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National Renewable Energy Laboratory

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National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401
303-275-3000 • www.nrel.gov

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1 Introduction

With the increased interest in remote sensing of wind information in recent years, it is important to determine the reliability and accuracy of new wind measurement technologies if they are to replace or supplement conventional tower-based measurements. In view of this, HYDROCHINA Corporation (HYDROCHINA) and the United States National Renewable Energy Laboratory (NREL) conducted a comparative test near a wind farm in Hebei Province, China. We present the results of an analysis characterizing the measurement performance of a state-of-the-art Sound Detection and Ranging (SODAR) device when compared to a traditional tower measurement program.

NREL performed the initial analysis of a three-month period and sent the results to HYDROCHINA. When another month of data became available, HYDROCHINA and their consultant Beijing Millenium Engineering Software (MLN) repeated NREL's analysis on the complete data set, also adding sensitivity analysis for temperature, humidity, and wind speed (Section 6). This report presents the results of HYDROCHINA's final analysis of the four-month period.

1.1 Measurement Project Description

This project collected data from a Second Wind Triton SODAR unit and from a 70 m meteorological tower located 80 m to the east.

This study compares data from a 120-day period covering January 1 to April 30, 2011.

1.2 Triton Configuration

The Second Wind Triton is a SODAR device designed for use in wind energy applications. The Triton uses a patent-pending hexagonal speaker array to efficiently focus sound beams to improve signal-to-noise ratio accuracy and decrease disruption. The array is housed in a tri-lobed acoustic enclosure to reduce the chance of sound artifacts disrupting data. Each of the three beams samples a volume of atmosphere at each measurement height that is within 5° of the beam centerline and about 20 m thick, centered on the measurement level. The unit is two meters tall, with a two meter by three meter footprint (Fig. 1), and includes internal controls to compensate for uneven ground. It has a built-in GPS to identify the time and location of the data. More information is available at http://www.secondwind.com.

The Triton was programmed to save one record every 10 minutes. Each record includes data from 11 heights, between 30 m and 200 m above the ground. The 50 m and 70 m heights coincided with the measurement heights on the meteorological tower. Data returned at each height includes wind direction, horizontal and vertical wind speeds, and turbulence intensity. The system also recorded data quality indicators (0% to 100%) for both wind speed and turbulence intensity. These data quality values, which incorporate signal-to-noise ratio, signal strength and data recovery rate, were used to screen the data for this analysis.

Figure 1. Triton installed at site. ***Photo by Dennis Elliott, NREL/PIX 19940***

1.3 Meteorological Tower Configuration

The meteorological tower is a 70 m guyed, 3-legged lattice tower (Fig. 2). The instrumentation was designed to conform to IEC Standard IEC 61400-12-1, Power Performance Measurements of Electricity Producing Wind Turbines. The two primary levels of instrumentation are located at 50 m and 70 m. Table 1 provides the details of the instrumentation used in this comparison study. (Additional sensors were present, but the measurements were not relevant to this study.) Anemometer calibration sheets are presented in Appendix 1.

Table 1. Instrumentation used in comparison study

Channel	Sensor	Model	Height agl	Boom Orientation	Boom Length	Notes
C1	Anemometer (eastern)	RISØ 2546A	70 m	90°	1.8 m	Calibrated SN#9899
C2	Anemometer (western)	RISØ 2546A	70 m	270°	1.8 m	Calibrated SN#9898
C3	Anemometer	RISØ 2546A	50 m	270°	1.8 m	Calibrated SN#9897
A1	Wind Vane	Second Wind PVI	68 m	270°	1.8 m	
A3	Wind Vane	Second Wind PVI	48 m	270°	1.8 m	

The face width of the tower is approximately 0.5 m. All three anemometers and both wind vanes are mounted on 1.8 m booms extending east and west of the tower.

There also were sonic anemometers (not shown in Fig. 2) installed at both the 50 m and 70 m levels on 1.5 m booms extending to the northeast.

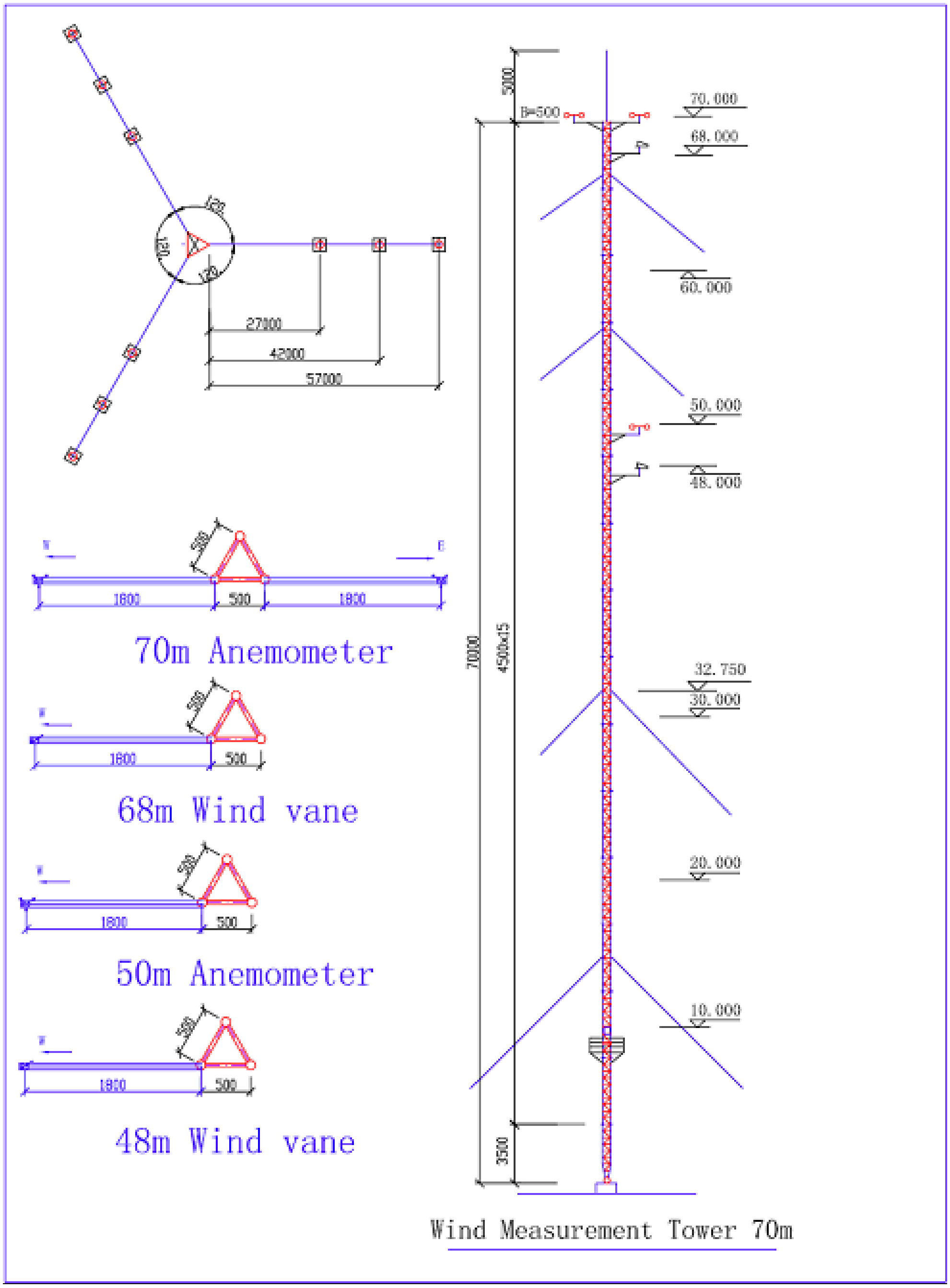

Figure 2. 70 m meteorological tower configuration

1.4 Site Layout and Typical Conditions

Vegetation surrounding the measurement sites is slightly rolling grassland. The Triton is at an altitude of approximately 1525 m. The 70 m lattice meteorological tower is 80 m east of the Triton, at an altitude of 1532 m. There is an operating wind turbine 210 m to the northeast of the Triton. The specific location of the measurement sites and the wind turbine are shown in Table 2, and a picture of the site is shown in Figure 3.

Prevailing winds during the period of record were predominantly from the northwest, with a small fraction from the south. The percentage of winds from other directions was insignificant.

Table 2. Location of measurement sites

Object description	Elevation	Distance from Triton	Height
Triton	1525 m	0	2 m
Wind turbine	1526 m	213 m	65m+37.5 m
Wind Tower	1532 m	83 m	70 m

Figure 3. Nearest turbine and meteorological tower as seen from Triton. ***Photo by Dennis Elliott, NREL/PIX 53709.***

2 Data Filtering

2.1 Triton Data Filtering

SODAR data was filtered to remove low-quality and spurious data before any analysis was performed. In this study, we used the Second Wind filtering criteria specified in Walls (2009):

1. Wind speed quality factor >= 90%
2. Vertical wind speed (absolute magnitude) <= 1.5 m/s
3. Turbulence quality factor >= 90% (used only for turbulence intensity analysis).

The second criterion removes records in which precipitation may be interpreted by the Triton as a strong vertical wind speed.

2.2 Tower Data Filtering

Data from the meteorological tower also must be filtered before analysis. Basic filtering consists of removing all records in which the recorded wind speed is less than 0.5 m/s. A typical anemometer has a calibration offset of about 0.35 m/s; therefore, setting a minimum wind speed of 0.5 m/s assures that the anemometer is measuring a wind speed greater than the offset.

Periods of suspected icing also were removed from the tower data. These were identified by a combination of low temperatures, very low standard deviations of wind vane readings, and large differences between the SODAR and tower wind speeds.

2.3 Directional Data Filtering

Initial analysis of the data showed that the prevailing direction was northwest, with more than 70% of the winds falling in the sector from 270° to 360°. A secondary (and much smaller) peak occurred around 170° to 180°.

A number of factors affected wind data from certain directions:

- a wind turbine located to the northeast of the Triton will affect the northeast wind;
- the tower structure affected the western cup when the wind was from the northeast to the southeast, and it affected the eastern cup when the wind was from the northwest to the southwest;
- the sonic anemometers affected the western cup anemometer values when the wind was from the northeast;
- there were very few samples recorded from the SE, increasing uncertainty in this sector;
- a wiring problem caused recorded tower wind speeds to be abnormally low when the wind was from the 0°-30° sector

Considering all these factors, we used only the data from the northwest sector (270° to 360°) for most analysis, although the southerly sector also is used for wind direction correlation to improve the fit.

3 Overall Triton Performance

3.1 SODAR Operational Uptime

Uptime is defined as a sampling period in which at least one wind speed measurement (at any level) is reported. Operational uptime of the Triton was 98.41% (17005 of 17280 samples). The longest data outage was 257 samples (about 43 hours) from 2011:02:12:0830 to 2011:02:14:0310, caused by a software error and compounded by a temporary loss in communication. There were also a few single sample outages. These short outages are caused by a database problem, and while the data are recoverable, they were not recovered for this study.

