAR system. Specific frequencies and Doppler shifts were fed into the system and results were compared to calculated values to give reasonable assurance that the system would produce representative results. No attempt was made to calibrate the SODAR to the tower as if the tower was the standard. The tower operator checked the level of the SODAR system weekly since the SODAR needs to be level to minimize the errors that may be associated with beam tilting effects.

The SODAR was oriented so that a direct comparison to the U and V components from the tower could be done. This configuration was selected to assist with the identification of bias or errors that may be systematic in nature.

3.3 Data Handling

The data from each measuring platform was handled by the operator of the platform. The tower operator was responsible for data verification of the tower data and creating the 5-minute data averages used in the comparison. It should be noted here that the frequency of the tower data measurements is 1 Hz, whereas the frequency of the SODAR data measurements was < 0.25 Hz for the range depth used in this study. The maximum number of valid SODAR measurements for a 5-minute sampling interval is 71 measurements. There were approximately 300 measurements in the tower 5-minute sampling interval.

Measurements for the SODAR include a reliability factor from 0 to 9. A reliability factor of 9 identifies the data passed all user specified acceptance criteria. The tower data does not include a reliability factor for the data. This generally is not a problem except for periods of frozen precipitation that can adversely impact sensors, producing a lower or no wind speed and wind directions with little to no variation temporally. Several days of comparative time series analyses were used in the beginning of the data collection period to assure the data were matched well, and identify potential bias or large variability between measurements that may not be easily explained.

3.4 Data Recovery

The data collection period began October 16, 2008, and ended February 2, 2009, for a total of approximately 100 days. Collection problems with each system occurred during the holiday period in December 2008 through the first part of January 2009, when no one was monitoring the instrumentation or available to restart the computer systems. Data between December 24, 2008, and January 5, 2009, were not available for the study due to these problems. Tower wind speed for the 74m and 116m level was omitted from the comparison the last five days of January 2009 due to icing problems.

The total daily data availability for the SODAR was 99 percent due to site specific configurations put in place to minimize communications problems. There were no observations available for the 1100 period each day due to communications resetting, and for a 5-minute time period around the beginning of each day due to automatic rebooting. The 0005 minute time period occasionally had data with a valid stamp, but only one observation in the 5-minute period.

All 0005 observations were omitted from the analysis. Data recovery was lower than the operational times due to periods of bad weather, neutral periods with low signal to noise ratio (SNR) for the SODAR, and the occasional data point dropped from the tower data stream. Monthly data recovery is listed in Table 1. It should be noted here that sometime toward the end of the field study the SODAR solar controller may have malfunctioned. The result of this malfunction affected a few data points during the day when the solar panels had fully charged the batteries, and the atmosphere was statically neutral. It is anticipated that most, but not all, bad samples were removed from the dataset for the comparison.

Table 1. Monthly data recoveries in percent during the field study.

Month	**SODAR (percent)**	**Tower (percent)**
November 2008	99	100
December 2008	86	74
January 2009	83	96
Total Data Recovery	89	90

4 DATA FILTERS

Initially, a few filters were applied to minimize the variability of the measurements that may be caused by tower effects, or too few samples in the 5-minute record of the SODAR. If data at any 1 level matched the filter, the whole 5-minute time period was omitted from the analysis. A cursory comparison of the data remaining after the initial filter identified that refined filtering would be useful in minimizing differences that may be related to uncertainties identified in Section 3.1. Figure 2 is an overview of the site with the near surface wind rose for perspective on wind directions.

4.1 Initial Data Filters

The initial filters used included a few basic elements of wind speed and tower effects. They included:

- Tower Effects … Wind Directions between 89.5 and 143.5 degrees at any tower level were omitted since wind coming from this section blows right through the tower. See Figure 2 for an overview of the field configuration with a near surface level wind rose from the Sodar.
- Tower Wind Speeds … Wind speeds less than 1.0 m/s at any level used were omitted from the comparison.
- SODAR … Wind speeds less than 1.0 m/s were omitted from the comparison.
- Measurement Comparability … SODAR data with less than 30 measurements for the 5-minute time period were omitted from the analysis. This filter was needed due to the much higher frequency of measurements with the tower data.

There were also a number of days omitted from the study due to weather related influences of the data. Frozen precipitation occurred on January 27, 2009. This effectively impacted the tower sensors for the rest of January 2009. Precipitation also affects the SODAR, since the vertical velocity component is contaminated by the fall velocity of the precipitation. This SODAR unit includes a precipitation sensor that closes the roof of the unit and sets the data reliability factor to 0. This minimizes time spent removing potentially contaminated data.

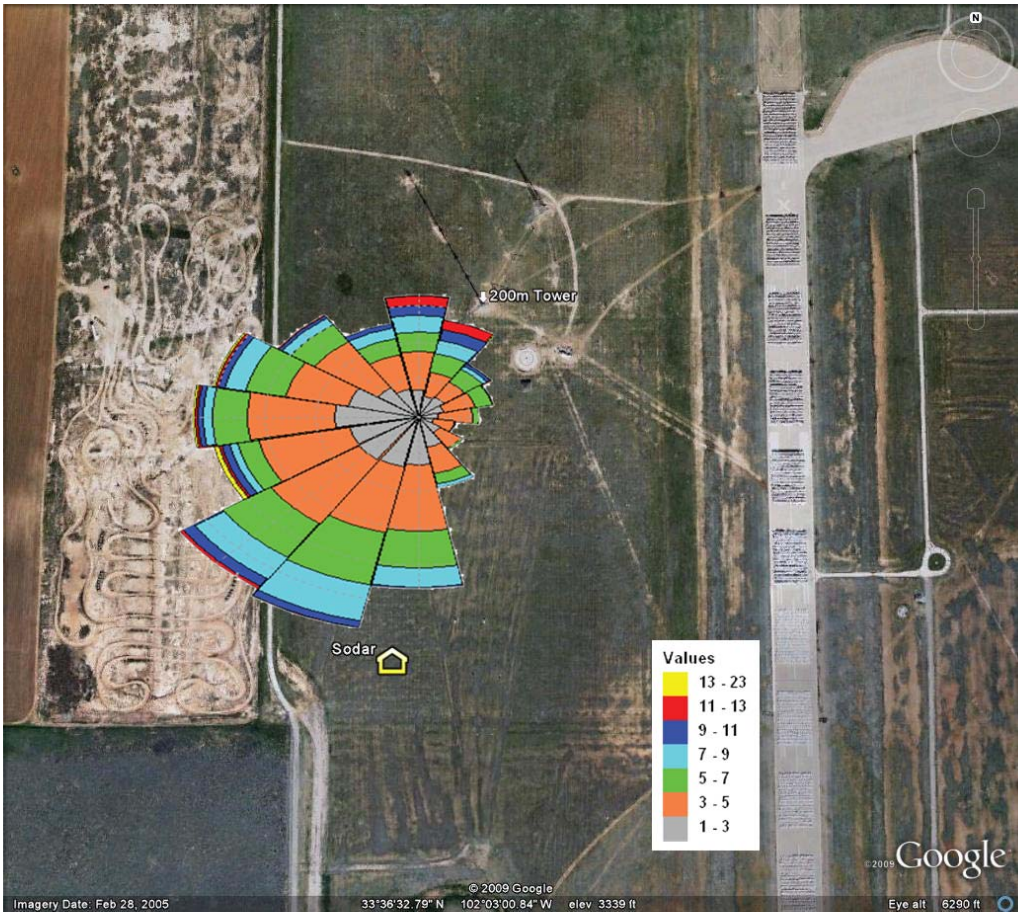

Figure 2. An Overview of the Sodar and Tower locations with the near surface Sodar wind rose. (The bars indicate the direction from which the wind blows.)

Figures 3 and 4 depict a few days of data after the initial filters were applied. There are some interesting aspects that come out of this 500-observation sample of the discrete data comparison. There are periods where the U and V components from each independent platform match extremely well, and periods where they poorly match. In addition, the differences between the V components of the data in Figures 3 and 4 are quite large compared to the differences between the U components. This suggests that it is not the SODAR uncertainty that is causing the differences, since it should appear on both the U and V components. Clearly there are other factors that are working to produce the variations between the observations. Possible factors listed in the uncertainty section are the actual wind field and off-axis response of the UVW instruments, and potential tower Arm effects. Figure 5 shows the instrument boom configuration.

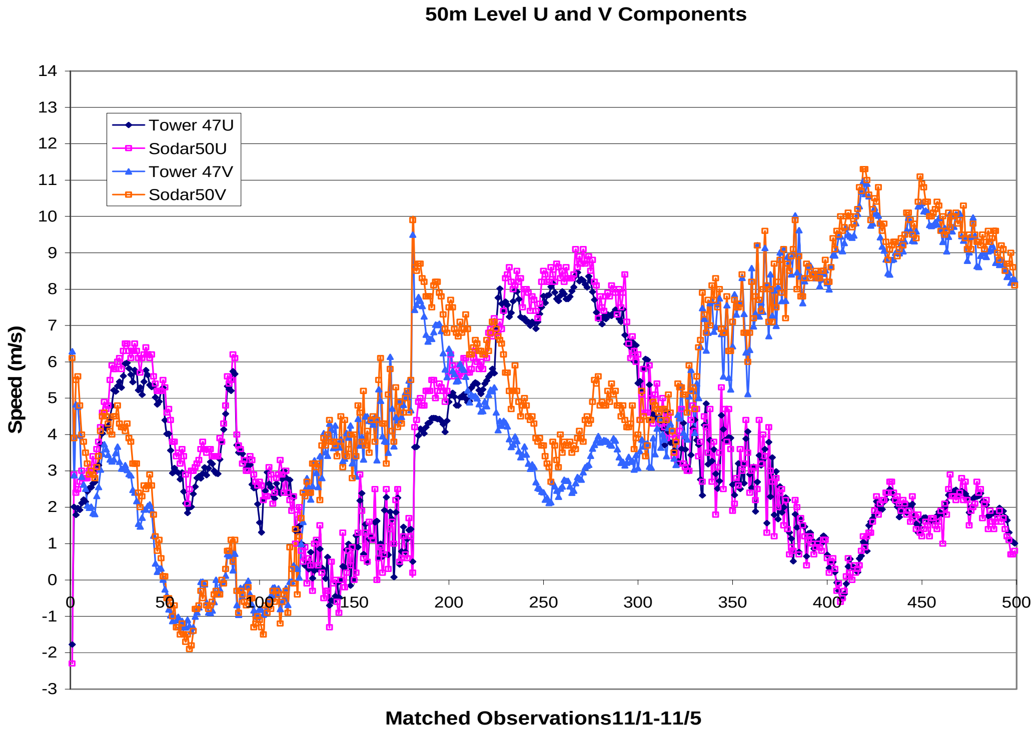

Figure 3. The 50m U and V components for the first 500 matched observations.

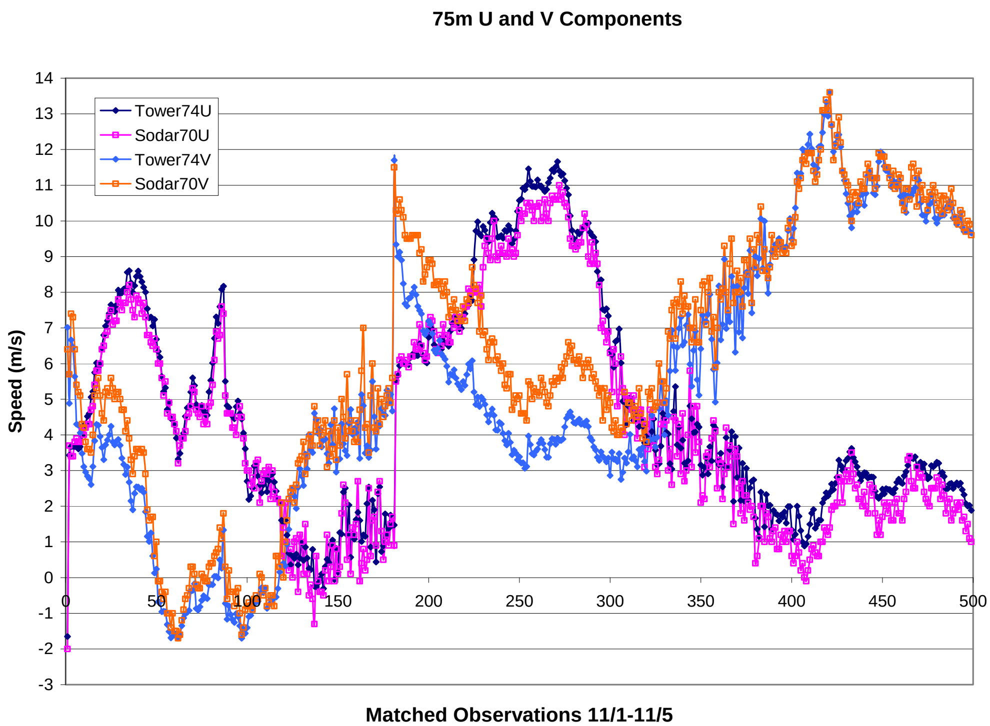

Figure 4. The 75m level U and V components for the first 500 matched observations.

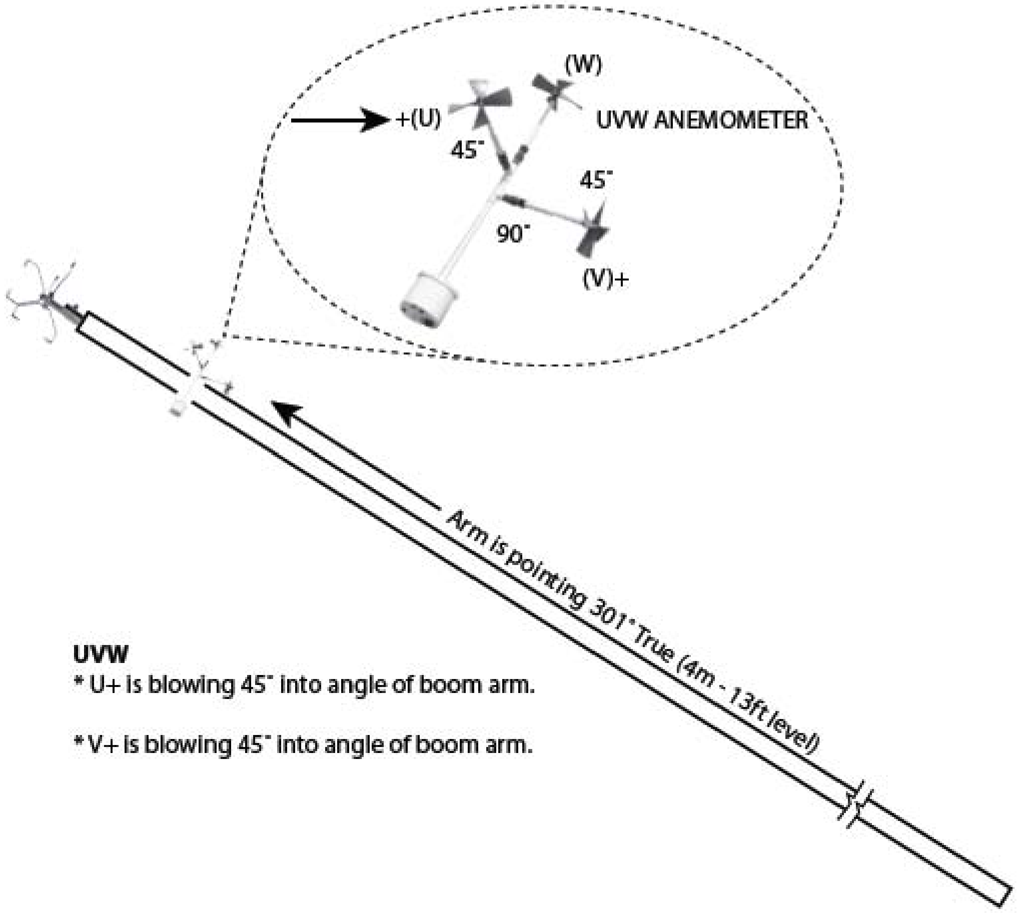

Figure 5. Configuration of Gill UVW tower sensors.

The U, V, and W components are always orthogonally oriented. It is possible that off-axis wind flow is affecting the component data. Some tower-SODAR comparison studies use only the observations that are ± 22.5 degrees of the orientation of the sensor. If there are off-axis effects, one or both components may include uncertainties in the resolved measurements. On-axis flow for this configuration will be when the wind is between 143.5 and 188.5 degrees, oriented down the V component, and between 233.5 and 278.5 degrees when oriented down the U component. Off-axis flows for both components will be when the wind is blowing from 211 (± 22.5) degrees.

Figures 6 through 9 show the comparison of matched 300 observations randomly selected from direct on-axis and off-axis wind directions. For the on-axis flows in Figures 6 and 7 where the wind is directly parallel to the sensor booms, there is generally good agreement for the matched component data between the SODAR and tower. The SODAR and tower V components match well when the wind is blowing down the tower V component, and the U components match well when the wind is blowing down the tower U component. There are variations in the matched opposing components, or off-axis components, for Figures 6 and 7. These off-axis differences will be minimized in the resolved wind speeds when it is windy, but may produce a 10 percent error with a 1 m/s difference in components for resolved speeds around 2 m/s.

