# WIND DATA REPORT

# Quincy Quarry Hills

August 2006 to August 2007

Prepared for

Massachusetts Technology Collaborative
75 North Drive
Westborough, MA 01581

by

Frederick Letson
James F. Manwell
Anthony L. Rogers
Anthony F. Ellis

October 19, 2007

Report template version 1.4

**R**enewable **E**nergy **R**esearch **L**aboratory
University of Massachusetts, Amherst
160 Governors Drive, Amherst, MA 01003
www.ceere.org/rerl • (413) 545-4359 • rerl@ecs.umass.edu

# NOTICE AND ACKNOWLEDGEMENTS

This report was prepared by the Renewable Energy Research Laboratory (RERL) at the University of Massachusetts, Amherst in the course of performing work sponsored by the Renewable Energy Trust (RET), as administered by the Massachusetts Technology Collaborative (MTC). The opinions expressed in this report do not necessarily reflect those of MTC or the Commonwealth of Massachusetts, and reference to any specific product, service, process, or method does not constitute an implied or expressed recommendation or endorsement of it.

Further, MTC, the Commonwealth of Massachusetts, and RERL make no warranties or representations, expressed or implied, as to the fitness for particular purpose or merchantability of any product, apparatus, or service, or the usefulness, completeness, or accuracy of any processes, methods or other information contained, described, disclosed, or referred to in this report. MTC, the Commonwealth of Massachusetts, and the contractor make no representation that the use of any product, apparatus, process, method, or other information will not infringe privately owned rights and will assume no liability for any loss, injury, or damage directly or indirectly resulting from, or occurring in connection with, the use of information contained, described, disclosed, or referred to in this report.

# TABLE OF CONTENTS

# TABLE OF FIGURES

# EXECUTIVE SUMMARY

All the work presented in this Wind Data Report including installation and decommissioning of the meteorological tower and instrumentation, and the data analysis and reporting was performed by the Renewable Energy Research Laboratory (RERL) at the University of Massachusetts, Amherst.

The sensors at the Quincy Quarry Hills site were installed on August 10th 2006, and have been in continuous operation until the present. The data are from two anemometers and one wind vane at each of 106.7 meters (350 ft) and 70.4 meters (231 feet). These sensors are mounted on a triangular lattice tower, and were installed by the tower owner in a position different from that given in the instructions from the RERL. The proximity of the sensors to the tower is a source of some uncertainty in wind speed measurements, as the wind speed close to a lattice tower is affected significantly by the tower's presence. Two anemometers and one wind vane were added at 70.4 meters on May 3rd 2007. These sensors are on longer booms to reduce the effect of the tower on wind speed and direction measurements.

This report covers wind data collected at the Quincy Quarry Hills Site from August 11th, 2006 through August 11th, 2007. During this year, the average wind speed measured at 107.6 meters was 6.95 m/s (15.5 mph)[1] and the prevailing wind was from the Southwest. The gross data recovery percentage (the actual percentage of expected data received) was 100% and the net data recovery percentage (the percentage of expected data which passed all of the quality assurance tests) was 94.5%.

Additional information about interpreting the data presented in this report can be found in the Fact Sheet, "Interpreting Your Wind Resource Data," produced by RERL and the Massachusetts Technology Collaborative (MTC). This document is found through the RERL website:

http://www.ceere.org/rerl/about_wind/RERL_Fact_Sheet_6_Wind_resource_interpretation.pdf

* 1 m/s = 2.237 mph.

---

[1] 1 m/s = 2.237mph

# SECTION 1 - Station Location

The Quincy Quarry Hills Site is located near the Granite Links Golf Club in Quincy, Massachusetts, off Ricciuti Drive. The tower stands at 42.24711° north and 71.04821° west, corresponding to the WGS 84 datum. The tower base is at an elevation of 50 meters above sea level.

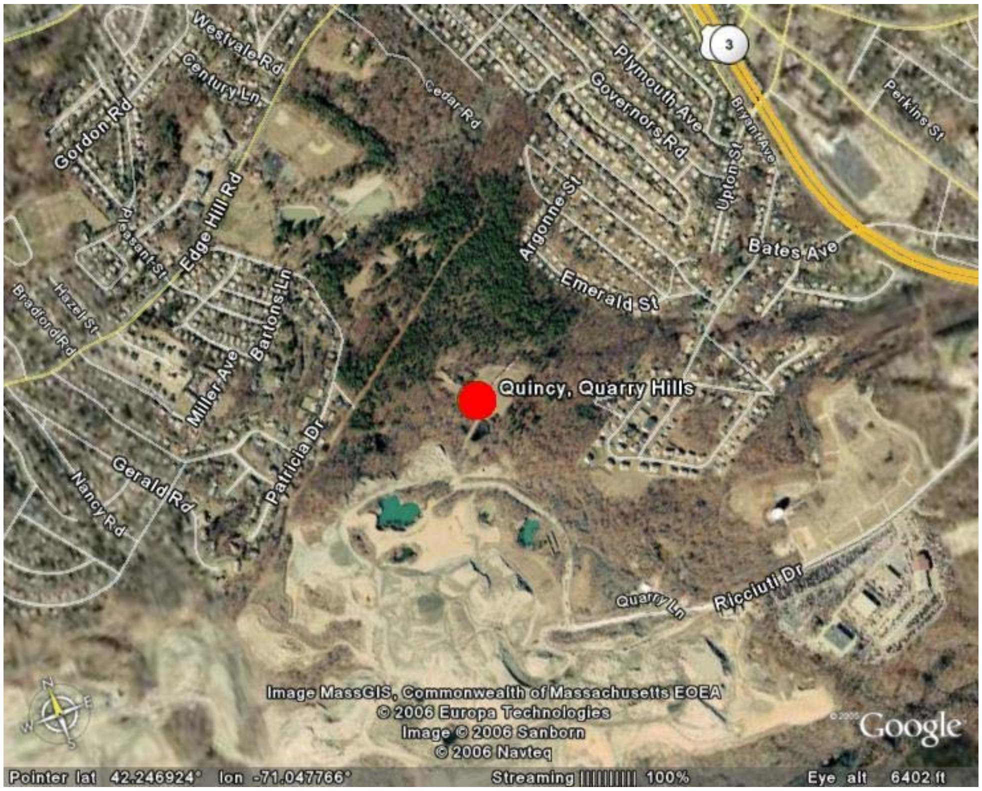

**Figure 1 - Map showing the location of the Quincy Quarry Hills site**

# SECTION 2 - Instrumentation and Equipment

The monitoring equipment at Quincy Quarry Hills is mounted on an existing triangular lattice tower owned by Industrial Communications. This equipment includes:

- Symphonie Data Logger
- Electrical enclosure box
- 6 – #40 Anemometers, standard calibration (Slope - 0.765 m/s, Offset – 0.350 m/s). Two anemometers are located at 107.6 m (350 ft)and four at 70.4 m (231 ft).
- 3 - #200P Wind direction vanes. 1 at a height of 107.6 m (350 ft) and 2 at 70.4 m (231 ft).
- 1 Temperature sensor #110S located at 2 meters
- Shielded sensor wire

The data from the Symphonie logger is mailed to the Renewable Energy Research Laboratory at the University of Massachusetts, Amherst on a regular basis. The logger samples wind speed and direction once every two seconds. These data are then combined into 10-minute averages and, along with the standard deviation for those 10-minute periods, are put into a binary file. These binary files are converted to ASCII text files using the NRG software BaseStation®. These text files are then imported into a database software program where they are subjected to quality assurance (QA) tests prior to using the data.

# SECTION 3 - Data Summary

A summary of the wind speeds and wind directions measured during the reporting period is included in Table 1. Table 1 includes the mean wind speeds measured at each measurement height, the maximum instantaneous wind speed measured at each measurement height and the prevailing wind direction measured at each measurement height. These values are provided for each month of the reporting period and for the whole reporting period.

On February 6th, 2007 at 10:30 am, the wind vane at 107.6 meters stopped functioning. Wind direction data for that height are not available after that time. Wind directions at 70.4 meters are used in their place in this report.

## Table 1. Wind Speed and Direction Data Summary

| Height | 107.6 meters | | 70.4 meters | | |
|---|---|---|---|---|---|
| | Mean Wind Speed | Max Wind Speed | Mean Wind Speed | Max Wind Speed | Prevailing Wind Direction |
| Units | [m/s] | [m/s] | [m/s] | [m/s] | [deg] |
| **Sep-06** | 6.43 | 14.96 | 5.60 | 13.96 | 225 |
| **Oct-06** | 7.61 | 20.71 | 6.62 | 18.94 | 238 |
| **Nov-06** | 6.63 | 19.99 | 5.68 | 15.44 | 255 |
| **Dec-06** | 7.57 | 20.39 | 6.57 | 18.96 | 244 |
| **Jan-07** | 7.24 | 15.45 | 6.38 | 14.43 | 257 |
| **Feb-07** | 7.85 | 20.50 | 7.08 | 19.20 | 266 |
| **Mar-07** | 8.43 | 20.02 | 7.48 | 17.62 | 256 |
| **Apr-07** | 7.20 | 23.95 | 6.36 | 20.62 | 330 |
| **May-07** | 6.61 | 13.77 | 5.86 | 12.25 | 271 |
| **Jun-07** | 6.31 | 13.68 | 5.66 | 12.28 | 259 |
| **Jul-07** | 5.84 | 15.51 | 5.17 | 14.57 | 222 |
| **Average** | **6.95** | **23.95** | **6.12** | **20.62** | **249.85** |

Wind data statistics in the table are reported when more than 90% of the data during the reporting period are valid. In cases when a larger amount of data are missing, the percent of the available data that are used to determine the data statistics is noted.

