WIND DATA REPORT

Ashburnham, MA

March 2009 to February 2010

Prepared for

Massachusetts Department of Energy Resources
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by

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NOTICE AND ACKNOWLEDGEMENTS

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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.

Wind monitoring equipment was installed at the Ashburnham site in November 2008. The base of the 50 meter meteorological tower is installed 422 meters above sea level. Anemometers and wind direction vanes are installed at 38 and 49 m (128 and 160.8 ft) above the tower base. There are redundant anemometers at both heights. There is a temperature sensor installed near the base of the tower.

This report summarizes the wind data collected during the calendar year between March 2009 and February 2010. The mean recorded wind speed was 5.70 m/s (12.75 mph*) at 49 m and the prevailing wind direction was from the west. The average turbulence intensity between 10 m/s and 11 m/s at 49 m height was 0.18.

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 93.95%.

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.

SECTION 1 - Station Location

The Ashburnham monitoring tower is located on a hill approximately 600 meters northeast from the intersection of Wag Hill and Byfield Roads in Ashburnham, MA. The 50 m (164 ft) tower is located at 42° 40’ 37.74” North, 71° 51’ 45.60” West. The tower base is 422 m (1,384.5 ft) above sea level. The tower is identified with a yellow box in the center of Figure 1 below.

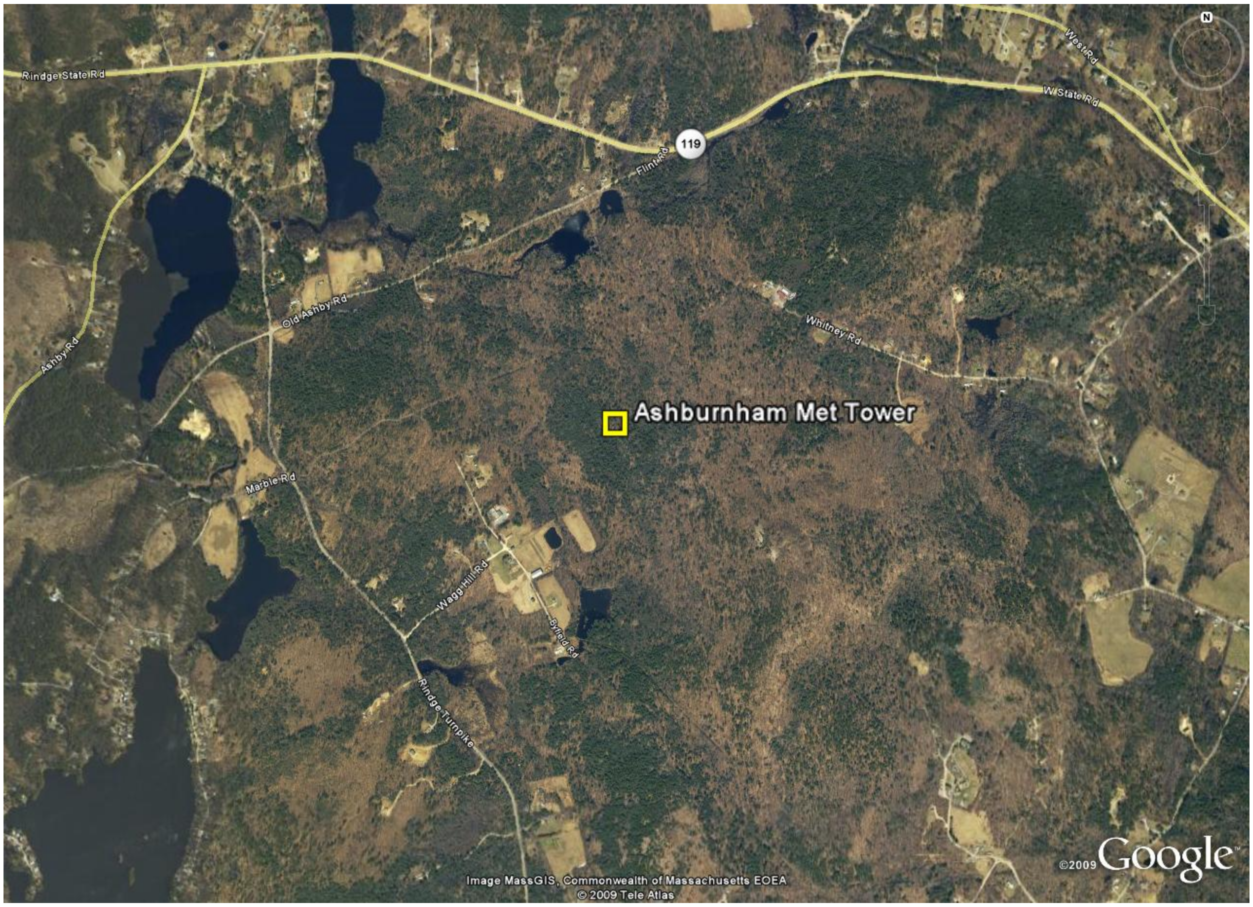

Figure 1 – Site Location

SECTION 2 - Instrumentation and Equipment

The wind monitoring equipment is mounted on a 50 m (164 ft) meteorological tower. The wind monitoring equipment comes from NRG systems and consists of the following items:

- NRG Symphonie data logger with internal temperature.
- 4 – NRG #40 Anemometers, standard calibration (Slope – 0.765 m/s, Offset – 0.350 m/s). Two anemometers are located at 49 m (160.8 ft) and two anemometers are located at 39 m (128 ft).
