

SAMPLE TRITON CORRELATION STUDY AND PERFORMANCE UPDATE

September 22, 2009

Prepared by Liz Walls

EXECUTIVE SUMMARY

The following report provides an example of an actual Triton-tower correlation study and a summary of the Triton's performance. Although the Triton and tower data included herein are results measured at a site over the stated time period, the exact location of the site has been omitted to ensure anonymity. Furthermore, all maps shown are illustrative and are not representative of the Triton's actual location.

On May 1st, 2009, a Second Wind Triton Sonic Profiler was installed at a flat test site approximately 100 m from a 60 m met tower. Data was collected from May 1st to June 1st, 2009 and the purpose of the installation was to correlate the Triton with the tower data such that the Triton could then be placed at various other locations for site characterization. For the analysis, the Triton data was filtered based on a minimum quality factor of 90% and a maximum vertical wind speed of +/- 1.5 m/s.

Overall, the Triton performed very well and demonstrated a strong correlation with the nearby tower. During the test interval, the reliability (or operational uptime) of the Triton was almost perfect at 99.9%. During operation, the percent of valid data was calculated as a function of height (i.e. from 40 to 200 m). High data recovery was observed and it was found that the Triton measured 99% valid data at 40 m and 84% valid data at 120 m.

The wind speeds measured by the 60 m tower were compared to the 60 m Triton wind speeds. The two data sets tracked very well and a correlation coefficient of 0.989 was found. The average wind speed measured by the Triton and tower at 60 m were determined and it was found that the two average wind speeds differed by -1.0%.

The Triton and tower wind direction data were also compared. An offset of approximately 12° was observed when comparing the Triton and 60 m vane data. When the Triton data was then plotted against the 30 m vane data, a very small offset of ~1° was seen and a correlation coefficient of 0.995 was found. Based on these observations, the 60 m boom appears to be aligned incorrectly. Both the Triton and tower data showed that the prevailing wind direction was from the south.

The turbulence intensities measured by the Triton and tower were analyzed and it was found that the two devices gave similar turbulence values with the Triton reading slightly higher. On average, the tower recorded a turbulence intensity of 0.093 while the Triton measured an average turbulence intensity of 0.099.

Finally the Triton data was used to analyze the wind shear and inflow angle distribution at the test site. The average wind speed profile was determined and a power law profile was fit to the data. The average wind shear exponent was found to be 0.176. Also, the diurnal wind shears were analyzed and a wind shear exponent of 0.074 was found during daytime hours while the average nighttime profile produced a wind shear exponent of 0.282. The inflow angle was determined in each wind direction sector and it was found that, during southerly winds, there was a slight downward flow with an average inflow angle of -2°.

Based on this analysis, the results of the study are very good and the correlation study can be deemed complete. The Triton can now be relocated to other positions for purposes of site characterization or other information gathering endeavors.

TABLE OF CONTENTS

| | |
|--|----|
| Introduction | 4 |
| How is the Triton performing?..... | 6 |
| How is the Triton data comparing to the tower data? | 8 |
| Triton and Tower Wind Speed Correlation Comparison | 8 |
| Triton and Tower Wind Speed Average Wind Speed Comparison..... | 9 |
| Triton and Tower Wind Direction Comparison | 11 |
| Triton and Tower Turbulence Comparison..... | 13 |
| Shear and Inflow Angle Analysis | 15 |
| Wind Speed Shear and Inflow Angle at the site | 15 |
| Angle of Attack (Inflow Angle)..... | 16 |
| Summary and Conclusions..... | 17 |

LIST OF FIGURES

| | |
|---|----|
| Figure 1: Topographic Map of Triton Site..... | 4 |
| Figure 2: Google Earth Screen Shot of Triton Site..... | 5 |
| Figure 3: Percent of Valid Data vs. Height | 6 |
| Figure 4: Average Signal-to-Noise Ratio vs. Height..... | 7 |
| Figure 5: Triton and Tower 60 m Wind Speed Time Series..... | 8 |
| Figure 6: 60 m Triton vs. 60 m Tower (Max of 2 anems.) Wind Speed | 9 |
| Figure 7: Triton vs. Tower 60 m Average Wind Speed | 10 |
| Figure 8: Histogram of Percent Difference in Measured Wind Speeds | 11 |
| Figure 9: 60 m Triton vs. 60 m Tower Wind Direction..... | 12 |
| Figure 10: 60m Triton vs. 30m Tower Wind Direction..... | 12 |
| Figure 11: Triton and Tower Wind Roses | 13 |
| Figure 12: Triton 60m Turbulence vs. Wind Speed | 14 |
| Figure 13: Tower 39m Turbulence vs. Wind Speed..... | 14 |
| Figure 14: Average 60 m TI by Wind Speed bin | 14 |
| Figure 15: Overall Wind Shear Profile..... | 15 |
| Figure 16: Average Daytime Wind Speed Profile..... | 16 |
| Figure 17: Average Nighttime Wind Speed Profile..... | 16 |
| Figure 18: Inflow Angle Distribution | 16 |

LIST OF TABLES

| | |
|---|----|
| Table 1: % Valid vs. Height..... | 6 |
| Table 2: Avg. SNR vs. Height | 7 |
| Table 3: Wind Direction Distributions | 13 |
| Table 4: Average 60 m TI by Wind Speed bins | 14 |
| Table 5: Estimated Wind Shear Exponents..... | 15 |
| Table 6: Inflow Angles and Average Vertical Wind Speeds | 16 |

INTRODUCTION

The following report provides an example of an actual Triton-tower correlation study and a summary of the Triton's performance. Although the Triton and tower data included herein are results measured at a site over the stated time period, the exact location of the site has been omitted to ensure anonymity. Furthermore, all maps shown are illustrative and are not representative of the Triton's actual location.

On May 1st, 2009, the Triton was installed at the test site approximately 100 m from a 60 m met tower. Figure 1 shows a topographic map of the Triton location and Figure 2 shows a screenshot of the location from GoogleEarth. The 60 m met tower is equipped with cup anemometers mounted at 30, 45 and 60 m. The following report summarizes the Triton-tower comparison from May 1st to June 1st, 2009, the evaluation of the Triton's overall performance and the site's wind shear and inflow angle distribution.