No measurement of wind speed or direction can be perfectly accurate. Wind speed measurement errors occur due to anemometer manufacturing variability, anemometer calibration errors, the response of anemometers to turbulence and vertical air flow and due to air flows caused by the anemometer mounting system. Every effort is made to reduce the sources of these errors. Nevertheless, the values reported in this report have an expected uncertainty of about ± 2% or ± 0.2 m/s, whichever is greater. Wind direction measurement errors occur due to sensor measurement uncertainty, tower effects, boom alignment measurement errors and twisting of pipe sections during the raising of a pipe tower. Efforts are also made to reduce these errors, but the reported wind directions are estimated to have an uncertainty of +/- 5 degrees.

A summary of the turbulence intensity and mean wind shear measured at each measurement height during the reporting period is included in Table 2. These values are provided for each month of the reporting period and for the whole reporting period. Turbulence Intensity is calculated by dividing the standard deviation of the wind speed by the mean wind speed and is a measure of the gustiness of a wind resource. Lower turbulence results in lower mechanical loads on a wind turbine. Turbulence intensity varies with wind speed. The average turbulence intensity presented in Table 2 is the mean turbulence intensity when the wind speed at the highest measurement height is between 9.5 and 10.5 m/s.

Shear coefficients provide a measure of the change in wind speed with height. When data at multiple heights are available, shear coefficients, α, have been determined. They can be used in the following formula to estimate the average wind speed, $U(z)$, at height $z$, when the average wind speed, $U(z_r)$, at height $z_r$ is known:

$$U(z)=U(z_r)\left(\frac{z}{z_r}\right)^{\alpha}$$

The change in wind speed with height is a very complicated relationship related to atmospheric conditions, wind speed, wind direction, time of day and time of year. This formula will not always provide the correct answer at any given site. Nevertheless the calculated shear coefficient, based on measurements at two heights, can be used to characterize the degree of increase in wind speed with height at a site.

The mean wind shear coefficient that is provided here is calculated based on the mean wind speeds in Table 1, where $z_{high}$ and $z_{low}$ are the heights of the higher and lower mean wind speeds used in the calculation and $U(z_{low})$ and $U(z_{high})$ are the mean wind speeds at the two heights.

$$\alpha = \log\left(\frac{U(z_{high})}{U(z_{low})}\right)\Big/\log\left(\frac{z_{high}}{z_{low}}\right)$$

## Table 2. Shear and Turbulence Intensity Data Summary

| | Mean Turbulence Intensity at 10.5 m/s | | Mean Shear Coefficient Between 70.4 and 106.7 m |
|---|---|---|---|
| **Date** | **107.6 m** | **70.4 m** | |
| **Sep-06** | 0.10 | 0.16 | 0.33 |
| **Oct-06** | 0.13 | 0.16 | 0.33 |
| **Nov-06** | 0.11 | 0.16 | 0.36 |
| **Dec-06** | 0.13 | 0.16 | 0.33 |
| **Jan-07** | 0.15 | 0.17 | 0.30 |
| **Feb-07** | 0.16 | 0.19 | 0.24 |
| **Mar-07** | 0.15 | 0.18 | 0.28 |
| **Apr-07** | 0.16 | 0.19 | 0.29 |
| **May-07** | 0.14 | 0.14 | 0.28 |
| **Jun-07** | 0.12 | 0.17 | 0.26 |
| **Jul-07** | 0.10 | 0.18 | 0.29 |
| **Average** | **0.13** | **0.17** | **0.30** |

## SECTION 4- Capacity Factor

The capacity factor of a wind turbine at a given site depends on the hub height, wind speed distribution at the hub height, the wind turbine power curve and any assumptions about down time and losses due to wake effects from upwind wind turbines, etc. If the hub height wind speed is estimated from data at lower heights, then the capacity factor will also depend on the estimated wind shear and the wind speeds measured at lower heights. No simple estimate of capacity factor at a site could take all of these effects and choices into account. Nevertheless, an estimate of the capacity factor of a wind turbine at this site is provided here to help the reader understand the order of magnitude of the wind resource at this site.

The estimates assume a hub height of 80 m, a 1.8 MW wind turbine with a rotor diameter of 80 m and the mean wind speed at the highest measurement height and the mean wind shear at the site, in order to determine the mean hub height wind speed. The capacity factor (CF) is then estimated from (see G.M. Masters, Renewable and Efficient Electric Power Systems, Wiley, 2004):

$$CF = (0.087)U_{hub} - \frac{P_{rated}}{D^2}$$

where $U_{hub}$ is the mean annual hub height wind speed in m/s, $P_{rated}$ is the rated power of the wind turbine in kW and D is the diameter of the rotor in meters. Based on this equation, the estimated capacity factor of a wind turbine at this site would be about 0.27.

## SECTION 5- Graphs

This report contains several types of wind data graphs. Unless otherwise noted, each graph represents data from one calendar year (August 11, 2006 to August 10th, 2007). The following graphs are included:

- Time Series, Figure 2 – 10-minute average wind speeds are plotted against time. This graph includes all of the collected data. The highest recorded wind speeds for the year are in late March.

- Wind Speed Distribution, Figure 3 – A histogram plot giving the percentage of time that the wind is at a given wind speed. The most frequent wind speeds are between 6 and 8 m/s.

- Monthly Average, Figure 4 – A plot of the monthly average wind speed over a 12-month period. This graph shows the trends in the wind speed over the whole period of data collection. This graph shows that it was windiest in the spring months. The August 2006, and August 2007 averages are both based on less than a complete month of data (20 days in 2006 and 10 days in 2007).

- Diurnal, Figure 5 – A plot of the average wind speed for each hour of the day. There is less wind on average during the day, and more wind during the night.
- Turbulence Intensity, Figure 6 – A plot of turbulence intensity as a function of wind speed. Turbulence Intensity is calculated as the standard deviation of the wind speed divided by the wind speed and is a measure of the gustiness of a wind resource. Lower turbulence results in lower mechanical loads on a wind turbine. As expected, turbulence intensities are higher at low wind speeds
- Wind Rose, Figure 7. – A plot, by compass direction showing the percentage of time that the wind comes from a given direction and the average wind speed in that direction. The prevailing wind direction at Quarry Hills during the reporting period was southwest.

Data for the wind speed histograms, monthly and diurnal average plots, and wind roses are included in APPENDIX B.