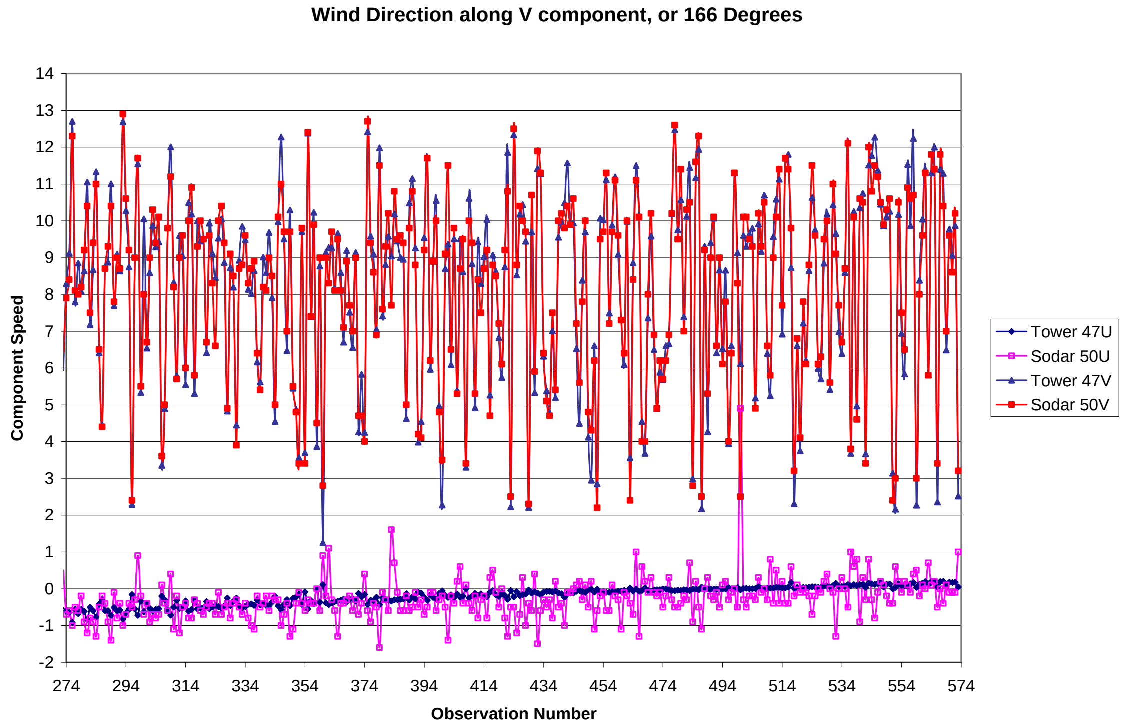

Figure 6. Matched component data for the 47 and 50 meter levels wind directions around 166 degrees, down the V component, for 300 random observations.

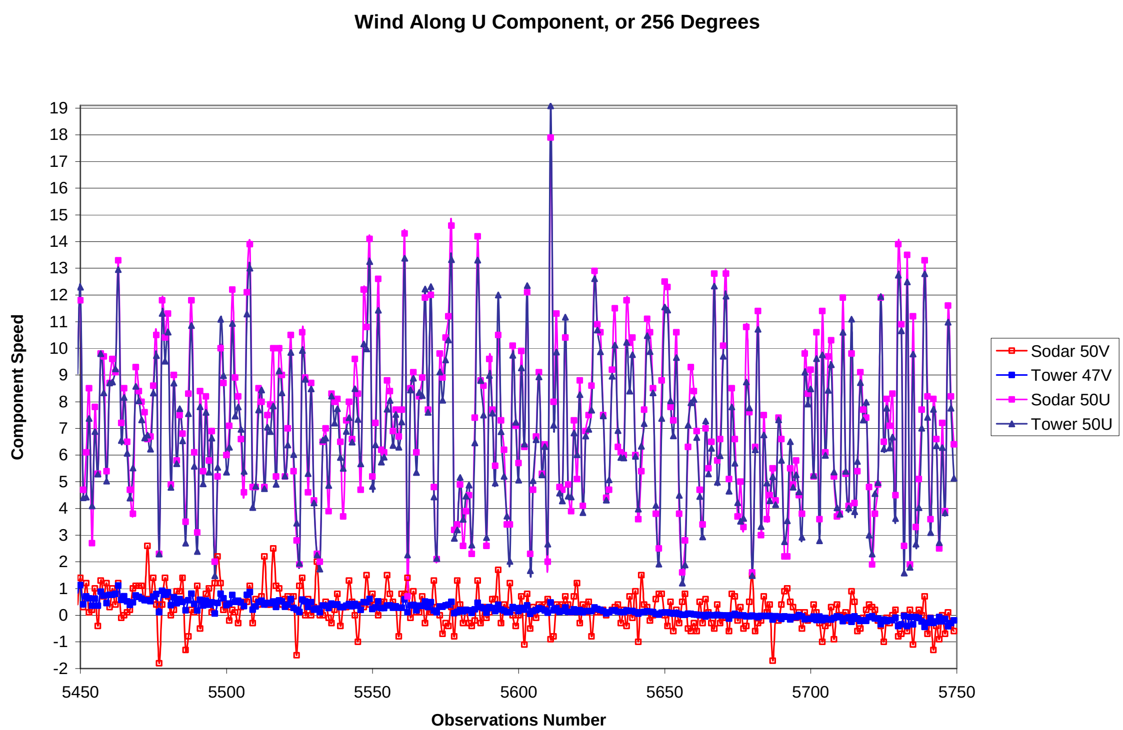

Figure 7. Matched component data for the 47 and 50 meter levels wind directions around 256 degrees, down the U component, for 300 random observations.

Figures 8 and 9 identify the matched observations for off-axis flow centered at 211 degrees. Note the large difference between the SODAR and tower components for the off-axis flow in Figures 8 and 9.

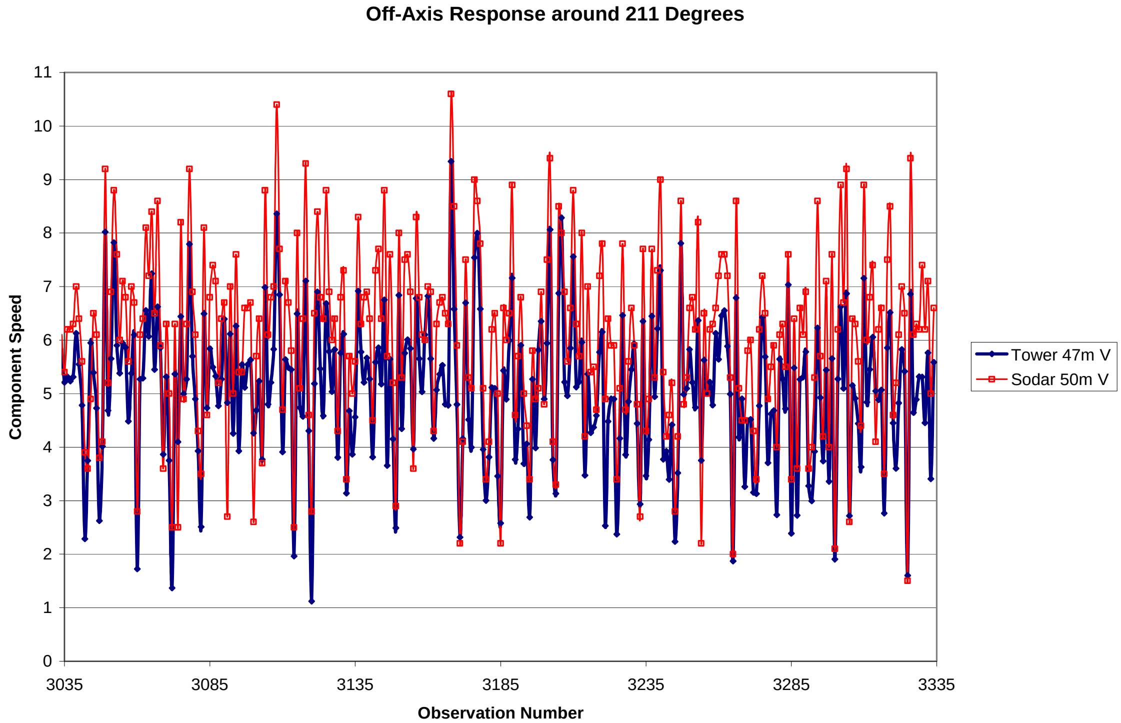

Figure 8. The off-axis response of the tower V component when tower winds are from 211 degrees for 300 random observations.

The tower speed components are much lower than the SODAR components in off-axis flow, with potential dramatic differences in resolved speed. This is not a temporal or spatial artifact. Most observations of the tower V and U components are below 6 m/s while many SODAR observations are above 6 m/s in Figures 8 and 9, respectively. To minimize potential uncertainties produced by tower and associated instrument configuration, additional filters are used in the tower-SODAR comparison. Figures 6 through 9 indicate that using only the on-axis wind flow is appropriate.

Another filter to minimize the effects of wind flowing over the tower arm is used to minimize uncertainties associated with the 6-inch diameter tower arm. All winds that flow over the arm will be omitted from the comparison. Note that this leaves basically 90 degrees of wind direction from which observations are used to generate the statistical relationships between the tower and the SODAR in the comparison section. The resulting variations between the different observing platforms will then mostly be a function of the uncertainties produced by the SODAR and the spatial and temporal variations. Small uncertainties in tower instruments may remain.

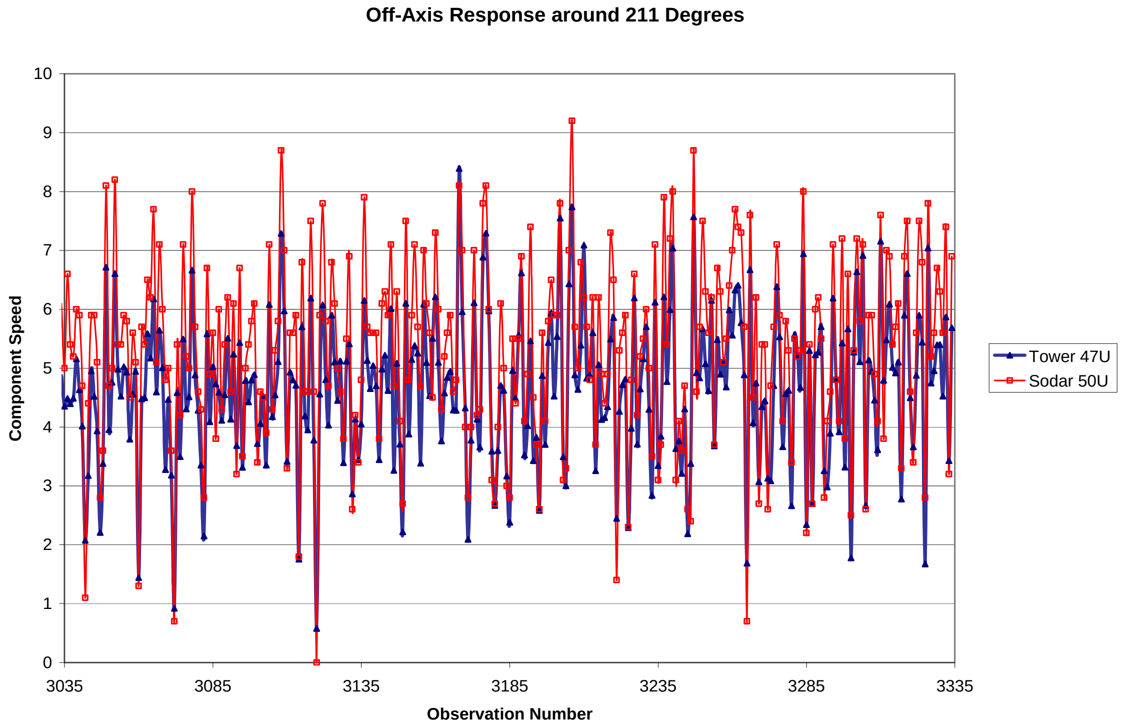

Figure 9. The off-axis response of the tower U component when tower winds are from 211 degrees for 300 random observations.

4.2 Final Filters used for Tower-SODAR Comparison Section

4.2.1 Tower

- Tower Effects…Wind Directions between 89.5 and 143.5 degrees at any tower level were omitted since wind coming from this section blows right through the tower.
- Boom Arm Effects…Wind Direction between 301 and 121 degrees at the tower were omitted in the comparison section due to boom effects. Data for these wind directions were included in subsequent analyses.
- Instrument Off-Axis Effects…Wind Directions between 188.5 and 233.5 degrees were omitted from the analysis, as well as wind directions between 278.5 and 301 degrees.
- Wind Speeds less than 1.0 m/s at any level used in the comparison were omitted from the comparison.

This leaves data from 143.5 through 188.5 degrees and 233.5 through 278.5 degrees used for the tower-SODAR comparison.

4.2.2 SODAR

- Wind speeds less than 1 m/s at any level that would be compared to the tower.
- Observations where there were less than 30 measurements for the 5 minute time period were omitted from the analysis. This filter was needed due to the much higher frequency of measurements with the tower data.

5 TOWER-SODAR DATA COMPARISONS

Applications of the final filters produced a dataset of 3377 observations that are compared in this section. Table 2 identifies the statistics for the 3377 observations.

Table 2. Descriptive Statistics for the comparison data.

Component	Mean	SE Mean	Minimum	Q1	Median	Q3	Maximum
Sodar 50U	3.96	0.0741	-3.50	0.30	2.80	7.70	17.90
Tower 47U	3.82	0.069	-2.45	0.33	2.62	7.33	19.09
Sodar 50V	4.51	0.0747	-4.30	0.60	4.00	8.60	15.20
Tower 47V	4.29	0.0737	-4.39	0.46	3.45	8.53	14.26
Sodar 50 WS	**8.09**	**0.0483**	**1.40**	**6.00**	**8.40**	**10.25**	**17.90**
Tower 47 WS	**7.77**	**0.0465**	**1.20**	**5.78**	**8.13**	**9.77**	**19.15**
Sodar 70U	4.57	0.0835	-3.90	0.50	3.10	8.95	17.10
Tower 75U	4.94	0.0809	-2.99	0.97	3.38	9.10	20.24
Sodar 70V	4.82	0.0826	-3.80	0.60	4.20	9.40	16.10
Tower 75V	4.33	0.0886	-5.29	-0.18	3.45	9.44	15.11
Sodar 70 WS	**9.00**	**0.0537**	**1.00**	**6.70**	**9.40**	**11.40**	**17.10**
Tower 75 WS	**9.07**	**0.0535**	**1.25**	**6.79**	**9.53**	**11.42**	**20.35**
Sodar 110U	5.69	0.0994	-7.90	0.90	3.80	11.00	20.70
Tower 116U	5.73	0.0991	-4.36	0.88	3.60	11.04	21.13
Sodar 110V	5.31	0.0994	-9.40	0.70	4.60	10.65	17.80
Tower 116V	5.22	0.101	-6.49	0.43	4.20	10.79	17.12
Sodar 110 WS	**10.61**	**0.0664**	**1.00**	**7.80**	**11.10**	**13.40**	**21.20**
Tower 116 WS	**10.65**	**0.0658**	**1.21**	**7.91**	**11.16**	**13.44**	**21.20**

The descriptive statistics in Table 2 suggest the following:

- There is good agreement between the speed means, although the 47 meter tower mean seems a little low or the SODAR a little high.
- There is a decreasing variation between the means as height increases for this comparison.
- Temporal differences due to spatial separation, or occasional large differences in samples in an averaging interval, are minimized in the mean. The differences may be quite apparent in discrete comparisons.
- The quartile data points are also quite close for most of the measured components and resolved speeds, though the maximum resolved SODAR speed is lower than the tower speed at two of the three heights.

It is noted in a review of the data that the difference in the means, varies correctly with the difference in the measuring height. The SODAR 50m measurement is higher than the tower 47, and the tower 75 and 116 mean is higher than the SODAR mean taken at 70 and 110 meters. The means at the 110 and 116 meter level are, from a practical measurement perspective, and calculating purposes, equal.

Figures 10 through 12 depict the discrete wind speed data observations and correlations for the 5-minute averages. There is good general agreement and high correlation with the discrete data, though there is the anticipated scatter. Note that there seems to be a slight offset in the lower speeds for the 75-meter component data seen in the residuals data that seems to smooth out in the resolved speed. Also, the correlation coefficient is the lowest at the 47-meter level, which may be a function of the higher slope found for the U component. Figure 13 includes the correlation of the wind directions for data. There does seem to be slightly more scatter to the data with winds from the west, or down the U component for this instrument configuration.

Given the short averaging frequency of 5 minutes, and the potential uncertainties associated with the temporal and spatial differences, the data in Table 2 agree within 1 percent, except at the lowest level where a 4 percent variation is noted. This is quite good for 2 separate measuring systems not calibrated to each other.