In comparison, the meteorological tower recorded data 99.97% of the time at all three anemometers. (There was loss of five samples from 2011:01:12:0110 to 2011:01:12:0150 [5 of 17280 samples].)

3.2 Percent of Valid Data versus Height

Table 3 and Figure 4 show the percentage of samples at or above a given wind speed data quality rating. Percentages are relative to the number of all records with data observations (17005 samples). A separate comparison filters the data to eliminate samples with high absolute values of vertical wind speed.

Table 3. Percentage of data samples and quality ratings for Triton

Height (m)	**All Samples**				**Samples with abs(WS(vert)) < 1.5ms**			
	Q95	Q90	Q85	Q80	Q95	Q90	Q85	Q80
30	91.25%	98.23%	98.79%	99.05%	91.10%	98.06%	98.62%	98.88%
40	90.33%	98.28%	98.97%	99.28%	90.16%	98.07%	98.76%	99.06%
50	89.93%	97.85%	98.72%	99.26%	89.79%	97.65%	98.52%	99.05%
60	88.01%	96.31%	97.52%	98.19%	87.88%	96.15%	97.32%	97.99%
70	85.14%	94.57%	96.08%	96.82%	85.05%	94.44%	95.94%	96.66%
80	80.56%	92.17%	94.22%	95.32%	80.51%	92.05%	94.08%	95.17%
100	67.26%	83.85%	87.29%	89.64%	67.21%	83.78%	87.20%	89.56%
120	50.26%	69.71%	74.37%	78.30%	50.26%	69.71%	74.37%	78.30%
140	33.00%	52.76%	58.65%	63.52%	33.00%	52.76%	58.65%	63.52%
160	19.58%	35.99%	41.69%	46.82%	19.58%	35.99%	41.69%	46.82%
200	6.67%	14.33%	17.94%	21.16%	6.66%	14.24%	17.80%	20.96%

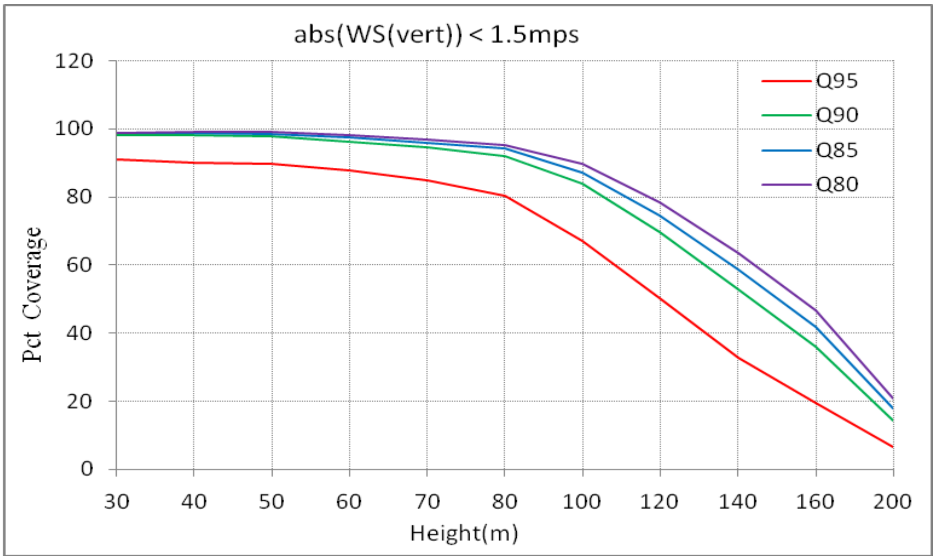

Figure 4. Triton recovery rate by height and signal quality (samples with high vertical wind speed excluded)

These recovery rates are slightly lower than the average rates observed at other Triton installations. For example, in NREL's previous study of a Triton in west Texas, recovery rates (Q90 with vertical wind speed filtering) at 60 m and 80 m were 97.4% and 94.9% respectively, about 1% to 3% greater than those observed at the site. A possible explanation is that the data were collected over four winter months, resulting in an average ambient temperature of -7.74°C.

SODAR signal strength is affected by atmospheric conditions. Moisture and turbulence both enhance signal returns. The cold dry night air at the test site represents the most likely cause for the slight decrease in data recovery rates as compared to the Texas site.

4 Correlation Comparison: Triton versus Meteorological Tower

In this section, we present the sample-by-sample correlation of Triton data with data from the meteorological tower. Except for the wind direction analysis, only samples from the 270° to 360° sector were used in this analysis. Periods of suspected icing events also were removed.

4.1 Correlation Coefficient at Tower Heights

Only 50 m and 70 m wind speeds were available for correlation. At 70 m, the western (C2) anemometer was used since the eastern anemometer was strongly affected by tower shadow when winds were from the prevailing direction. SODAR wind speeds tend to be very slightly less than the corresponding meteorological tower speeds, as shown by the following linear fits and in Figures 5 and 6. Ratios of average SODAR speed to average tower speed were 0.9904 at 70 m and 0.9851 at 50 m.

70m: SODAR = 0.977 *Met + 0.111 R^2 = 0.971 (R 0.985) Npts = 9931

50m: SODAR = 0.994*Met - 0.076 R^2 = 0.973 (R 0.986) Npts = 10279

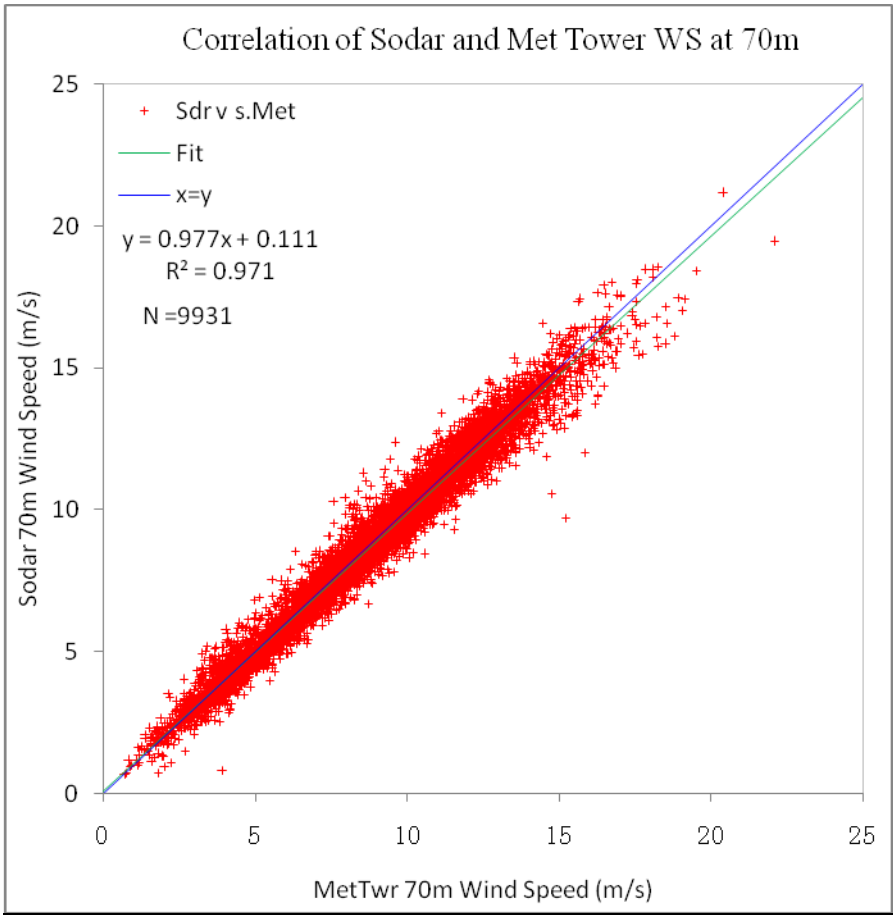

Figure 5. Comparison of wind speed data from 70 m height

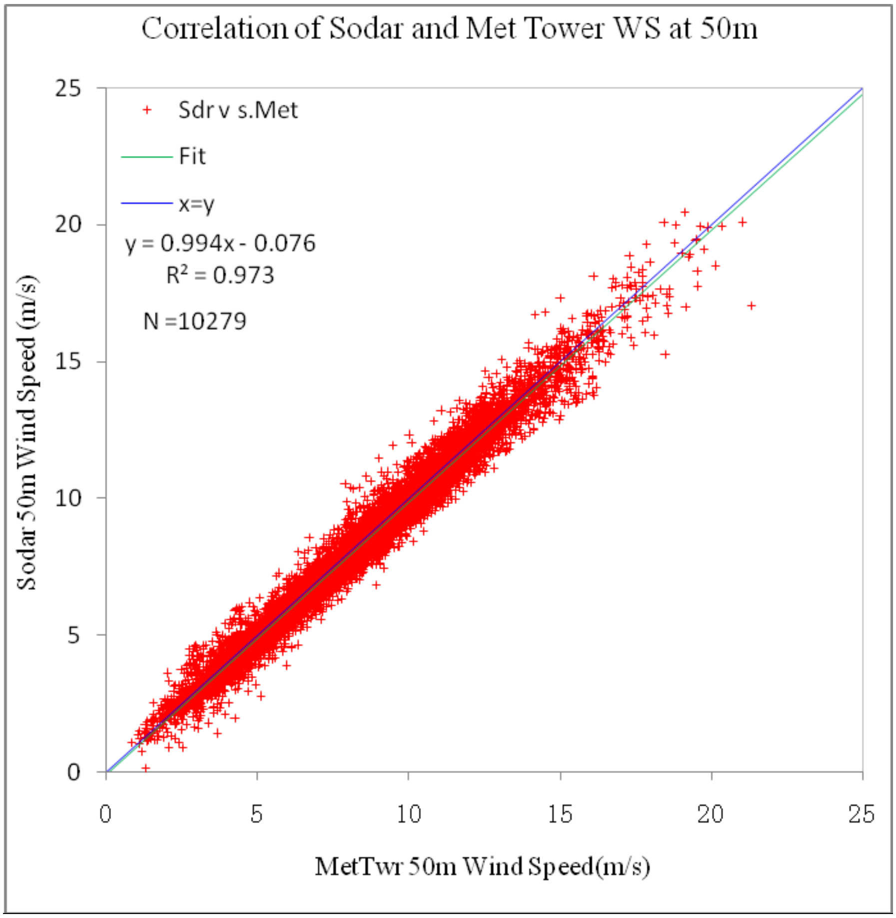

Figure 6. Comparison of wind speed data from 50 m height

Figures 7 and 8 show the frequency distribution curves by wind speed at 70 m and 50 m, respectively, for the Triton and the tower. The distribution curves between the Triton and the tower are in very good agreement. The max deviation is 0.6% (in 8-8.5 bin) at 70 m and 0.93% (in 4.5-5 bins) at 50 m, as shown in the table in Appendix 2.