## Wind Speed Time Series

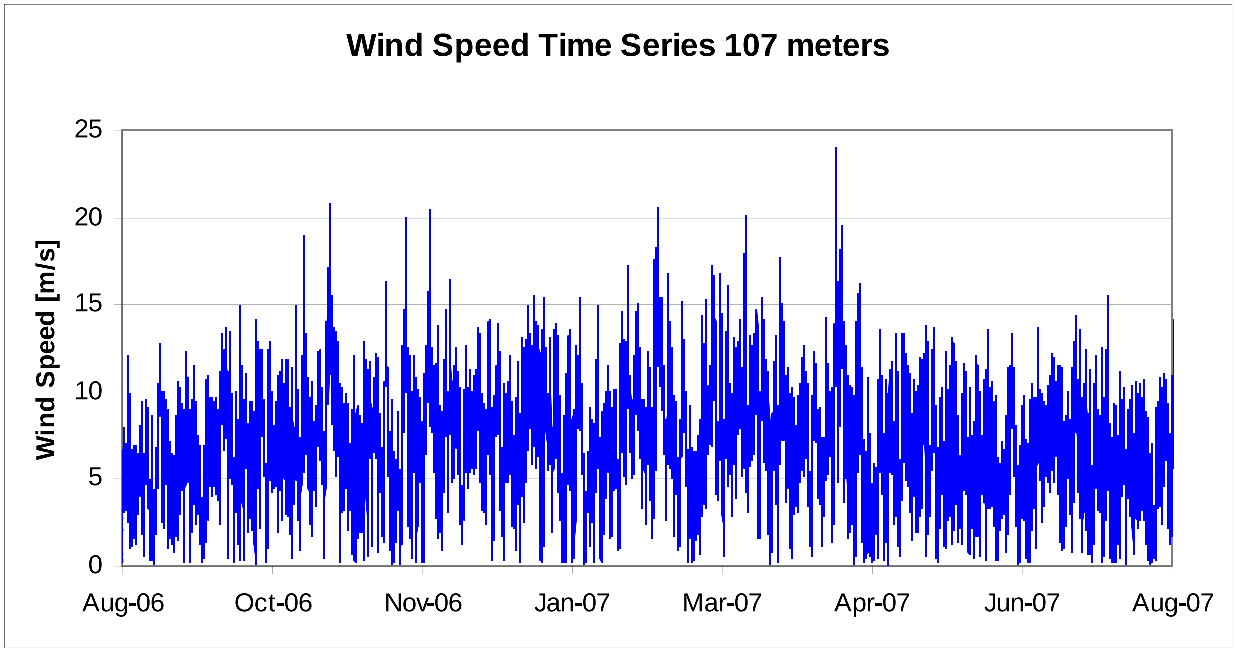

**Figure 2 – Wind Speed Time Series Quincy Quarry Hills 107 m**

# Wind Speed Distributions

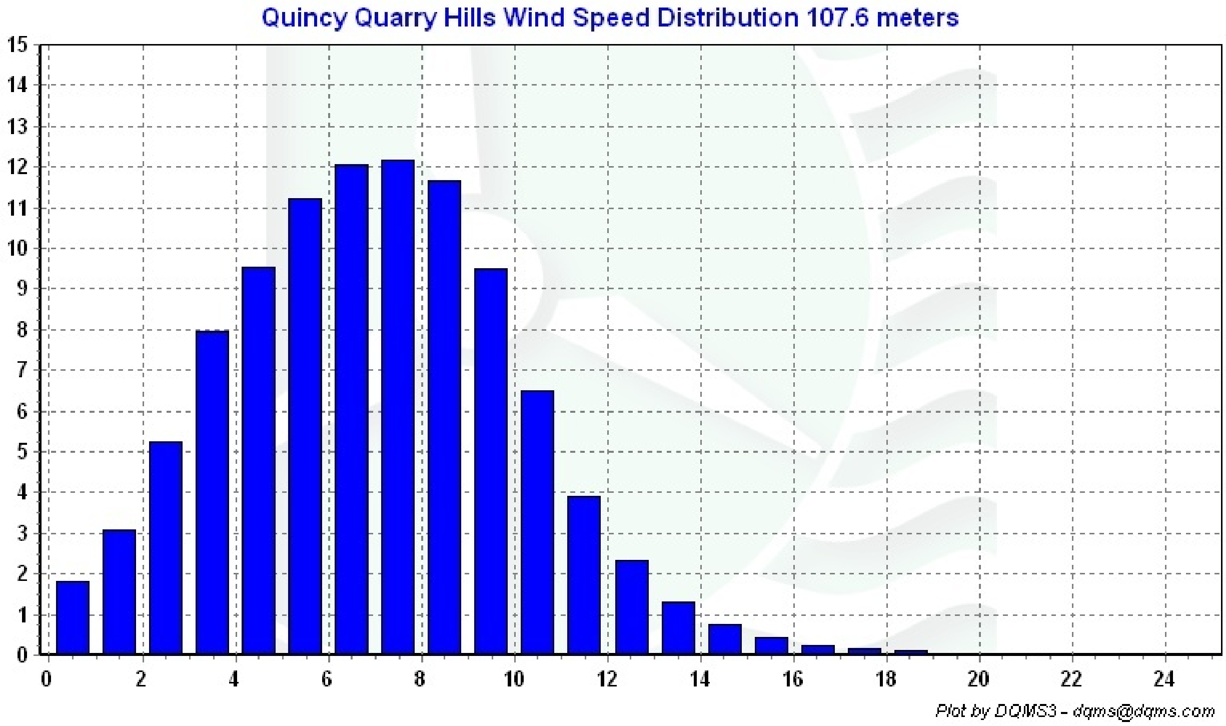

**Figure 3 – Wind Speed Distribution Quincy Quarry Hills 107 m**

# Monthly Average Wind Speeds

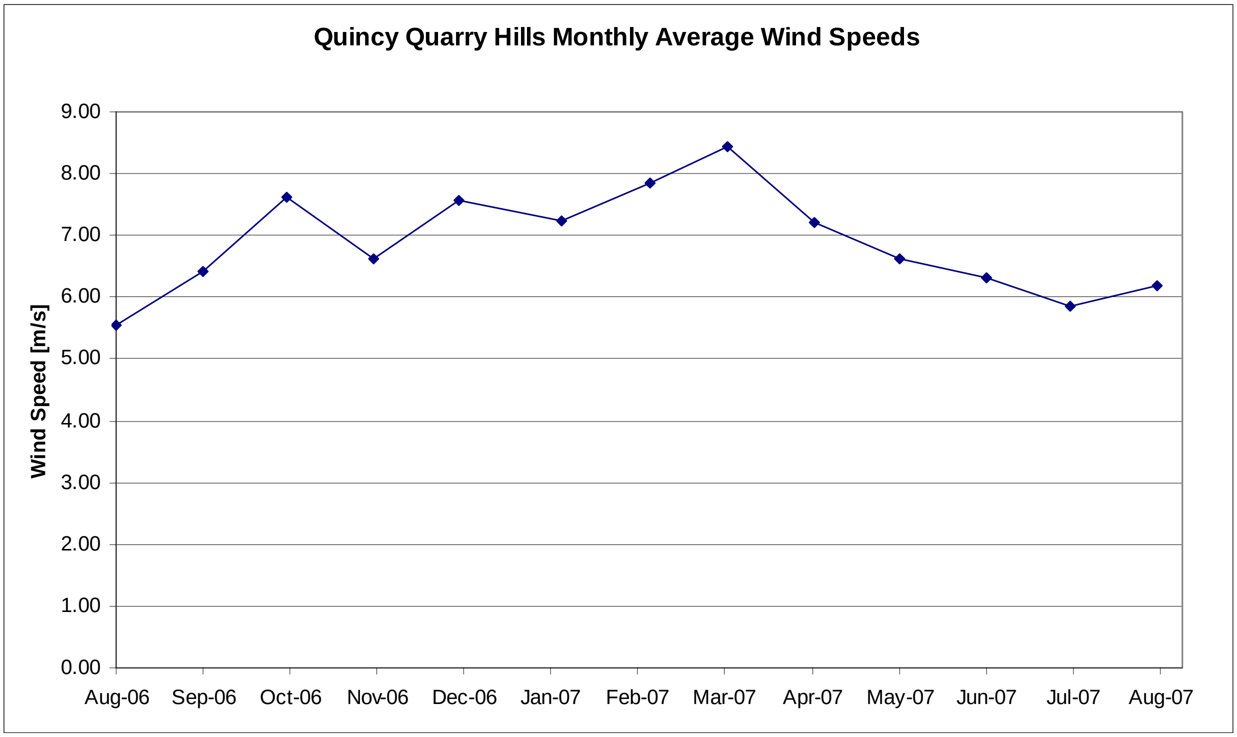

**Figure 4 – Monthly Average Wind Speeds Quincy Quarry Hills 107 m**

## Diurnal Average Wind Speeds

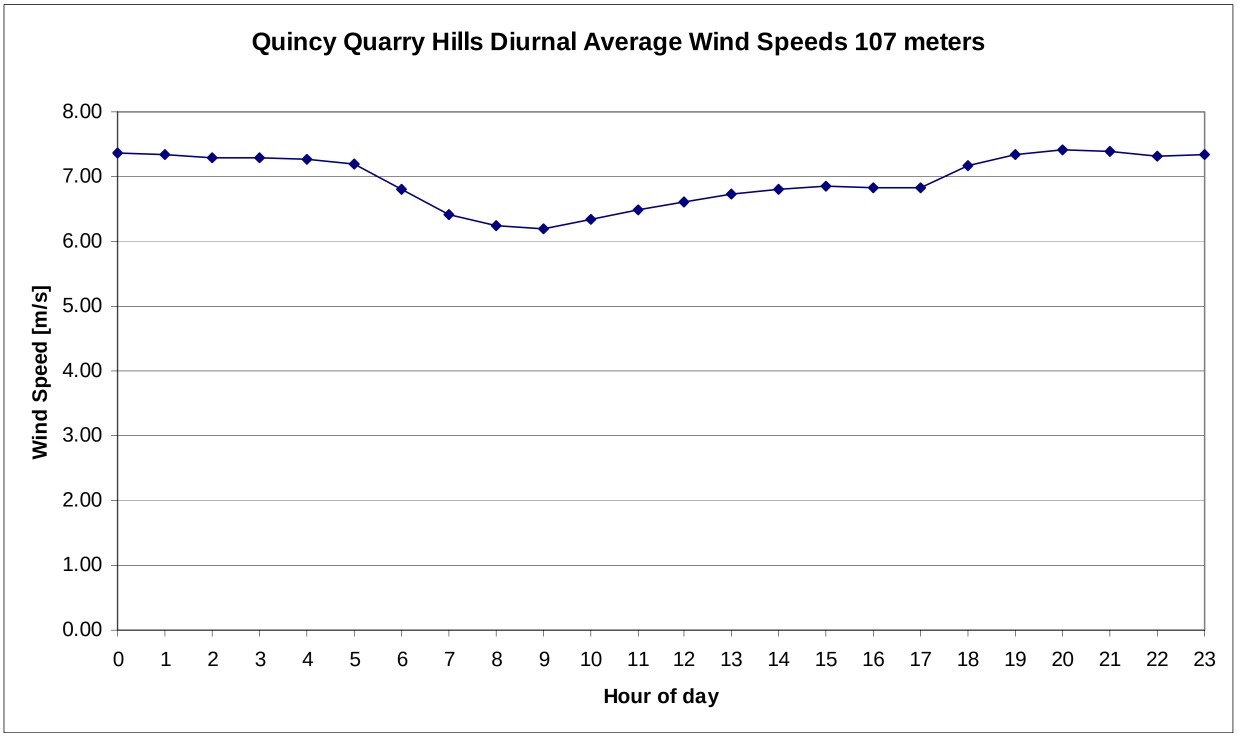

**Figure 5 – Diurnal Average Wind Speeds Quincy Quarry Hills 107 m**

## Turbulence Intensities

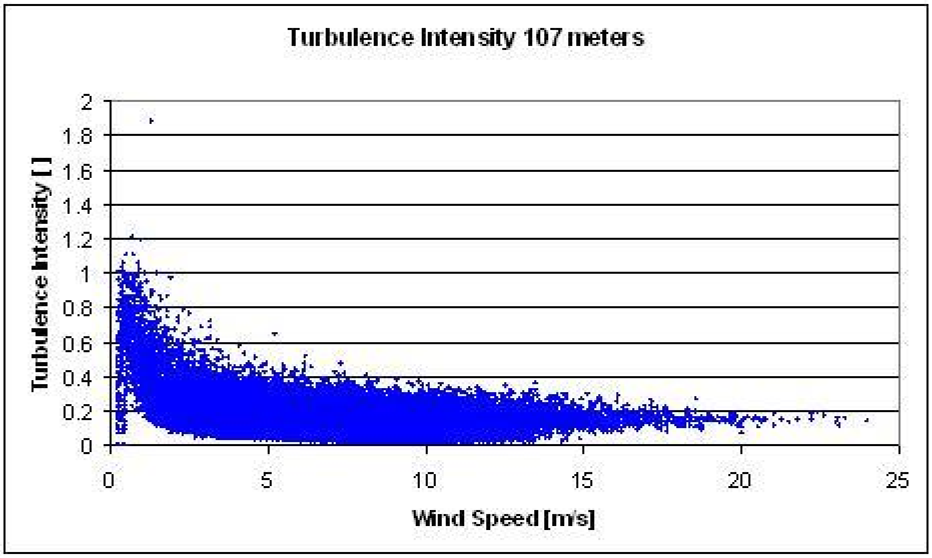

**Figure 6 – Turbulence Intensities by Wind Speed Quincy Quarry Hills 107 m**

## Wind Roses

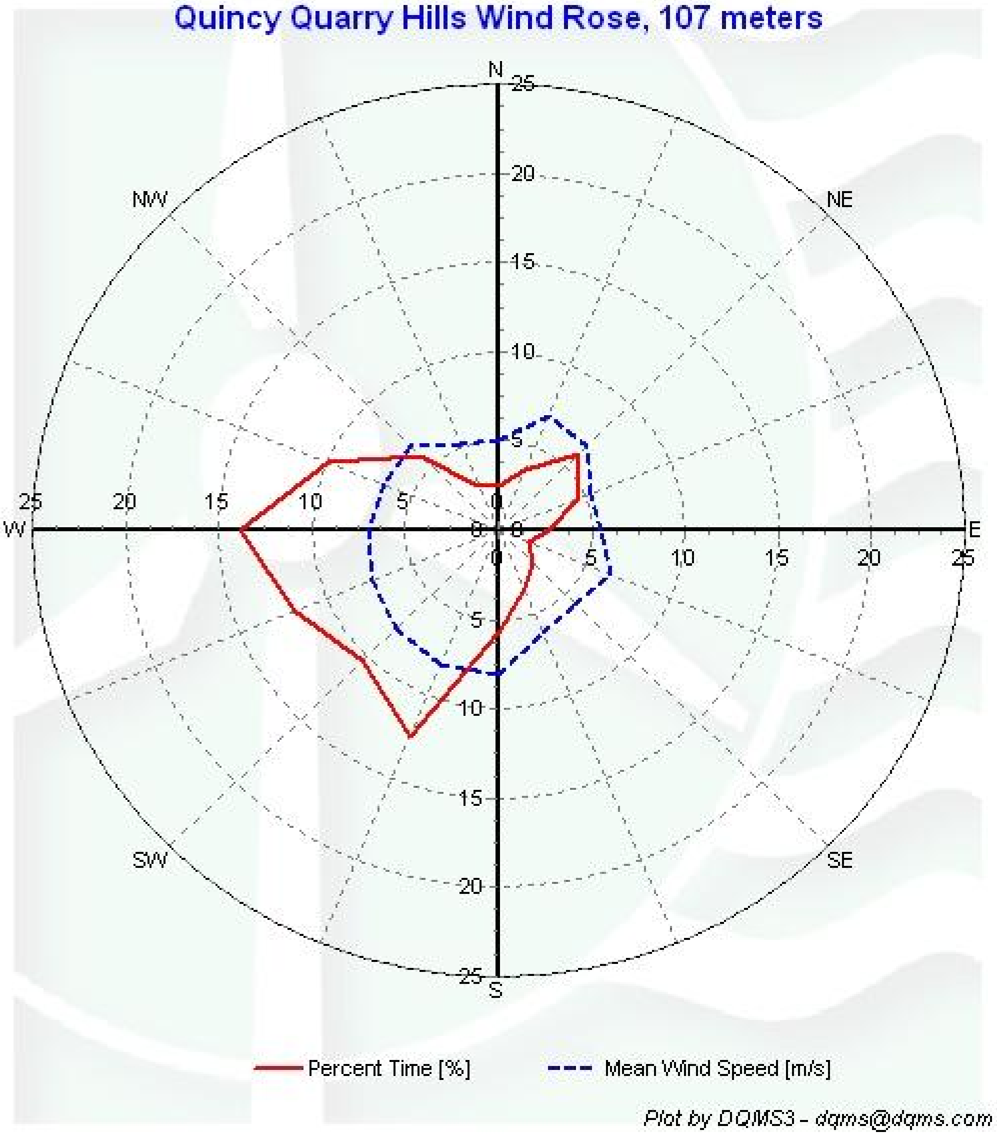

**Figure 7 – Wind Roses Quincy Quarry Hills 70.4 m**

## SECTION 6 - Significant Meteorological Events

There were no meteorological events in Quincy between august 2006 and August 2007 significant enough to effect yearly statistics.

# SECTION 7 - Data Collection and Maintenance

## Sensor Positions

The Quincy, Quarry Hills site originally had two anemometers and one wind vane at each of two heights: 70.4 and 107.6 meters. These instruments are mounted north and south of the triangular lattice tower. The sensors mounted north of the tower are referred to as the A sensors, while those to the south are referred to as B sensors. A schematic of the tower and the sensor placement, as seen from above, is shown in Figure 1. On May 3rd, a new set of two anemometers and one wind vane were placed at the 70.4 meter height on longer booms, west of the tower, where they would be less affected by tower shadow during winds from the prevailing wind directions. The new booms extend 2.6 meters out from the tower, the faces of which are 2.12 meters wide. These sensors are labeled New A and New B in Figure 8.

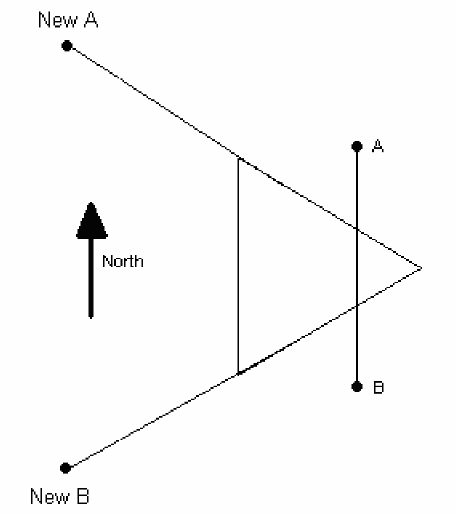

**Figure 8 - Sensor Positions**

## Tower Effects on Measured Wind Speed

The placement of the original sensor so close to the tower had a significant effect on the wind speed data. The tower also affected the new sensors, but not to the same degree. The details of the effects are described here.