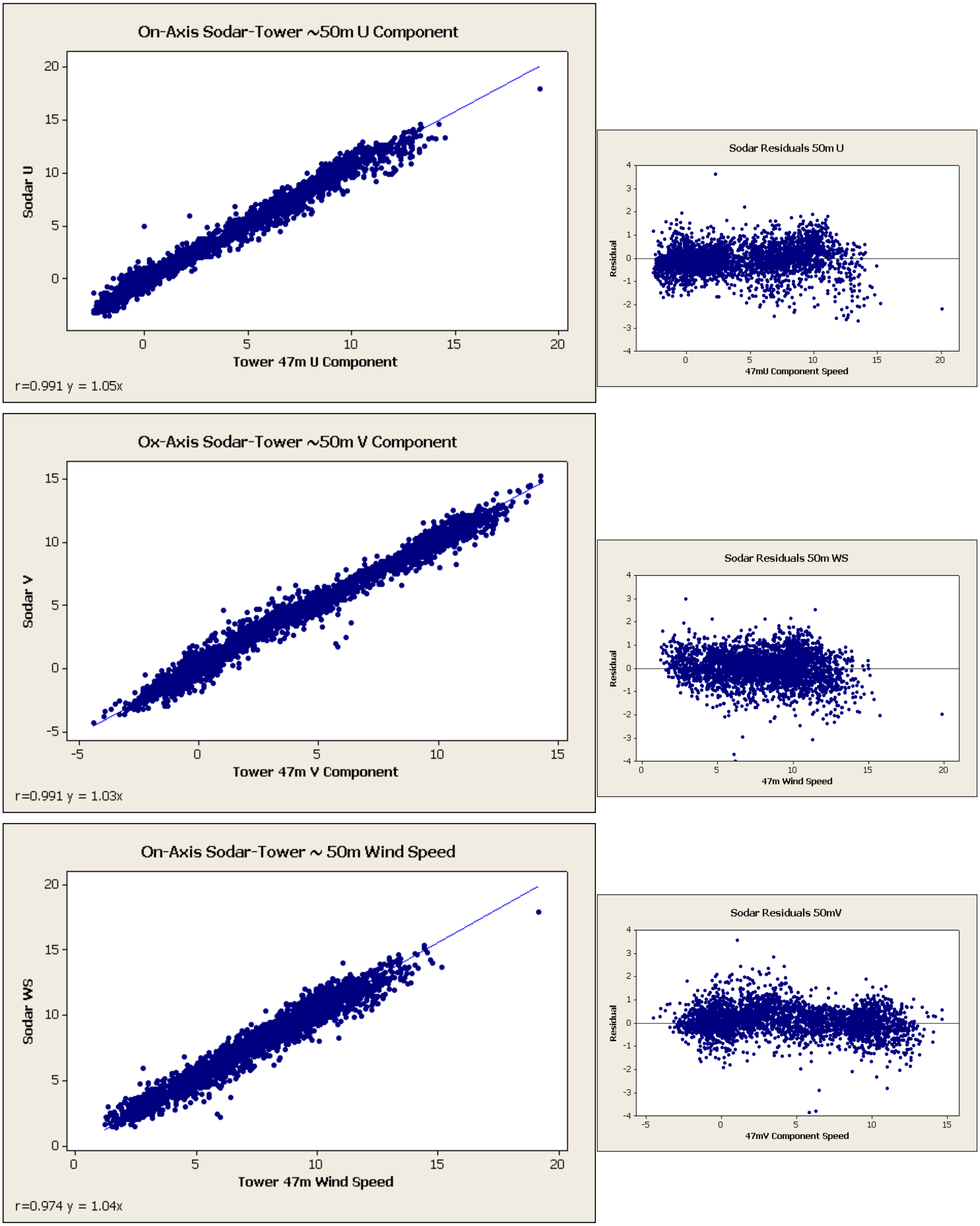

Figure 10. The discrete wind speed data comparison for the 47- and 50-meter data.

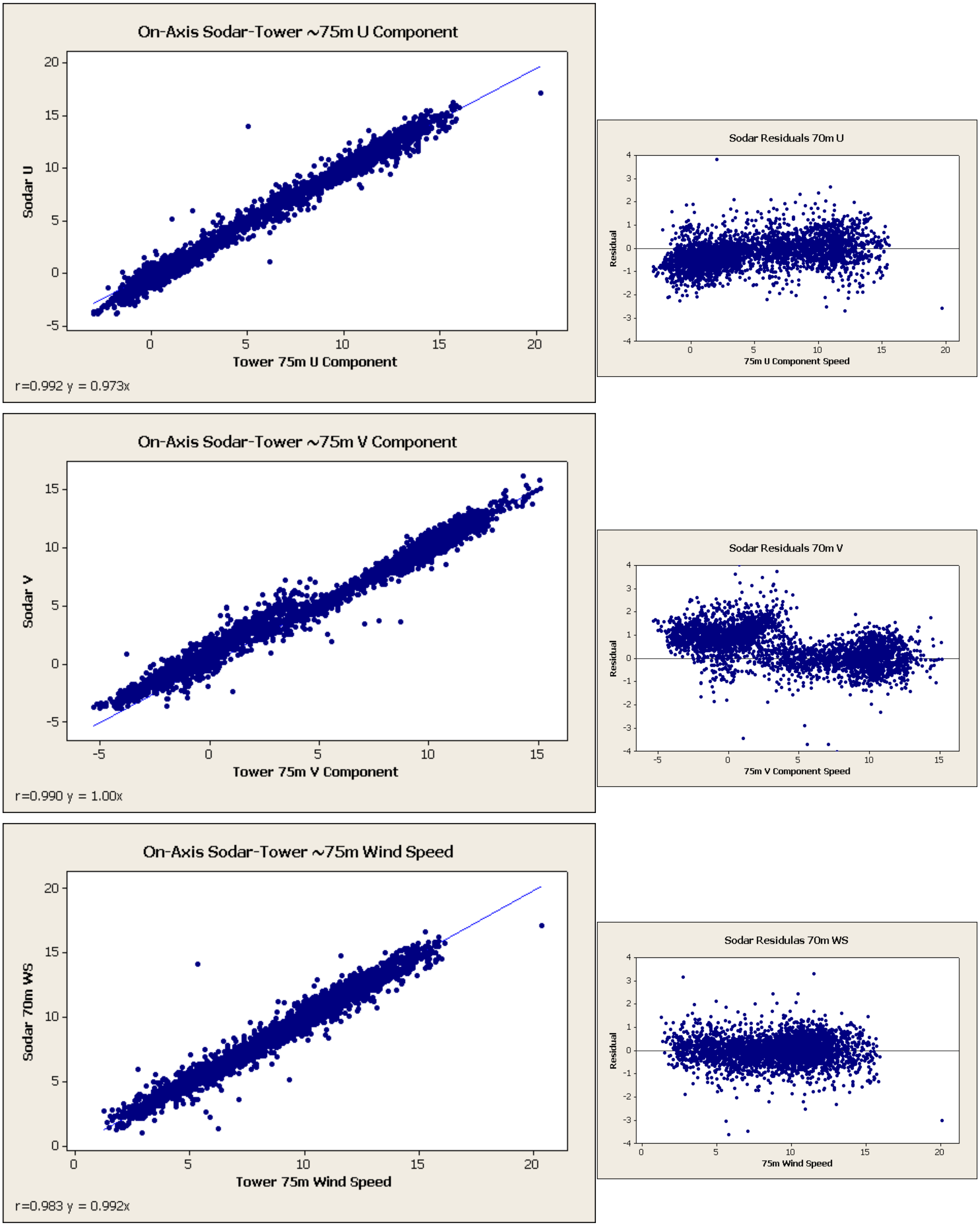

Figure 11. The discrete wind speed data comparison for the 70- and 75-meter level.

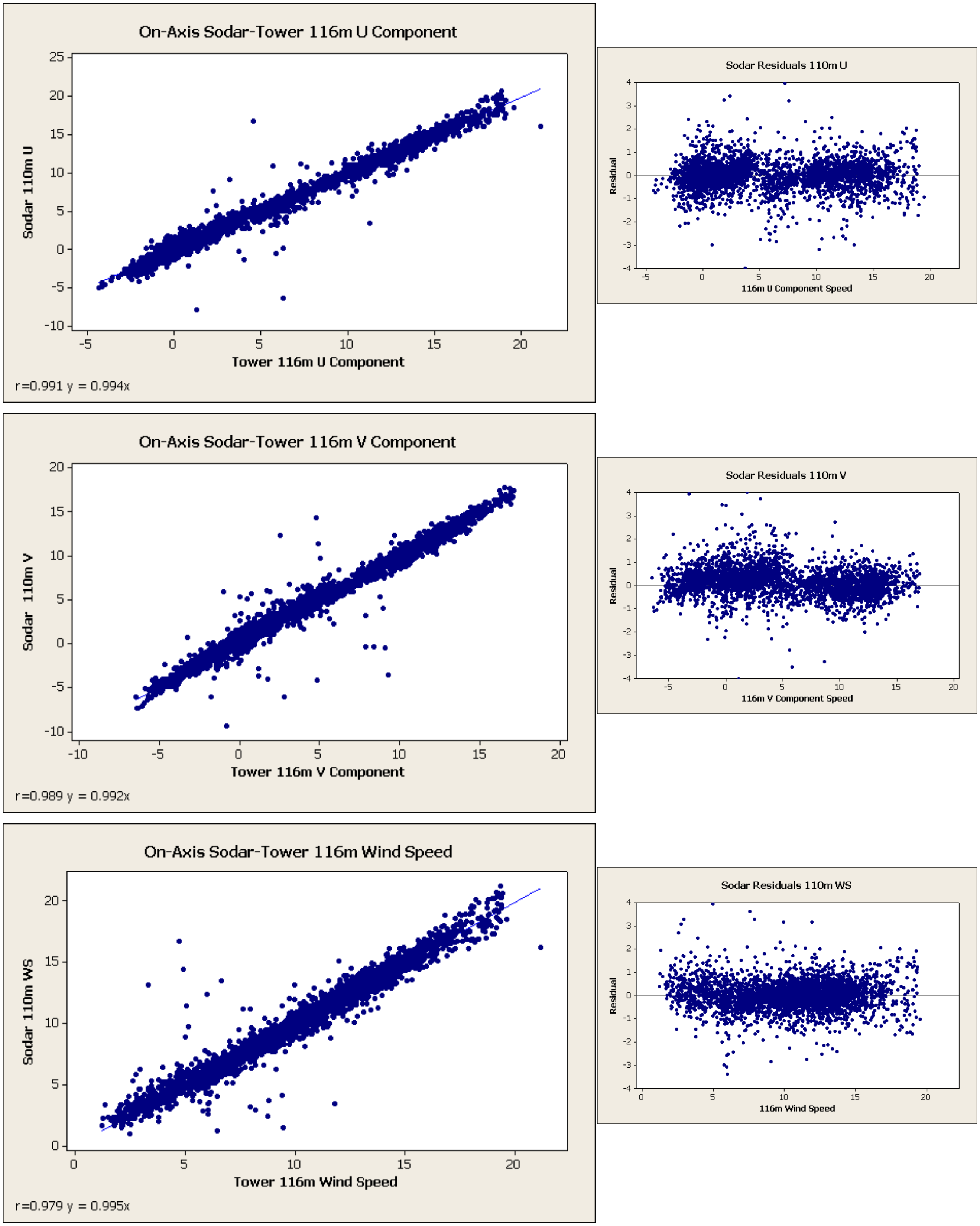

Figure 12. The discrete wind speed comparison for the 110- and 116-meter level.

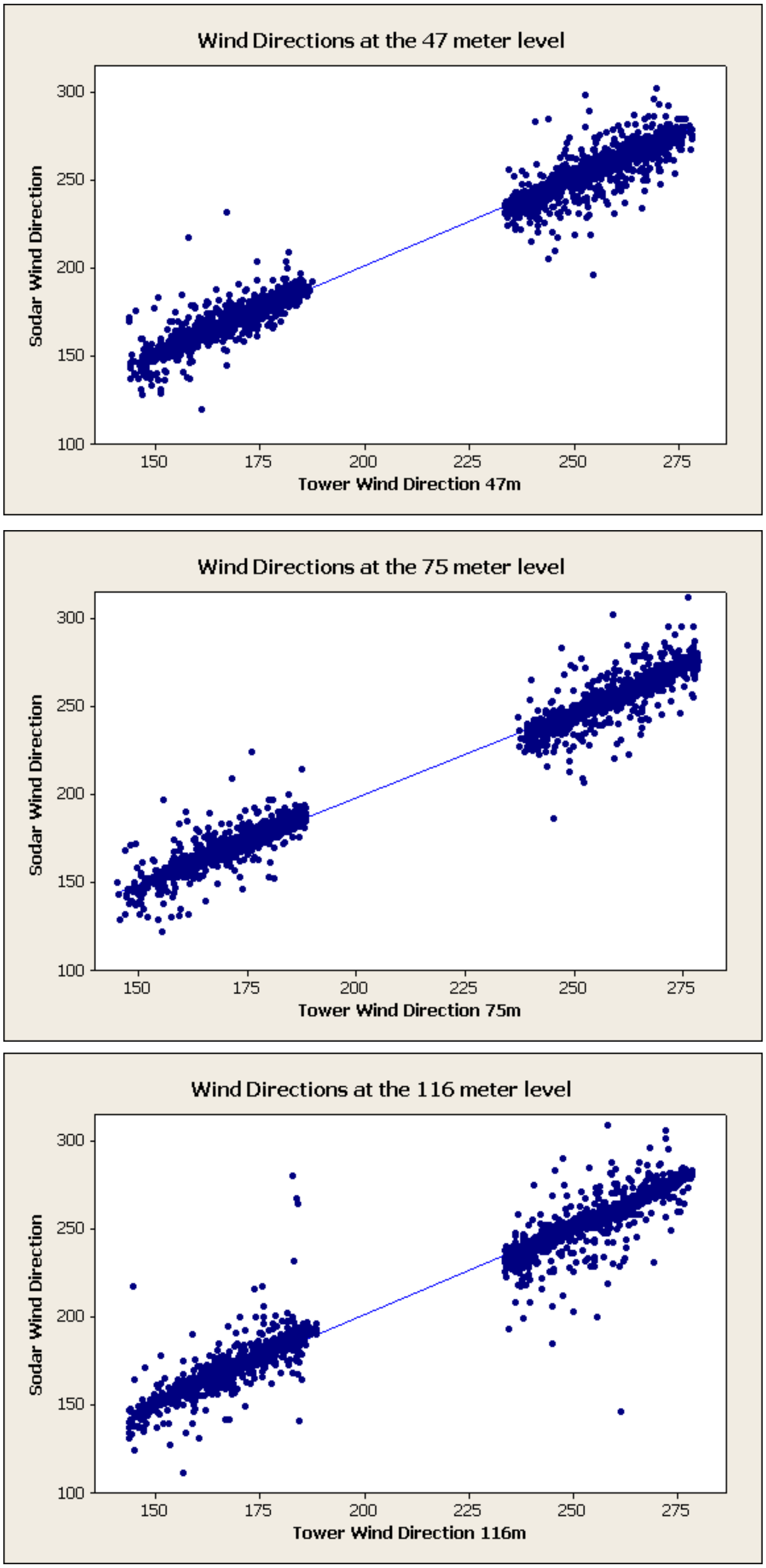

Figure 13. Plots of resolved wind directions for the three comparison levels.

6 THE ATMOSPHERIC BOUNDARY LAYER

The atmospheric boundary layer (ABL) is generally defined as the lowest part of the atmosphere where the behavior is directly influenced by the earth's surface. The ABL depth changes over the day, has large fluxes of momentum, heat and matter, and is where turbulent convective motions exist along with mechanical turbulent motions [8]. Over land, it may be only 50 to 100 meters deep in very stable conditions and 2 to 3 km in unstable conditions. It can be deeper during the day in desert environments. The ABL has both an inner and outer region. The inner region sits closer to the earth's surface than the outer layer, just above the roughness layer at and above the earth's surface. The inner region, which is characterized as approximately 10 percent of the ABL, is where the shear is the largest and the generation of turbulent kinetic energy (TKE) is the greatest. Wind turbines on land generally operate in this inner layer.

The inner atmospheric boundary layer is also known as the inertial sub-layer (ISL). It is this sub-layer where, during statically neutral conditions, the velocity profile is logarithmic. During stable and unstable conditions, the velocity profile varies from logarithmic. While the turbulent motions during the unstable daytime conditions work to decrease wind speed differences with height, stable conditions can produce large speed differences with height. That does not imply that during stable conditions there is a lack of turbulent motions. Several investigations [9, 10] of the nocturnal boundary layer have shown that the decoupling of the boundary layer from the surface layer creates large wind shears and low level jets (LLJ), in various states in the US Great Plains. Turbulence can be generated from above, in the form of Kelvin-Helmholtz Instability (KHI), in the sheared environment below the LLJ, and moves downward toward the surface. It is believed that it is the nocturnal stable boundary layer turbulence that contributes to turbine failure or excessive loads. In summary, the atmospheric layer where wind turbines operate is the layer that has the greatest diurnal changes and speed variations over the shortest distances.