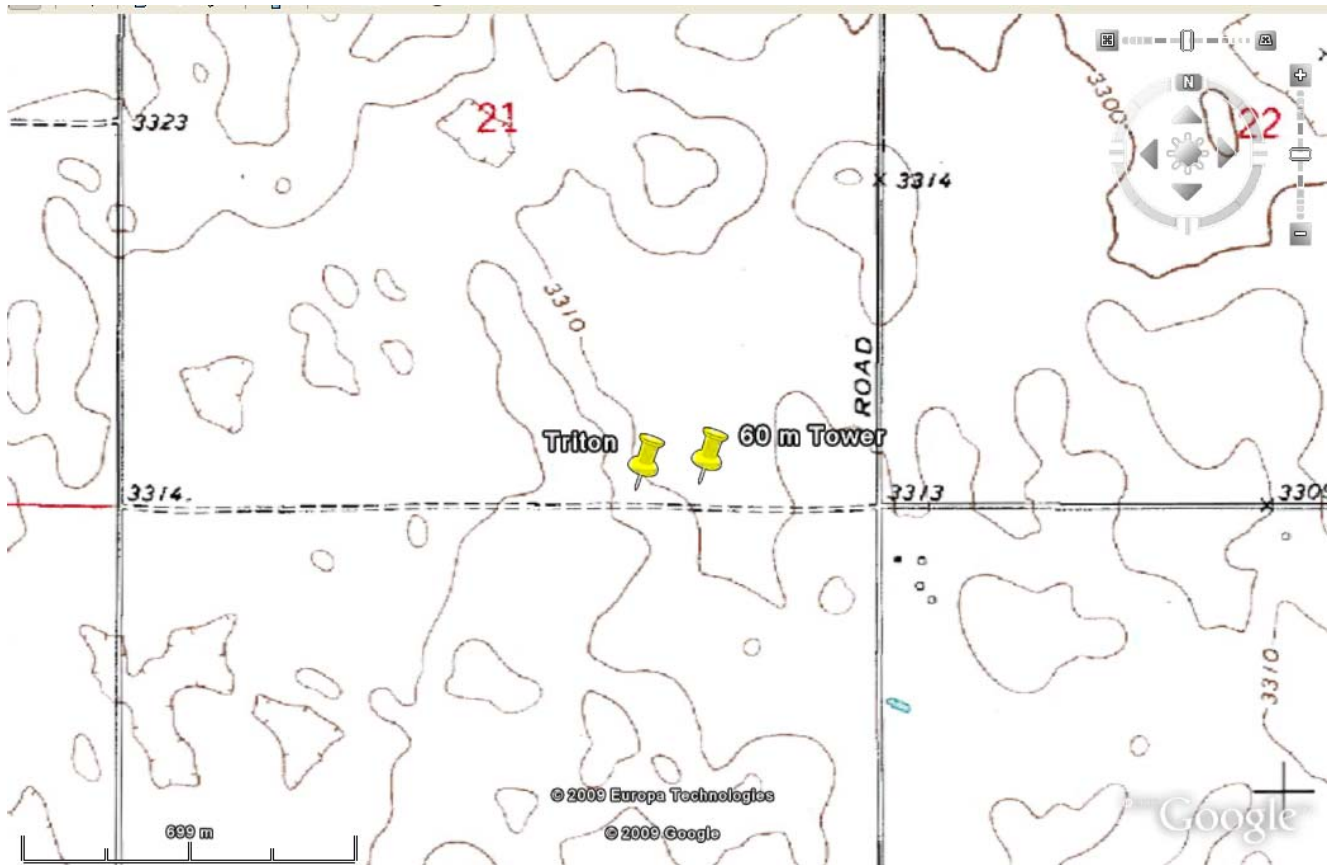


Figure 1: Topographic Map of Triton Site

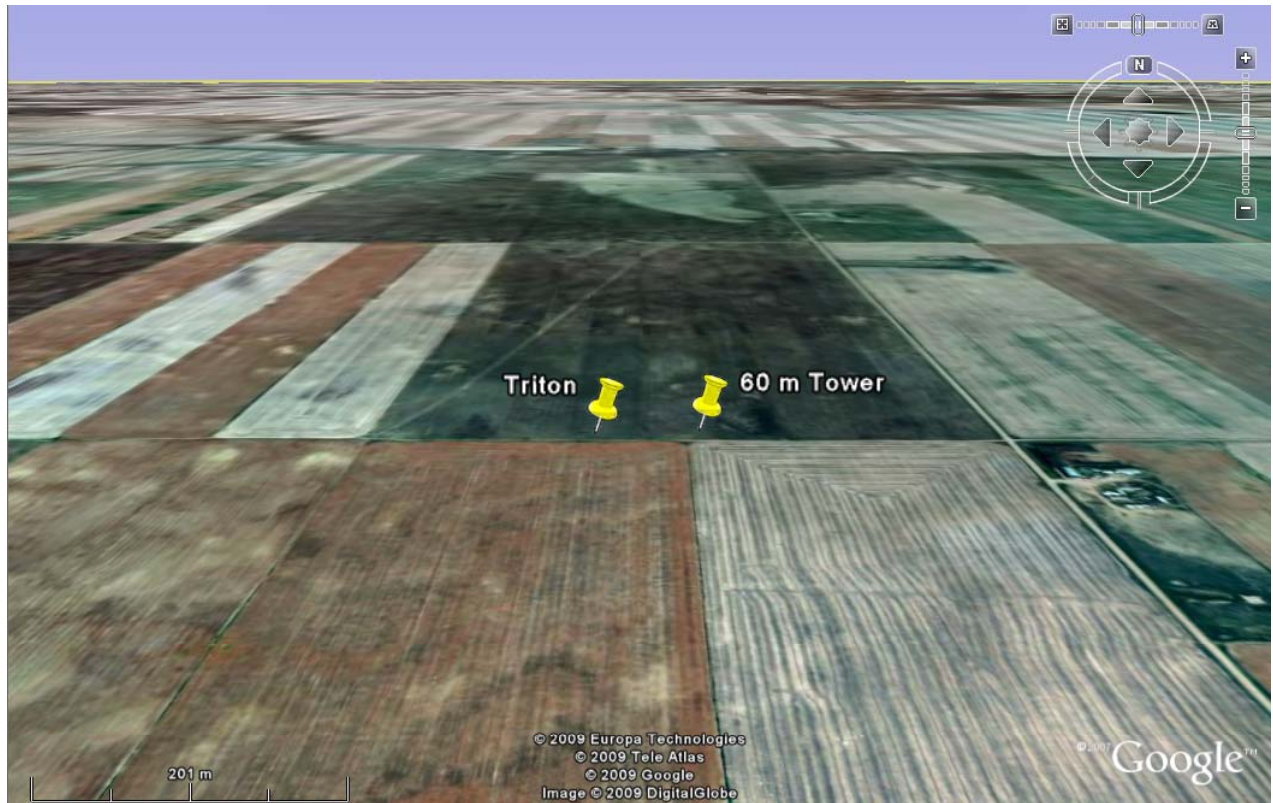


Figure 2: Google Earth Screen Shot of Triton Site

The report is comprised of three main sections. In the first section, the overall performance of the Triton is analyzed. The gross operational uptime is presented, which represents the percent of time that the Triton was operational and collecting data. The data recovery at all heights is also examined and this refers to the percent of valid data that was collected from 40 – 200 m over the data collection interval.

In the second section, the 60 m Triton data is compared to the 60 m anemometer data. First, the horizontal wind speed data is presented as a time series and then as a scatterplot. A correlation coefficient is calculated for the two data sets. A histogram of the difference between the Triton and tower 60 m wind speed measurements are then shown and the mean difference between the data sets is presented. Following this, the wind direction distribution as measured by the Triton is compared to the tower data and both distributions are shown in a wind rose. Finally, the Triton and tower turbulence data are presented as scatterplots and then as average values measured in 1 m/s wind speed bins.

The last section of the report contains information regarding the wind shear measured at the site and the inflow angle distribution. Using the Triton data, the average wind shear profile is determined and the overall wind shear exponent is presented. The shear profiles and exponents for day and night are also shown. The average inflow angle (or angle of attack) is then presented for each wind direction sector.

HOW IS THE TRITON PERFORMING?

From May 1st to June 1st, 2009, the Triton was operational and collecting data **99.9 %** of the time. During the operational uptime, wind data was recorded at every ten-minute interval and at heights of 40 to 200 m. For each ten-minute average and at every height, a quality factor was calculated. The quality factor is a function of the signal-to-noise ratio (SNR) and the number of valid data points that were collected over the ten-minute period. Based on several previous correlation studies, it is recommended to implement a minimum quality factor of 90%. Also, it is recommended to apply a vertical wind speed filter where data is removed if the vertical wind speed is outside the range of +/- 1.5 m/s. This vertical wind speed filter omits data affected by precipitation and other extraneous noise sources. From May 1st to June 1st, the percent of valid data (i.e. data with $Q \geq 90\%$ and vertical wind speed between +/- 1.5 m/s) was calculated and is shown in Figure 3. Over the typical swept area of a turbine (40 m to 120 m), the percent of valid data is very high and ranges from ~99% at 40 m to ~84% at 120 m.