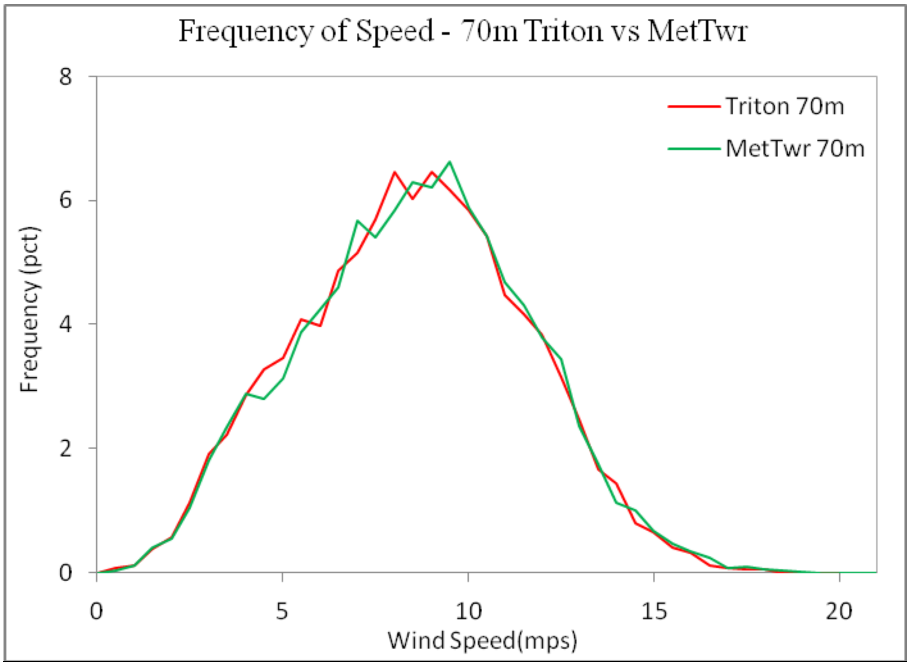

Figure 7. 70 m wind speed distributions from Triton and met tower

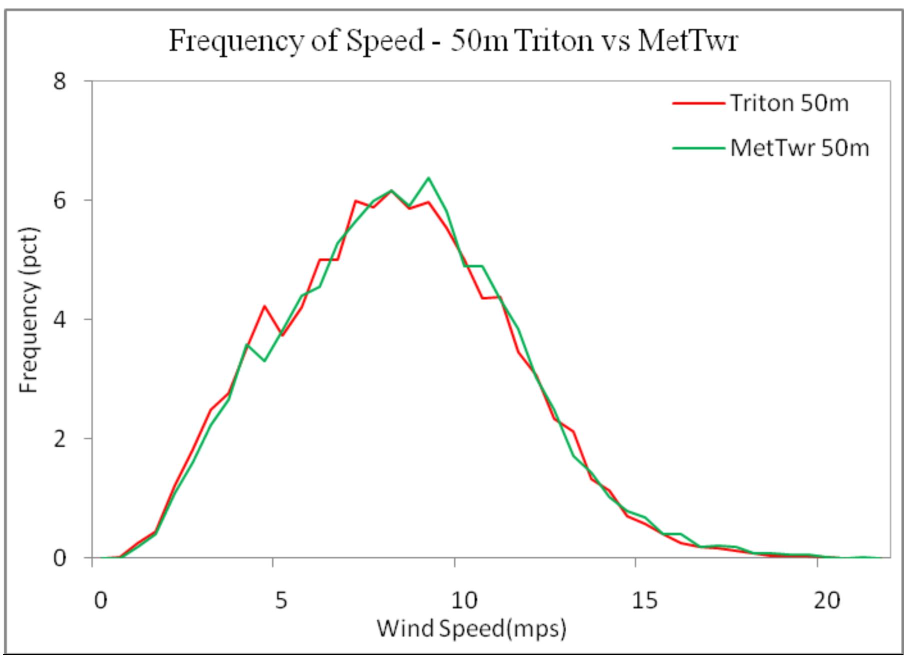

Figure 8. 50 m wind speed distributions from Triton and met tower

4.2 Wind Direction Comparison

When analyzing wind direction data, it is important to exclude samples where the wind speed is low, since the associated wind direction may be meaningless. In this study, wind direction samples in which the wind speed was less than 3.0 m/s were ignored.