- 2 – NRG #200P Wind direction vanes. The vanes are located at 49 m (160.8 ft) and 39 m (128 ft).

Data from the Symphonie logger is sent to RERL via a cellular modem once a day. The logger samples wind speed and direction once every two seconds. These samples are combined into 10-minute averages and are put into a binary file along with the maximum, minimum and standard deviation for each 10-minute interval. The binary files are converted to ASCII text files using NRG software. These text files are then imported into a database software program where they are subjected to quality assurance tests prior to data usage.

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, the prevailing wind direction measured at each measurement height, and the percentage of valid data collected. These values are provided for each month of the reporting period and for the whole reporting period.

Table 1. Wind Speed and Direction Data Summary

Date	Mean Wind Speed	Max Wind Speed	Prevailing Wind Direction	Mean Wind Speed	Max Wind Speed	Prevailing Wind Direction	Net Data Recovery Percentage
Height Units	**49 m [m/s]**	**49 m [m/s]**	**49 m [m/s]**	**38 m [m/s]**	**38 m [m/s]**	**38 m [m/s]**	**[%]**
Dec 2008	7.65	19.41	WSW	7.21	18.26	SW	74.86
Jan 2009	6.09	16.71	W	5.76	15.74	W	69.08
Feb 2009	7.27	17.15	NW	6.76	16.05	W	85.50
Mar 2009	5.84	17.19	WSW	5.39	16.13	WSW	93.26
Apr 2009	6.25	16.66	W	5.75	15.61	W	93.99
May 2009	5.72	13.82	WSW	5.24	13.14	WSW	94.00
Jun 2009	4.16	11.41	NE	3.74	10.44	NE	91.53
Jul 2009	5.01	12.21	W	4.60	11.59	W	93.86
Aug 2009	4.57	10.83	WSW	4.17	9.85	WSW	91.96
Sept 2009	4.96	12.05	WSW	4.51	11.01	WSW	94.12
Oct 2009	5.71	16.16	W	5.17	15.17	WSW	91.87
Nov 2009	5.81	16.54	ENE	5.38	15.47	WSW	95.05
Dec 2009	7.05	17.36	W	6.51	17.74	WSW	94.04
Jan 2010	6.69	17.39	WNW	5.99	15.93	W	95.77
Feb 2010	6.85	16.9	WNW	6.45	15.5	WSW	95.45
Mar 2009 – Feb 2010	**5.70**	**17.39**	**W**	**5.23**	**17.74**	**WSW**	**93.95**

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 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 each measurement height is between 10 and 11 m/s.