Table 1: % Valid vs. Height

| Height | % of Valid Data |
|--------|-----------------|
| 40 | 98.68% |
| 50 | 98.39% |
| 60 | 97.49% |
| 80 | 94.44% |
| 100 | 90.34% |
| 120 | 83.59% |
| 140 | 73.54% |
| 160 | 60.74% |
| 180 | 47.96% |
| 200 | 35.09% |

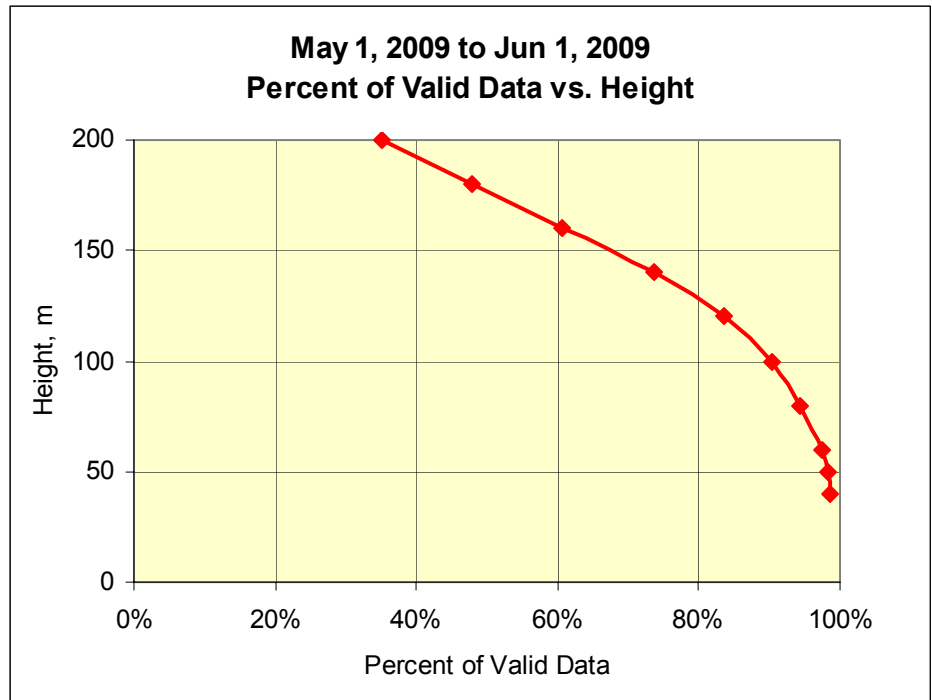


Figure 3: Percent of Valid Data vs. Height

Another method of evaluating Triton performance is to examine the average SNR in each beam direction as a function of height. The average SNR was calculated in each direction from May 1st, 2009 to June 1st, 2009 and these values are tabulated and plotted in Figure 4. An SNR of 9.0 typically represents high quality data and, as shown in Figure 4, the average SNR was greater than 9.0 up to a height of 160 m.

Table 2: Avg. SNR vs. Height

| Height | Avg A SNR | Avg B SNR | Avg C SNR |
|--------|-----------|-----------|-----------|
| 40 | 17.77 | 18.49 | 17.37 |
| 50 | 17.59 | 18.22 | 17.20 |
| 60 | 17.19 | 17.70 | 16.79 |
| 80 | 15.95 | 16.44 | 15.60 |
| 100 | 14.44 | 14.84 | 14.06 |
| 120 | 12.78 | 13.16 | 12.44 |
| 140 | 11.16 | 11.55 | 10.86 |
| 160 | 9.70 | 10.05 | 9.43 |
| 180 | 8.41 | 8.76 | 8.21 |
| 200 | 7.31 | 7.64 | 7.16 |

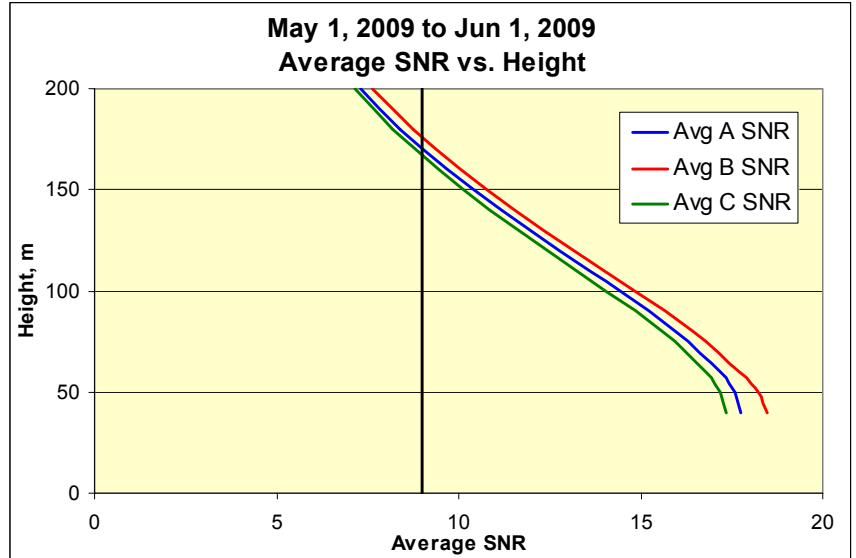


Figure 4: Average Signal-to-Noise Ratio vs. Height

Based on the above analysis, the Triton is performing very well at this test site. The reliability of the system was demonstrated by the high operational uptime of 99.9 %. Also, very good data recovery was observed with the Triton reporting valid wind speeds ~84% of the time at 120 m and ~94% of the time at 80 m.

HOW IS THE TRITON DATA COMPARING TO THE TOWER DATA?

In this next section, the 60 m Triton data is compared to the 60 m anemometer data. Before comparing the Triton and tower measurements, the Triton data was filtered based on a minimum quality factor of 90% and vertical wind speed limits of ± 1.5 m/s. The quality factor filter is effective at removing noisy data while the vertical wind speed filter omits data that may have been affected by precipitation. There are two cup anemometers mounted on the 60 m boom and, for correlation purposes, the maximum of the two wind speeds was selected for each ten-minute interval. By using the maximum wind speed of the two anemometers, tower shadow effects are minimized. (Note: In subsequent sections where the average wind speeds are compared, more stringent filters are applied to the Triton and tower data.)

Triton and Tower Wind Speed Correlation Comparison

First, the wind speeds measured by each instrument are plotted as a time series as shown in Figure 5. As shown, the two data sets track each other very well over a range of wind speeds.