Wind direction data were available at 50 m and 70 m from the Triton and at 48 m and 68 m from the meteorological tower. After removing samples with low wind speed or suspected vane icing, correlation was very good over the remaining samples (Fig. 9 and 10). A linear fit gives the following correlation:

```
70m: SODARWD= 1.004*MetWD + 4.57 R² = 0.998 (R 0.999) Npts = 14778
50m: SODARWD= 1.007*MetWD + 4.134 R² = 0.997 (R 0.998) Npts = 15083
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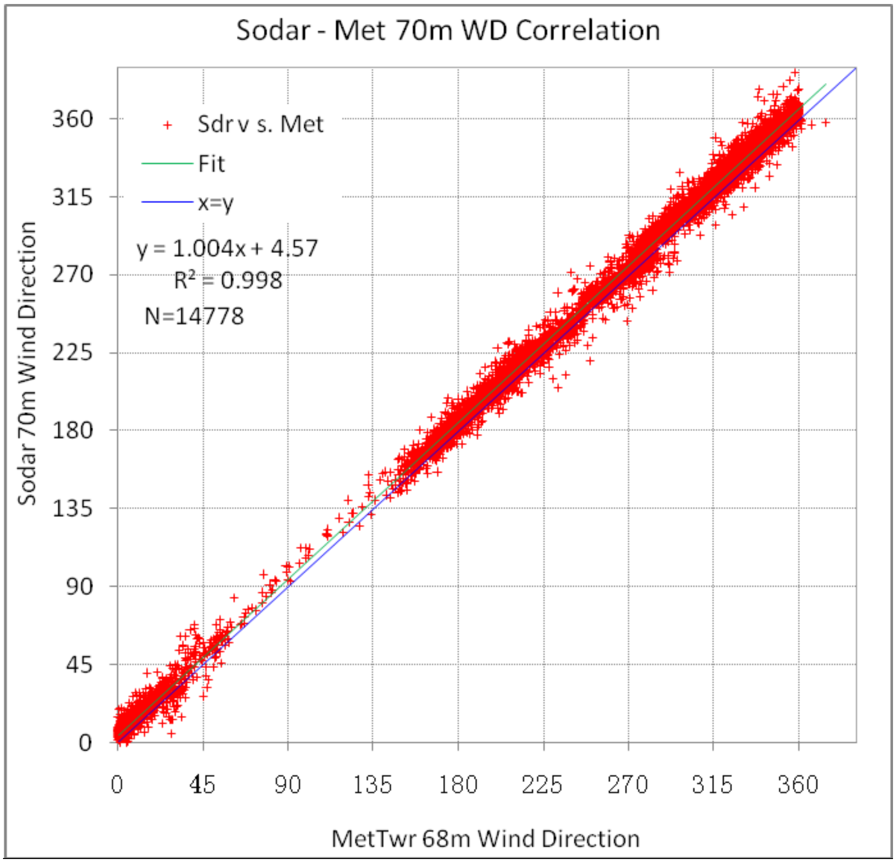


Figure 9. Comparison of wind direction data from 70 m height

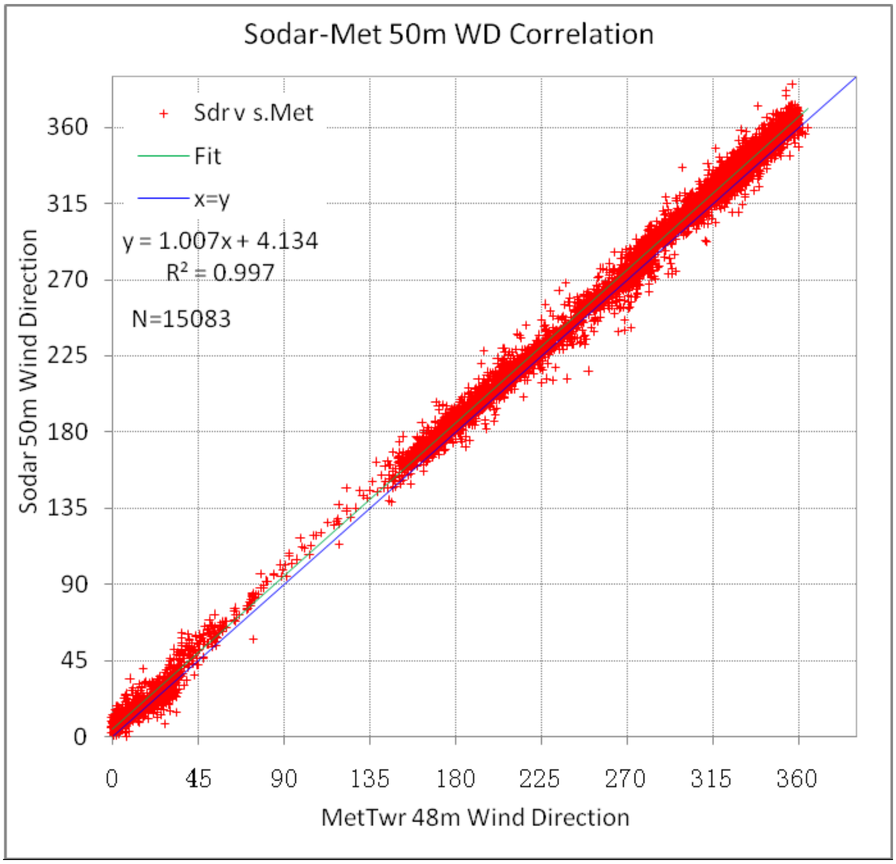


Figure 10. Comparison of wind direction data from 50 m height

Figures 11 and 12 show the wind direction distributions measured by the tower and the SODAR at the 70 m and 50 m heights, respectively. The overall shape and magnitude of the distributions are in very good agreement, although there is a slight clockwise rotation (about 5°) in the SODAR distribution. This same rotation is seen in the correlation of Figures 9 and 10, and is most likely caused by the alignment of the tower to magnetic north while the Triton was aligned to true north.

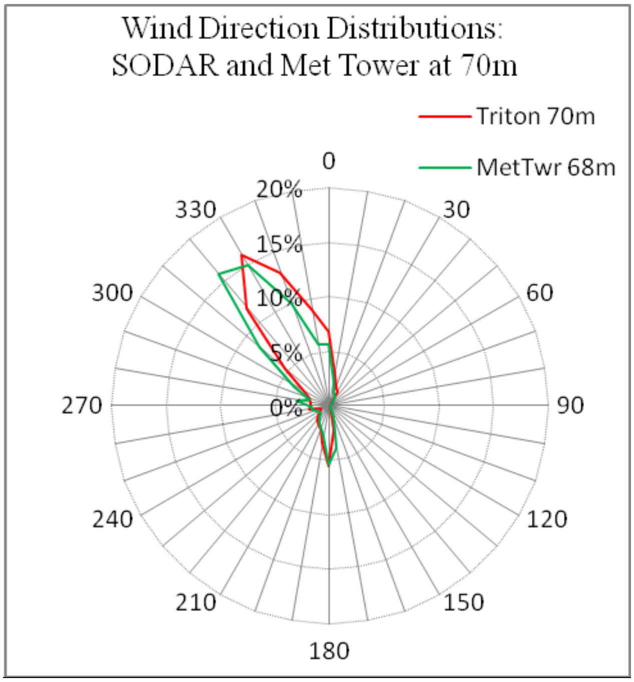


Figure 11. Wind direction distributions at 70 m

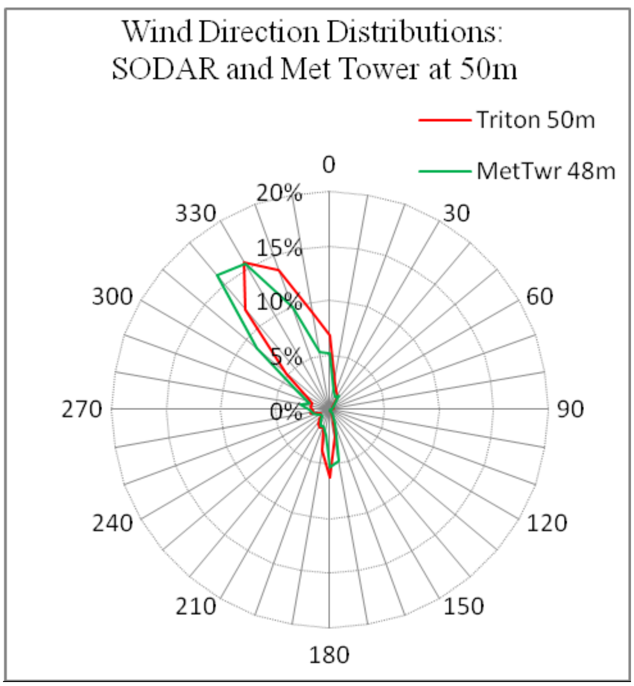


Figure 12. Wind direction distributions at 50 m

4.3 Wind Shear Profile Analysis

Wind shear on the meteorological tower could only be computed between the 50 m and 70 m levels, using the 50 m anemometer and the 70 m C2 (western) anemometer (both oriented at 270°). Shear was only computed when the 50 m speeds on both the tower and the SODAR were at least 3.0 m/s. The shear calculation was further restricted to only the most frequent wind direction sector of 270° to 360°. Shears also were categorized into daytime and nighttime shears, with daytime being defined as 0800 to 1750 local time (an approximation for the winter months).

As shown in Table 5, the average shears measured by the Triton were somewhat higher than those from the meteorological tower, with most of the differences occurring in the nighttime hours. It should be noted that 20 m (70 m – 50 m) is a relatively thin layer over which to compute wind shear, and that uncertainty may be higher.

Table 4. Wind shear exponent analyses

	SODAR	Met	Nsamp
All	0.166	0.141	10012
Day	0.056	0.058	4287
Night	0.249	0.203	5725

Figure 13 shows the comparison of average shears for each 10-minute interval during the day. The difference between the nighttime shears for the SODAR and the met tower is unclear, but some of the causes of this difference can be seen from an analysis of the diurnal wind speeds. The spread between the SODAR 50 m speed and the met tower 50 m speed is larger during the nighttime than it is in the daytime, while the 70 m speeds track each other much better. The overall effect is to increase the SODAR shear during the night. The cause of this difference should be investigated to see if the effect is dependent on wind speed, seasonal variations, or other factors. Under conditions of very high shear, SODAR measurements at low heights can be slightly lower than point (anemometer) measurements due to the low speeds at the bottom of the sample volume. These speed differences, which are more pronounced at the lower levels, can lead to an increase in the shear exponent. It should be noted that the nighttime Triton speeds are about 1% lower than the anemometer values at 70 m, and about 2.5% lower at 50 m. The narrow 20 m interval used for calculating shear can cause these small speed differences to result in a relatively large shear exponent difference.

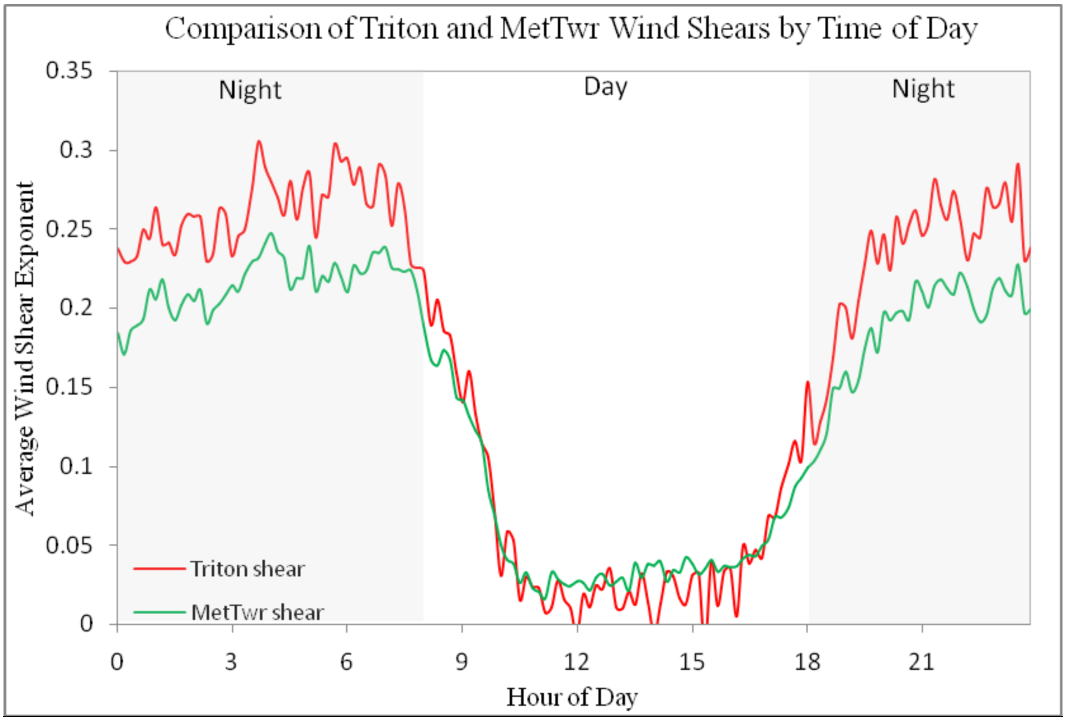


Figure 13. Wind shear profile analysis of Triton and wind tower

4.4 Turbulence Intensity Comparison (Triton versus Tower)

Turbulence intensity (TI) measurements from the SODAR are inherently different from those of the meteorological tower. The SODAR measures over volume and the meteorological tower measures at a single point. In addition, the meteorological tower measures the horizontal component of the turbulence, while the SODAR captures mainly the vertical variability.

Over most wind speeds, the SODAR and met tower average TI are generally in good agreement as shown in Figures 14 and 15, with the SODAR measuring slightly lower turbulence intensity than the met tower. At 70 m, the SODAR TI appears to be higher than the met tower value at higher wind speeds (above about 12 m/s), but a lack of data in this speed range make it difficult to quantify. SecondWind has performed a study comparing the TI values measured by 11 Tritons with those from adjacent met towers, and the results observed here are consistent with SecondWind's empirical relationship, at least over the predominant wind speed range around 7 m/s.

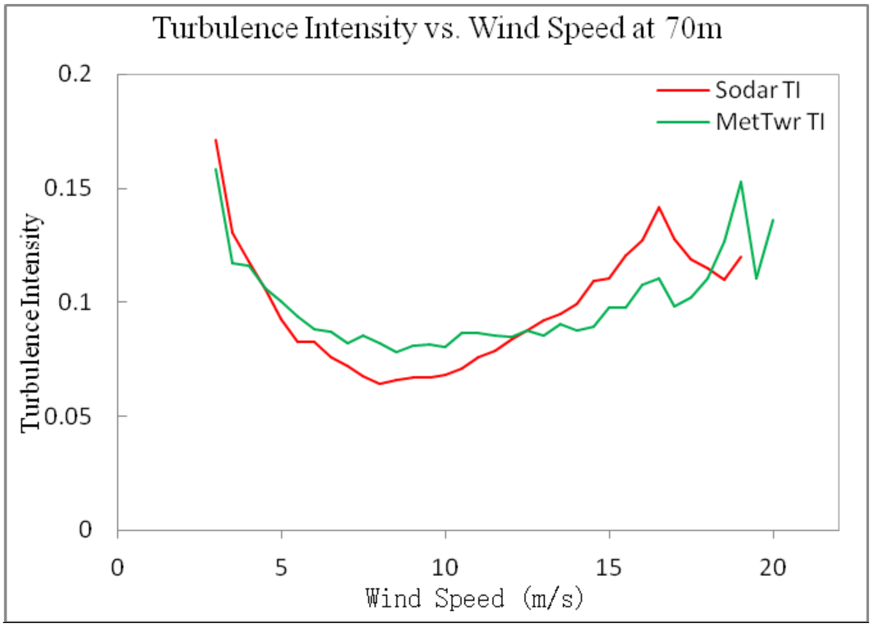


Figure 14. Comparison of turbulence intensity at 70 m height

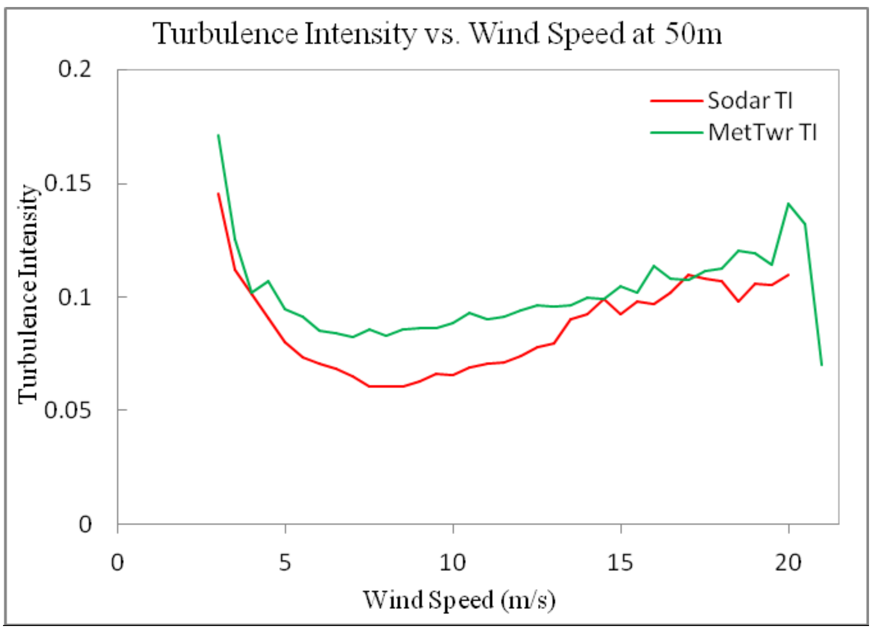


Figure 15. Comparison of turbulence intensity at 50 m height

5 Average Wind Speed Comparison with Stringent Filters Applied

