WIND DATA REPORT

Massachusetts Military Reservation, Buzzards Bay, MA

July 1 – September 30, 2012

Prepared for

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November 30, 2012

Report template version 3.1.2

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NOTICE AND ACKNOWLEDGEMENTS

This report was prepared by the Wind Energy Center (WEC) at the University of Massachusetts, Amherst in the course of performing work sponsored by the Renewable Energy Trust (RET), as administered by the Massachusetts Clean Energy Center (MassCEC). The opinions expressed in this report do not necessarily reflect those of MassCEC 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.

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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 Wind Energy Center (WEC) at the University of Massachusetts, Amherst.

This report covers wind data measured at the Massachusetts Military Reservation in Buzzards Bay, MA. Installed on November 10, 2009, the wind monitoring sensors have been in continuous operation to this day. Two cup anemometers and one wind vane are mounted at each height of 49m (161 ft), and 38m (125 ft).

The period covered by this report is July 2012 through September 2012. The mean recorded wind speed was 4.48 m/s (10.02 mph) at 49 m and the prevailing wind direction was from the south-southwest. The average turbulence intensity at 49 m was 0.21. 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 81.27%. This low data recovery percentage is due to one of the sensors at 49 m malfunctioning.

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

www.umass.edu/windenergy/publications/published/communityWindFactSheets/RERL_Fact_Sheet_6_Wind_resource_interpretation.pdf

* 1 m/s = 2.237 mph.

SECTION 1 - Station Location

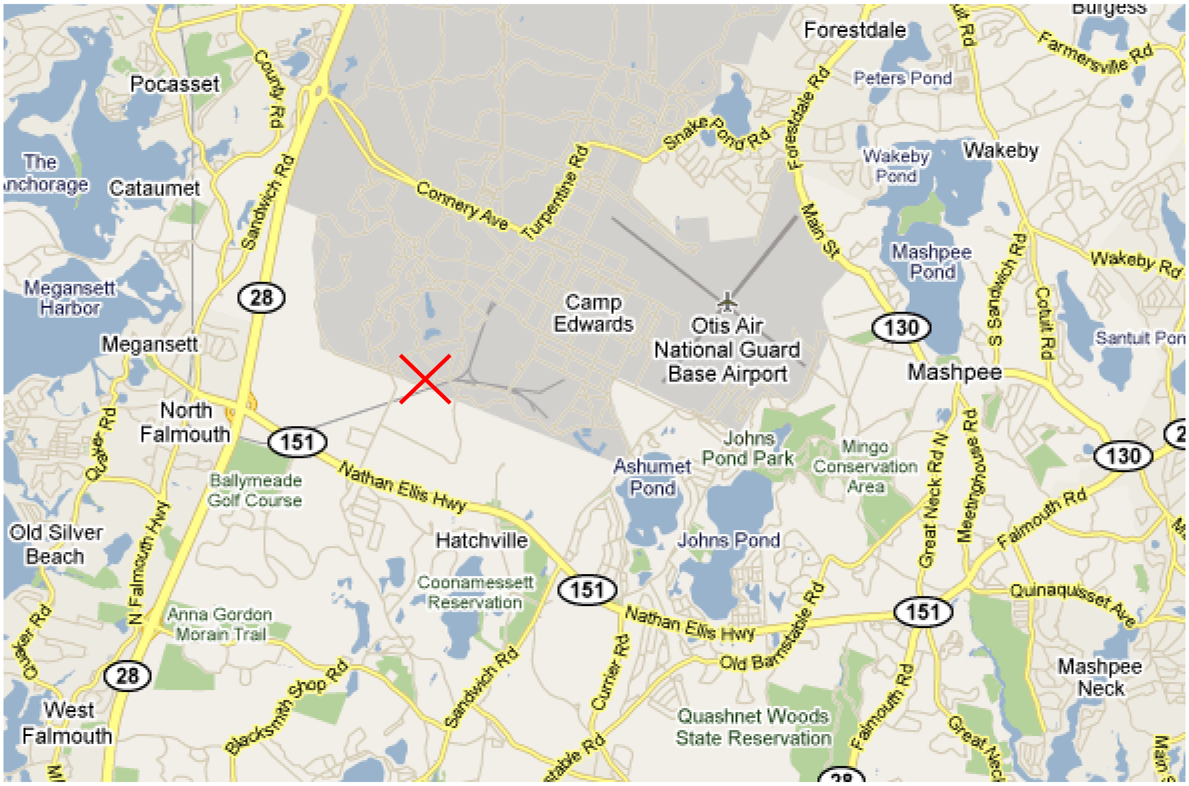

Figure 1 – MMR Site Location in Buzzards Bay, Ma

The tower is located in Eastern Cape Cod, along the southern edge of the Massachusetts Military Reservation (MMR), in the town of Buzzards Bay. The site coordinates are 41° 38.967' N, 70° 34.413' W. These coordinates correspond to the NAD83 datum.