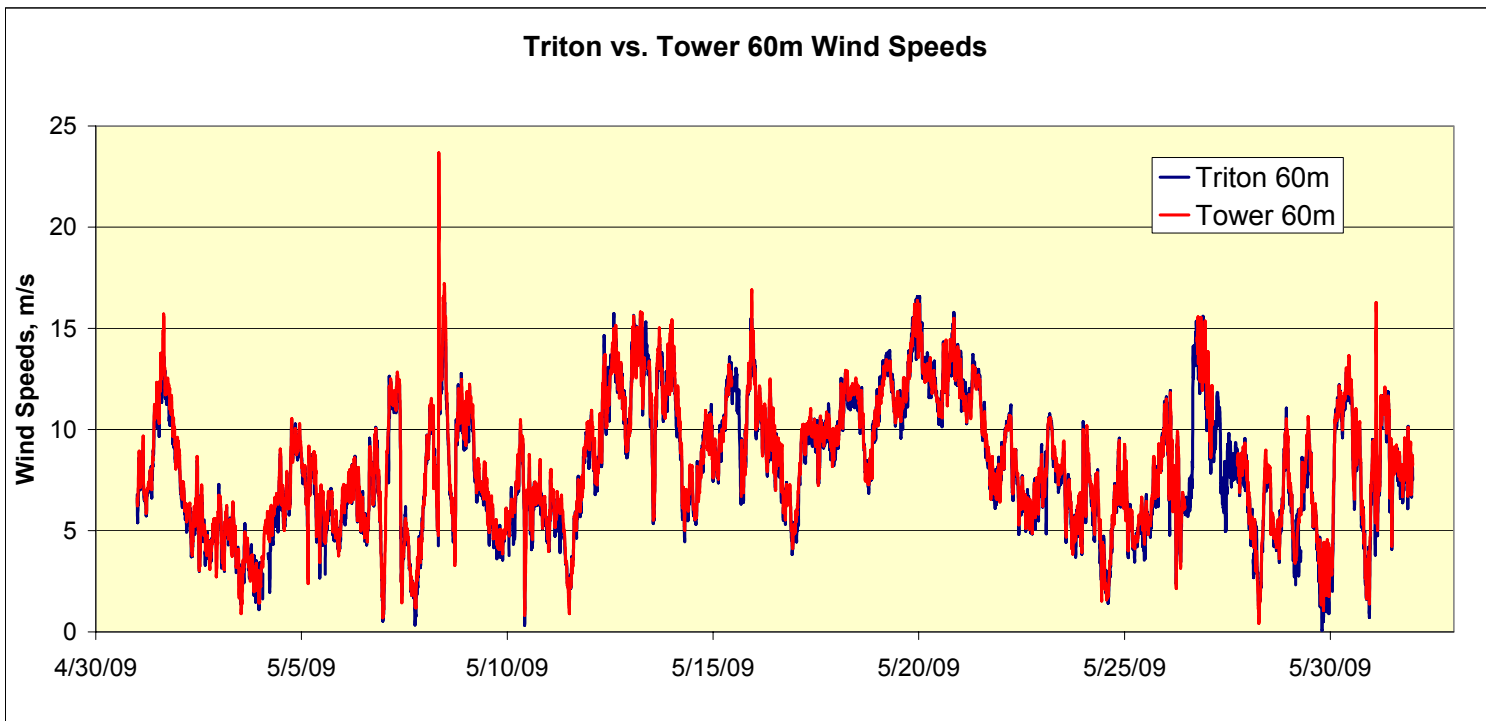


Figure 5: Triton and Tower 60 m Wind Speed Time Series

Next, the 60 m wind speeds are plotted on a scatterplot in Figure 6. In this figure, the red solid line represents a 1:1 relationship and the black line is the regression best-fit line. As shown, the slope of the line is 1.0 and there is an offset of -0.2 m/s. Recall that, to avoid tower shadow effects, the maximum of the two anemometers readings is used in the comparison. This is intended for the correlation analysis and not for an average wind speed comparison. In a following section, directional filtering will be carried out and the average of the anemometer readings will be compared to the Triton data. In other words, the offset of -0.2 is not representative of the difference between the Triton and tower wind speeds. In the scatterplot, there are 4120 data points and **the correlation coefficient between the two data sets was found to be excellent at 0.989.**

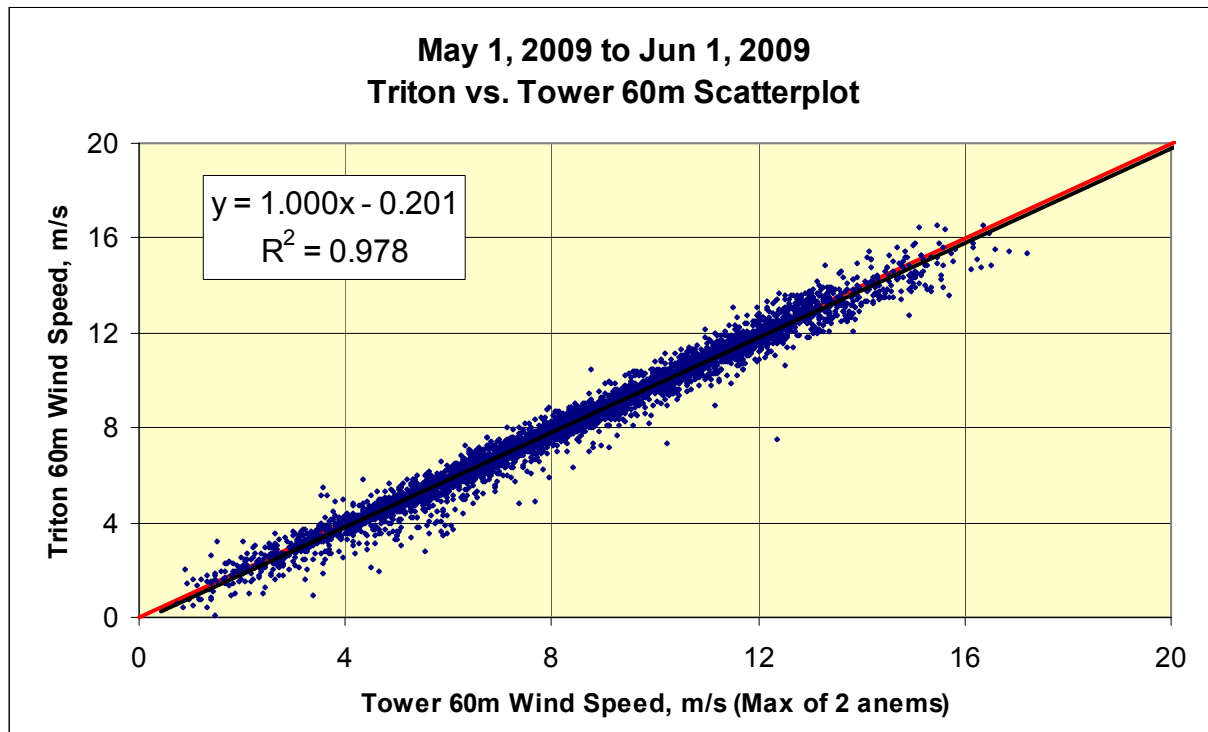


Figure 6: 60 m Triton vs. 60 m Tower (Max of 2 anems.) Wind Speed

Triton and Tower Wind Speed Average Wind Speed Comparison

In the previous section, a correlation analysis was conducted where the 60 m Triton wind speeds were compared to the 60 m anemometer data where, for each ten-minute average, the maximum anemometer reading was used to avoid tower shadow effects. In the following section, the average wind speeds measured by the Triton and tower are compared and, in order to do so, a more intensive filtering process is carried out.

There are several factors that can impact the average wind speed comparison such as tower shadow, anemometer overspeeding, precipitation and off-horizontal flow. To take these factors into account, the following set of filters are applied:

1. Triton Minimum Quality = 95%

2. Triton Maximum Vertical Wind Speed = +/- 1 m/s
3. Ratio of Anemometer readings = 0.98 – 1.02
4. Anemometer Minimum Wind Speed = 2 m/s
5. Directional Filter: Sectors 45° from booms (30° wide)

The first two filters help to minimize the amount of noise in the Triton data set. The quality filter is designed to remove erroneous data averages and the vertical wind speed filter should be implemented to remove data affected by precipitation. The vertical wind speed filter also removes tower data that may be incorrect due to off-horizontal flow.

The last three filters are designed to remove anemometer data that may be suspect. In the previous analysis, the maximum anemometer measurement, for every ten-minute average, was used to compare to the Triton data. While this was adequate when calculating correlation coefficients, this can introduce a high bias when comparing the average wind speeds. In this type of analysis, the average anemometer reading should be used but only if the two sensors agree within 2%. The anemometers should also be filtered based on a minimum wind speed of 2 m/s. Finally, a directional filter should be applied such that only data that fall in a direction sector 45° from the booms (with a window 30° wide) should be kept. These filters remove erroneous data averages that may have been affected by tower shadow or some mechanical artifact of the sensor.

All five filters were applied to the data and the resulting scatterplot is shown in Figure 7. Again, the red line shows a 1:1 relationship and the regression line is shown in black. The correlation coefficient was found to be 0.991 for this filtered data set.