For a more precise comparison of average wind speeds between the SODAR and the tower, more stringent filters need to be applied to extract the highest quality data from both the SODAR and the tower. It is desirable to use a combination of two cup anemometers for the tower speed to reduce bias and direction effects. However, due to the placement of the eastern 70 m anemometer in the tower shadow of the prevailing northwesterly winds, its data were not judged to be of high enough quality, so we were forced to do the analysis with a single cup anemometer (70 m western).

Additional directional filtering also should be applied to the meteorological tower data to remove tower shadow and other flow distortion effects. Guidelines from Second Wind (Walls, 2009) suggested limiting the direction sectors to two 30° bands oriented 45° away from the booms: 210° to 240° and 300° to 330°.

The following filters were applied:

- SODAR data quality at least 95%
- SODAR vertical wind speed (absolute value) less than 1.0 m/s
- 70 m (50 m) meteorological tower wind speed at least 2.0 m/s
- SODAR wind direction at 70 m (50 m) is from 210° to 240° or 300° to 330°.

After all these filters were applied, 4473 records (26% of total) and 4596 records (27% of total) were used to compute the average wind speeds, and the correlation analyses are shown in Figures 16 and 17 for 70 m and 50 m, respectively. At 70 m, the average SODAR wind speed was 8.450 m/s and the average tower speed was 8.481 m/s, a SODAR-to-tower ratio of 0.996. At 50 m, the average SODAR wind speed was 8.126 m/s and the average tower speed was 8.198 m/s, a SODAR-to-tower ratio of 0.991. The linear fits were:

70m: WS(SODAR) = 0.986*WS(met) + 0.142 R^2 = 0.965 (R 0.982) Npts = 4473

50m: WS(SODAR) = 0.974*WS(met) + 0.282 R^2 = 0.965 (R 0.982) Npts = 4596

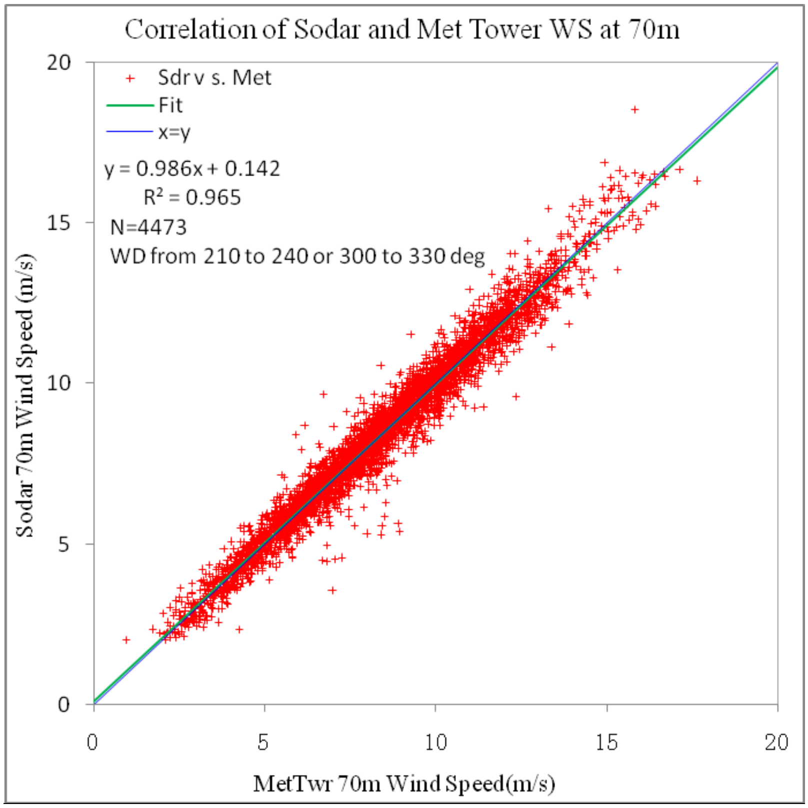


Figure 16. Comparison of highest quality wind speed data at 70 m with stringent filters applied

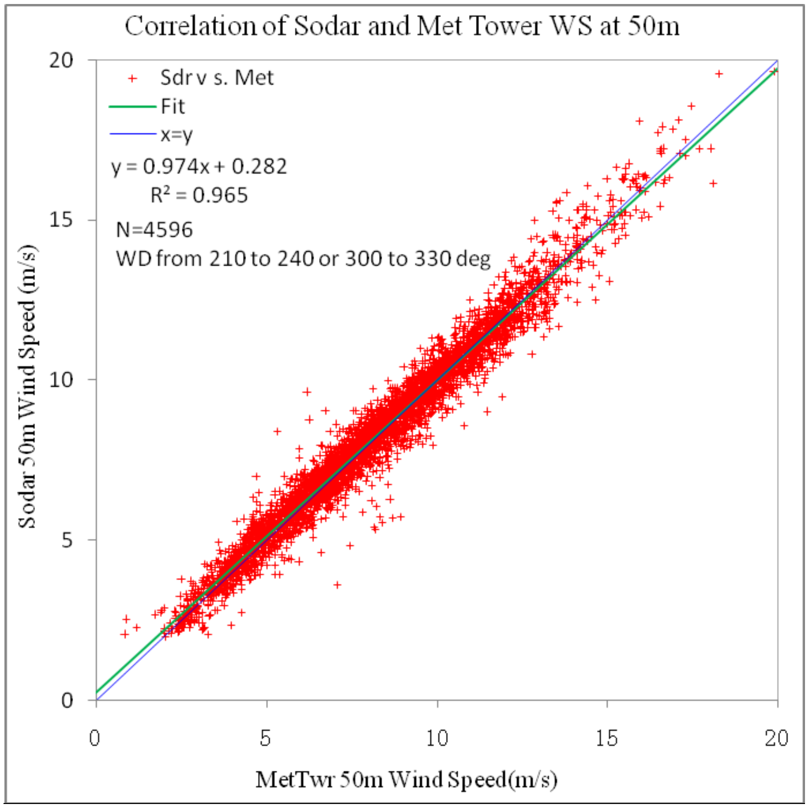


Figure 17. Comparison of highest quality wind speed data at 50 m with stringent filters applied

6 Analysis for Possible Causes of Wind Speed Bias

Although the Triton and tower measurements are in generally good agreement, there is a certain amount of bias to the wind speed data. To eliminate concerns over possible effects of other variables, HYDROCHINA investigated the dependence of wind speed bias on various factors. For this analysis, wind speed bias is defined as the Triton wind speed minus the met tower wind speed.

The following filters were applied:

- Triton Wind speed quality factor >= 90%
- Triton Vertical wind speed (absolute magnitude) <= 1.5 m/s
- Tower Wind speed >= 0.5 m/s
- Triton and tower direction >= 270°

6.1 Temperature

To analyze the influence of temperature on wind speed bias, we plotted the bias versus measured temperature (Fig. 18). There is no apparent effect of temperature on wind speed bias. No effects were observed at 50 m either.

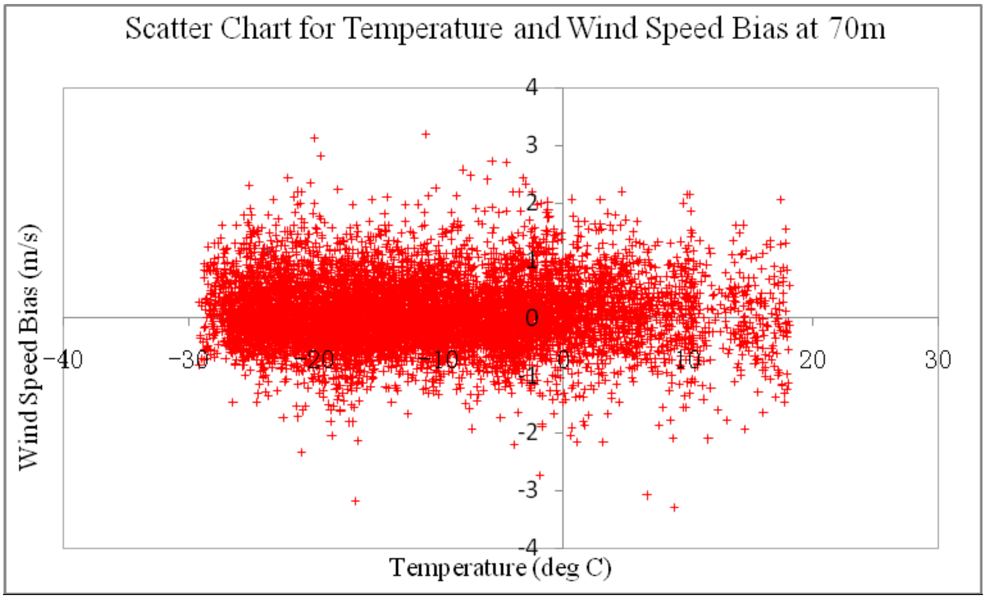


Figure 18. 70 m high wind speed bias and temperature plot

6.2 Humidity

To analyze the influence of humidity on wind speed bias, we plotted the bias versus measured humidity (Fig.19). No obvious effects of humidity on wind speed bias can be seen. No effects were observed at 50 m either.

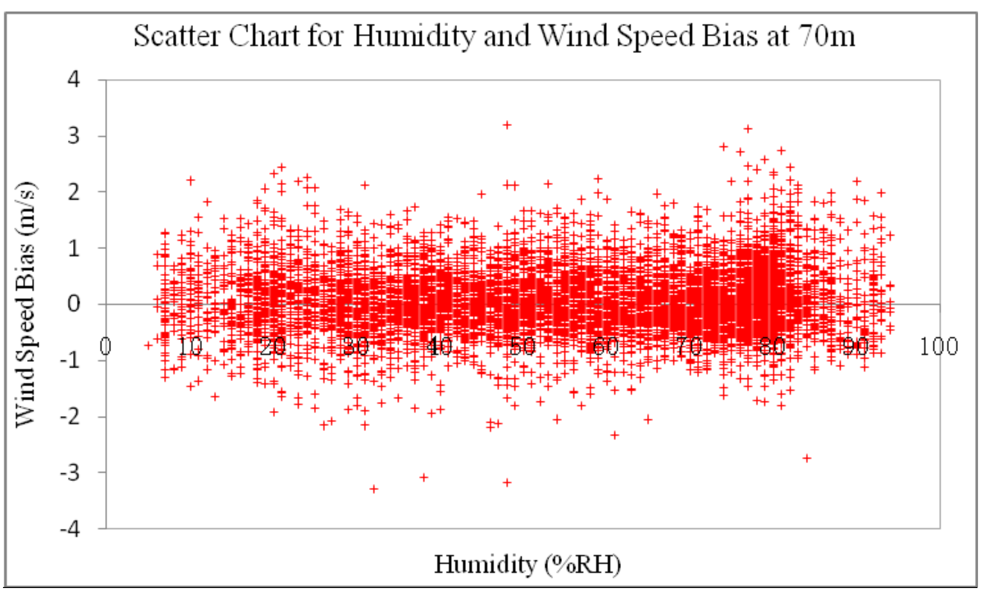


Figure 19. Deviation of 70 m high wind speed and humidity scatter

6.3 Wind Direction

To analyze the influence of wind direction on wind speed bias, we plotted the bias versus wind direction (Fig.20) over the northwest quadrant. No obvious effects of wind direction on wind speed bias can be seen.

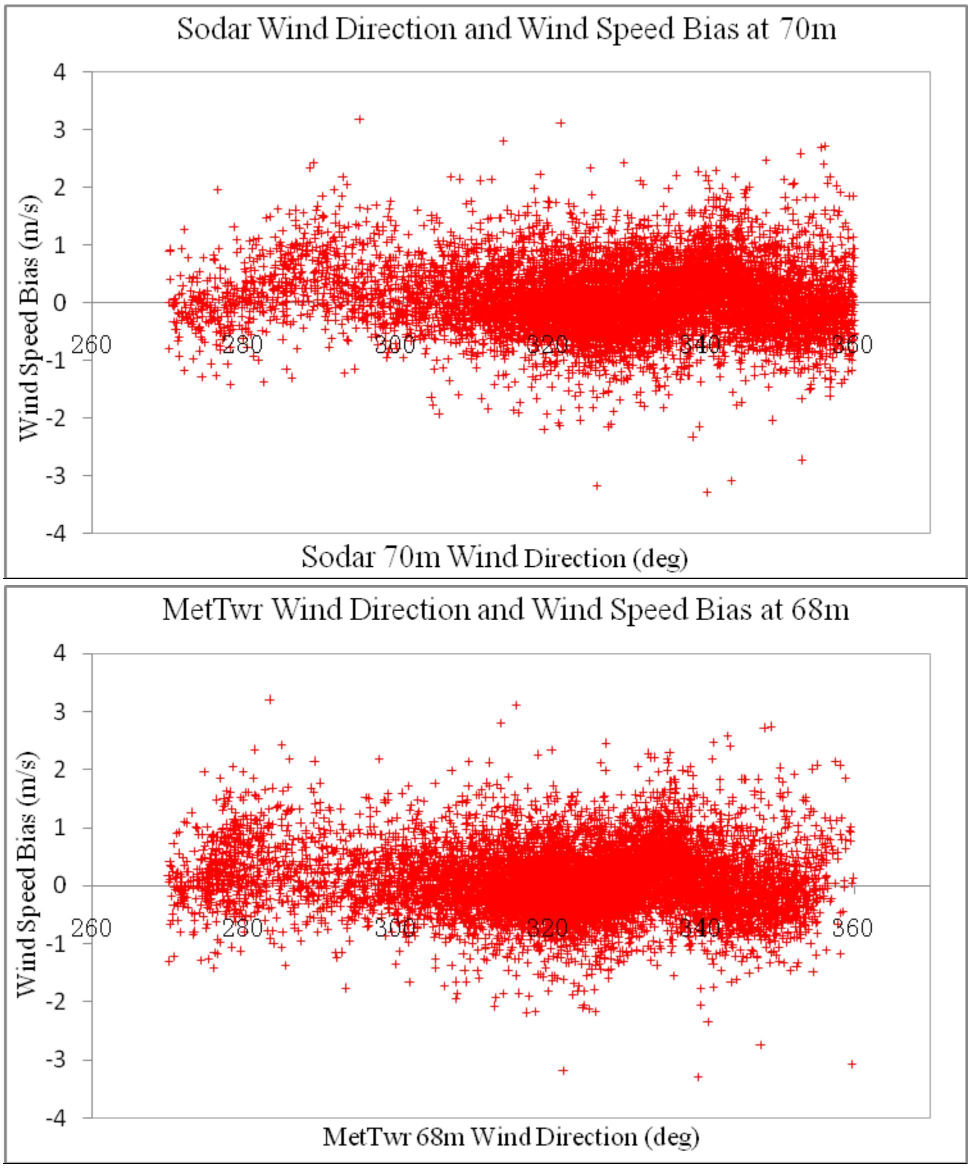


Figure 20. 68 m high mast wind direction and speed deviation plot

7 Conclusions

We have completed an analysis of the wind resource data over a 120-day period based on ten-minute data samples. Data was collected at a 70 m meteorological tower and a Triton SODAR system from a measurement program conducted in China's Hebei Province.

Our analysis of the wind speeds and directions measured by the Triton shows excellent agreement with the tower measurements, with correlation coefficients of 0.96 or better and slopes very near unity. Given the 80 m distance between the SODAR and the meteorological tower, it would be unreasonable to expect a perfect correlation between the two datasets. Based on our analysis of the data, we offer the following observations:

- The operational uptime was 98.4%, demonstrating the Triton's operational reliability during this 120-day period.
- The percent of valid high quality data (Q >= 90%) measured by the Triton was 94.4% at 70 m and 83.8% at 100 m.
- The Triton's measured wind speeds correlated well to the meteorological tower, and were generally within 1% to 2% of the tower value. The ratio of the average SODAR speed to the average tower speed was approximately 0.99 at 70 m and 0.985 at 50 m. The correlation coefficients were greater than 0.965 at both heights (50 m and 70 m).
- The Triton's measured wind direction also correlated very well to the tower data when the sectors with bad or no data were removed. The correlation coefficients calculated between the Triton and the wind vane were 0.998 at both 50 m and 70 m.