Table 2. Turbulence Intensity Data Summary

Date Height Units	Turbulence Intensity at 10 m/s 49 m [-]	Turbulence Intensity at 10 m/s 38 m [-]	Shear Coefficient Between Heights 49 – 38 m [-]
Dec 2008	0.17	0.19	0.23
Jan 2009	0.18	0.19	0.21
Feb 2009	0.18	0..20	0.29
Mar 2009	0.17	0.17	0.31
Apr 2009	0.19	0.20	0.33
May 2009	0.17	0.20	0.34
Jun 2009	0.20	0.21	0.42
Jul 2009	0.19	0.21	0.33
Aug 2009	0.19	0.23	0.36
Sept 2009	0.20	0.19	0.37
Oct 2009	0.19	0.21	0.39
Nov 2009	0.16	0.18	0.30
Dec 2009	0.19	0.21	0.31
Jan 2010	0.18	0.20	0.43
Feb 2010	0.18	0.19	0.24
Mar 2009 – Feb 2010	**0.18**	**.20**	**0.34**

SECTION 4- Long Term Estimate and Capacity Factor

Wind speed varies year by year and the mean obtained over the measurement period may be less or more compared to what is seen over a longer time period. Therefore, the use of the long term mean at the site is preferred when projecting the performance of a wind turbine. The long term mean at a site may be estimated by using the Measure-Correlate-Predict (MCP) method.

The MCP method correlates wind speed measurements at the target site to a reference site which collects data over the same period of time and has been collecting data for a much longer period. Based on this correlation, the reference wind speed data is used to predict long term mean at the site.

Long term data from Logan Airport between January 1st, 1996 and February 28th, 2010 is used as reference in the case of Ashburnham. Correlation between the two sites are obtained from concurrent data between December 1st, 2008 and February 28th, 2010. The long term mean at Ashburnham at 49 m is estimated to be 6.06 m/s with an uncertainty of 3% for the MCP process. This estimate may also be used to calculate the long term mean at different heights by using the mean wind shear at site and the equation described in the previous section. The long term mean wind speed at 80 m height is estimated at 7.16 m/s.

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 GE 1.5 sl turbine with a hub height of 80 m and the long term mean wind speed estimate at the highest measurement height and the mean wind shear at the site, in order to determine the mean hub height wind speed, in this case 6.73 m/s. The wind speed probability distribution is assumed to be given by a Rayleigh distribution. The average wind turbine power is then estimated from:

$$\overline{P_W} = \int_0^\infty P_W(U)\, p(U)\, dU$$

where $P_W(U)$ is the wind turbine power curve and $p(U)$ is the wind speed probability distribution. The capacity factor is then calculated from:

$$CF = \frac{\overline{P_W}}{P_{rated}}$$

where P_{rated} is the rated capacity of the turbine, i.e., 1500 kW. Based on this equation, the estimated capacity factor of a wind turbine at this site would be about 0.336.

SECTION 5- Graphs

This report contains several types of wind data graphs. Unless otherwise noted, each graph represents data from 1 quarter (3 months). The following graphs are included:

- Time Series – 10-minute average wind speeds are plotted against time.
- Wind Speed Distribution – A histogram plot giving the percentage of time that the wind is at a given wind speed.
- Monthly Average – A plot of the monthly average wind speed over a 12-month period. This graph shows the trends in the wind speed over the year.
    - For this reporting period, December 2008 and January 2009 are not shown due to their low net data recovery percentages.
- Diurnal – A plot of the average wind speed for each hour of the day.
- Turbulence Intensity – 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.
- Wind Rose – 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.