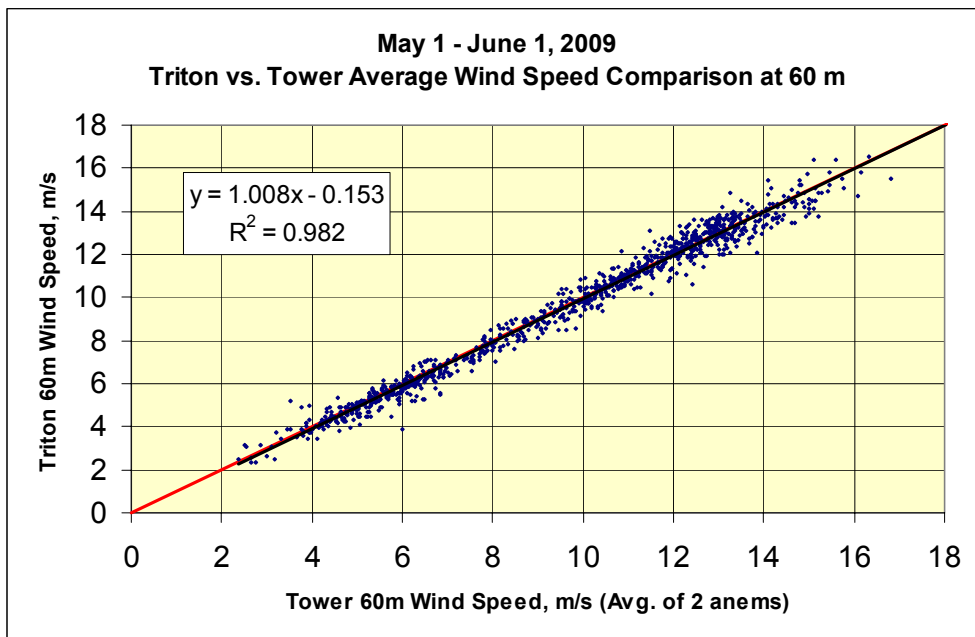


Figure 7: Triton vs. Tower 60 m Average Wind Speed

The percent difference measured between the Triton and tower wind speeds are now considered. Figure 8 shows a histogram of the percent difference, which is defined as $(\text{Triton} - \text{Tower}) / \text{Tower} * 100$. The mean of the distribution was found to be -1.0% . In other words, on average, the Triton measured approximately 1% lower than the tower. The standard deviation of the percent difference was 5.7% and this can be attributed to the uncertainty of the anemometers, the uncertainty of the Triton as well as spatial variability. (Recall that the Triton is ~ 100 m from the tower). Overall, the Triton and tower data agree very well with a high correlation coefficient of 0.991 and average wind speeds that agree within 1%

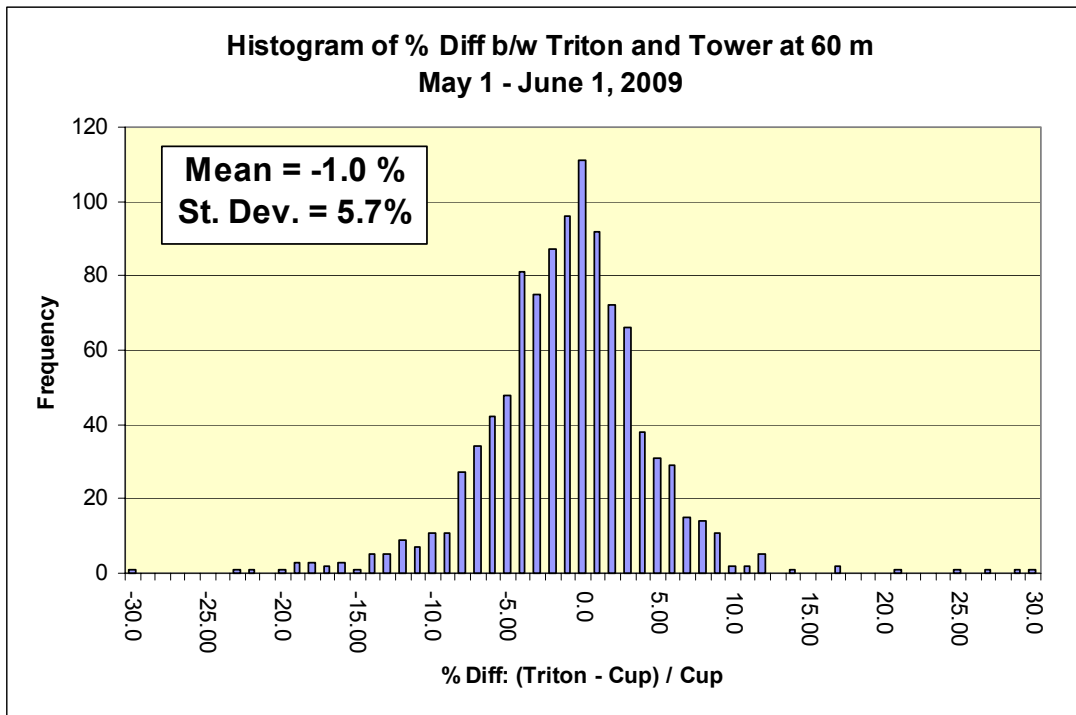


Figure 8: Histogram of Percent Difference in Measured Wind Speeds

Triton and Tower Wind Direction Comparison

Next, the wind direction distributions as measured by the Triton and wind vanes are compared. Figure 9 shows a scatterplot of the 60 m Triton and tower wind direction data (with $U > 3$ m/s). Similar to the wind speed scatterplots, the red line depicts a 1:1 relationship and the black line shows the best-fit regression line. The correlation coefficient measured between the two data sets is high at 0.987 however there is an offset of approximately 12° . Also, there is a cluster of data points in the northern sector that do not agree with the rest of the distribution (circled in red). It appears as though either the boom or the Triton was not oriented correctly.

To determine which instrument was reading the incorrect wind direction, the Triton data was plotted against the wind direction as measured by the 30 m vane (Figure 10). In this comparison, the correlation coefficient was found to be very high at 0.995 and the offset was small at $\sim 1^\circ$. Also, the outlying data points in the northern sector are no longer present. Based on this analysis, it appears as though the 60 m boom was not oriented correctly and may be sticking (or entering a dead band zone) when the winds are coming from the north.