- The wind direction distributions as measured by the Triton and the tower were consistent. A slight rotation of the directions is caused by the alignment of the tower to magnetic north while the Triton was aligned to true north.
- The site is characterized by very low wind shear during the daylight hours (0900 to 1700 local time), and both instruments capture this very well. Nighttime shears are considerably higher, and the Triton nighttime shears are about 23% higher than those measured on the tower. This appears to be caused by low SODAR wind speeds at 50 m (but not at 70 m) during the nighttime hours, but the reason for these low speeds has not been determined.
- Average turbulence intensity values from the SODAR and the met tower are in generally good agreement, with the SODAR measuring slightly lower average turbulence intensity (0.080) than the tower (0.088).
- An examination by HYDROCHINA of the SODAR and tower wind speed bias versus air temperature, humidity, and wind direction did not indicate any significant dependence of the bias on any of these quantities.
- Using data based on the most stringent data filtering (SODAR signal quality >= 95% and restricted wind directions), the average wind speed measured by the Triton and tower were very similar at both heights. The ratio of average

wind speeds between the Triton and the meteorological tower was 0.996 at 70 m and 0.991 at 50 m. However, using the stringent filtering did not provide a significant improvement over the results obtained using the basic data filtering. The stringent filtering resulted in a slight improvement in the ratio of average wind speeds, but a slight reduction in the correlation coefficient.

- The validation test and subsequent data analysis did not include an investigation into the effects of precipitation, or extreme weather events on Triton's performance. Further work is recommended to determine whether, and by how much, the Triton's performance is improved or degraded under such conditions.

The Triton showed a high data recovery rate in the test period and acceptable correlation with the mast data. It could be applied in wind resource assessment in conjunction with a measurement mast for a better understanding of wind characteristics, and can be used as a good reference for micrositing of wind turbines.

The purpose of this test was to validate the Triton's reliability and data accuracy by correlating Triton data with that from a nearby tower, and that purpose has been satisfied. The four-month test period only enabled a partial analysis of performance during various seasonal climatic conditions. Should the wind farm developer wish to analyze Triton's performance over various seasons, an extended system test and data analysis would be recommended.

8 References

International Electrotechnical Commission (2005). *Wind Turbines – Part 12-1: Power Performance Measurements of Electricity Producing Wind Turbines.* IEC Technical Report 61400-12-1. Geneva, Switzerland.

Scott, G.; Elliott, D.; Schwartz, M. (2010). Comparison of Second Wind Triton Data with Meteorological Tower Measurements. http://www.nrel.gov/docs/fy10osti/47429.pdf 18 pp.; NREL Report No. TP-550-47429.

Walls, Liz (2009), Guidelines for Triton Data Analysis and Comparison to Nearby Met Tower Measurements, Second Wind, Inc. http://www.secondwind.com/PDFdocs/CorrelationStudy092209.pdf

Appendix 1

Anemometer Calibration Sheets

Svend Ole Hansen ApS

SCT. JØRGENS ALLÉ 7 · DK-1615 KØBENHAVN V · DENMARK

TEL: (+45) 33 25 38 38 · FAX: (+45) 33 25 38 39 · WWW.SOHANSEN.DK

WIND ENGINEERING FLUID DYNAMICS

CERTIFICATE FOR CALIBRATION OF CUP ANEMOMETER

Certificate number: 10.02.5373 **Date of issue:** September 8, 2010

Type: WindSensor P2546A Cup Anemometer **Serial number:** 9899

Manufacturer: WindSensor, Søkrogen 9, 4000 Roskilde, Denmark

Client: Second Wind Inc., 366 Summer Street, Somerville, MA 02144, USA

Anemometer received: September 3, 2010 **Anemometer calibrated:** September 4, 2010

Calibrated by: jj **Calibration procedure:** IEC 61400-12-1, MEASNET

Certificate prepared by: soh **Approved by:** Calibration engineer, soh

Svend Ole Hansen

Calibration equation obtained: v [m/s] = 0.63363 · f [Hz] + 0.19039

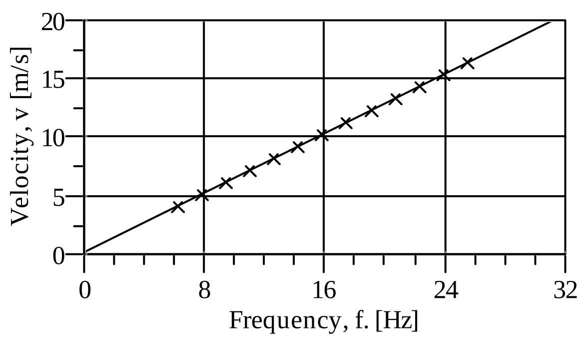
Standard uncertainty, slope: 0.00078 **Standard uncertainty, offset:** 0.04379

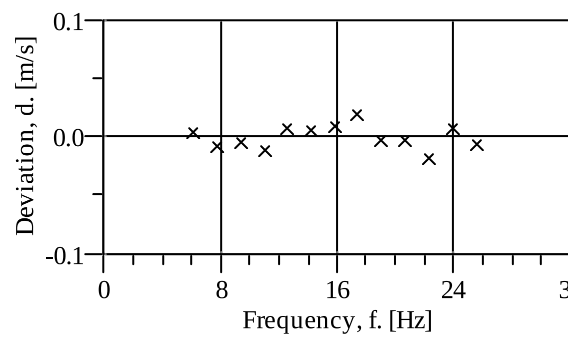
Covariance: -0.0000038 (m/s)²/Hz **Coefficient of correlation:** $\rho = 0.999997$

Absolute maximum deviation: 0.019 m/s at 11.242 m/s

Barometric pressure: 1025.2 hPa **Relative humidity:** 28.8%

Succession	Velocity pressure, q. [Pa]	Temperature in wind tunnel [°C]	Temperature in control room [°C]	Wind velocity, v. [m/s]	Frequency, f. [Hz]	Deviation, d. [m/s]	Uncertainty u_c (k=2) [m/s]
2	9.99	30.0	23.1	4.128	6.2082	0.004	0.028
4	15.44	29.9	23.1	5.130	7.8094	-0.008	0.032
6	22.14	29.7	23.1	6.142	9.4002	-0.005	0.037
8	30.17	29.6	23.0	7.168	11.0315	-0.012	0.042
10	39.34	29.5	23.0	8.184	12.6039	0.007	0.048