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

Wind Speed Time Series

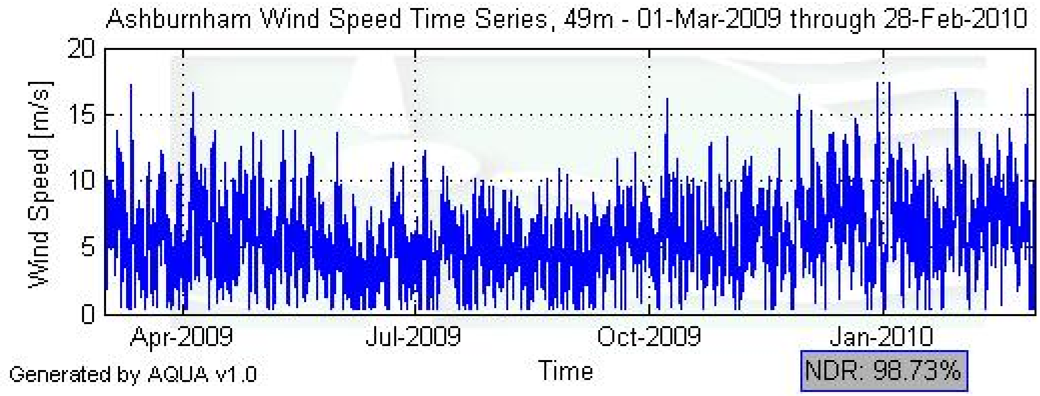

Figure 2 – Wind Speed Time Series, Mar 1, 2009 – Feb 28, 2010

Wind Speed Distributions

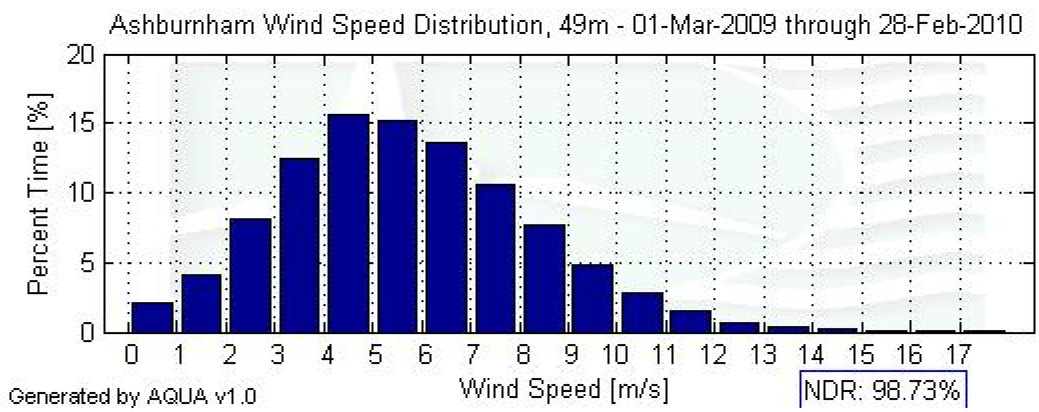

Figure 3 – Wind Speed Distribution, Mar 1, 2009 – Feb 28, 2010

Monthly Average Wind Speeds

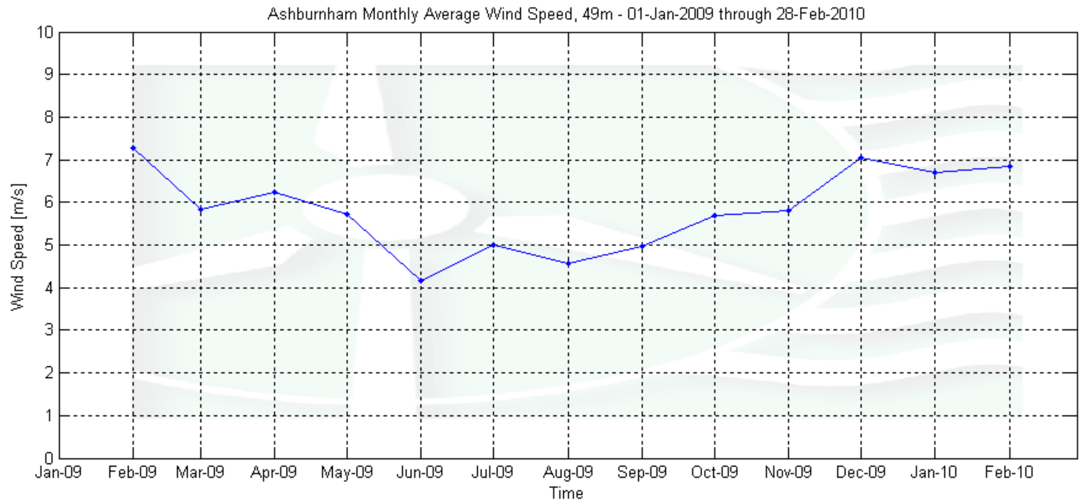

Figure 4 – Monthly Average Wind Speed, Mar 1, 2009 – Feb 28, 2010

Diurnal Average Wind Speeds

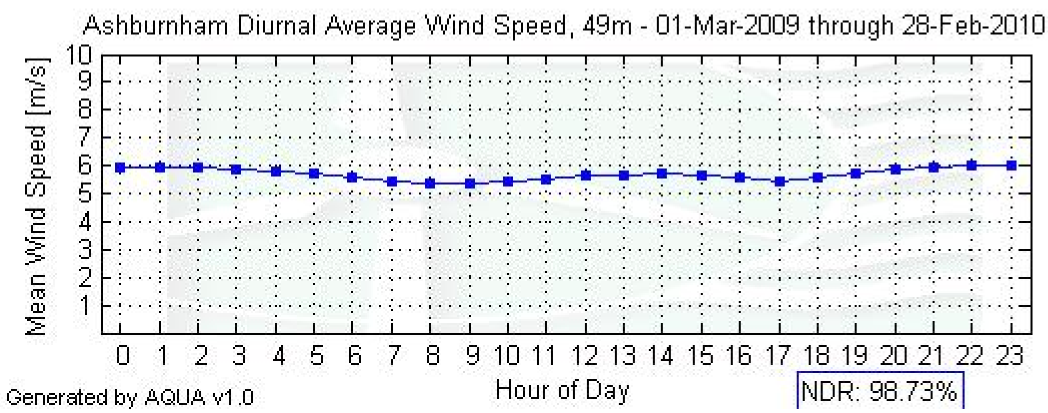

Figure 5 – Diurnal Average Wind Speeds, Mar 1, 2009 – Feb 28, 2010

Turbulence Intensities

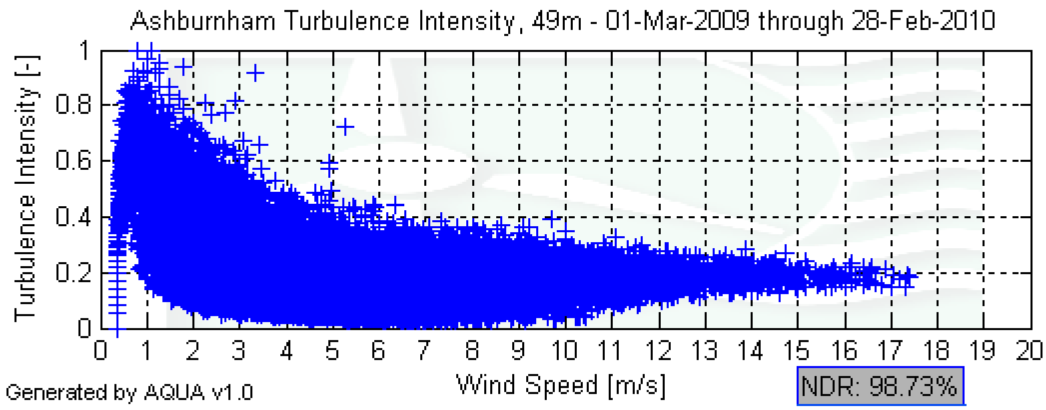

Figure 6 – Turbulence Intensity vs. Wind Speed, Mar 1, 2009 – Feb 28, 2010