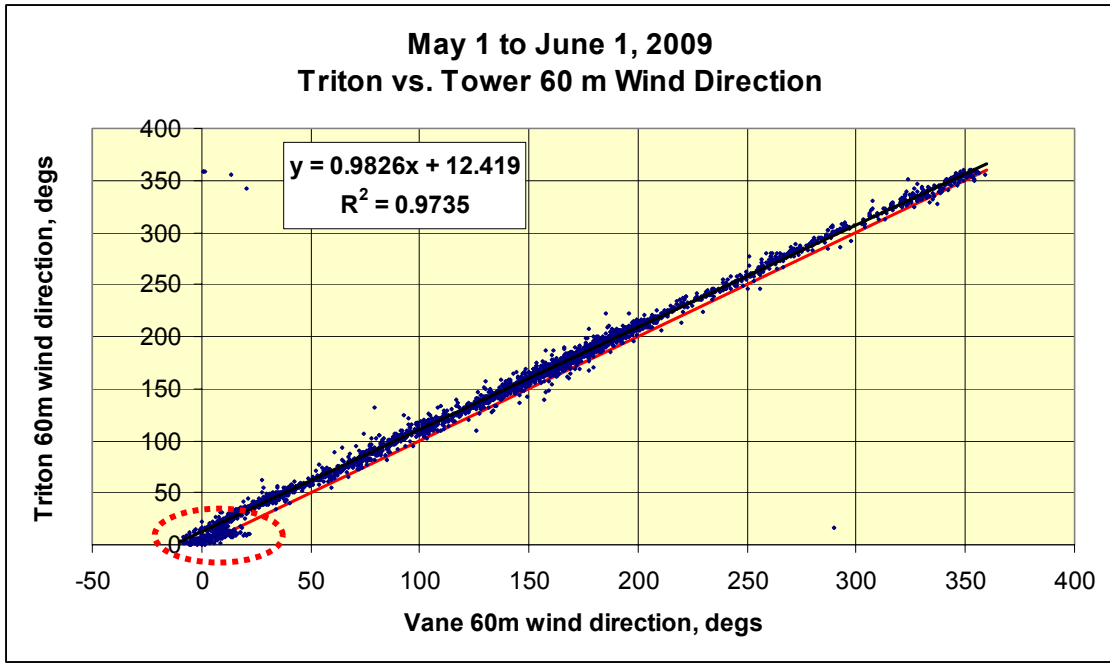


Figure 9: 60 m Triton vs. 60 m Tower Wind Direction

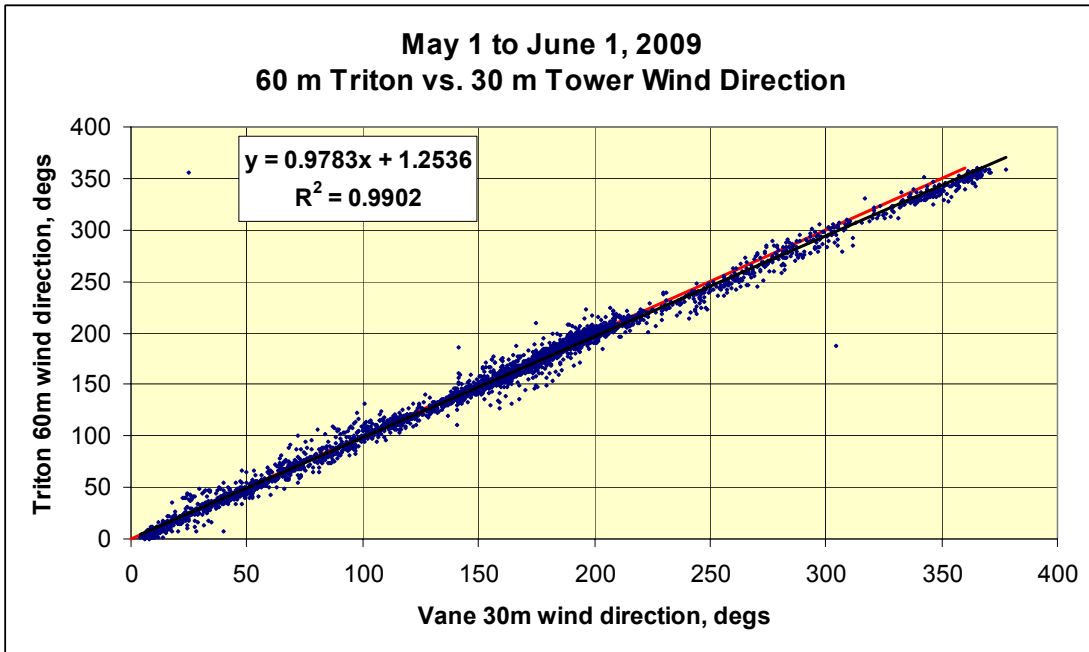


Figure 10: 60m Triton vs. 30m Tower Wind Direction

The wind direction data was then binned into 45° bins and the frequency of occurrence was found for each bin. Table 3 shows the tabulated values and Figure 11 presents a wind rose comparing the 60 m Triton and 30 m tower wind direction data. Both instruments measured nearly identical wind roses and both show the prevailing wind direction to be from the south.

Table 3: Wind Direction Distributions

Triton Data

| Direction | Count | % Data |
|-----------|-------|--------|
| N | 474 | 10.9% |
| NE | 577 | 13.3% |
| E | 396 | 9.1% |
| SE | 653 | 15.0% |
| S | 1490 | 34.3% |
| SW | 381 | 8.8% |
| W | 176 | 4.0% |
| NW | 200 | 4.6% |

Tower Data

| Direction | Count | % Data |
|-----------|-------|--------|
| N | 446 | 10.4% |
| NE | 612 | 14.2% |
| E | 419 | 9.8% |
| SE | 618 | 14.4% |
| S | 1585 | 36.9% |
| SW | 310 | 7.2% |
| W | 190 | 4.4% |
| NW | 116 | 2.7% |

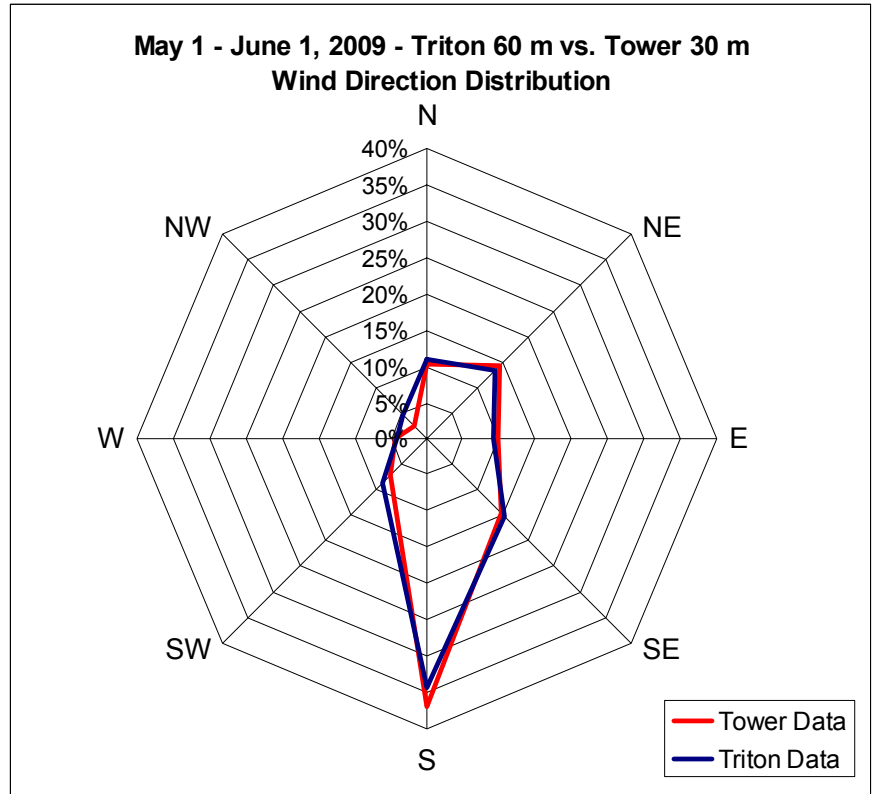


Figure 11: Triton and Tower Wind Roses

Triton and Tower Turbulence Comparison

Lastly, the turbulence data as measured by the Triton and tower are presented. The Triton turbulence data was filtered based on a minimum turbulence quality factor of 90%. The turbulence quality factor is identical to the wind speed quality factor but decreases at wind speeds less than 3.5 m/s to eliminate erroneously high turbulence values. It should be noted that there are fundamental differences in the turbulence intensity measured by a tower as opposed to that measured by a Triton. Anemometers measure a point in space while the Triton measures over a volume and differences in turbulence intensity are therefore expected. Figures 12 and 13 show scatterplots of the Triton and tower turbulence versus wind speed. As shown, the turbulence distributions are quite similar with the tower reading a slightly lower turbulence than the Triton. On average, the Triton measured a turbulence intensity of 0.099 while the tower reported an average TI of 0.093.