12	50.14	29.5	23.0	9.238	14.2711	0.005	0.054
13-last	61.77	29.4	23.0	10.253	15.8665	0.009	0.060
11	74.24	29.5	23.0	11.242	17.4118	0.019	0.065
9	88.34	29.6	23.0	12.266	19.0611	-0.002	0.071
7	103.60	29.7	23.1	13.286	20.6699	-0.002	0.077
5	119.72	29.8	23.1	14.285	22.2737	-0.019	0.083
3	138.06	30.0	23.1	15.344	23.9026	0.009	0.089
1-first	156.81	30.3	23.2	16.361	25.5292	-0.005	0.095





DANAK
CAL Reg.nr. 452
Accreditation to ISO 17025

EQUIPMENT USED

Serial number	Description
-	Boundary layer wind tunnel.
1256	Control cup anemometer.
-	Mounting tube, D = 25 mm
t1	PT100 temperature sensor, wind tunnel.
t2	PT100 temperature sensor, control room.
9904031	PPC500 Furness pressure manometer
X4650038	HMW71U Humidity transmitter
X4350042	PTB100AVaisala analogue barometer.
P11	Pitot tube
001551	Computer Board. 16 bit A/D data acquisition board.
-	PC dedicated to data acquisition.

Traceable calibrations of the equipment are carried out by external accredited institutions: Furness (PPC500) and Saab Metech. A real-time analysis module within the data acquisition software detects pulse frequency.

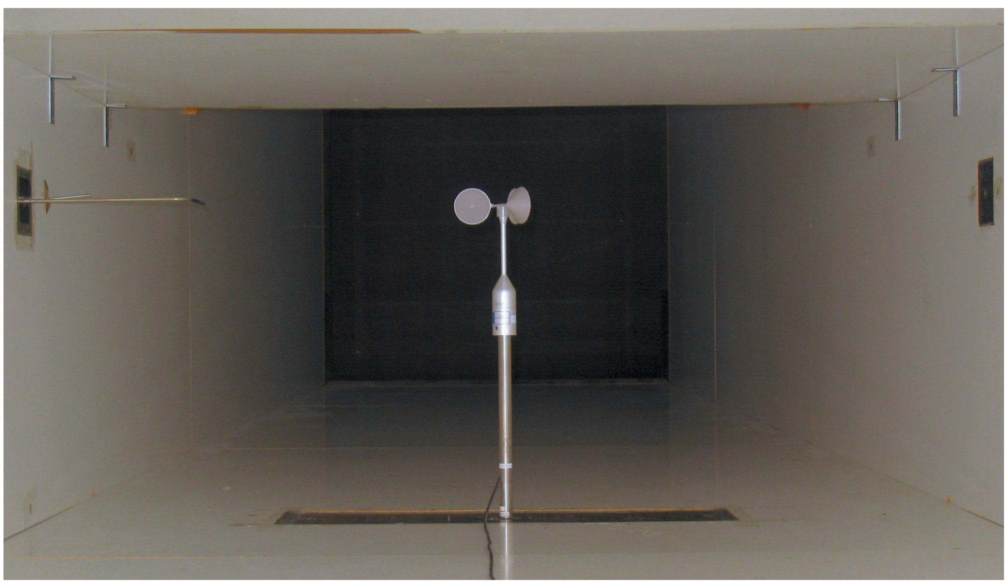


Photo of a cup anemometer in the wind tunnel. The shown anemometer is of the same type as the calibrated one.

UNCERTAINTIES

The documented uncertainty is the total combined uncertainty at 95% confidence level (k=2) in accordance with EA-4/02. The uncertainty at 10 m/s comply with the requirements in the MEASNET procedure that prescribes an absolute uncertainty less than 0.1 m/s at a mean wind velocity of 10 m/s, that is 1%. See Document 97.00.004 “MEASNET - Test report on the calibration campaign” for further details.

Certificate number: 10.02.5373

Svend Ole Hansen ApS
SCT. JØRGENS ALLÉ 7 · DK-1615 KØBENHAVN V · DENMARK
TEL: (+45) 33 25 38 38 · FAX: (+45) 33 25 38 39 · WWW.SOHANSEN.DK

WIND ENGINEERING FLUID DYNAMICS

CERTIFICATE FOR CALIBRATION OF CUP ANEMOMETER

Certificate number: 10.02.5370

Date of issue: September 8, 2010

Type: WindSensor P2546A Cup Anemometer

Serial number: 9898

Manufacturer: WindSensor, Søkrogen 9, 4000 Roskilde, Denmark

Client: Second Wind Inc., 366 Summer Street, Somerville, MA 02144, USA

Anemometer received: September 3, 2010

Anemometer calibrated: September 4, 2010

Calibrated by: mfh

Calibration procedure: IEC 61400-12-1, MEASNET

Certificate prepared by: soh

Approved by: Calibration engineer, soh

Svend Ole Hansen

Calibration equation obtained: v [m/s] = 0.63253 · f [Hz] + 0.20004

Standard uncertainty, slope: 0.00080

Standard uncertainty, offset: 0.04275

Covariance: -0.0000040 (m/s)²/Hz

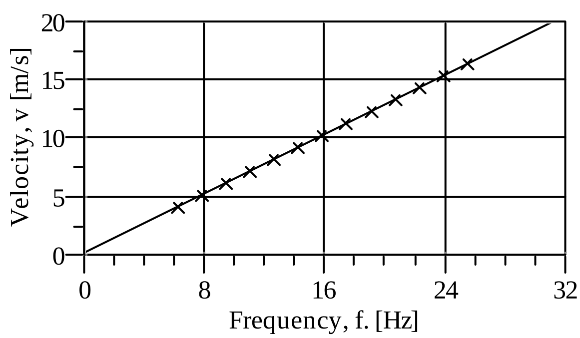
Coefficient of correlation: $\rho = 0.999997$

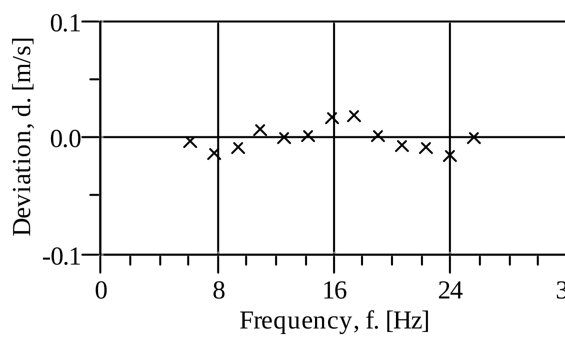
Absolute maximum deviation: 0.020 m/s at 11.247 m/s

Barometric pressure: 1024.7 hPa

Relative humidity: 29.0%

Succession	Velocity pressure, q. [Pa]	Temperature in wind tunnel [°C]	Temperature in control room [°C]	Wind velocity, v. [m/s]	Frequency, f. [Hz]	Deviation, d. [m/s]	Uncertainty u_c (k=2) [m/s]
2	9.97	29.5	23.2	4.120	6.2030	-0.003	0.028
4	15.51	29.3	23.2	5.138	7.8282	-0.013	0.032
6	22.18	29.2	23.2	6.143	9.4057	-0.007	0.037
8	30.14	29.1	23.2	7.160	10.9919	0.007	0.042
10	39.40	29.0	23.1	8.184	12.6228	0.000	0.048
12	50.07	29.0	23.1	9.226	14.2666	0.002	0.054
13-last	61.56	28.9	23.1	10.229	15.8264	0.018	0.060
11	74.40	29.0	23.1	11.247	17.4332	0.020	0.065
9	88.39	29.1	23.2	12.261	19.0624	0.003	0.071
7	103.54	29.2	23.2	13.273	20.6772	-0.006	0.077
5	120.14	29.3	23.2	14.300	22.3024	-0.007	0.083
3	137.97	29.5	23.2	15.328	23.9403	-0.015	0.089
1-first	156.92	29.8	23.2	16.356	25.5397	0.001	0.095





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EQUIPMENT USED

Serial number	Description
-	Boundary layer wind tunnel.
1256	Control cup anemometer.
-	Mounting tube, D = 25 mm
t1	PT100 temperature sensor, wind tunnel.
t2	PT100 temperature sensor, control room.
9904031	PPC500 Furness pressure manometer
X4650038	HMW71U Humidity transmitter
X4350042	PTB100AVaisala analogue barometer.
P11	Pitot tube
001551	Computer Board. 16 bit A/D data acquisition board.
-	PC dedicated to data acquisition.

Traceable calibrations of the equipment are carried out by external accredited institutions: Furness (PPC500) and Saab Metech. A real-time analysis module within the data acquisition software detects pulse frequency.

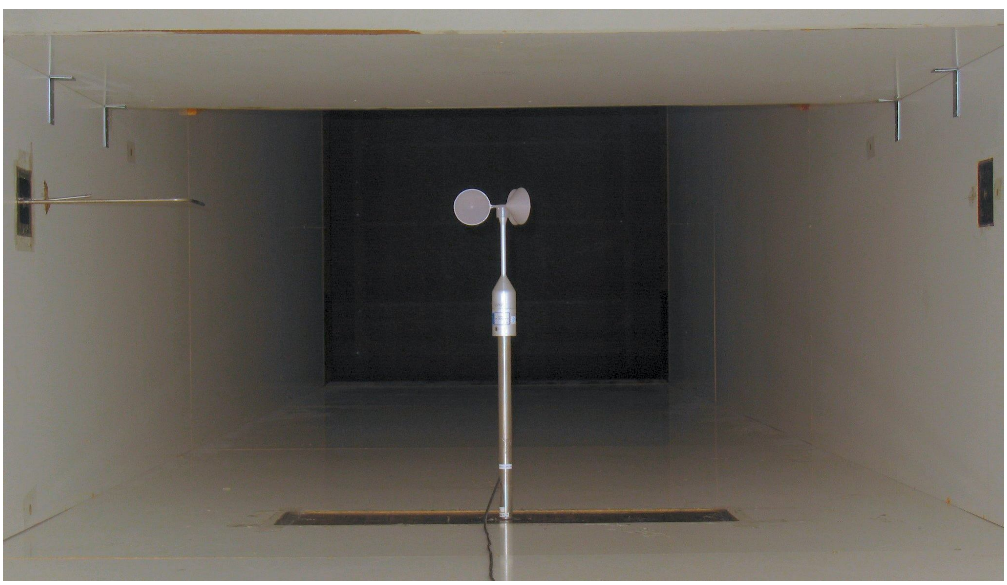

Photo of a cup anemometer in the wind tunnel. The shown anemometer is of the same type as the calibrated one.

UNCERTAINTIES

The documented uncertainty is the total combined uncertainty at 95% confidence level (k=2) in accordance with EA-4/02. The uncertainty at 10 m/s comply with the requirements in the MEASNET procedure that prescribes an absolute uncertainty less than 0.1 m/s at a mean wind velocity of 10 m/s, that is 1%. See Document 97.00.004 “MEASNET - Test report on the calibration campaign” for further details.

Certificate number: 10.02.5370

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TEL: (+45) 33 25 38 38 · FAX: (+45) 33 25 38 39 · WWW.SOHANSEN.DK

WIND ENGINEERING
FLUID DYNAMICS

CERTIFICATE FOR CALIBRATION OF CUP ANEMOMETER