### Original Sensors

Since the original sensors are mounted less than one tower-width away from the tower (that is, the distance from the tower to the sensors is less than the width of the tower), the aerodynamic effects of the tower have a significant effect on the measured wind speeds. The measured wind speeds will be lower than free-stream velocity when an anemometer is in the wind shadow of the tower, and can be high when it is in an area where wind is accelerating around the tower. Figure

9 shows the difference in measured wind speeds between the A and B anemometers at 107.6 meters plotted against the measured wind direction. Clearly sometimes one anemometer is measuring a higher wind speed than the other, with noticeable effects when one anemometer is in the wind shadow of one of the legs.

A positive speed on this graph indicates a wind direction for which the A anemometer reads higher that the B anemometer. A negative speed indicates a direction for which the B anemometer reads higher. These discrepancies are due to a combination of the slow down in wind speed down wind of the tower and the speed up that can occur to either side. The difference between the two sensors is often as large as 2 m/s and sometimes much more.

In the analysis that follows, the value of the higher sensor at each height is used as the most appropriate estimate of the correct wind speed. This ensures that a sensor in the wind shadow of part of the tower is not used to characterize the wind speed. On the other hand, choosing the higher of the original sensors may still introduce errors due to the proximity of the sensors to the tower legs.

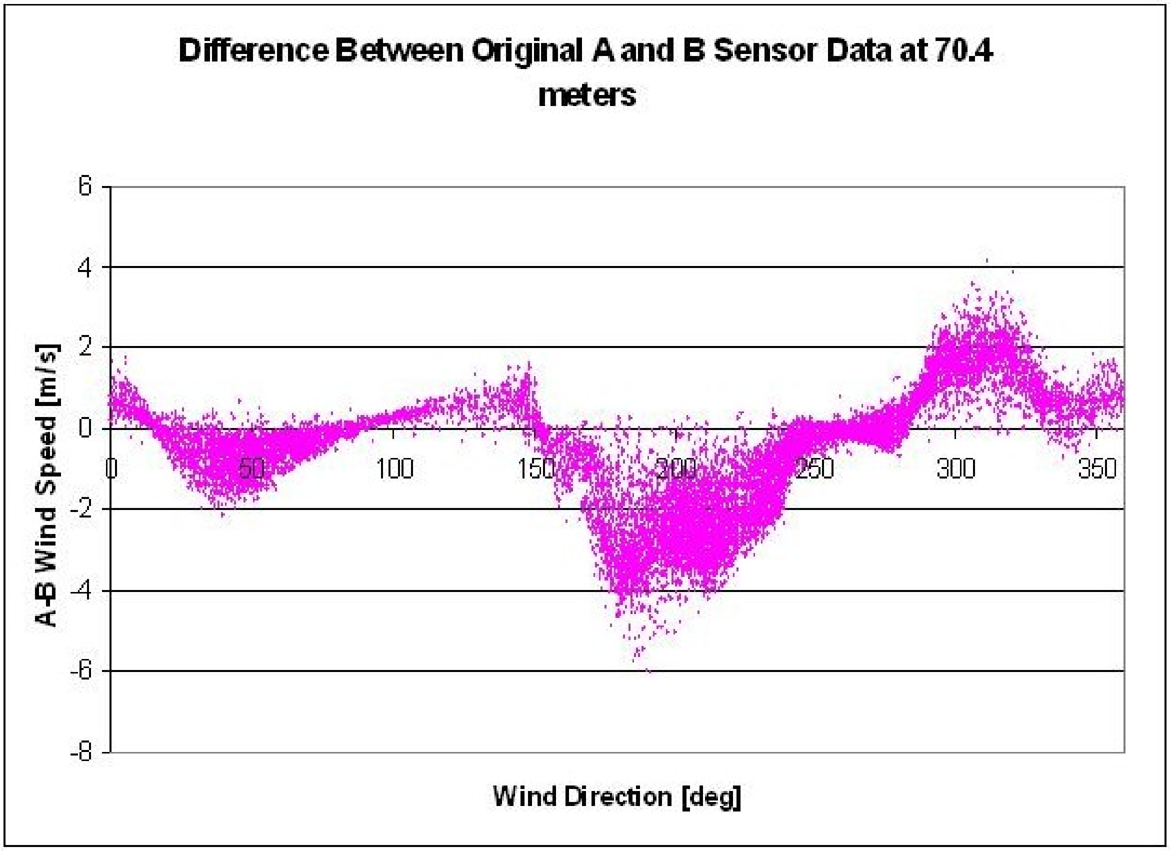

**Figure 9 - Difference in measured wind speeds, original anemometers**

## New Sensors

The new sensors installed at 70.4 m are farther from the tower and are upwind of the tower when the wind is from the prevailing wind directions. Each of these characteristics results in higher quality data and ensures that much of the time at least one sensor is providing a fairly reliable wind speed measurement. There is still a notable effect of tower shadow when the wind direction is northeast or southeast, placing a sensor in the lee of the tower. This can be seen below in Figure 10, which is a comparison of the New A and New B anemometers at 70.4 m as a function of wind direction. At wind directions around 45° and 125°, the magnitude of the difference between the two new sensors is large (one sensor is in the tower shadow and the other is clear of the tower shadow).