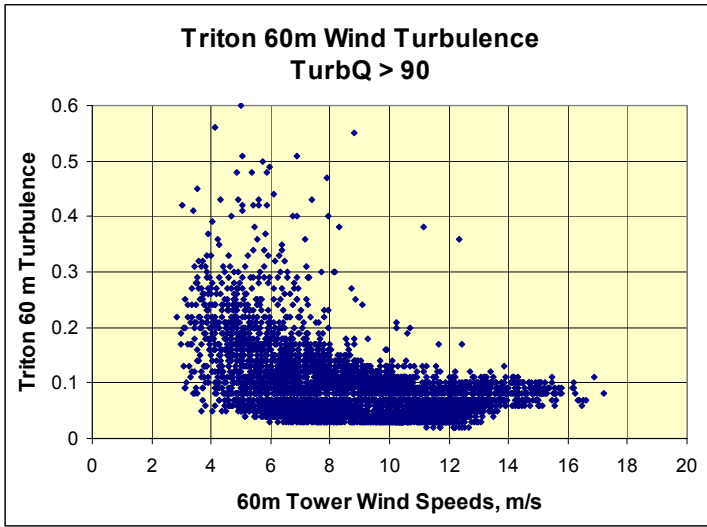


Figure 12: Triton 60m Turbulence vs. Wind Speed

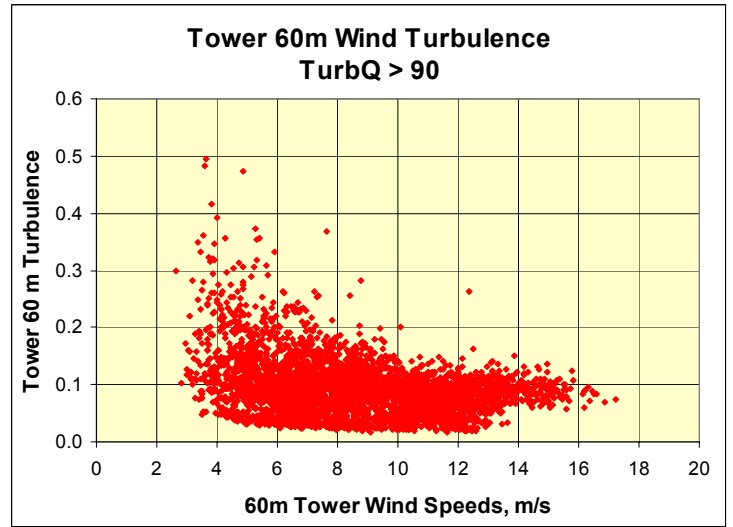


Figure 13: Tower 39m Turbulence vs. Wind Speed

The turbulence data was then sorted by wind speed and the average TI was calculated for each 1 m/s bin. The results are shown in Table 4 and Figure 14. The Triton and tower reported very similar turbulence values over a range of wind speeds.

Table 4: Average 60 m TI by Wind Speed bins

| Wind Speed bins, m/s | Triton Avg Turb | Tower Avg Turb | Count |
|----------------------|-----------------|----------------|-------|
| 3 to 4 | 0.200 | 0.169 | 102 |
| 4 to 5 | 0.171 | 0.134 | 274 |
| 5 to 6 | 0.142 | 0.108 | 437 |
| 6 to 7 | 0.108 | 0.094 | 539 |
| 7 to 8 | 0.097 | 0.093 | 485 |
| 8 to 9 | 0.087 | 0.089 | 420 |
| 9 to 10 | 0.078 | 0.083 | 363 |
| 10 to 11 | 0.066 | 0.074 | 368 |
| 11 to 12 | 0.060 | 0.068 | 333 |
| 12 to 13 | 0.066 | 0.074 | 295 |
| 13 to 14 | 0.076 | 0.088 | 165 |
| 14 to 15 | 0.083 | 0.092 | 81 |
| 15 to 16 | 0.083 | 0.088 | 38 |
| 16 to 17 | 0.081 | 0.082 | 10 |
| 17 plus | 0.080 | 0.073 | 1 |
| Total Count: | | | 3911 |

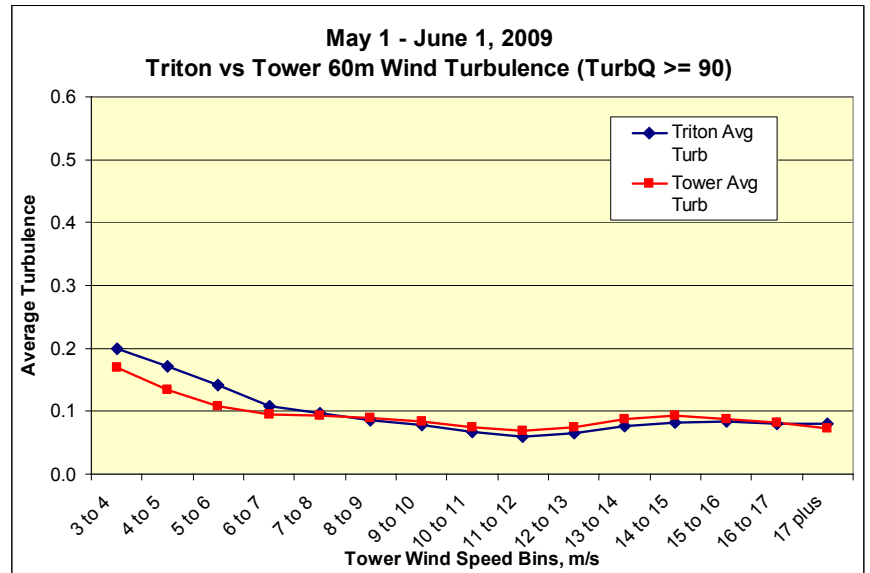


Figure 14: Average 60 m TI by Wind Speed bin

SHEAR AND INFLOW ANGLE ANALYSIS

Wind Speed Shear and Inflow Angle at the site

The last section of the report presents results of the wind shear and inflow angle analysis of the Triton data. Firstly, the wind shear results are given. From May 1st to June 1st, 2009, the average wind speeds from 40 to 120 m (i.e. the typical swept area of a turbine) were determined and are shown in Figure 13. A power law profile was then fit to the measured Triton data and a power law exponent, alpha, was estimated. For this data collection period, the overall shear exponent was found to be 0.176. The data was also separated into daytime and nighttime and the power law exponents were estimated for both. It was found that, during the day, the average shear exponent was 0.074 while, at night, the average shear exponent was higher at 0.282. Figures 14 and 15 show the day and nighttime wind shear profiles.

Table 5: Estimated Wind Shear Exponents

| Triton Shear Exponents | Power Law Exponent |
|------------------------|--------------------|
| Overall Shear | 0.176 |
| Nighttime Shear | 0.282 |
| Daytime Shear | 0.074 |