In the previous section, it was shown that both SODAR and tower data may have uncertainties of various magnitudes associated with the resolved data. The uncertainties were generally associated with small obstruction influences within a fluid medium, and instrument uncertainties. Uncertainties will be present in any field measurement campaign, the scale may be greater or smaller, but the uncertainty will not be zero. When a physical or mechanical device is embedded within the medium in which it is measuring, distortion of the flow is possible, affecting the potential uncertainty associated with the measurement.

In the next section of the report, a larger dataset was used. The dataset includes only the original filters outlined in Section 4.1 of this report. The larger dataset is used, because it will be similar to a dataset used in wind resource evaluations. There will be larger differences between the means found with each measurement platform, since previously described differences and uncertainties are incorporated into each dataset. These differences are probably smaller than the data variability that may exist when using available data from existing measuring platforms in an exploratory phase prior to establishing a specific site to perform wind characterizations and resource assessments.

7 SODAR DATA COLLECTION AND EVALUATION IN WIND ASSESSMENTS

Current methodologies in wind assessments focus on measurements of the horizontal winds, since that is the wind characteristic that drives the turbines. However, that does not mean that the vertical characteristics of a given site do not influence the turbine or the wind power derived at that site. The vertical component and the turbulent variation of it may work to reduce the effective wind power derived from a turbine, or create additional stresses on the turbine, producing a need for more frequent maintenance. While the nature of the horizontal scalar winds are a good first estimate for site characterization, the vertical nature of the wind may provide additional information needed for refined calculations for wind assessments or turbine behavior modeling. On-site measurements of both horizontal and vertical winds through the rotor plane reduce the need for estimation of wind characteristics above hub-height.

Information that can be collected by the use of SODARs in wind assessments include, but are not limited to:

- Horizontal wind speed analysis through the whole rotor plane
- Characterizations of the directional and speed shears through the whole rotor plane
- Vertical wind characterization.

7.1 Analysis of Horizontal Wind Speeds through the Rotor Plane

A common method of developing an estimate of winds above a 50-meter tower is the use of a logarithmic exponent based on the wind speeds found at lower levels. This estimation introduces uncertainty into the wind characterization, especially in complex terrain settings. It should also be noted that the power law exponent actually varies as a function of stability, varies with height, and is a function of surface roughness [11]. The power law approximation is written as

$$U(z_1)/U(z_2) = (z_1/z_2)^{\alpha}$$

Where U is the wind speed and z is the height. Average α generally falls around 0.2, but is highly site and stability specific.

Many factors, therefore, can work to make the exponent derived with two measurements not representative of the whole turbine profile as indicated by the exponent variation with roughness or complexity of the terrain, stability conditions, and the measurement heights.

Table 3 lists the average measured wind speeds, the exponent derived from the measured speeds, and estimated winds using the exponents. The reference height used to derive the exponents was the 10m level for the tower and the 30m level for the SODAR. Since this tower has measurements above hub height, a comparison of the actual and estimated wind speeds can be reviewed. For this particular site, in this simple terrain setting, there is good agreement of the measured and estimated mean values, with only a 1 to 2 percent error, basically within the accuracy of the instruments. In different locations, and complex terrain settings, estimates may not be as accurate.

Table 3. Measured and estimated winds using the exponent method.

Tower Height	LN Height	Measured Avg WS	Calculated Exponent	Estimated WS	WS (>4.0) Average	Calculated Exponent	Estimated WS
10m	2.303	4.93	(ref 10m)	Avg WS	5.127	for WS >4.0	WS >4.0
17m	2.833	5.70	0.27246		5.938	0.27651	
47m	3.850	7.41	0.26267	7.523	7.756	0.26743	7.866
74m	4.304	8.48	0.27069	8.544	8.892	0.27506	8.951
116m	4.754	9.78	0.27909	9.622	10.246	0.28244	10.098
SODAR Height	**LN Height**	**Measured Avg WS**	**Calculated Exponent**	**Estimated WS**	**WS (>4.0) Average**	**Calculated Exponent**	**Estimated WS**
6 m	1.792	4.69	All WS	Avg WS	4.863	for WS >4.0	WS >4.0
30m	3.401	7.06	(ref 30m)		7.390	(ref 30m)	
40m	3.689	7.63	0.26970	7.630	7.992	0.27213	7.992
50m	3.912	8.08	0.26457	8.103	8.473	0.26778	8.492
70m	4.248	8.87	0.26937	8.873	9.307	0.27214	9.307
90m	4.500	9.58	0.27735	9.495	10.043	0.27920	9.965
100m	4.605	9.91	0.28174	9.769	10.392	0.28317	10.255
110m	4.700	10.24	0.28646	10.024	10.733	0.28726	10.525

It is also noted that the exponent calculated varies somewhat depending on the second measurement height. Using different exponents will yield different results for the estimated wind speed values. While the difference between the estimated and measured wind speeds is small in this dataset, due to the cubed nature of wind power estimate, even these small errors at these speeds can produce a 3 to 5 percent difference in actual versus estimated power production.

An additional method of estimating wind profiles is plotting the height and wind speeds to derive a logarithmic profile, under neutral stability conditions. The height of the lowest measuring point is important in this method since the lowest height anchors the profile, but must be in the ISL, not in the roughness elements near the surface [12]. Figure 14 depicts the logarithmic profiles of the site using the tower and the SODAR data, for data where the SODAR 50-meter winds are greater than 4.0 m/s. Using 4.0 m/s as a threshold satisfies 2 conditions: it tends to identify “near-neutral” conditions, based on mechanical speed and mixing, not thermal/static stability; and it also identifies the data for which turbines would be in motion. The profiles in Figure 14 match fairly well through the assumed rotor plane, though there is more variation in the altitudes below 50 meters. The rotor plane in Figures 14 through 16 is depicted by green and blue horizontal reference lines, and lies between 50 and 110 meters. The wind profiles in Figure 14 converge to the geostrophic wind speed between 400 and 1000 meters (e6 and e7).

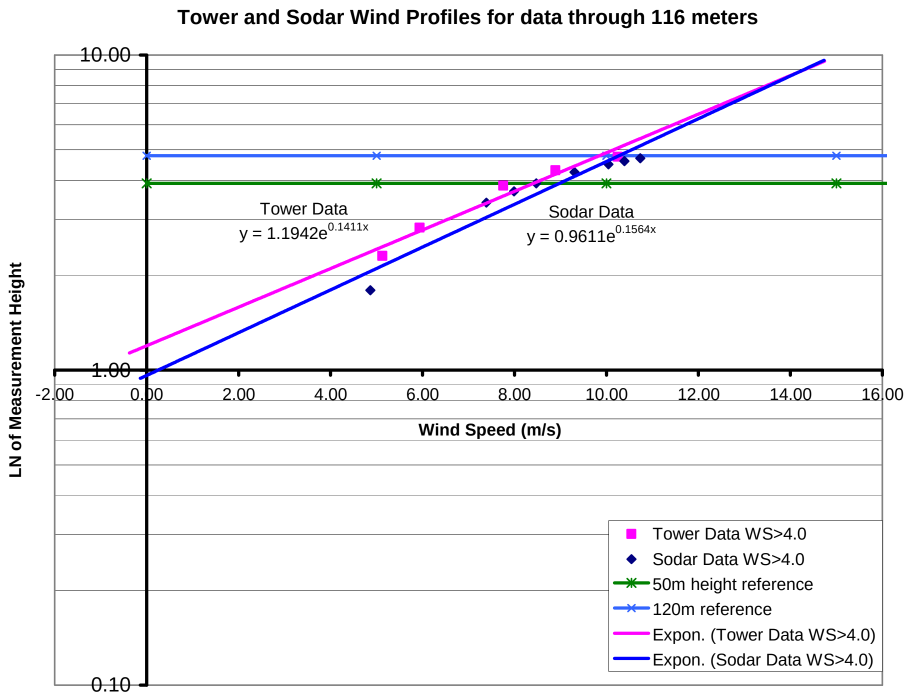

Figure 14. Near-neutral logarithmic profiles for the SODAR and tower.

Figures 15 and 16 show how the profiles can differ using only a few points, at different altitudes. Note that with only a few points along the profile at or below hub height, estimates can vary by 1 m/s within the rotor plane altitudes for this particular site. Using data from both methods when winds speeds are > 4 m/s, an underestimation of the wind speed occurs at higher heights, resulting in a slight under prediction of the potential wind resource at this location.

For the goal of estimating surface roughness, larger errors are anticipated using this entire dataset since statically unstable and stable conditions are mixed into the "near-neutral" profiles identified in Figures 14 through 16. If the goal is calculating surface roughness, strict adherence to data meeting neutral conditions is required, and only a small subset of this data would be used. It is important to reiterate here that only in the inertial sub-layer and only during thermally/statically neutral conditions is the assumption of a logarithmic profile which terminates at the surface roughness length valid [6].

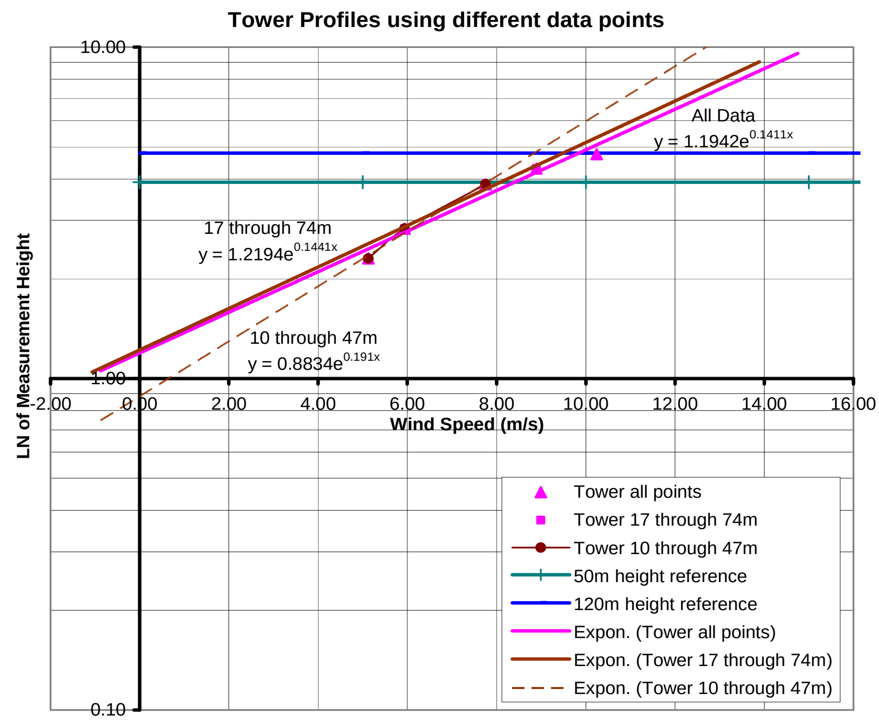

Figure 15. Profile variations for the tower based on different measurement points.

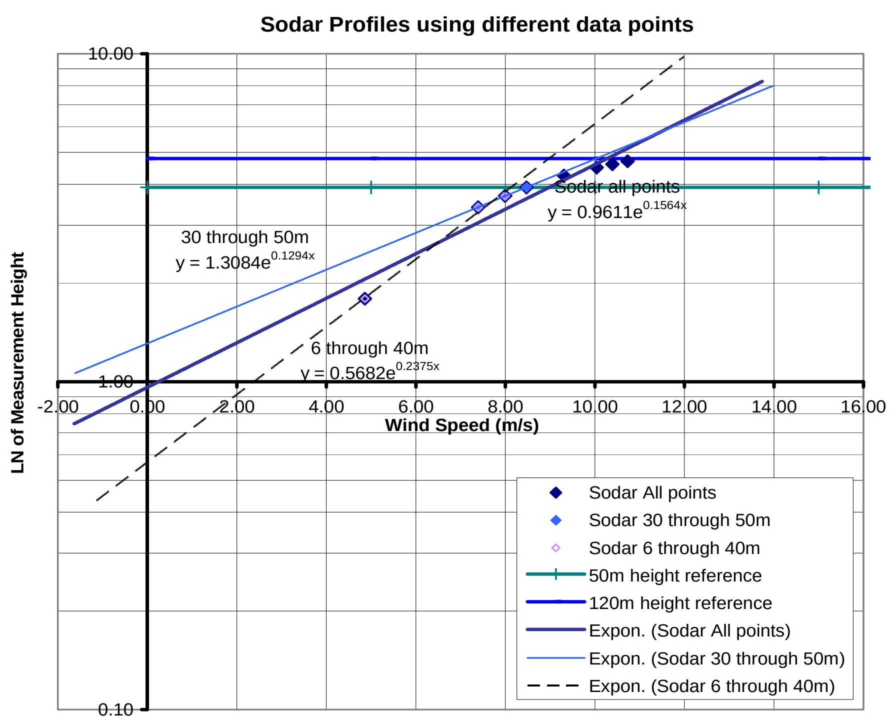

Figure 16. Profile variations for the SODAR with different measurement points.

7.2 Identifying Shears through the Rotor Plane

7.2.1 Wind Direction Rotational Shear

Currently few directional shear, or "veer", determinations are performed with 50-meter towers. Any directional shear identified will be at or below most hub heights, identifying only half of the picture. It is generally not a good assumption to assume a linear relationship of wind directional shear above and/or below 2 tower data points that do not include the whole turbine profile. Numerous variables such as surface roughness, local topographic effects, and varying vegetative cover and heights can influence the wind direction (WD) in the lower levels. Wind direction aloft is known to vary with height through the atmospheric boundary layer.

Directional veer can add stress to the turbine rotors, and may influence the electrical power derived from the turbine. There is little in the literature on the intensity and the sign of the influence that wind direction differences may exert on the rotors. Intuitively, wind direction variability may exert either a positive or negative force on the rotor, which may either add or subtract slightly from the derived power.

A simple calculation of wind veer through the rotor plane is to subtract the wind directions to get the directional shear between the top and bottom rotors. Directional variation in the atmosphere can be larger with low wind speeds, and will not be important to power generation when the rotor blades are still. The data used for the WD rotational shear comparisons was filtered to omit the data points where the SODAR wind speed was less than 4 m/s at the 50m level. The SODAR was used as the filter since it seemed there may be a slight low speed bias at the tower 47-meter level. The data in Figures 17 and 18 represent 10,747 observations.

Figures 17 and 18 identify the difference between the 5-minute average wind directions going from the lowest to highest altitude within a general turbine profile. The 110 m (116m) direction was subtracted from the 50m (47m) direction so negative rotational shear in Figures 17 and 18 indicate a clockwise rotation or veer of wind direction from lower to higher measurement levels. It is easily identified that the variation in veer with height has a reverse relationship with the average wind speed at the lowest rotor tip height.

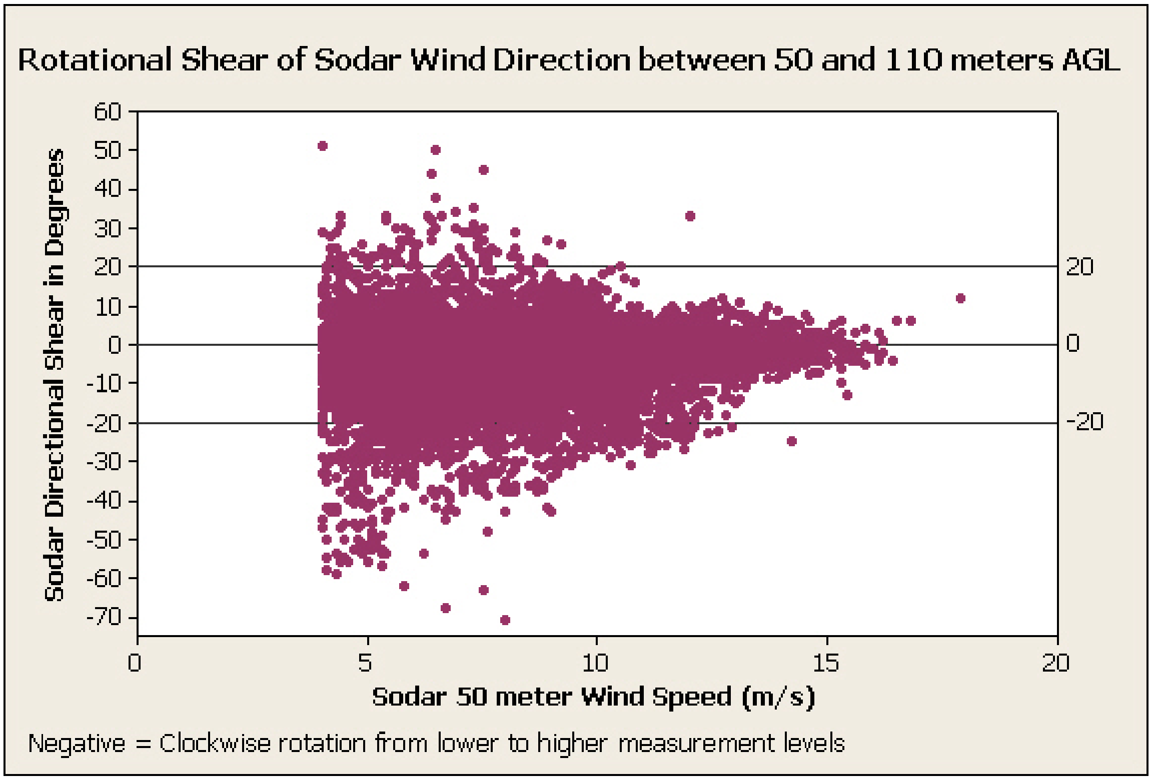

Figure 17. SODAR Wind Direction Rotational Shears between 50 and 110 meters.