These new sensors show a much clearer pattern than that of the original sensors – when one is in the wake of a tower leg, the other is not. Thus, it is more clearly justifiable to select data from the sensor measuring the higher wind speed.

Flow effects, when the sensors are not in the tower shadow, are also lower than with the original sensors. At wind directions from between 150° and 360°, there is still a disagreement between the two sensors, due to flow around the tower, but this is on the order of +/– 0.6 m/s, a significant improvement over the original sensors.

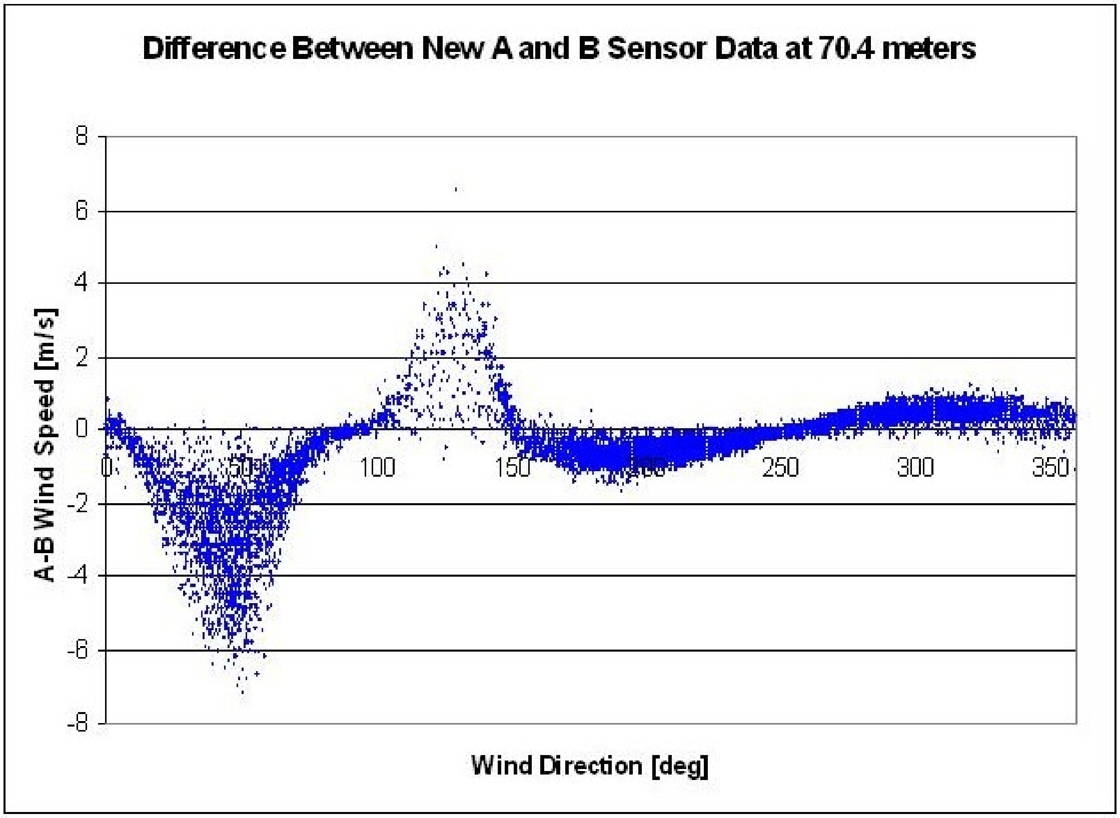

Figure 10 - Difference in measured wind speeds, new anemometers

## SECTION 8 Determining the Long-term Mean Wind Speeds at Quarry Hills

The long-term mean wind speeds at Quarry Hills were determined using the four months of data from the new sensors and the year of data that was available from the original sensors. The same MCP process described above was used for this analysis. In this case, the short-term data is the good data from the new sensors at 70 m and the long-term data is the data from the original sensors at 70 m. The long-term data represent one year: August 11th 2006 to August 10th 2007. The Short term data are from May 3rd 2007 to August 16th 2007.

### MCP at 70.4 Meters

The UMass MCP algorithm analyzes the data by wind direction sector. It determines a linear relationship between the primary sensor of the original sensor set and the primary sensor of the new sensors. It also determines the correlation coefficient between the two data sets. A correlation coefficient closer to 1 indicates that the relationship between the two data sets is more closely linear. The correlation coefficient for each direction sector is listed in Table 3 and shown in Figure 11. The correlation coefficients close to 1 are an indication that there is a strong linear relationship between the primary sensor data from the original sensors and that from the new sensors.

**Table 3 - Correlation Coefficients**

| Direction Sector Midpoint | Correlation Coefficient |
|---|---|
| 0 | 0.9938235 |
| 45 | 0.998196 |
| 90 | 0.9965125 |
| 135 | 0.9756951 |
| 180 | 0.9956372 |
| 225 | 0.9875205 |
| 270 | 0.9884471 |
| 315 | 0.9925429 |

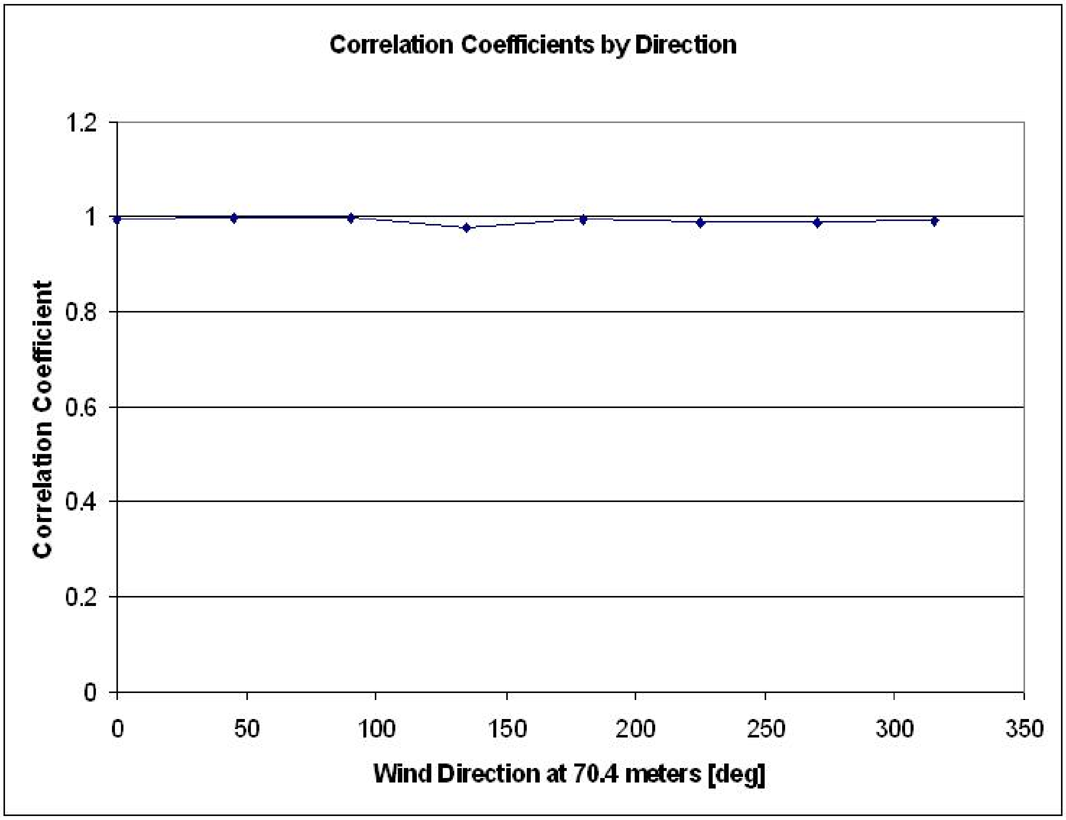

**Figure 11 - Correlation Coefficients**

Figure 12 illustrates the relationships between the data from each set of primary sensor data and how it varies with wind direction. Each graph is for data from a specific wind direction sector.