SECTION 2 - Instrumentation and Equipment

The wind monitoring equipment is mounted on an NRG Systems 50 meter meteorological tower. The wind monitoring equipment includes:

- 1 – Calibrated MAX 40 Anemometer (Slope - 0.756 m/s, Offset – 0.45 m/s). The anemometer is located at a height of 49m (161 ft)
- 3 – Comptus C3 Wind Anemometer (Slope - 0.765 m/s, Offset – 0.35 m/s). One anemometer is located at a height of 49m (161 ft), and two at 38m (125 ft).
- 2 – NRG Systems #200P wind direction vanes. One vane is located at each station height.
- #110S thermistor (temperature sensor). The sensor is located 1.5 m (5 ft) from the tower base.
- NRG Systems Symphonie data logger

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.

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
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]**
Apr 2012	4.37	10.62	SSW	3.98	10.15	SSW
May 2012	4.29	11.46	SSW	3.99	10.66	SSW
Jun 2012	4.81	12.55	SSW	4.45	11.58	S
Apr 2012 – Jun 2012	**4.48**	**12.55**	**SSW**	**4.14**	**11.58**	**SSW**

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 is 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 each measurement height is between 10 and 11 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

Date	**Turbulence Intensity at 10 m/s**	**Turbulence Intensity at 10 m/s**	**Mean Wind Shear Coefficient, α**
Height Units	**49 m [-]**	**38 m [-]**	**Between 49 m and 38 m [-]**
Apr 2012	0.16	0.19	0.37
May 2012	0.21	0.21	0.28
Jun 2012	0.21	0.21	0.31
Apr 2012 – Jun 2012	**0.21**	**0.21**	**0.32**

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 Thompson Island between October 16th, 2004 and October 24th, 2012 is used as reference in the case of MMR. Correlation between the two sites are obtained from concurrent data between November 11th, 2009 and October 24th, 2012. The long term mean at MMR at 49 m is estimated to be 5.87 m/s with an uncertainty of 2% 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 6.90 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 6.90 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 0.352.

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 since the start of the measurement period. This graph shows the trends in the wind speed over the year.
- Diurnal – A plot of the average wind speed for each hour of the day. On average the wind speed was relatively uniformly distributed throughout the day. A slight peak can be observed over the middle 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. The data exhibits a normal trend of decreasing turbulence intensity with higher wind speed.
- 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