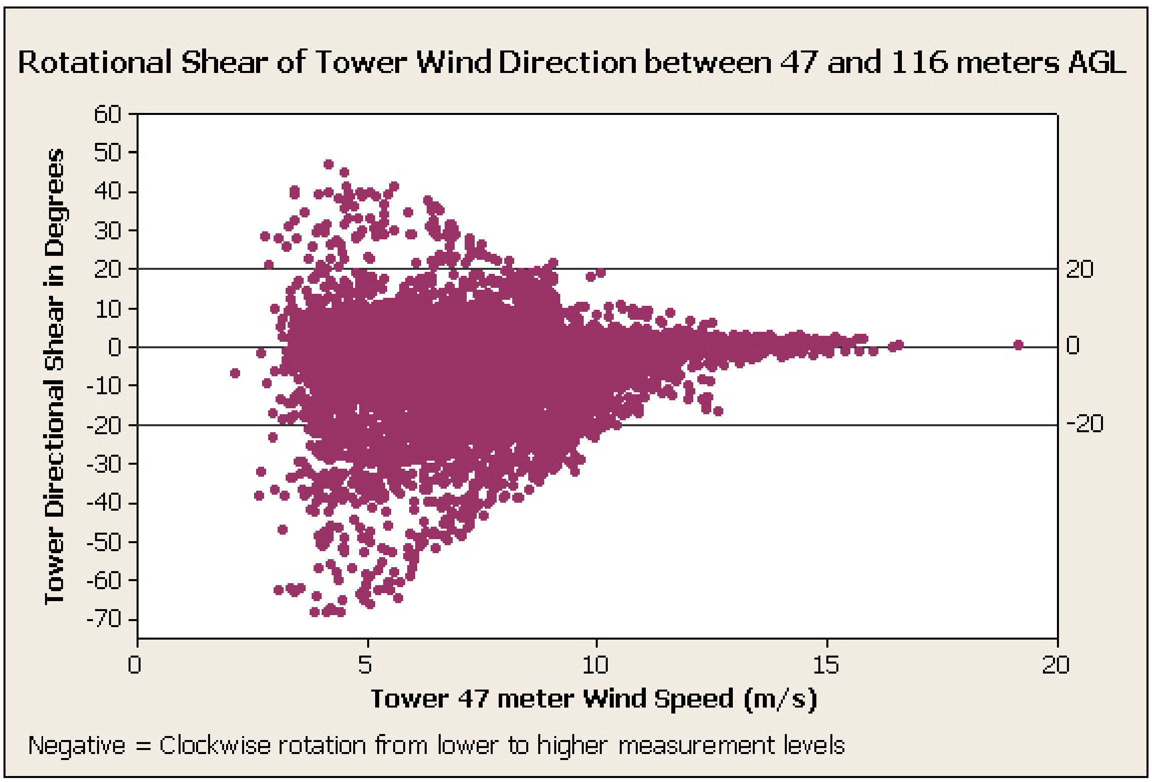

Figure 18. Tower Wind Direction Rotational Shears between 47 and 116 meters.

The larger the wind speed at the bottom of the layer emphasized, the smaller the directional shear between the top and bottom of the profile in general. It is significant that there can be large directional veers while a turbine is trying to spin.

The greater percentage in clockwise rotation of direction from the surface is expected for this area based on surface friction, the Eckman spiral, and synoptic considerations. Directional veering with height is more frequent than backing with height here and in many locations in mid-latitudes where synoptic weather systems quite frequently come from the westerly directions.

Figures 19 and 20 present the cumulative density functions for the directional veer data. At this site, when the turbines are moving, approximately 8 to 10 percent of the time, there will be directional veers greater than 20 degrees. How does this influence the power generation for these time intervals? What do these rotational veers of wind directions do to the loads? It should be emphasized that this is a simple presentation of directional shear, and using multiple points in the turbine profile available with a SODAR may provide additional details.

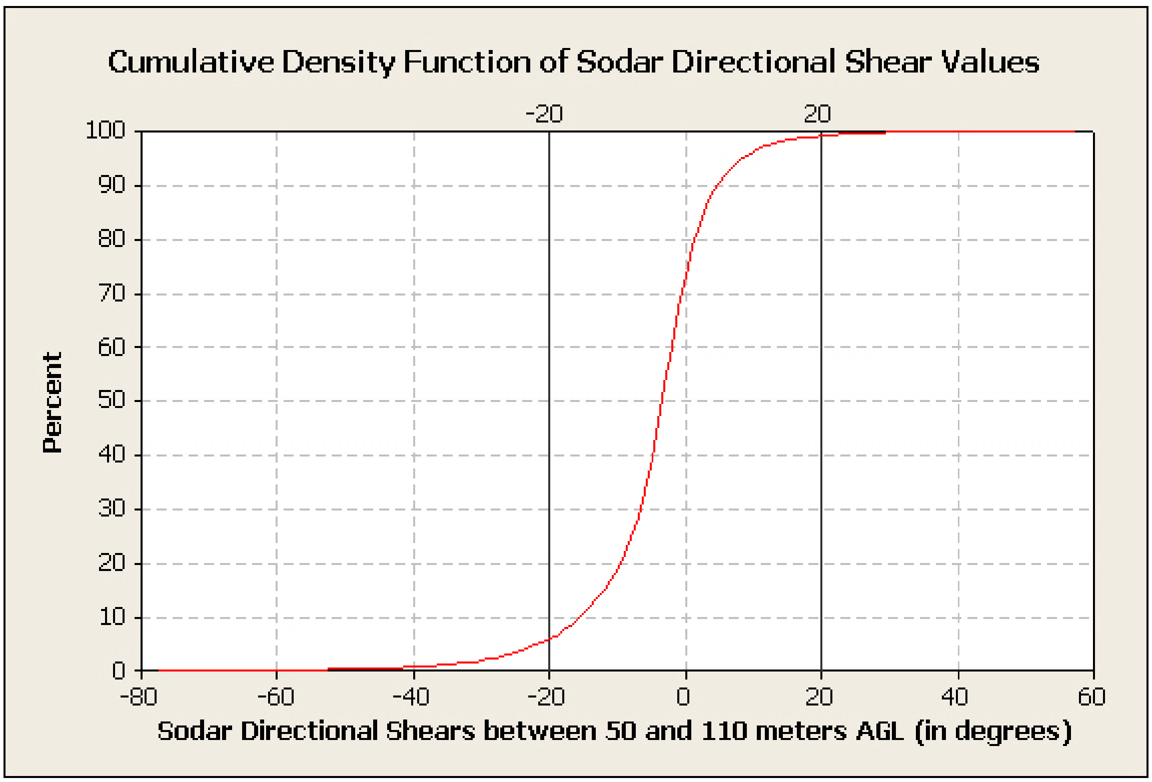

Figure 19. Cumulative densities for SODAR directional shears.

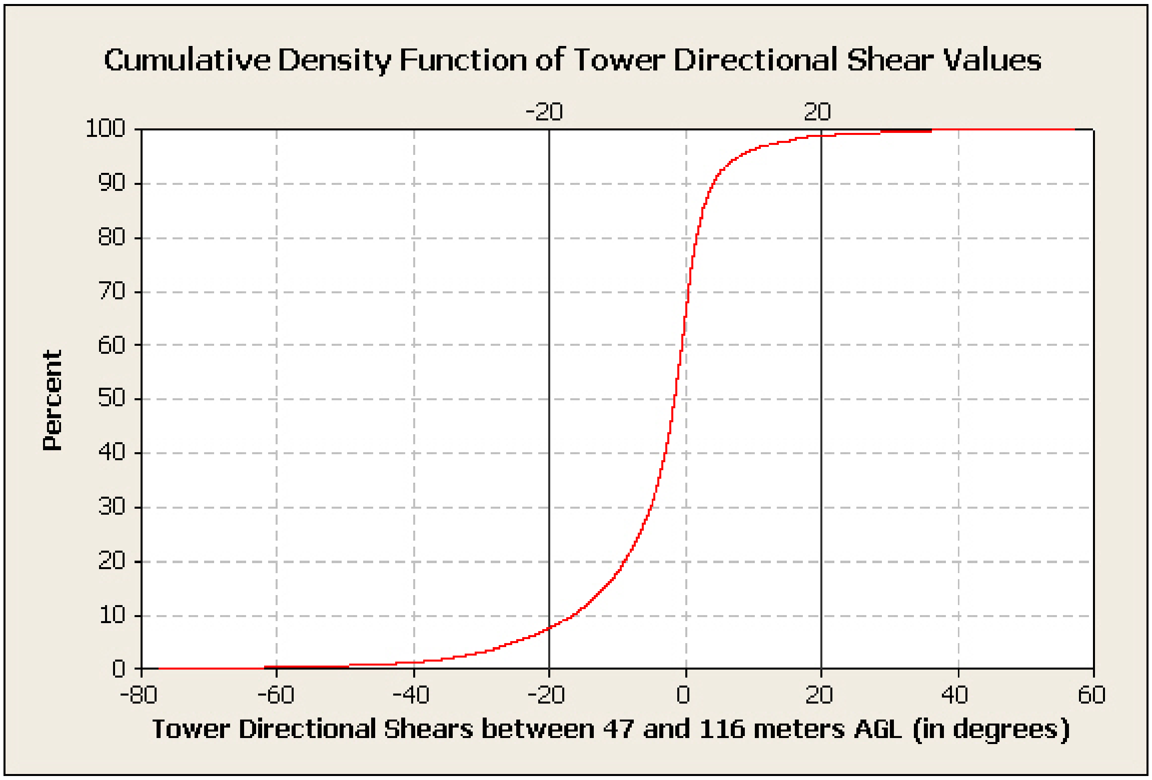

Figure 20. Cumulative densities for Tower directional shears.

7.2.2 Measured Wind Speed Shears through the Rotor Plane

Wind speed shears and wind power law exponents should generally be thought of as site specific. Certain areas will have similar shears and exponents, and these parameters will follow similar patterns, but assuming a general profile for all terrain configurations and land use areas introduces uncertainty in the anticipated operating environment. Complete characterization of the turbine profile will minimize some uncertainty in the productivity of a wind farm site and may provide site specific information on the frequency of large load producing shears.

The speed difference between the top and bottom of the assumed rotor plane for 10,747 observations are plotted against the wind speeds in Figures 21 and 22. These plots verify that there can be large and various speed shears, and the speed at the top level is somewhat correlated with the intensity of the shear. This is typical of atmospheric profile variation throughout the day, though the frequency and range of large shears may vary with each particular site. The differences of speeds were normalized over the entire rotor plane layer so that the normalized speed shear (dU/dz) is presented in the histograms in Figures 23 and 24.

The distributions seem to be binomial, and are probably associated with the static stability, or, very generally, the time of day, so that the well mixed unstable day time tends to have the smallest shears with a large frequency around 0.005, while the stable stratified night time periods tend toward the larger shears. Note that Figures 21 through 24 also show negative shear, with a lower wind speed at the upper measurement level, approximately 4 to 6 percent of the time using the histograms.

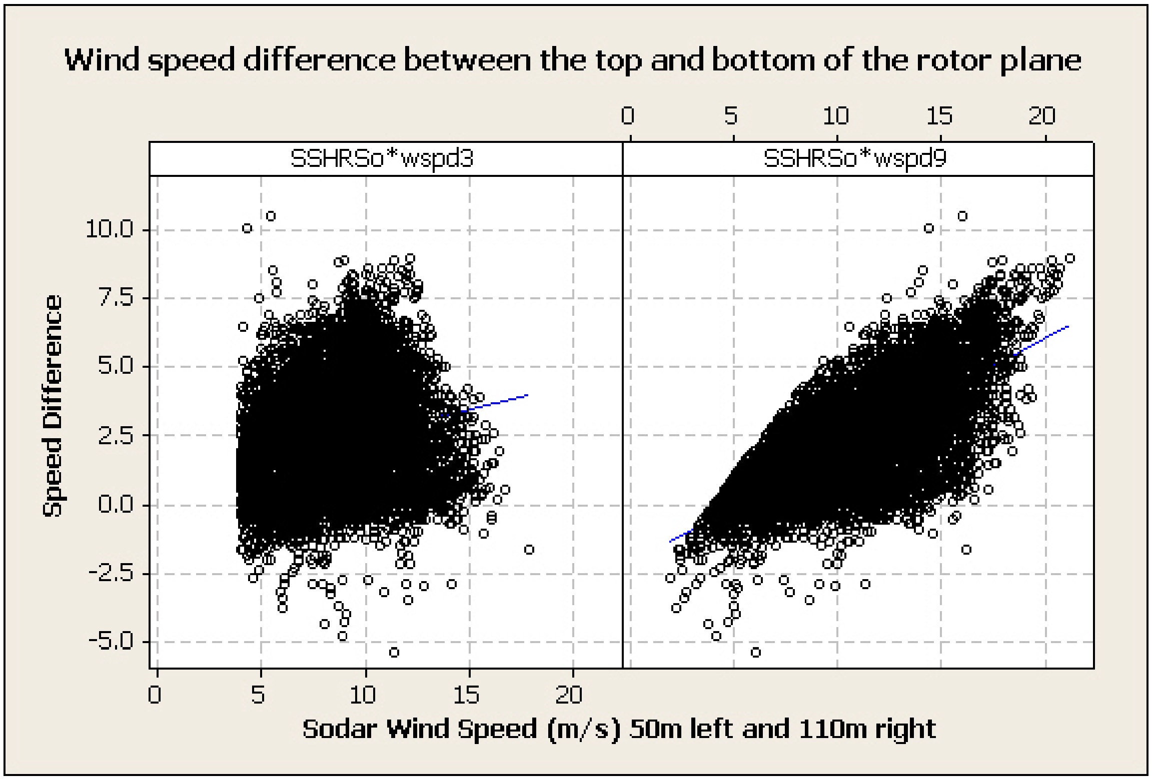

Figure 21. SODAR wind speed differences between the 50- and 110-meter levels.

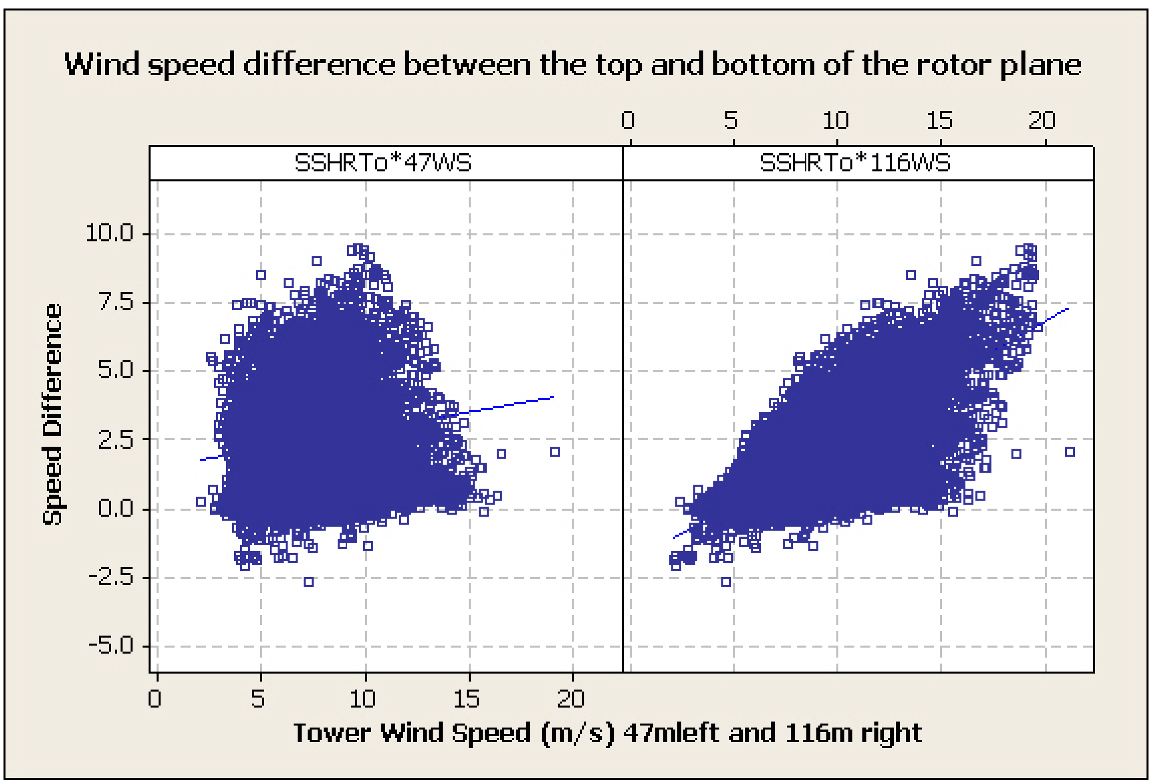

Figure 22. Tower wind speed differences between the 47- and 116-meter levels.