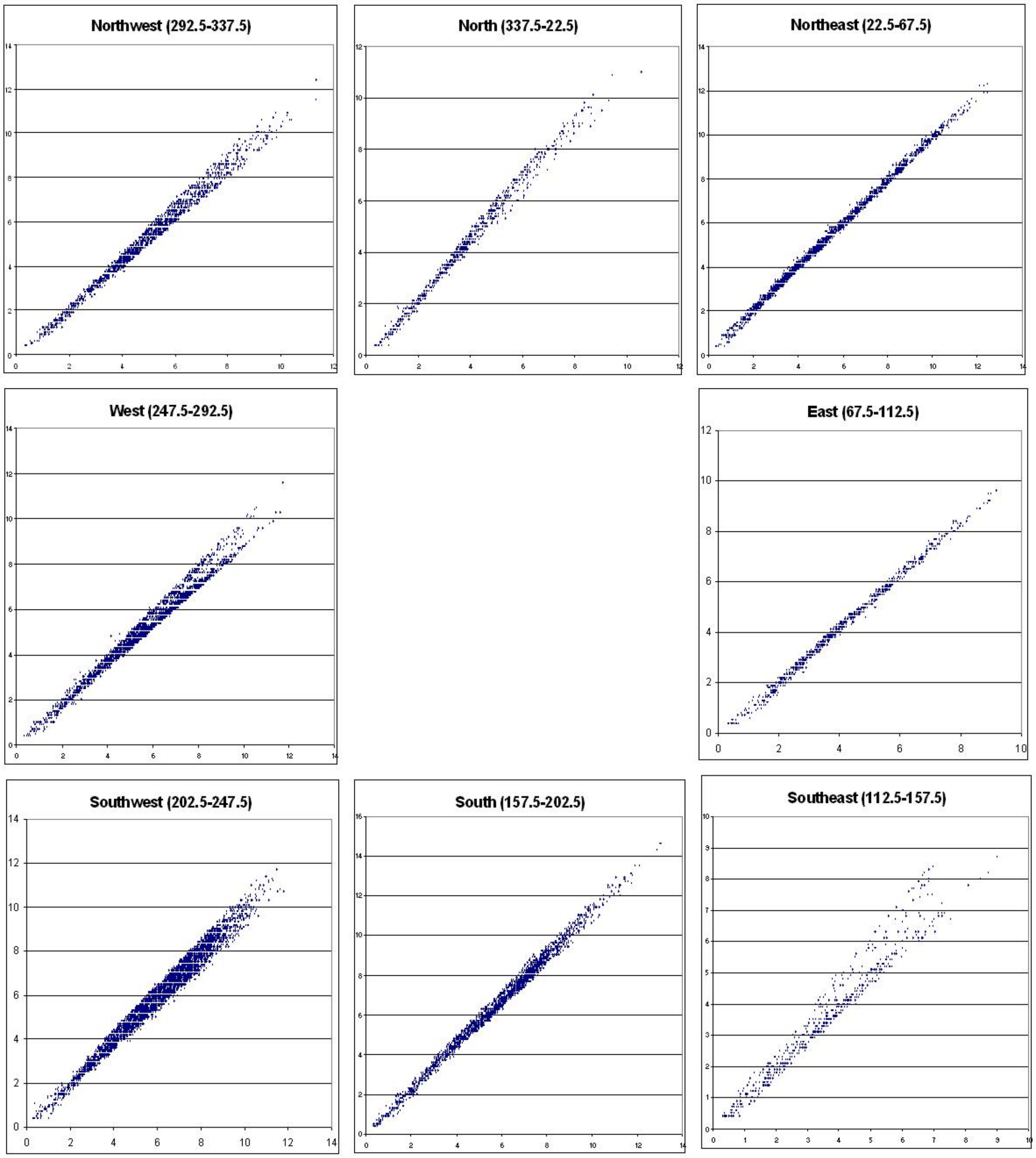

**Figure 12 – A set of scatter plots, one for each direction sector, each depicting the relationship between the wind speed measured by the old sensors (bottom axis) and that of the new sensors (left axis). Wind speeds are in meters per second.**

One can see in Figure 5, most prominently in the west direction sector, that there is sometimes more than one linear relationship that exists between the two data sets in a single sector. This does not invalidate the use of MCP, since we are seeking only average wind speeds, rather than a wind speed for any particular moment in time. The linear relation used in the MCP process will be, in a sense, a weighted average of the two linear relationships that can be seen in the scatter plot. If the relative probability of these 2 different conditions (whatever they might be) remains constant over time, then the wind speed characteristics predicted by MCP will be accurate.

This means that we can make a valid prediction of the wind speed characteristics at Quarry Hills using MCP.

Another visual representation of the relation between the primary sensor data from the original sensors and the new sensors is shown in Figure 13. Figure 13 is a scatter plot showing how the ratio of primary sensor data from the original sensors and the new ones varies by wind direction. The value of this ratio corresponds to the slope of the linear relationship used in the MCP analysis, and the slope of the plots in Figure 12.

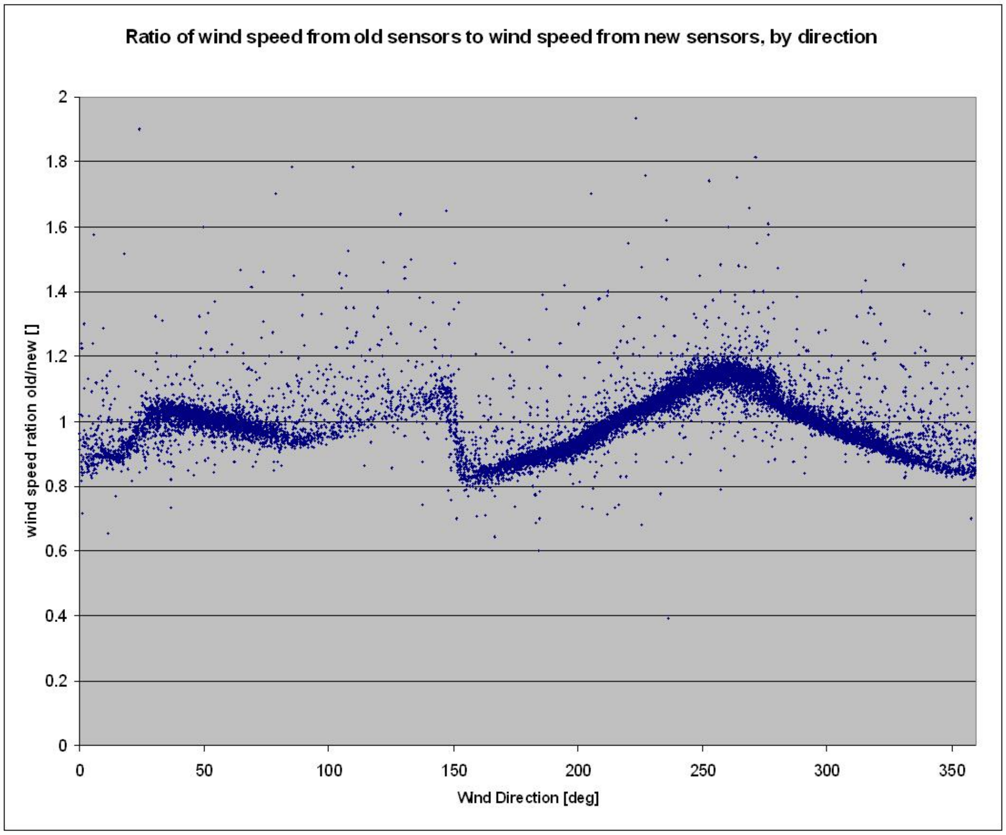

**Figure 13 - Ratio of old sensors to new, by direction**

In Figure 6, you can see some symmetry around 270° (west) and 90° (east). This is expected since the tower and instruments are symmetric when viewed from these directions. This supports the use of MCP, and is an effective reality check.

**Results**

The MCP analysis uses the relationship between the long-term data and the short term data to predict a long term wind speed distribution, characterized by the Weibull C and K parameters. These parameters determine the shape of the predicted wind speed distribution, shown in Figure 14.

| | |
|---|---|
| Weibull K: | 2.429 |
| Weibull C: | 6.903 |
| Predicted Mean Wind Speed: | 6.12 m/s |

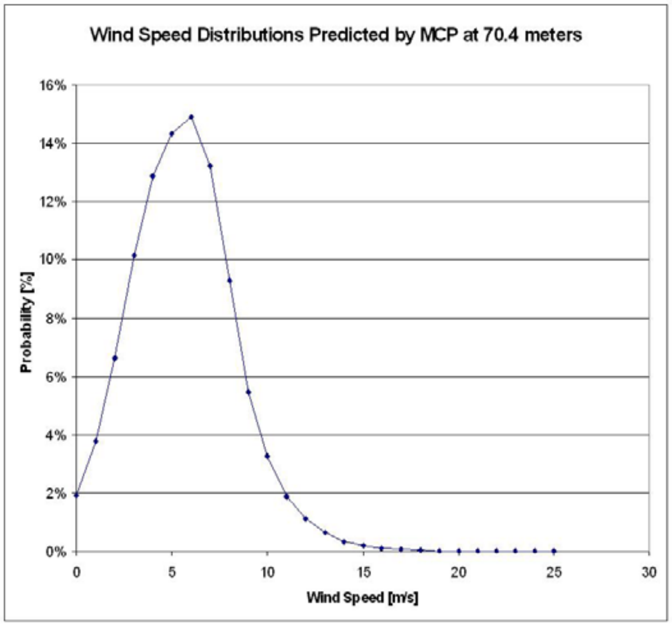

**Figure 14 - Predicted Wind Speed Distribution at 70.4 meters**

## MCP at 107.6 Meters

Since there are no high-quality data available at 107.6 m that can be used to correct the data from the original sensors at this height, the only available option is to assume that the sensor placement or the original sensor at 107.6 m is the same as that of the sensors at 70.4 m. In that case, the same relationship that was used to determine an improved 70.4 m wind speed estimate from the original sensors at 70.4 m can be applied to the original 107.6 m sensors to determine an improved estimate of the wind speeds at 107.6 m.

Installation documentation indicates that both sets of original sensors were installed in the same configuration. In order to be satisfied that the sensor configuration and, therefore, the tower effects on the data are, in fact, the same at 107.6 meters as they are at 70.4 meters, one can examine the tower effects on the difference between the A and B sensor measurements at each sensor height. Figure 15 shows the difference between the A and B sensor data (A – B) at the higher and lower sensor heights. One can see that the tower effects on the measured wind speed, while not exactly the same, are very similar at the two heights. This provides confidence that using the same relationship to improve data quality at 107.6 meters that was used at 70.4 meters will provide a reasonable wind speed estimate.