Certificate number: 10.02.5371 **Date of issue:** September 8, 2010

Type: WindSensor P2546A Cup Anemometer **Serial number:** 9897

Manufacturer: WindSensor, Søkrogen 9, 4000 Roskilde, Denmark

Client: Second Wind Inc., 366 Summer Street, Somerville, MA 02144, USA

Anemometer received: September 3, 2010 **Anemometer calibrated:** September 4, 2010

Calibrated by: mfh **Calibration procedure:** IEC 61400-12-1, MEASNET

Certificate prepared by: soh **Approved by:** Calibration engineer, soh

Svend Ole Hansen

Calibration equation obtained: v [m/s] = 0.62927 · f [Hz] + 0.22882

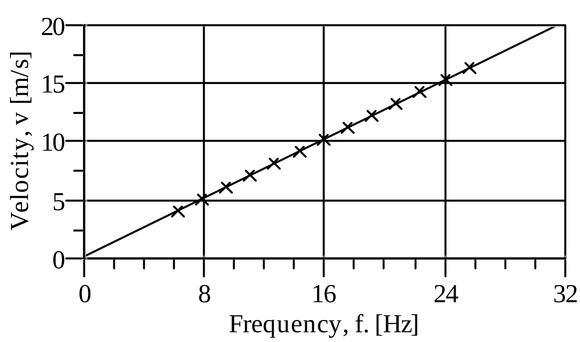
Standard uncertainty, slope: 0.00076 **Standard uncertainty, offset:** 0.03561

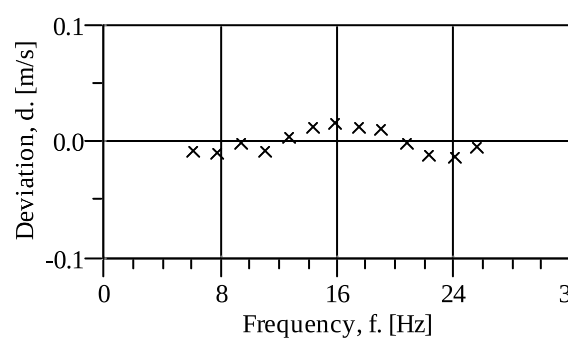
Covariance: -0.0000036 (m/s)²/Hz **Coefficient of correlation:** $\rho = 0.999997$

Absolute maximum deviation: 0.015 m/s at 10.264 m/s

Barometric pressure: 1024.8 hPa **Relative humidity:** 28.9%

Succession	Velocity pressure, q. [Pa]	Temperature in wind tunnel [°C]	Temperature in control room [°C]	Wind velocity, v. [m/s]	Frequency, f. [Hz]	Deviation, d. [m/s]	Uncertainty u_c (k=2) [m/s]
2	9.95	29.7	23.2	4.118	6.1922	-0.007	0.028
4	15.53	29.5	23.2	5.143	7.8258	-0.010	0.032
6	22.15	29.4	23.2	6.141	9.3977	-0.001	0.037
8	30.31	29.3	23.2	7.182	11.0620	-0.007	0.043
10	39.49	29.2	23.1	8.196	12.6557	0.004	0.048
12	50.16	29.1	23.1	9.237	14.2952	0.012	0.054
13-last	61.95	29.1	23.1	10.264	15.9227	0.015	0.060
11	74.62	29.2	23.1	11.266	17.5205	0.012	0.066
9	88.01	29.3	23.2	12.238	19.0657	0.012	0.071
7	103.37	29.4	23.2	13.265	20.7182	-0.001	0.077
5	119.66	29.5	23.2	14.276	22.3389	-0.010	0.083
3	137.82	29.7	23.2	15.324	24.0097	-0.013	0.089
1-first	156.85	30.0	23.2	16.357	25.6378	-0.005	0.095





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EQUIPMENT USED

Serial number	Description
-	Boundary layer wind tunnel.
1256	Control cup anemometer.
-	Mounting tube, D = 25 mm
t1	PT100 temperature sensor, wind tunnel.
t2	PT100 temperature sensor, control room.
9904031	PPC500 Furness pressure manometer
X4650038	HMW71U Humidity transmitter
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P11	Pitot tube
001551	Computer Board. 16 bit A/D data acquisition board.
-	PC dedicated to data acquisition.

Traceable calibrations of the equipment are carried out by external accredited institutions: Furness (PPC500) and Saab Metech. A real-time analysis module within the data acquisition software detects pulse frequency.

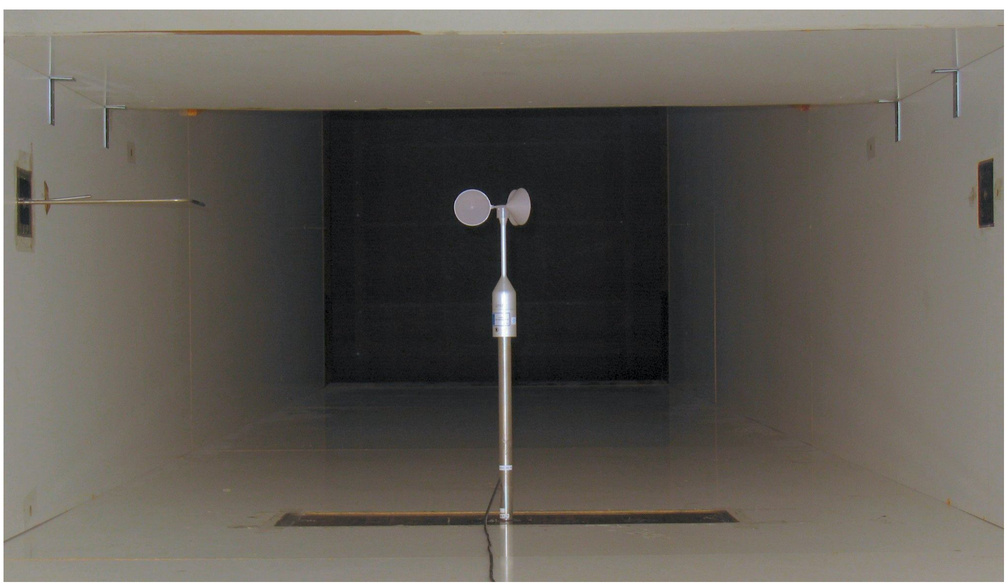

Photo of a cup anemometer in the wind tunnel. The shown anemometer is of the same type as the calibrated one.

UNCERTAINTIES

The documented uncertainty is the total combined uncertainty at 95% confidence level (k=2) in accordance with EA-4/02. The uncertainty at 10 m/s comply with the requirements in the MEASNET procedure that prescribes an absolute uncertainty less than 0.1 m/s at a mean wind velocity of 10 m/s, that is 1%. See Document 97.00.004 “MEASNET - Test report on the calibration campaign” for further details.

Certificate number: 10.02.5371

Appendix 2

Comparison of Wind Speed Distributions – Triton vs. Meteorological Tower

Table 2-1 Deviation between Triton and MetTwr in each bin

Wind speed bin (m/s)	Frequency (pct) at 50 m			Frequency (pct) at 70 m		
	Triton	MetTwr	Triton minus MetTwr	Triton	MetTwr	Triton minus MetTwr
[0-0.5)	0.01	0.01	0.00	0	0	0.00
[0.5-1)	0.03	0.01	0.02	0.08	0.05	0.03
[1-1.5)	0.26	0.19	0.07	0.13	0.12	0.01
[1.5-2)	0.45	0.41	0.04	0.39	0.42	-0.03
[2-2.5)	1.22	1.09	0.14	0.57	0.56	0.01
[2.5-3)	1.83	1.60	0.22	1.13	1.06	0.07
[3-3.5)	2.49	2.24	0.24	1.91	1.82	0.09
[3.5-4)	2.77	2.67	0.10	2.24	2.36	-0.12
[4-4.5)	3.51	3.58	-0.07	2.87	2.89	-0.02
[4.5-5)	4.23	3.30	0.93	3.28	2.80	0.48
[5-5.5)	3.74	3.83	-0.09	3.46	3.13	0.33
[5.5-6)	4.21	4.40	-0.18	4.08	3.88	0.20
[6-6.5)	4.99	4.55	0.44	3.99	4.26	-0.27
[6.5-7)	5.00	5.28	-0.28	4.86	4.61	0.25
[7-7.5)	5.98	5.64	0.34	5.16	5.68	-0.52
[7.5-8)	5.88	6.00	-0.12	5.70	5.42	0.28
[8-8.5)	6.16	6.17	-0.01	6.45	5.85	0.60
[8.5-9)	5.85	5.91	-0.06	6.03	6.30	-0.27
[9-9.5)	5.96	6.38	-0.42	6.44	6.22	0.22
[9.5-10)	5.53	5.82	-0.28	6.16	6.63	-0.46
[10-10.5)	4.99	4.90	0.09	5.84	5.88	-0.04
[10.5-11)	4.36	4.89	-0.53	5.43	5.44	-0.01
[11-11.5)	4.37	4.33	0.04	4.48	4.69	-0.21
[11.5-12)	3.45	3.85	-0.41	4.17	4.31	-0.14
[12-12.5)	3.08	3.02	0.06	3.84	3.80	0.04
[12.5-13)	2.33	2.50	-0.17	3.15	3.45	-0.30
[13-13.5)	2.12	1.73	0.39	2.47	2.38	0.09
[13.5-14)	1.34	1.44	-0.10	1.66	1.75	-0.09
[14-14.5)	1.15	1.03	0.12	1.44	1.14	0.30
[14.5-15)	0.72	0.79	-0.07	0.81	1.01	-0.20
[15-15.5)	0.57	0.69	-0.12	0.66	0.68	-0.02
[15.5-16)	0.42	0.42	0.00	0.41	0.47	-0.06
[16-16.5)	0.26	0.41	-0.15	0.33	0.34	-0.01
[16.5-17)	0.19	0.18	0.01	0.12	0.24	-0.12

[17-17.5)	0.17	0.21	-0.05	0.08	0.09	-0.01
[17.5-18)	0.14	0.19	-0.06	0.07	0.10	-0.03
[18-18.5)	0.09	0.08	0.01	0.06	0.06	0.00
[18.5-19)	0.05	0.09	-0.04	0.01	0.05	-0.04
[19-19.5)	0.05	0.07	-0.02	0.01	0.02	-0.01
[19.5-20)	0.04	0.07	-0.03	0.00	0.01	-0.01
[20-20.5)	0.03	0.02	0.01	0.00	0.01	-0.01
[20.5-21)	0.00	0.00	0.00	0.00	0.00	0.00
[21-21.5)	0.00	0.02	-0.02	0.01	0.00	0.01
[21.5-22)	0.00	0.01	-0.01	0.00	0.00	0.00
≥ 22	0.00	0.00	0.00	0.00	0.01	-0.01