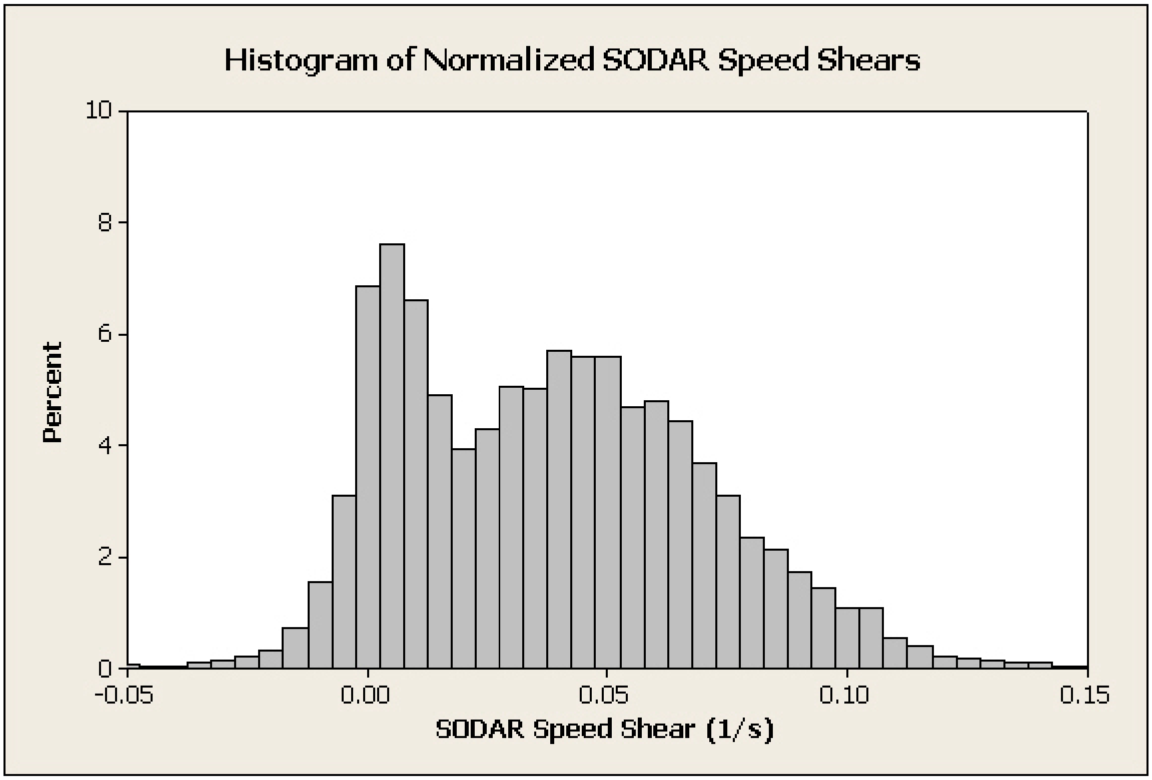

Figure 23. Histogram of normalized speed shears for the SODAR.

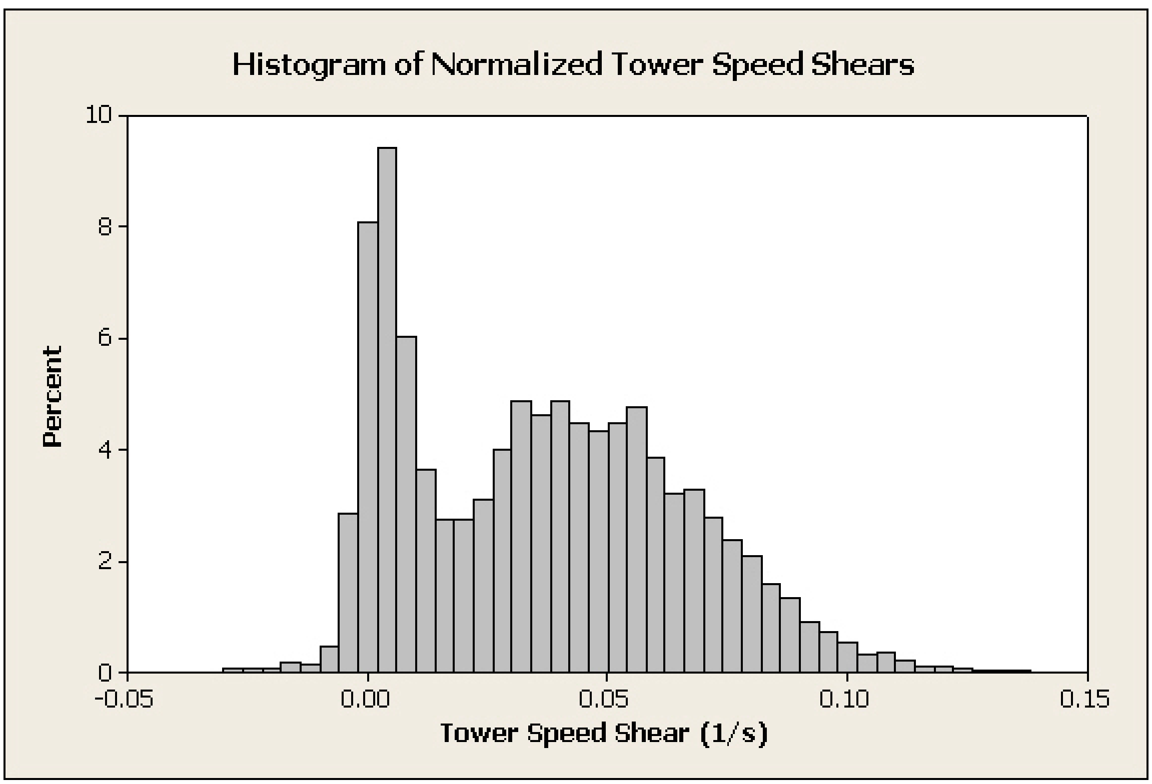

Figure 24. Histogram of normalized speed shears for the Tower.

Another point emphasized in Figures 21 through 24 is that there are many observations where the difference between the top and bottom of the rotor plane approaches 6 m/s (0.1/sec). Turbine performance during some of these larger shears may deviate from anticipated or nominal operation, and effect electrical production.

The normalized speed shears are plotted along with the normalized directional shears in Figures 25 and 26. This plot combines both the directional differences and the speed differences for each measurement pair for the same time interval. Note that most of the observations indicate some kind of shear is always present at this location. The right side indicates a positive speed shear, and the lower right quarter indicates a clockwise directional shear is generally coupled with the positive speed shear. Measurements indicate that large speed shears and large directional shears can coincide.

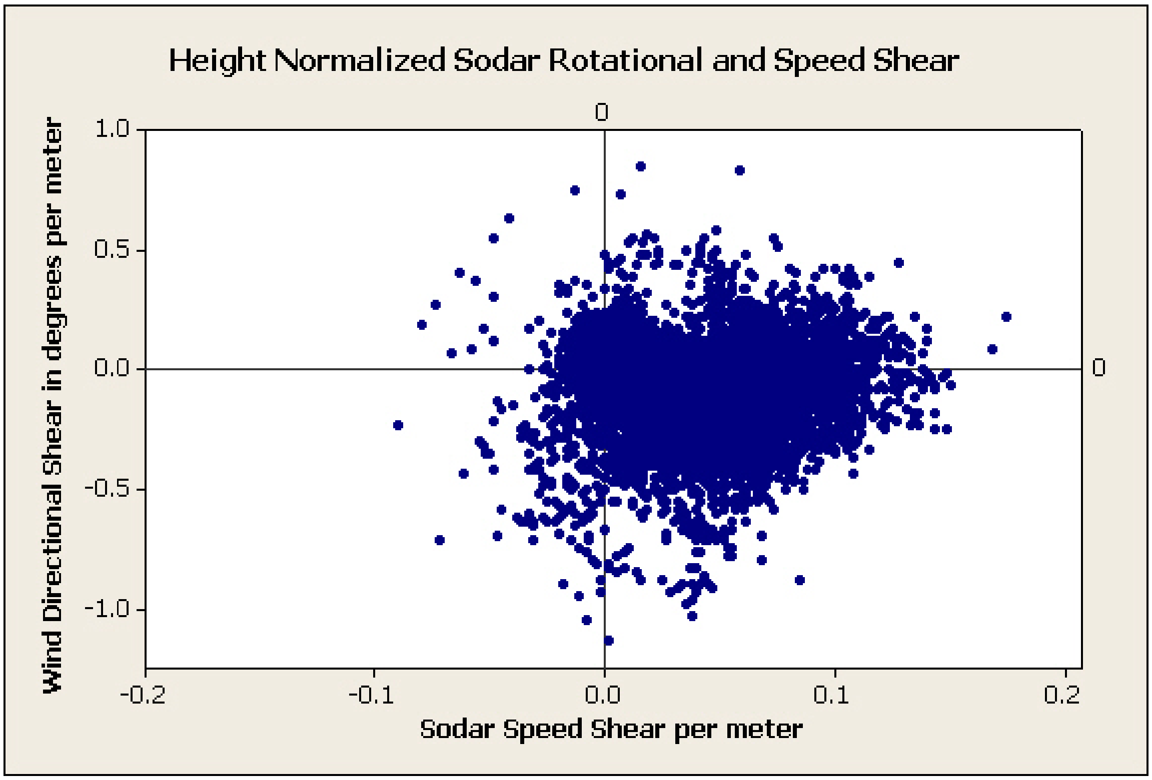

Figure 25. SODAR plot of normalized speed and directional shears.

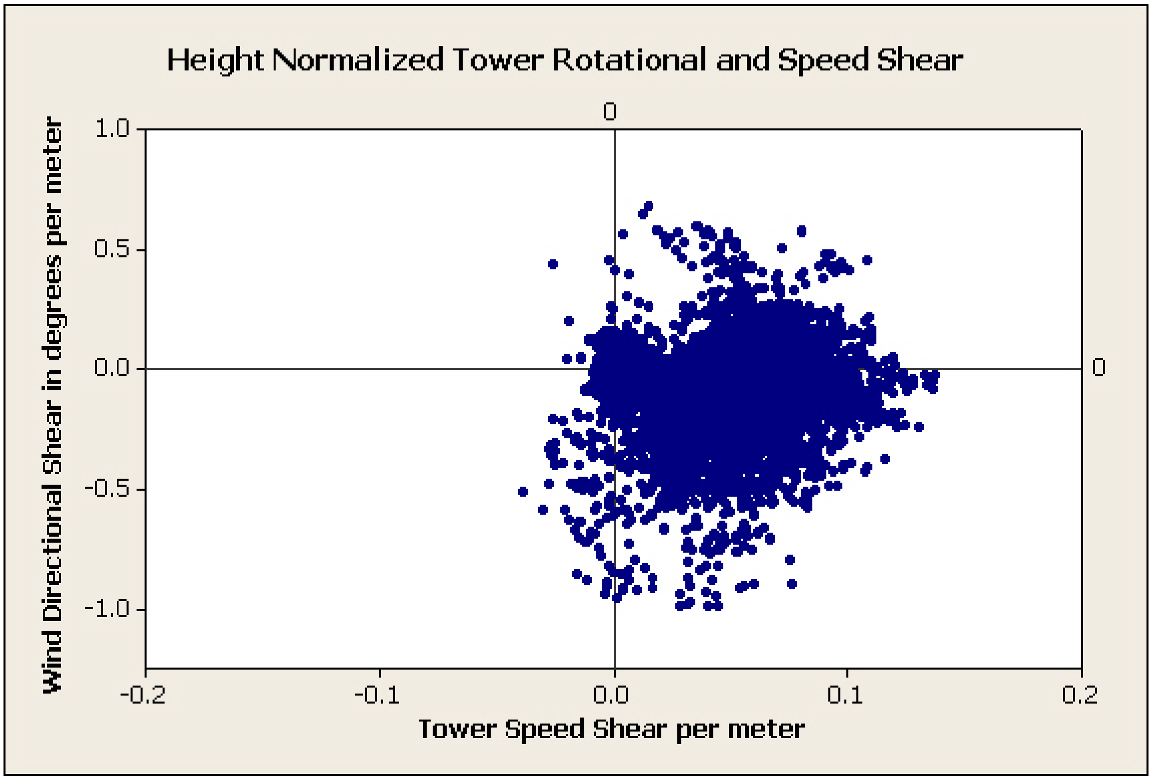

Figure 26. Tower plot of normalized speed and directional shears.

7.3 Measurements of the Vertical Wind and Standard Deviations

Generally the vertical motions in the atmosphere are smaller than the horizontal motions driving the turbines. While turbines are designed to derive power from the horizontal winds, the three-dimensional nature of the wind may exert forces that can alter the power anticipated from the measurement of the horizontal wind. The vertical motions of the local wind field are site specific and will be influenced by general synoptic considerations, static stability, intensity of shears, and topography or roughness. Characterizing the vertical motions adds another dimension to the turbulence that may be present at a site.

It has been shown that turbulence can create unbalanced loads on the rotors [9]. Current methods of data gathering include using the standard deviation of the horizontal wind speed measurements to infer turbulence intensity (TI). This representation of turbulence is a two-dimensional feature, though vertical motion is at least partially included in the TI based on horizontal speed. Vertical motions are seldom measured during routine data collection for wind assessments. Direct measurement of the vertical component of the wind is possible with the SODAR.

Table 4 shows the statistics of the vertical velocities (VV) taken with the SODAR. Data from 10,775 measurements are included in Table 4 and Figure 27. The data show basically what is expected in vertical velocity measurements. In the mean, vertical velocities are generally near zero, as oscillations and turbulent motions on various time and length scales balance each other over time. However, short term measurements show the variability of both the average and standard deviation of the vertical velocity. The standard deviations of the sampling interval vertical speeds, indicated as Sigw in Table 4, is close to 0.5 m/s.

Table 4. The summary statistics for the vertical velocities (w) and standard deviations at 50-, 80-, and 110-meter levels.

Variable	Mean	StDev	Minimum	Q1	Median	Q3	Maximum
50m w	-0.03621	0.15809	-0.87000	-0.11000	-0.04000	0.02000	1.67000
80m w	-0.03175	0.19875	-1.87000	-0.13000	-0.05000	0.03000	1.55000
110m w	-0.01066	0.26503	-2.31000	-0.14000	-0.04000	0.06000	2.34000
50m sigw	0.47848	0.24450	0.11000	0.27000	0.42000	0.65000	2.87000
80m sigw	0.49304	0.26877	0.11000	0.27000	0.42000	0.68000	2.78000
110m sigw	0.51717	0.29139	0.13000	0.28000	0.43000	0.70000	2.85000

Figure 27 depicts the mean velocities and standard deviations of the vertical motion, or W component of the wind speed.

There are several important features identified in Figure 27:

- There are periods where the mean W is zero, but there are large standard deviations
- There are periods of relatively large Ws (- or +) coincident with large standard deviations
- There is additional scatter of the data with height.

While several bad data points at the 110-meter level are included in these plots, it is possible that several of these observations of the large negative and positive motions at the 110-meter level are valid. Figure 27 implies there are short periods of time where the vertical motions that the rotors are subject to are very different at the top and bottom of the rotor plane.

Some observations of the potential differences in vertical motions over a sampling interval are presented in Figures 28 and 29. Figures 28 and 29 are 500 samples taken from the first few days in November 2008, split into day time and night time observations. In these particular samples there is no surprising information. The vertical motions and changes in vertical motions can be different for different measurement heights. The vertical velocities and standard deviations are quite variable through the day hours in Figure 29, and not as much at night. Note that towards the right side of the night time graph in Figure 28, both the vertical motion and standard deviations between sample numbers 370 and 400 are larger than the rest of the observations.