## Results

Using the direction-dependant relationships developed at 70.4 meters, we can predict a long term wind speed distribution, characterized by the Weibull C and K parameters. These parameters determine the shape of the predicted wind speed distribution, shown in Figure 16.

- Weibull K: 2.398
- Weibull C: 7.844
- Predicted Mean Wind Speed: 6.98 m/s

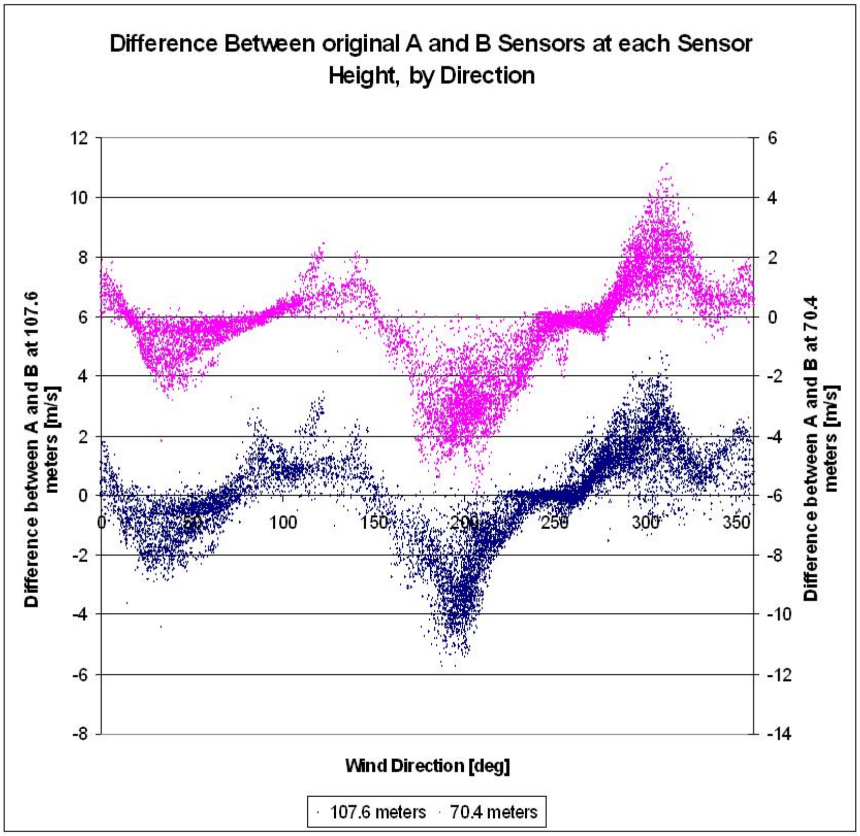

**Figure 15 - Tower Effects on Wind Speed at Both Sensor Heights**

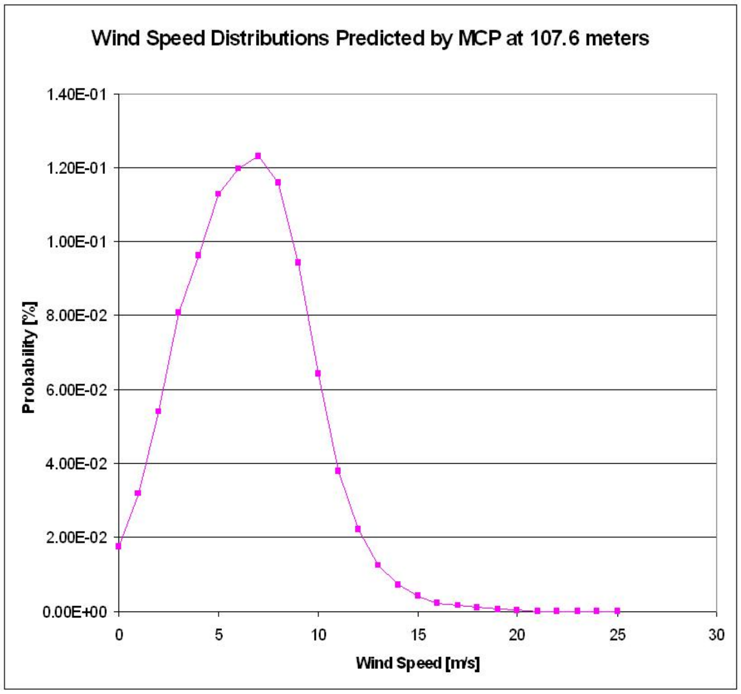

**Figure 16 - Predicted Wind Speed Distribution at 70.4 meters**

## Uncertainty of Estimates

To determine the uncertainty of these estimates one needs to include the measurement uncertainty, the MCP estimation uncertainty and the uncertainty related to long term variations in wind speed. The uncertainties that were included in this analysis and the values that have been assumed here are shown in Table 4.

**Table 4. Sources of uncertainty for Quarry Hills data.**

| Cause of Uncertainty | Percent | Notes |
|---|---|---|
| Anemometer calibration | 1.5 | |
| Anemometer over-speeding | 0.3 | |
| Vertical flow effects | 0.5 | |
| Vertical turbulence effects | 2.0 | |
| Tower effects | 1.5 | Includes effect of sensor proximity to tower |
| Boom effects | 0.5 | |
| Data reduction | 0.0 | |
| **Overall Measurement Uncertainty** | **3.0** | |

*continued on next page*

**Table 4: - continued**

| | | |
|---|---|---|
| MCP uncertainty | 2.0 | Estimated |
| Climate change | 1.0 | 1.0 |
| **Overall Long-term extrapolation uncertainty** | **2.2** | **2.2** |
| | | |
| Long term variability | 6.0 | High due to only one year of long-term data |
| Variability over turbine lifetime | 1.0 | |
| **Overall long-term variability** | **6.1** | **6.1** |
| | | |
| **Overall uncertainty** | **7.1** | **7.1** |

The result of this analysis is that there is a 68% chance that the long-term mean wind speeds at the DPW tower will be within 7.1 % of the mean wind speeds calculated above. The long-term mean wind speeds, the uncertainty of those estimates and the mean wind speeds that will be exceeded with 90% confidence (the P90 values) are shown in Table 11.

**Table 5. Results for Quarry Hills site.**

| Height | Long-term Mean Wind Speed, m/s | Uncertainty, m/s | P90, m/s |
|---|---|---|---|
| 70 | 6.10 | 0.44 | 5.58 |
| 107 | 6.94 | 0.49 | 6.31 |

## SECTION 9 - Data Recovery and Validation

All raw wind data are subjected to a series of tests and filters to weed out data that are faulty or corrupted. Definitions of these quality assurance (QA) controls are given below under Test Definitions and Sensor Statistics. These control filters were designed to automate the quality control process and used many of the previous hand-worked data sets made at UMass to affect a suitable emulation. The gross percentage of data recovered (ratio of the number of raw data points received to data points expected) and net percentage (ratio of raw data points which passed all QA control tests to data points expected) are shown below.

| | |
|---|---|
| Gross Data Recovered [%] | 100 |
| Net Data Recovered [%] | 94.46* |

*Excluding the 107.6 meter vane which ceased to function on February 6th, the net data recovered are 99.46%

## Test Definitions

All raw data were subjected to a series of validation tests, as described below. The sensors tested and the parameters specific to each sensor are given in the Sensor Performance Report which is included in APPENDIX A. Data which were flagged as invalid were not included in the statistics presented in this report.

**MinMax Test:** All sensors are expected to report data values within a range specified by the sensor and logger manufacturers. If a value falls outside this range, it is flagged as invalid. A data value from the sensor listed in Test Field 1 (TF1) is flagged if it is less than Factor 1 (F1) or greater than Factor 2. This test has been applied to the following sensors (as applicable): wind speed, wind speed standard deviation, wind direction, temperature, and solar insolation.

$$F1 > TF1 > F2$$

**MinMaxT Test:** This is a MinMax test for wind direction standard deviation with different ranges applied for high and low wind speeds. A wind direction standard deviation data value (TF1) is flagged either if it is less than Factor 1, if the wind speed (TF2) is less than Factor 4 and the wind direction standard deviation is greater than Factor 2, or if the wind speed is greater than or equal to Factor 4 and the wind direction standard deviation is greater than Factor 3.

$$\begin{gathered}(TF1 < F1)\\ \text{or } (TF2 < F4 \text{ and } TF1 > F2)\\ \text{or } (TF2 \geq F4 \text{ and } TF1 > F3)\end{gathered}$$

**Icing Test:** An icing event occurs when ice collects on a sensor and degrades its performance. Icing events are characterized by the simultaneous measurements of near-zero standard deviation of wind direction, non-zero wind speed, and near- or below-freezing temperatures. Wind speed, wind speed standard deviation, wind direction, and wind direction standard deviation data values are flagged if the wind direction standard deviation (CF1) is less than or equal to Factor 1 (F1), the wind speed (TF1) is greater than Factor 2 (F2), and the temperature (CF2) is less than Factor 3 (F3). To exit an icing event, the wind direction standard deviation must be greater than Factor 4.

$$CF1 \leq F1 \text{ and } TF1 > F2 \text{ and } CF2 < F3$$

**CompareSensors Test:** Where primary and redundant sensors are used, it is possible to determine when one of the sensors is not performing properly. For anemometers, poor performance is characterized by low data values. Therefore, if one sensor of the pair reports values significantly below the other, the low values are flagged. At low wind speeds (Test Fields 1 and 2 less than or equal to Factor 3) wind speed data are flagged if the absolute difference between the two wind speeds is greater than Factor 1. At high wind speeds (Test Fields 1 or 2 greater than Factor 3) wind speed data are flagged if the absolute value of the ratio of the two wind speeds is greater is greater than Factor 2.

$$[\ TF1 \le F3 \text{ and } TF2 \le F3 \text{ and } abs(TF1 - TF2) > F1\ ]$$
$$\text{or } [\ (TF1 > F3 \text{ or } TF2 > F3) \text{ and } (abs(1 - TF1 / TF2) > F2 \text{ or } abs(1 - TF2 / TF1) > F2)\ ]$$

## Sensor Statistics

A summary of the results of the data collection and filtering are given in the Sensor Performance Report which is included in APPENDIX A. The following categories of information, tabulated for each sensor, are included in that report.