Wind Rose

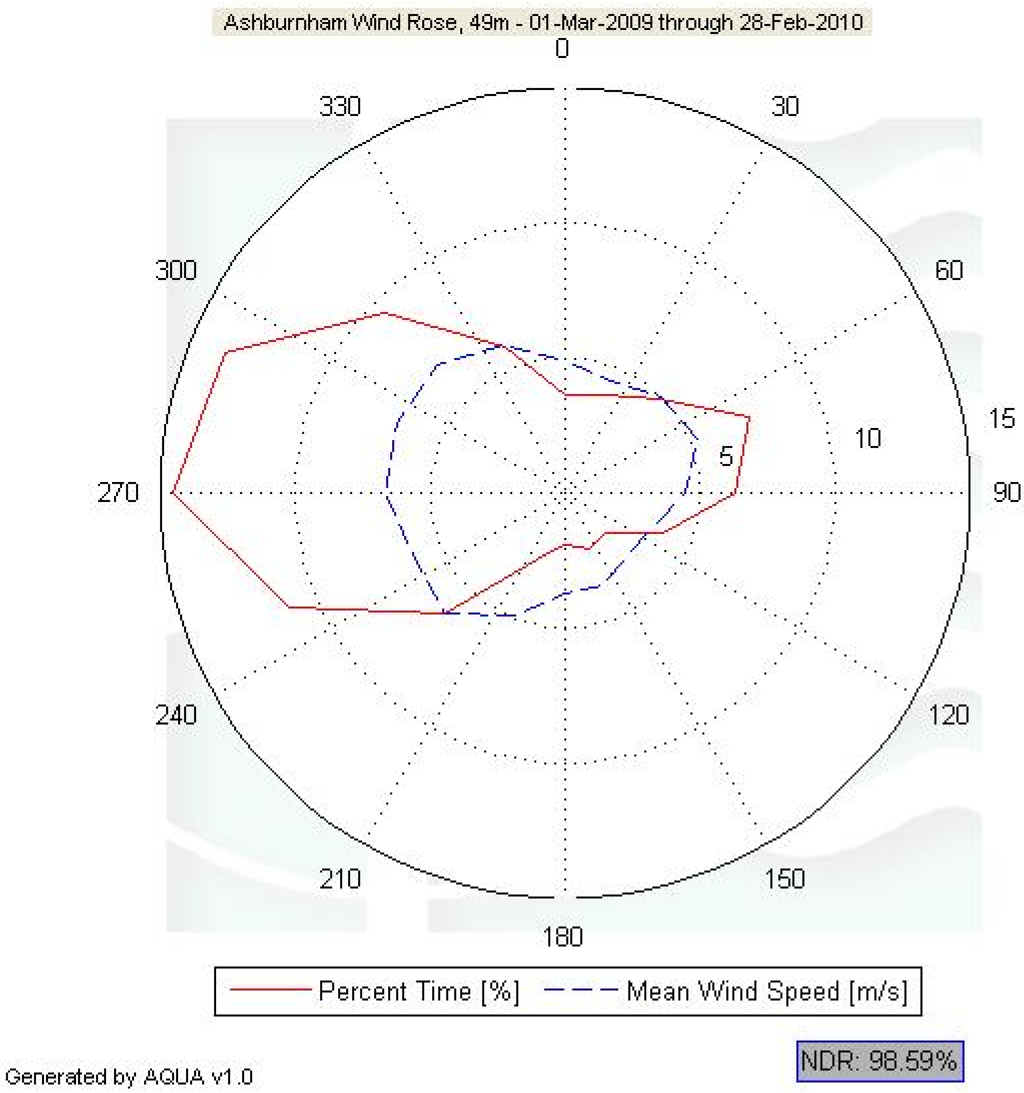

Figure 7 – Wind Rose, Mar 1, 2009 – Feb 28, 2010

SECTION 6 - Significant Meteorological Events

During the winter of 2008 there were several severe winter storms that cause long periods of sensor icing and damage to one of the secondary anemometers. This caused low net data recovery percentages in the months of December 2008, January 2009, and February 2009. For this reason the continuous calendar year selected begins in March of 2009 and ends the last day of February 2010. The highest recorded wind speed during this period was 17.39 m/s, however during December 2008 a wind speed of 19.41 m/s was measured.

SECTION 7- Data Collection and Maintenance

The secondary 49 meter anemometer sustained damage during an icing event in December and began reporting wind speeds significantly different than both the primary 49 meter anemometer and the anemometers situated at 38 meters. The data from the secondary 49 meter anemometer are flagged whenever the disagreement between the two 49 m sensors exceeds the limit defined by the Compare Sensors test (Test Definitions are in Section 7). No maintenance was performed during the reporting period.

SECTION 8 - 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 [%]	93.95

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.

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

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.