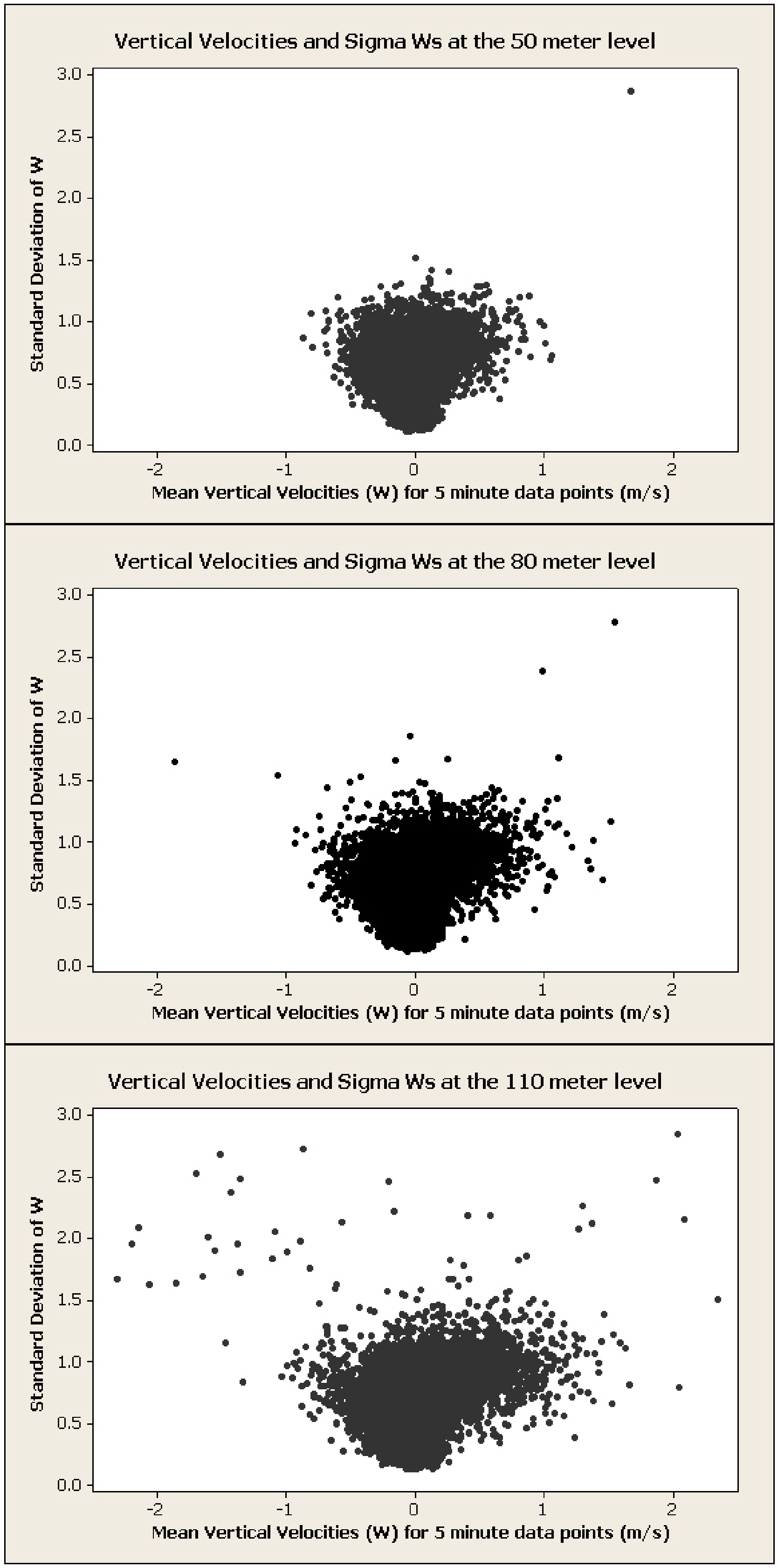

Figure 27. Vertical velocity and standard deviation measurements for the bottom (50m), hub height (80m), and top (110m) of a general turbine profile.

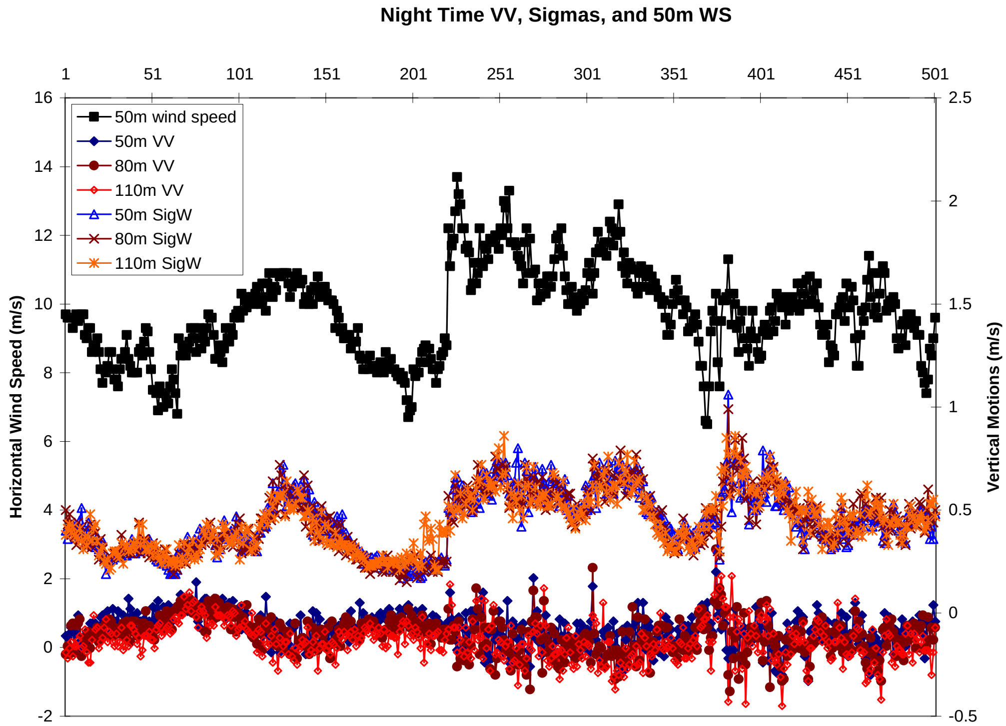

Figure 28. Night-time observation samples of vertical motions and the 50-meter wind speed.

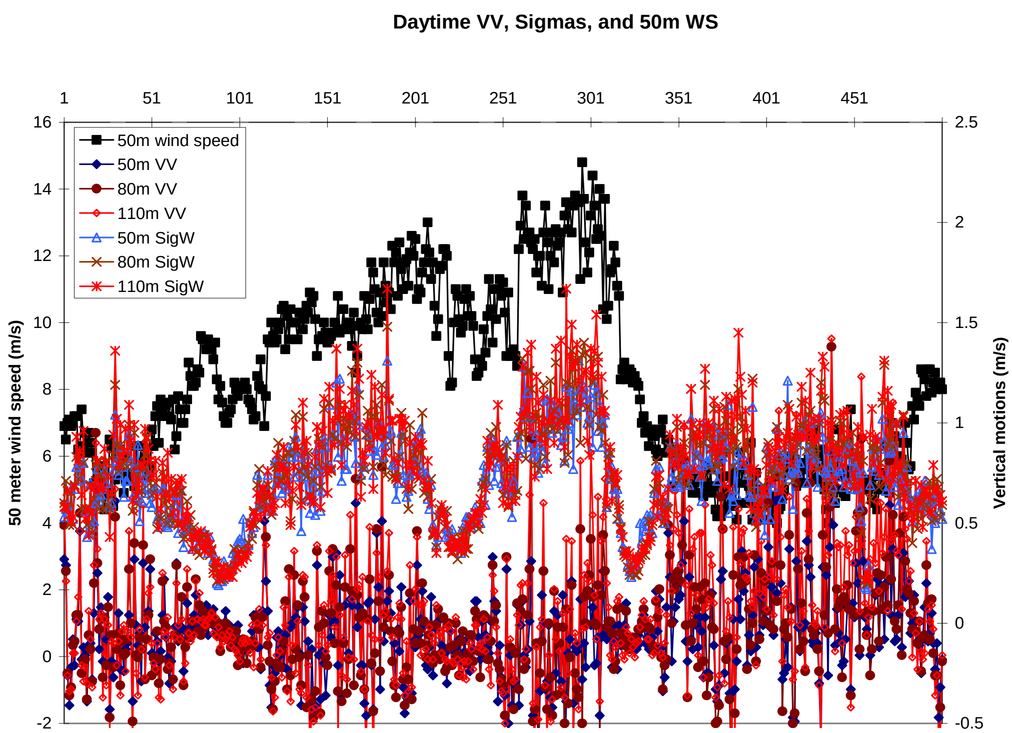

Figure 29. Day-time observation samples of vertical motions and the 50-meter wind speed.

To simplify the presentation of these motions, an elementary Vertical Motion Index (VMI) was created. The VMI is defined as ABS(W)+SigmaW for each data point. A large VMI represents vertical motions that either vary a great deal over time (large Sigma Ws), indicate a relatively large vector in the vertical (large Ws), or a combination of both. Table 5 lists the statistics for the VMI for the bottom, hub height, and top of the assumed rotor plane profile. Histograms for the VMIs are included in Figure 30. Data in Table 5 and Figure 30 suggest that most of the vertical motions or variations are below 1.0 m/s, but, the tail of the histograms distribution includes large motions or deviations that may need investigation into the effect on derived power. Currently, there is no specific threshold of VMI that may indicate a deviation from anticipated power production based on the measured horizontal wind speed.

Table 5. Summary Statistics for the VMI for the 50, 80, 110 meter levels.

Variable	Mean	StndDev	Minimum	Q1	Median	Q3	Maximum
VMI50m	0.59168	0.31937	0.13000	0.33000	0.51000	0.81000	4.54000
VMI80m	0.63038	0.36885	0.14000	0.34000	0.52000	0.85000	4.33000
VMI110m	0.68758	0.44191	0.14000	0.37000	0.55000	0.90000	4.88000

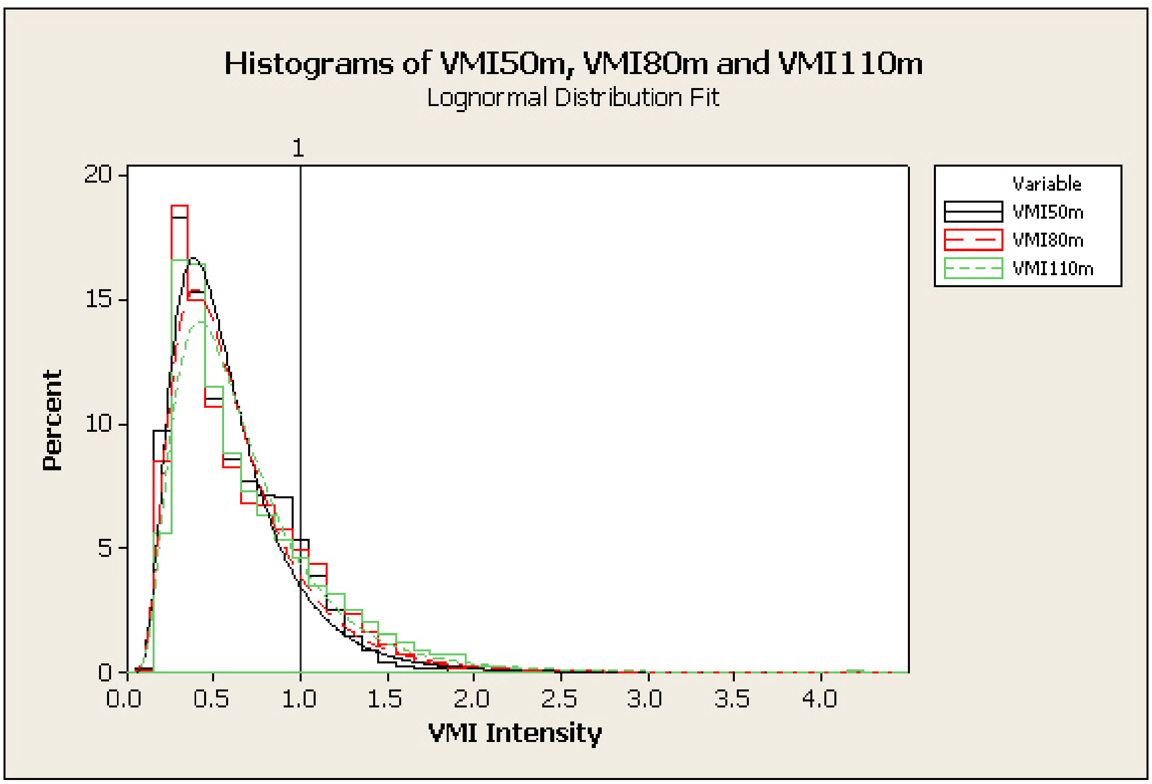

Figure 30. Histograms for the VMIs at 50, 80, and 110 meters.

It was noted that there was some dependence of the normalized speed and direction shears on wind speed in previous sections. Figure 31 shows the VMI plotted as a function of wind speed.

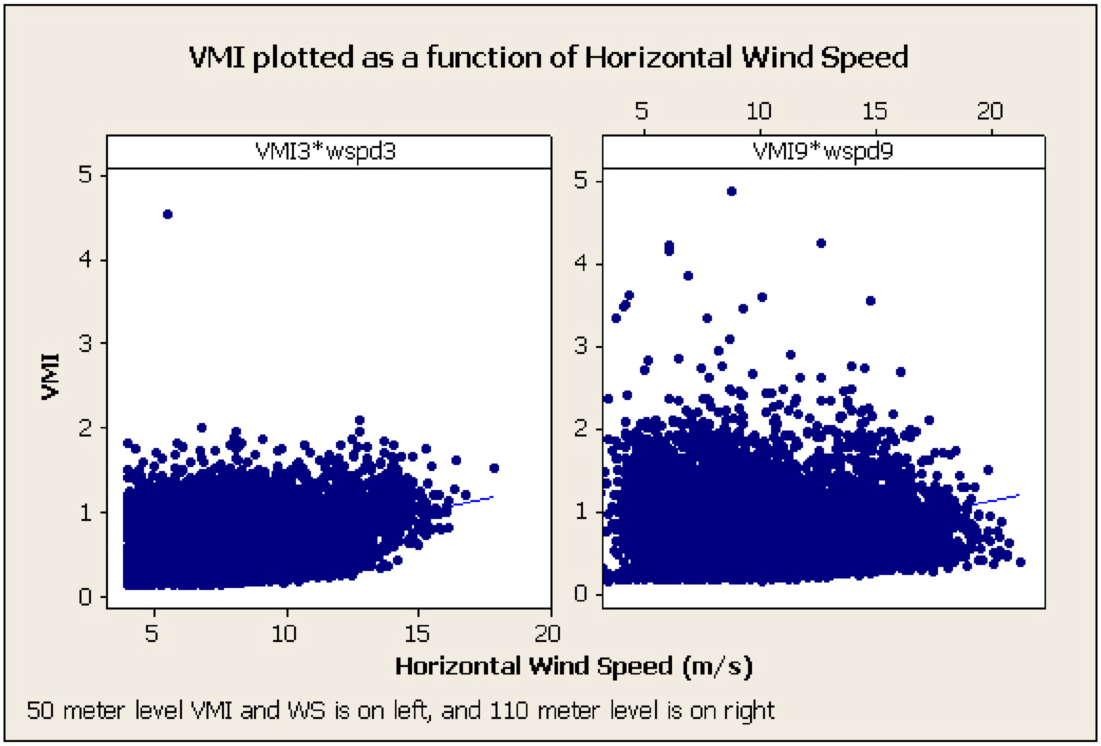

Figure 31. Graph of the VMI plotted as a function of horizontal wind speed.

There is not much correlation of VMI with wind speed in Figure 31, though there is less scatter of the data with larger speeds. Generally, larger VMI values will mostly be a function of convective or statically unstable periods, as suggested by the sample vertical motions and standard deviations in Figures 28 and 29. However, in a stratified verification of the largest VMI data, not included here, roughly 15 percent of the highest 50 VMI intensities occurred during the nocturnal hours. These large nocturnal VMIs may indicate some kind of turbulence associated with the LLJ [10]. They may also be an artifact of using the time of day instead of actual static stability. Complete investigation of large nocturnal vertical motions is beyond the scope of this data summary.

In previous sections it was noted that large shears in speed and direction can coincide. Figures 32 and 33 show the coincidence of large VMI with the normalized shears.

Figure 32 identifies that large directional shears can coincide with large vertical motions, though the incidence is small. In general as the VMI increases, the directional shear values tend to fall in a smaller range, but significant three-dimensional motions are present since a 0.25 deg/m shear represents a 15 degree difference in wind direction between the top and bottom of the rotor plane. The addition of large vertical motions on top of directional shears indicates a complexity of three-dimensional effects that should be modeled to understand the effect on the wind power produced. Figure 33 includes the normalized speed shear plotted as a function of VMI. As with the directional shears, speed shears tend to fall in a smaller range as the VMI intensity increases. Large speed shears can coincide with large VMI, as a 0.05 shear corresponds to a 3 m/s difference between the top and the bottom of the rotor plane. This is an equivalent of the alpha shear exponent of approximately 0.38 with a hub height wind speed of 10 m/s.