**Expected Data Points:** the total number of sample intervals between the start and end dates (inclusive).

**Actual Data Points:** the total number of data points recorded between the start and end dates.

**% Data Recovered:** the ratio of actual and expected data points (this is the *gross data recovered percentage*).

**Hours Out of Range:** total number of hours for which data were flagged according to MinMax and MinMaxT tests. These tests flag data which fall outside of an expected range.

**Hours of Icing:** total number of hours for which data were flagged according to Icing tests. This test uses the standard deviation of wind direction, air temperature, and wind speed to determine when sensor icing has occurred.

**Hours of Fault:** total number of hours for which data were flagged according to CompareSensors tests. These tests compare two sensors (e.g. primary and redundant anemometers installed at the same height) and flag data points where one sensor differs significantly from the other.

**% Data Good:** the filter results are subtracted from the gross data recovery percentage to yield the *net data recovered percentage*.

# APPENDIX A - Sensor Performance Report

## Test Definitions

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | | | | | TimeTest Insert | 0 | 0 | 0 | 0 |
| 4 | Etmp2aDEGC | | | | | MinMax | -30 | 60 | 0 | 0 |
| 5 | EtmpSD2aDEGC | | | | | MinMax | -30 | 60 | 0 | 0 |
| 10 | Anem101aMS | | | | | MinMax | 0 | 90 | 0 | 0 |
| 11 | Anem101bMS | | | | | MinMax | 0 | 90 | 0 | 0 |
| 12 | Anem67aMS | | | | | MinMax | 0 | 90 | 0 | 0 |
| 13 | Anem67bMS | | | | | MinMax | 0 | 90 | 0 | 0 |
| 16 | Anem70aMS | | | | | MinMax | 0 | 90 | 0 | 0 |
| 17 | Anem70bMS | | | | | MinMax | 0 | 90 | 0 | 0 |
| 20 | AnemSD101aMS | | | | | MinMax | 0 | 4 | 0 | 0 |
| 21 | AnemSD101bMS | | | | | MinMax | 0 | 4 | 0 | 0 |
| 22 | AnemSD67aMS | | | | | MinMax | 0 | 4 | 0 | 0 |
| 23 | AnemSD67bMS | | | | | MinMax | 0 | 4 | 0 | 0 |
| 26 | AnemSD70aMS | | | | | MinMax | 0 | 4 | 0 | 0 |
| 27 | AnemSD70bMS | | | | | MinMax | 0 | 4 | 0 | 0 |
| 30 | Vane101aDEG | | | | | MinMax | 0 | 359.9 | 0 | 0 |
| 31 | Vane67aDEG | | | | | MinMax | 0 | 359.9 | 0 | 0 |
| 32 | Vane70aDEG | | | | | MinMax | 0 | 359.9 | 0 | 0 |
| 50 | Turb101zNONE | | | | | MinMax | 0 | 2 | 0 | 0 |
| 51 | Turb67zNONE | | | | | MinMax | 0 | 2 | 0 | 0 |
| 56 | Turb70zNONE | | | | | MinMax | 0 | 2 | 0 | 0 |
| 60 | Wshr0zNONE | | | | | MinMax | -100 | 100 | 0 | 0 |
| 70 | Pwrd101zWMS | | | | | MinMax | 0 | 5000 | 0 | 0 |
| 71 | Pwrd67zWMS | | | | | MinMax | 0 | 5000 | 0 | 0 |
| 200 | VaneSD101aDEG | Anem101yMS | | | | MinMaxT | 0 | 100 | 100 | 10 |
| 201 | VaneSD67aDEG | Anem67yMS | | | | MinMaxT | 0 | 100 | 100 | 10 |
| 206 | VaneSD70aDEG | Anem70yMS | | | | MinMaxT | 0 | 100 | 100 | 10 |
| 300 | Anem101aMS | AnemSD101aMS | Vane67aDEG | VaneSD67aDEG | Etmp2aDEGC | Icing | 0.5 | 1 | 2 | 0 |
| 301 | Anem101bMS | AnemSD101bMS | Vane67aDEG | VaneSD67aDEG | Etmp2aDEGC | Icing | 0.5 | 1 | 2 | 0 |
| 302 | Anem67aMS | AnemSD67aMS | Vane67aDEG | VaneSD67aDEG | Etmp2aDEGC | Icing | 0.5 | 1 | 2 | 0 |
| 303 | Anem67bMS | AnemSD67bMS | Vane67aDEG | VaneSD67aDEG | Etmp2aDEGC | Icing | 0.5 | 1 | 2 | 0 |
| 306 | Anem70aMS | AnemSD70aMS | Vane70aDEG | VaneSD70aDEG | Etmp2aDEGC | Icing | 0.5 | 1 | 2 | 0 |
| 307 | Anem70bMS | AnemSD70bMS | Vane70aDEG | VaneSD70aDEG | Etmp2aDEGC | Icing | 0.5 | 1 | 2 | 0 |

# Sensor Statistics

| Sensor | Expected Data Points | Actual Data Points | % Data Recovered | Hours Out of Range | Hours of Icing | % Data Good |
|---|---|---|---|---|---|---|
| Anem101aMS | 52417 | 52417 | 100 | 0 | 81.167 | 99.071 |
| Anem101bMS | 52417 | 52417 | 100 | 0 | 84 | 99.038 |
| Anem67aMS | 52417 | 52417 | 100 | 0 | 69.167 | 99.208 |
| Anem67bMS | 52417 | 52417 | 100 | 0 | 74.333 | 99.149 |
| Anem70aMS | 14185 | 14185 | 100 | 0 | 0 | 100 |
| Anem70bMS | 14185 | 14185 | 100 | 0 | 0 | 100 |
| Vane101aDEG | 52417 | 52417 | 100 | 0 | 0 | 49.295 |
| Vane67aDEG | 52417 | 52417 | 100 | 0 | 97.667 | 98.882 |
| Etmp2aDEGC | 52417 | 52417 | 100 | 0 | 0 | 100 |
| Vane70aDEG | 14185 | 14185 | 100 | 0 | 0 | 100 |
| | | | | | | |
| Total | 409474 | 409474 | 100 | 0 | 406.334 | 94.4643 |

# APPENDIX B - Plot Data

## Wind Speed Distribution Data

| Wind Speed | Percent of time |
|---|---|
| [m/s] | [%] |
| 0.5 | 1.79 |
| 1.5 | 3.09 |
| 2.5 | 5.25 |
| 3.5 | 7.94 |
| 4.5 | 9.53 |
| 5.5 | 11.21 |
| 6.5 | 12.05 |
| 7.5 | 12.17 |
| 8.5 | 11.66 |
| 9.5 | 9.48 |
| 10.5 | 6.5 |
| 11.5 | 3.9 |
| 12.5 | 2.33 |
| 13.5 | 1.29 |
| 14.5 | 0.76 |
| 15.5 | 0.42 |
| 16.5 | 0.24 |
| 17.5 | 0.17 |
| 18.5 | 0.11 |
| 19.5 | 0.05 |
| 20.5 | 0.02 |
| 21.5 | 0.01 |
| 22.5 | 0.01 |
| 23.5 | 0.01 |
| 24.5 | 0 |

## Monthly Average Wind Speed Data

| Month | Average Wind Speed [m/s] |
|---|---|
| Aug-06* | 5.54 |
| Sep-06 | 6.43 |
| Oct-06 | 7.61 |
| Nov-06 | 6.63 |
| Dec-06 | 7.57 |
| Jan-07 | 7.24 |
| Feb-07 | 7.85 |
| Mar-07 | 8.43 |
| Apr-07 | 7.20 |
| May-07 | 6.61 |
| Jun-07 | 6.31 |
| Jul-07 | 5.85 |
| Aug-07* | 6.18 |

*These August averages are each based on less than a month of data, since the reporting period is August 11th 2006 to August 10th 2007.

Diurnal Average Wind Speed Data

| Hour of Day | Mean Wind Speed [m/s] |
|---|---|
| 0 | 7.36 |
| 1 | 7.35 |
| 2 | 7.29 |
| 3 | 7.30 |
| 4 | 7.26 |
| 5 | 7.19 |
| 6 | 6.80 |
| 7 | 6.41 |
| 8 | 6.24 |
| 9 | 6.19 |
| 10 | 6.34 |
| 11 | 6.49 |
| 12 | 6.62 |
| 13 | 6.74 |
| 14 | 6.80 |
| 15 | 6.85 |
| 16 | 6.82 |
| 17 | 6.84 |
| 18 | 7.17 |
| 19 | 7.34 |
| 20 | 7.41 |
| 21 | 7.40 |
| 22 | 7.31 |
| 23 | 7.35 |

## Wind Rose Data

| Wind Direction [deg] | Percent of Time [%] | Mean Wind Speed [m/s] |
|---|---|---|
| 0.00 | 2.49 | 5.00 |
| 22.50 | 3.65 | 6.88 |
| 45.00 | 6.05 | 6.66 |
| 67.50 | 4.65 | 5.32 |
| 90.00 | 2.65 | 5.51 |
| 112.50 | 1.76 | 6.49 |
| 135.00 | 2.52 | 5.79 |
| 157.50 | 3.58 | 6.19 |
| 180.00 | 5.75 | 8.03 |
| 202.50 | 12.44 | 8.17 |
| 225.00 | 10.34 | 7.76 |
| 247.50 | 11.79 | 7.33 |
| 270.00 | 13.81 | 6.95 |
| 292.50 | 9.92 | 6.64 |
| 315.00 | 5.91 | 6.65 |
| 337.50 | 2.68 | 5.28 |