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

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

Test Order	Test Field1	Test Field2	Test Field3	Calc Field1	Calc Field2	Test Type	Factor 1	Factor 2	Factor 3
1						TimeTest Insert	0	0	0
3	Batt2aVDC					MinMax	10.5	15	0
4	Etmp2aDEGC					MinMax	-30	60	0
5	EtmpSD2aDEGC					MinMax	-30	60	0
10	Anem49aMS					MinMax	0	90	0
11	Anem49bMS					MinMax	0	90	0
12	Anem38aMS					MinMax	0	90	0
13	Anem38bMS					MinMax	0	90	0
20	AnemSD49aMS					MinMax	0	4	0
21	AnemSD49bMS					MinMax	0	4	0
22	AnemSD38aMS					MinMax	0	4	0
23	AnemSD38bMS					MinMax	0	4	0
30	Vane49aDEG					MinMax	0	359.9	0
31	Vane38aDEG					MinMax	0	359.9	0
50	Turb49zNONE					MinMax	0	2	0
51	Turb38zNONE					MinMax	0	2	0
60	Wshr0zNONE					MinMax	0	100	0
200	VaneSD49aDEG	Anem49yMS				MinMaxT	0	100	100
201	VaneSD38aDEG	Anem38yMS				MinMaxT	0	100	100
300	Anem49aMS	AnemSD49aMS	Vane49aDEG	VaneSD49aDEG	Etmp2aDEGC	Icing	0.5	1	2
301	Anem49bMS	AnemSD49bMS	Vane49aDEG	VaneSD49aDEG	Etmp2aDEGC	Icing	0.5	1	2
302	Anem38aMS	AnemSD38aMS	Vane38aDEG	VaneSD38aDEG	Etmp2aDEGC	Icing	0.5	1	2
303	Anem38bMS	AnemSD38bMS	Vane38aDEG	VaneSD38aDEG	Etmp2aDEGC	Icing	0.5	1	2
400	Anem49aMS	Anem49bMS				CompareSensors	1	0.25	3
401	Anem38aMS	Anem38bMS				CompareSensors	1	0.25	3

Sensor Statistics

	Expected Data Points	Actual Data Points	% Data Recovered	Hours Out of Range	Hours of Icing	Hours of Fault	%Data Good
Temp00	52560	52560	100	0	0	0	100
IntBatt00	52560	52560	100	0	0	0	100
Anem38a	52560	52560	100	0.667	91.167	9.667	98.845
Anem38b	52560	52560	100	0.667	90.833	19.5	98.767
Vane38a	52560	52560	100	2.5	91.167	0	98.931
Anem49a	52560	52560	100	1.333	118.667	2.167	98.624
Anem49b	52560	52560	100	1.833	100	3615.667	57.801
Vane49a	52560	52560	100	3.167	118.667	0	98.609
Total	**420480**	**420480**	**100**	**10.167**	**610.5**	**3647**	**93.947**

APPENDIX B - Plot Data

Wind Speed Distribution Data

Bin Center Wind Speed [m/s]	Percent Time [%]
0.5	2.03
1.5	4.07
2.5	8.12
3.5	12.48
4.5	15.57
5.5	15.16
6.5	13.54
7.5	10.6
8.5	7.76
9.5	4.89
10.5	2.8
11.5	1.49
12.5	0.71
13.5	0.38
14.5	0.23
15.5	0.1
16.5	0.05
17.5	0.01
18.5	0

Monthly Average Wind Speed Data

Month	49 m Mean 10 min [m/s]
December 08	7.65
January 09	6.09
February 09	7.27
March 09	5.84
April 09	6.25
May 09	5.72
June 09	4.16
July 09	5.01
August 09	4.57
September 09	4.96
October 09	5.71
November 09	5.81
December 09	7.05
January 10	6.69
February 10	6.85

Wind Rose Data

	Jun - Aug 2009	
Direction	**Percent Time [%]**	**Mean Wind Speed [m/s]**
N	3.6	4.88
NNE	3.97	4.52
NE	4.96	5.08
ENE	7.42	5.29
E	6.34	4.45
ESE	3.97	3.48
SE	2.06	3.26
SSE	2.26	3.68
S	1.91	3.74
SSW	2.67	4.91
SW	6.34	6.25
WSW	11.1	6.09
W	14.51	6.64
WNW	13.64	6.77
NW	9.41	6.68
NNW	5.85	5.96

Diurnal Average Wind Speed Data

Hour of Day	Mean Wind Speed [m/s]
0	5.95
1	5.96
2	5.92
3	5.88
4	5.82
5	5.73
6	5.59
7	5.47
8	5.33
9	5.37
10	5.47
11	5.53
12	5.64
13	5.64
14	5.73
15	5.67
16	5.56
17	5.46
18	5.57
19	5.74
20	5.88
21	5.96
22	5.98
23	5.99