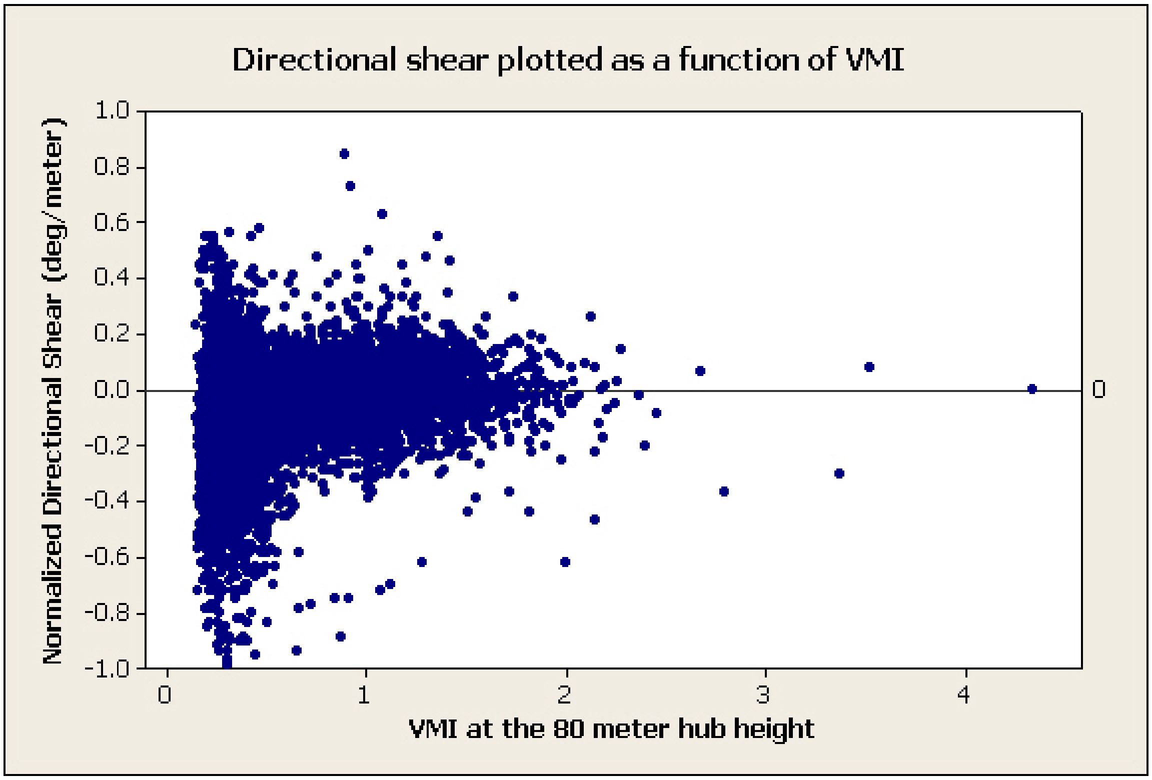

Figure 32. VMIs at the 80-meter hub height and normalized directional wind shear.

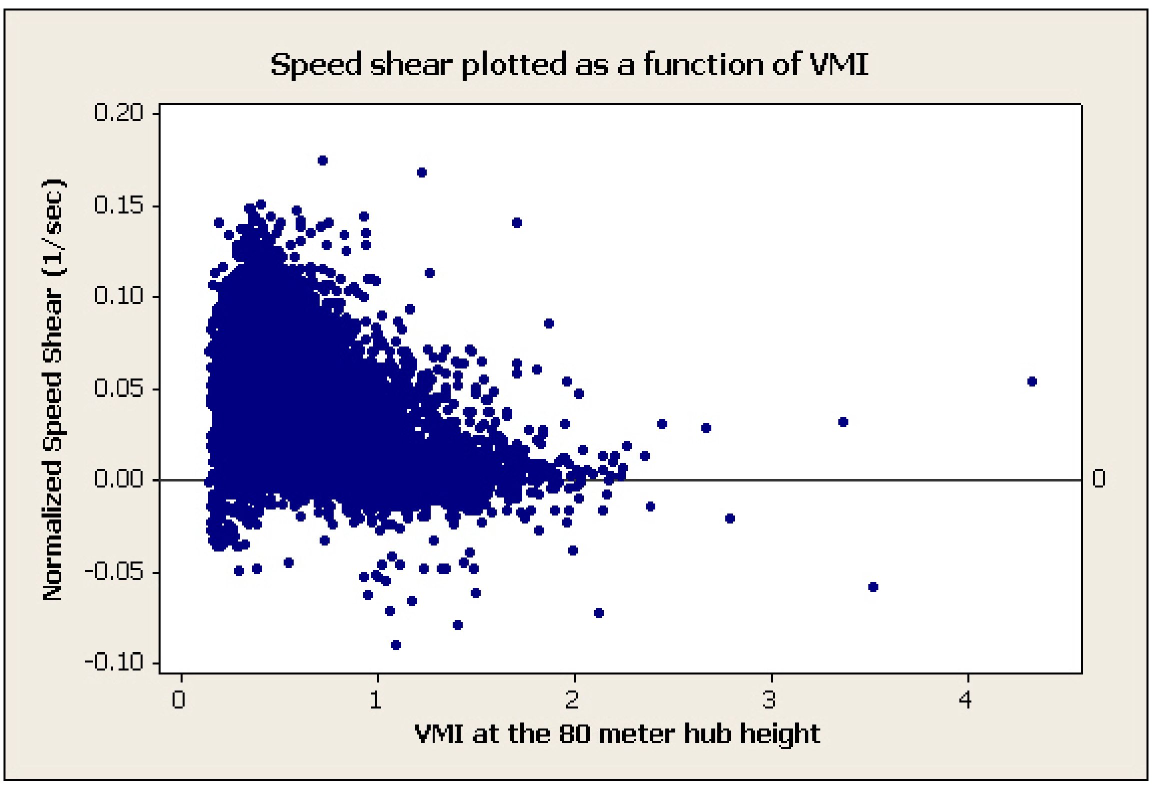

Figure 33. VMIs at the 80-meter level and normalized wind speed shear.

8 DISCUSSION

The data in this report indicate that a SODAR can effectively summarize the forces in the entire rotor plane for wind resource assessment purposes. Documenting the actual extreme speed and directional shears and comparing them to the design standards in a wind resource assessment may add value to the resource report and decrease some uncertainties associated with operation and maintenance of a site specific wind farm. Having a one year record of frequencies of large shears and three-dimensional wind variations may also improve the anticipated maintenance schedule and operational costs of a wind farm.

The potential wind power at a site is usually assessed by measuring horizontal wind speeds and pressure, and calculating the wind power density (WPD). The WPD is calculated from the following equation:

$$WPD = 1/2n \sum \rho \upsilon i^{\ 3}$$

Where
n = the number of records in the averaging interval;
ρ = the air density (kg/m^3); and
vi^3 = the cube of the i^{th} wind speed (m/s) value.

It follows from this equation that only the horizontal speeds are used to estimate the potential wind power. Additional forces or three-dimensional effects that may act to slow, speed up, or stress the rotor, are not taken into account.

Data taken with a SODAR for approximately 90 days shows the three-dimensional wind has large temporal variability, large shears, and non-horizontal forces that may be significant in the actual performance of a turbine. The nature and frequency of these shears and forces will be site specific. In this sample of the southern Great Plains, 15 to 20 percent of the samples showed large enough variations in speed or directional shears, or vertical motions, to prompt the question of how these forces actually affect the power derived from the wind during that interval. A subset of these samples may have a measureable impact on the power derived for a given horizontal wind speed. Additional investigations can include modeling of turbine power output with and without these 3 dimensional forces, or actual field studies with the SODAR measuring the three-dimensional wind inflow into a turbine and correlating the measurements with the actual power output.

The SODAR data include information along the three-dimensional x,y,z axes generally used in meteorology. The u, v, w data along these axes can be used, along with the variance of these measures, to model the site and time specific forces on the turbine.

The sampling frequency of a SODAR is limited by the depth of the layer of interest, and the speed of sound. In the case of this phased array mono-static SODAR, a pulse of sound is emitted along each of the 3 beams approximately 1 second (1Hz) for a 150-meter range of interest, so the sampling interval along each beam is approximately 3 seconds. It would be twice as long, therefore twice as slow a sampling rate, for a full range of 300 meters. High frequency turbulence may not be well characterized by the use of a SODAR due to this slow sampling frequency.

The engineering standards for turbine design [13] include certain vertical velocities and shears, but these forces are generally not quantitatively included in a site's wind resource assessment. A number of studies [9, 10, 14] have shown that the three-dimensional winds may vary significantly from the mean profile, and expose turbines to conditions outside of the current engineering standards. Figure 34 represents the different forces and shears that may influence the wind speed at a turbine. The results from these studies emphasize the importance of complete characterization of the wind through the anticipated rotor plane. The extreme shears and vertical data taken with the SODAR suggest that there may be some type of modifying or stressing effect for power production and unbalanced turbine loads when certain three-dimensional features are present. Identifying these features and the specific quantitative impact on power output can lead to refined resource assessments, especially in complex terrain settings. It is hypothesized that a different form of the WPD equation may reflect a more applicable wind speed when certain features are present.

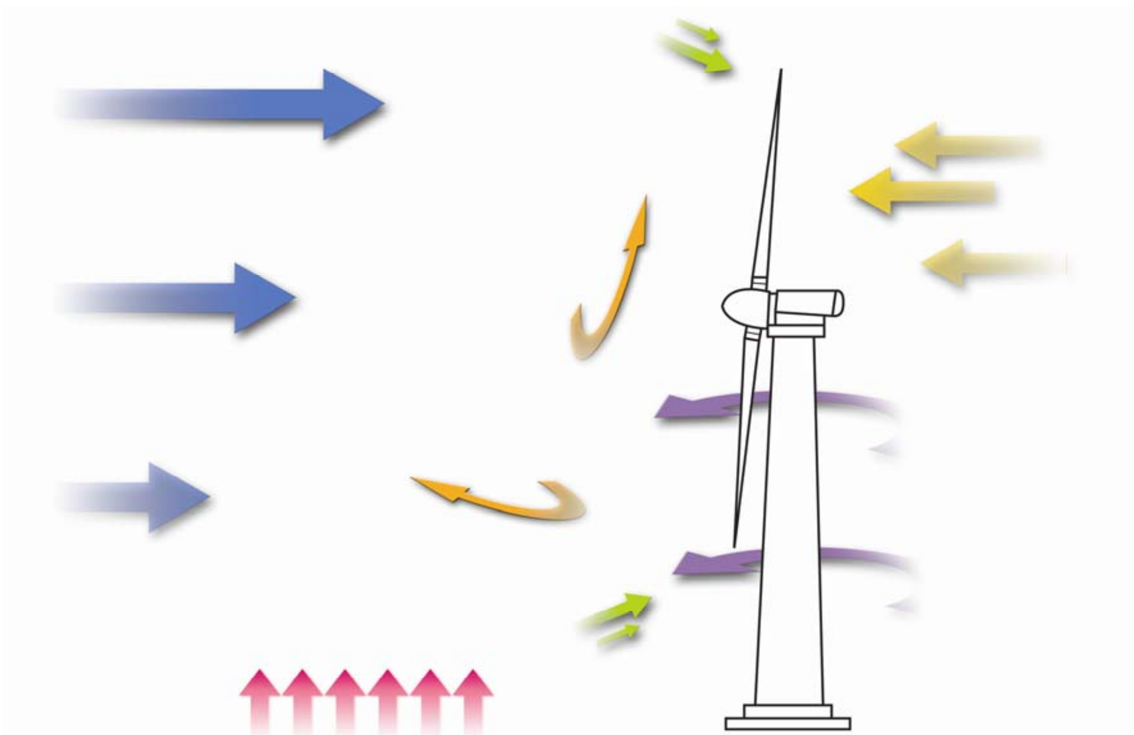

Figure 34. A representation of the various shears and turbulence present in the wind field.

9 RECOMMENDATIONS FOR FUTURE WORK

There are many benefits to measuring the winds through the entire rotor plane. Reducing the uncertainty of the operating environment and measuring the actual speed and directional shears and frequency of these shears can provide information to decision makers on locating or operating wind turbines and wind farms. Results from this field study indicate that SODARs can reproduce wind information that is currently used in resource assessments, and has the potential to add important information above hub heights.

Intuitively, one might expect minimal benefits of intensive investigation of the rotor plane profile in smooth and simple terrain sites, since operating a SODAR needs weekly attention. This may add to the cost of a resource assessment. While wind profiles and shear exponents may be well behaved in their "means", the shape of the wind profiles vary as a function of stability, and the diurnal evolution of the boundary layer generates large exponents and types of shears that should not be ignored. Data gathered in Minnesota and Texas show the regular occurrence of large exponent values in the range of 0.3 and 0.4, and 0.4 and 0.6 respectively [14, 15]. It should not be assumed that simple terrain and relatively smooth sites will not benefit from SODAR analysis of the whole rotor plane.

Data summarized and referenced in this report identifies speed shear in excess of current design criteria. Large directional shears and vertical motions were also noted. Vertical motions are significant from the perspective that some of the vertical component may be included in horizontal wind measurements. At sites where regional characteristics induce more frequent or intense vertical motions, a notable difference between the data used in wind resource characterization and the actual horizontal wind available to the turbine may be present. Large shears may lead to unbalanced loads, and modify the actual versus the anticipated electricity produced by a turbine.

9.1 Additional Investigation or Verification of Large Shear Effects

The following items identify potential future work that follows naturally from the results presented in this report. Similar work or studies may have been conducted in the past with limited shear or short term data, and for conditions that may not be representative of the larger rotor dimensions and sweep areas that are currently available.

- Quantify the effects of directional shear through the rotor plane on the actual electric power produced. While more sophisticated methods of control include yaw and pitch control to orient the turbine or blades into the wind, directions may vary 20 or 25 degrees from the bottom to the top of the rotor plane, mostly during the stable nocturnal periods. A quantifiable difference in power, calculated to be a function of the yaw degree error may be noted, as well as potential unbalanced loads. This could be verified in field testing. While the resulting electrical power losses and fatigue may be turbine specific, documenting the frequency of directional shears having measureable effects on power produced and loads and would be an aid to certain stakeholders in the wind industry.
    - Documenting these directional shear conditions in wind resource assessments for sites prior to development and operation may add value to the resource assessment.

  - Various modeling studies may be used to evaluate yaw control and offsets in these types of sheared environments.

- Investigation of the large vertical motion variations on power production should be pursued. While the vertical component of the wind can not be utilized by a turbine, non-horizontal forces may vary the electrical power produced or load on a turbine. The magnitude of a non-horizontal force that produces non-nominal effects may be turbine specific, but noting the magnitude and frequency of these types of forces at potential wind farm sites may aid certain stakeholders in the wind industry. A field test using a SODAR in a location with suspected vertical motions or a noted decrease from ideal electrical power based on measured horizontal speed may reveal the specific environmental wind element that is the root cause of the low electrical output. Modeling is also an option using SODAR data, see the following bullet.

- SODAR data through the rotor plane can be used in wind industry models. The SODAR u, v, w component data and variances through the rotor plane can be input into power production type models instead of using one measurement point, assumptions, turbulence models, and design criteria to bound calculations. This may require some modification to the models. In addition, the model can also be field tested at an operating farm by comparing the model results using SODAR data and the actual measured output of the turbine closest to the SODAR.
  - The model could eventually replace the summation equation currently used in resource assessments. Another potential benefit from this work could be to suggest a modification to the existing wind power equation to include a factor or coefficient that varies with each 10-minute time step based on knowledge gained. Recent modeling investigations using multiple wind speed measurements and actual profiles show a better correlation of wind input and power output than with one hub-height wind speed [16].

- Investigation of the SODAR u, v, w data and its variance with height may provide insight into high frequency turbulence. This should be pursued to see if there are signals in SODAR data that can infer this high frequency intense turbulence that may induce fatigue or pre-mature failures. Instruments generally require a much higher sampling rate to capture turbulence structures, but there may be signals within the SODAR data that could infer the presence of intense turbulence. This could be established in field testing by co-locating a SODAR with high frequency sampling instruments. Currently, this kind of information is included in wind resource assessments only through the horizontally measured and estimated turbulence intensity.

9.2 Wind Resource Assessment Work

Data compiled in wind resource assessments generally does not include complete characterization of sampling interval data. Speed shear is usually summarized in some fashion, whether in identifying the average shear value, characterized in a diurnal fashion, or averaged in hourly values or over the entire sampling period. Wind directional shear is not generally addressed in wind assessments. The following recommendations are offered to enhance the meteorological information identified in wind resource assessments:

- The sampling interval frequency and magnitudes of both speed and directional shear data should be added to data presentations in the wind resource reports. The data taken during the characterization phase includes the speed information, but it is not currently detailed in such fashion in the report. This information may be relevant to turbine selection, operation, and maintenance.

    - SODAR data, and remote sensing data in general, can provide additional benefits to this by providing speed and directional shear data through the entire rotor plane, not just to hub height. More and more studies suggest that as the size of the sweep area increases using one or more points at and below hub height does not adequately characterize the wind above hub height.

- Methodologies for using SODAR data vertical component and standard deviations need to be developed. Understanding the magnitude and deviations of the force that impacts power production from the ideal should be completed prior to developing the methodologies. This work folds into the concept that the horizontal wind measured in wind assessments may not adequately characterize the wind available to a turbine for power production. This may be especially true when wind resource assessments only include measurements below hub height.

- It may be beneficial to co-locate SODARs with conventional meteorological towers for sub-intervals of resource assessments. Co-location of measurement resources will provide a better estimate of the rotor plane environment, even if only 8 to 10 weeks of the collection period includes both measurement platforms. It should be noted that seasonal and annual variability is likely, so investigation into the correct season to gather the best data should be performed prior to temporary deployments. It should also be noted that findings and conditions identified in one season may not characterize the conditions present during other seasons. An additional benefit of co-locating a tower and SODAR is the calculation of static stability to adequately characterize and categorize the complete wind profiles measured with the SODAR.

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