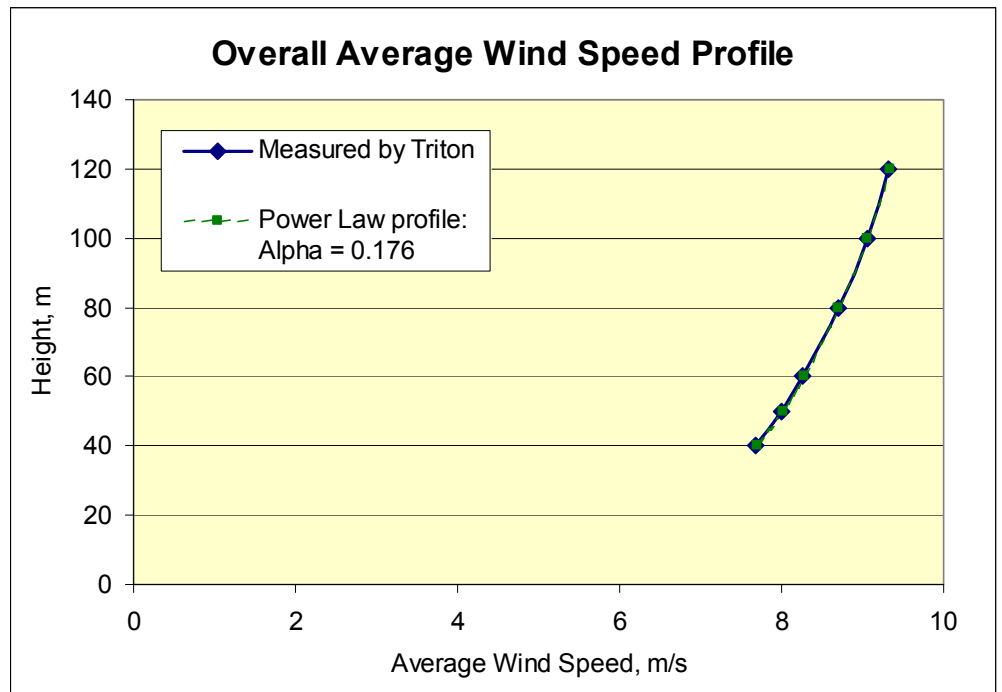


Figure 15: Overall Wind Shear Profile

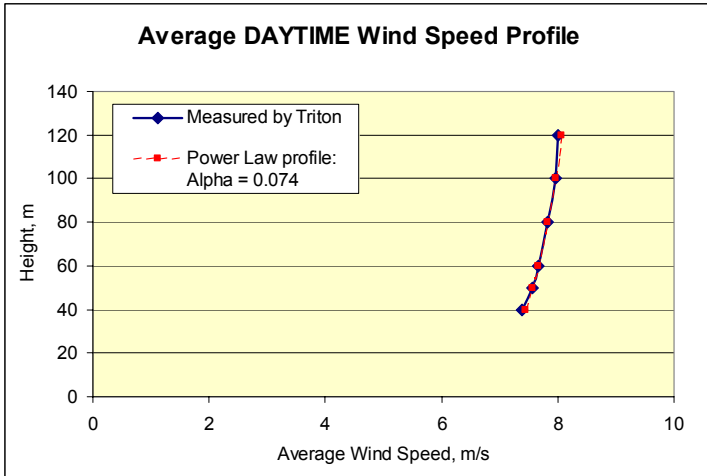


Figure 16: Average Daytime Wind Speed Profile

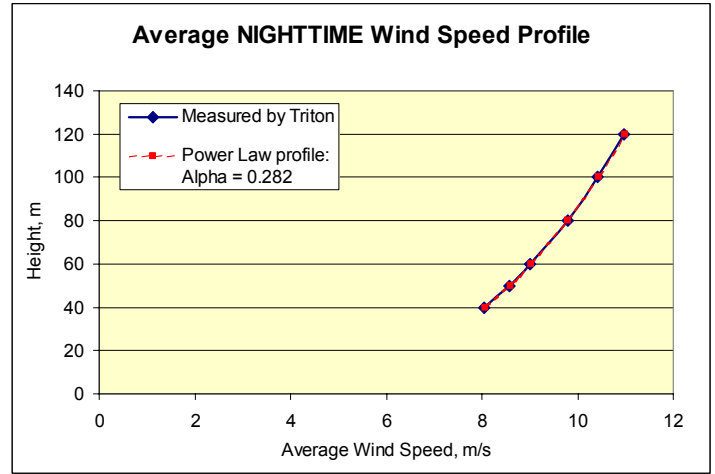


Figure 17: Average Nighttime Wind Speed Profile

Angle of Attack (Inflow Angle)

Lastly, the angle of attack as a function of direction is examined. The angle of attack or inflow angle is defined as the angle of the wind speed off horizontal where a positive angle is indicative of an upward flow and a negative angle implies downward movement. The data collected from May 1st to June 1st, 2009 was sorted into 45° direction bins and the average inflow angle was determined for each bin. The results of the analysis are shown in Table 6 and Figure 16. As shown, the average angle of attack was found to be negative when the wind direction was from the south while a positive AOA was calculated during periods of northern winds. The largest AOA was found in the north sector at -2.08° .

Table 6: Inflow Angles and Average Vertical Wind Speeds

| Wind Direction Sector | Avg Vert Wind Speed, m/s | Inflow Angle, degs |
|-----------------------|--------------------------|--------------------|
| N | 0.16 | 0.80 |
| NE | 0.13 | 0.96 |
| E | -0.05 | -0.58 |
| SE | -0.24 | -1.77 |
| S | -0.35 | -2.08 |
| SW | -0.31 | -2.05 |
| W | -0.05 | -0.34 |
| NW | 0.09 | 0.67 |

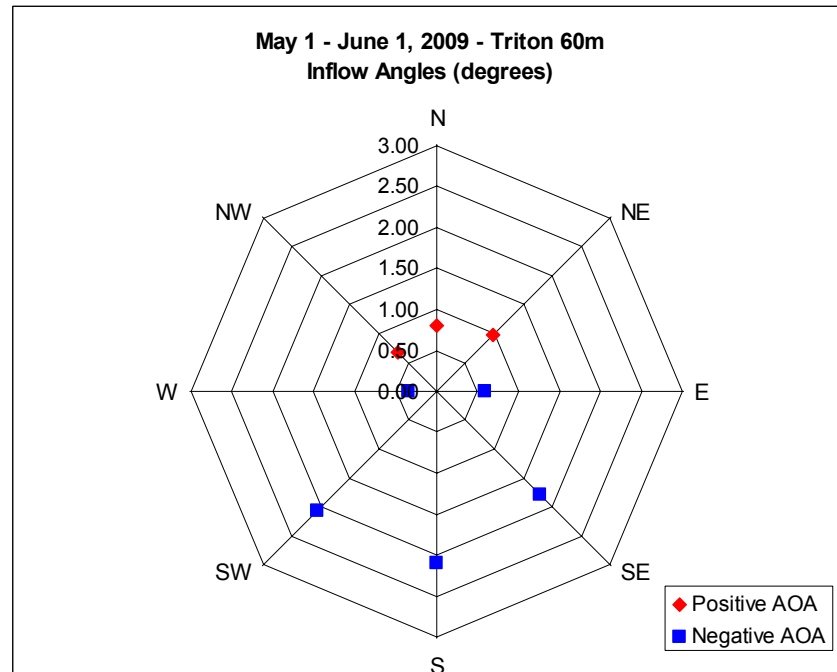


Figure 18: Inflow Angle Distribution

SUMMARY AND CONCLUSIONS

Overall, the Triton at the test site performed very well. This summary report included data collected at the test site from May 1st to June 1st, 2009. In the report, the following observations were made:

- 1) The reliability (or operational uptime) of the Triton was almost perfect at 99.9%.
- 2) During operation, the percent of valid data was calculated as a function of height (i.e. from 40 to 200 m). High data recovery was observed and it was found that the Triton measured 99% valid data at 40 m and 84% valid data at 120 m.
- 3) The wind speeds measured by the 60 m tower were compared to the 60 m Triton wind speeds. The two data sets tracked very well and a correlation coefficient of 0.989 was found.
- 4) The average wind speed measured by the Triton and tower at 60 m were analyzed and it was found that the two average wind speeds differed by only -1%.
- 5) The Triton and tower wind direction data were also compared. An offset of approximately 12° was observed when comparing the Triton and 60 m vane data. When the Triton data was then plotted against the 30 m vane data, a very small offset of ~1° was seen and a correlation coefficient of 0.995 was found. Based on these observations, the 60 m boom appears to be aligned incorrectly. Both the Triton and tower data showed that the prevailing wind direction was from the south.
- 6) The turbulence intensity as measured by the Triton and tower were analyzed and it was found that the two devices gave similar turbulence values with the Triton reading slightly higher. On average, the tower recorded a turbulence intensity of 0.093 while the Triton measured an average turbulence intensity of 0.099.
- 7) The Triton data was used to analyze the wind shear at the test site. The average wind speed profile was determined and a power law profile was fit to the data. The average wind shear exponent was found to be 0.176. Also, the diurnal wind shears were analyzed and a wind shear exponent of 0.074 was found during daytime hours while the average nighttime profile produced a wind shear exponent of 0.282.
- 8) Finally, the inflow angle was determined in each wind direction sector and it was found that, during southerly winds, there is a slight downward flow with an average inflow angle of -2°.

Based on this analysis, the results of the study are very good and the correlation study can be deemed complete. The Triton can now be relocated to other positions for purposes of site characterization or other information gathering endeavors.