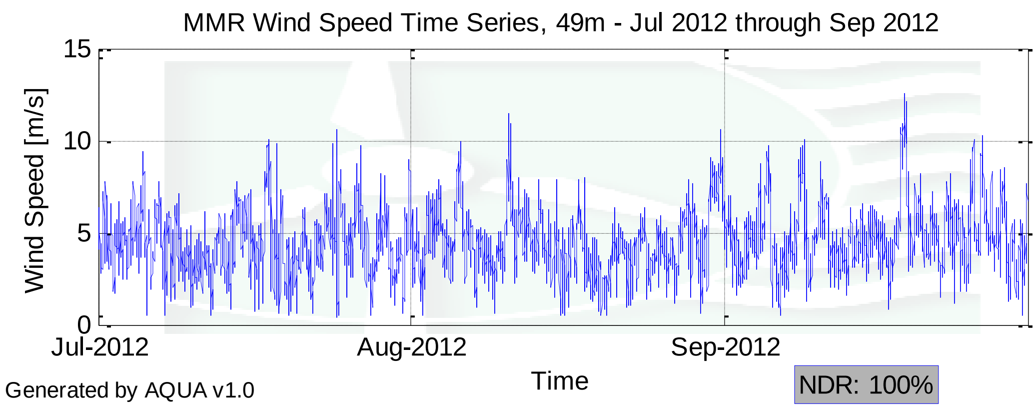

Figure 2 – MMR Wind Speed Time Series for July 1 to September 30, 2012

Wind Speed Distributions

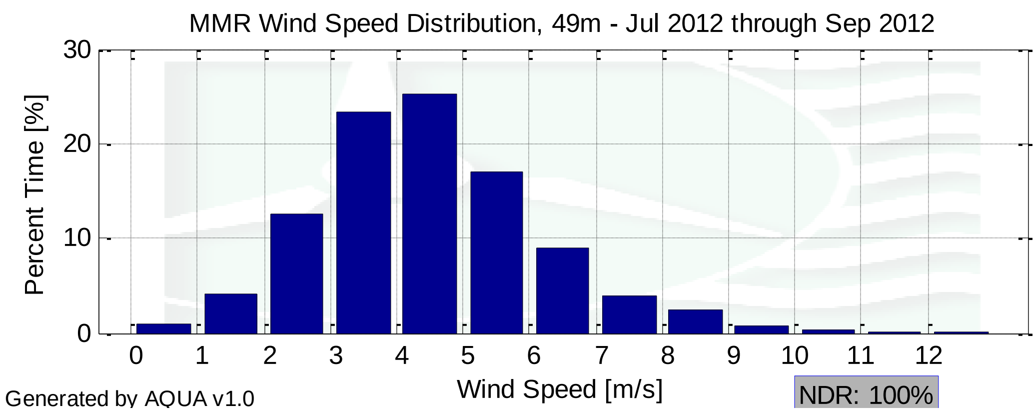

Figure 3 – MMR Wind Speed Distribution July 1 to September 30, 2012

Monthly Average Wind Speeds

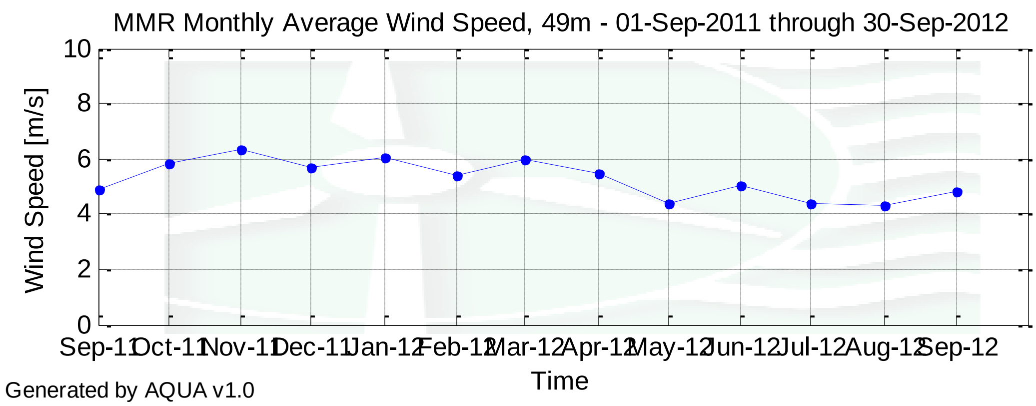

Figure 4 – MMR Monthly Wind Speed Averages for September 1 2011 to September 30, 2012

Diurnal Average Wind Speeds

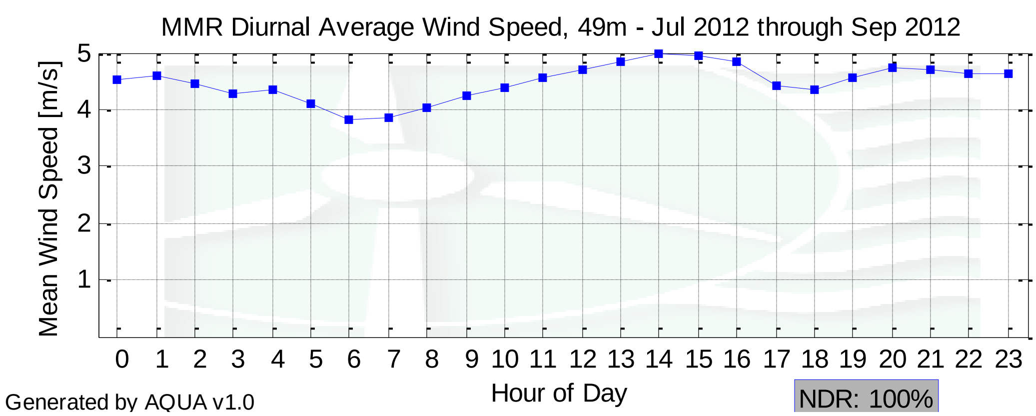

Figure 5 – MMR Diurnal Average Wind Speeds for July 1 to September 30, 2012

Turbulence Intensities

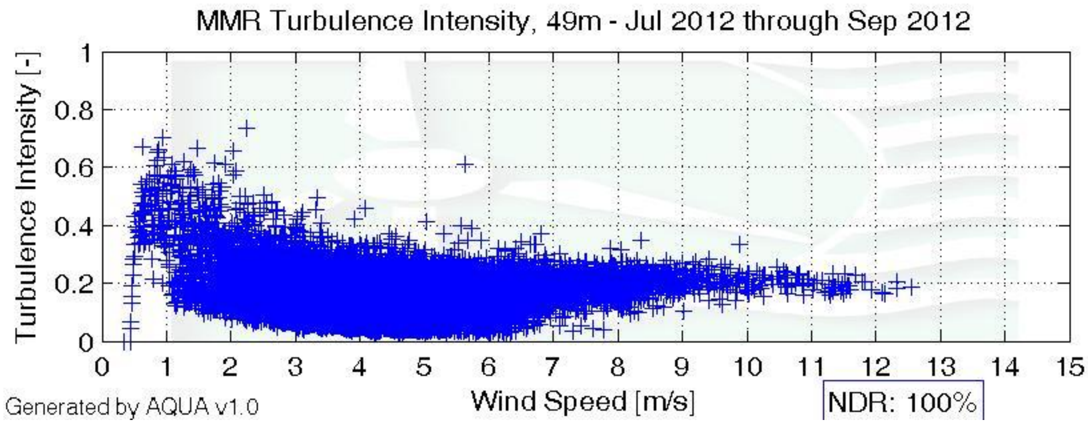

Figure 6 – MMR Turbulence Intensity for July 1 to September 30, 2012

Wind Roses

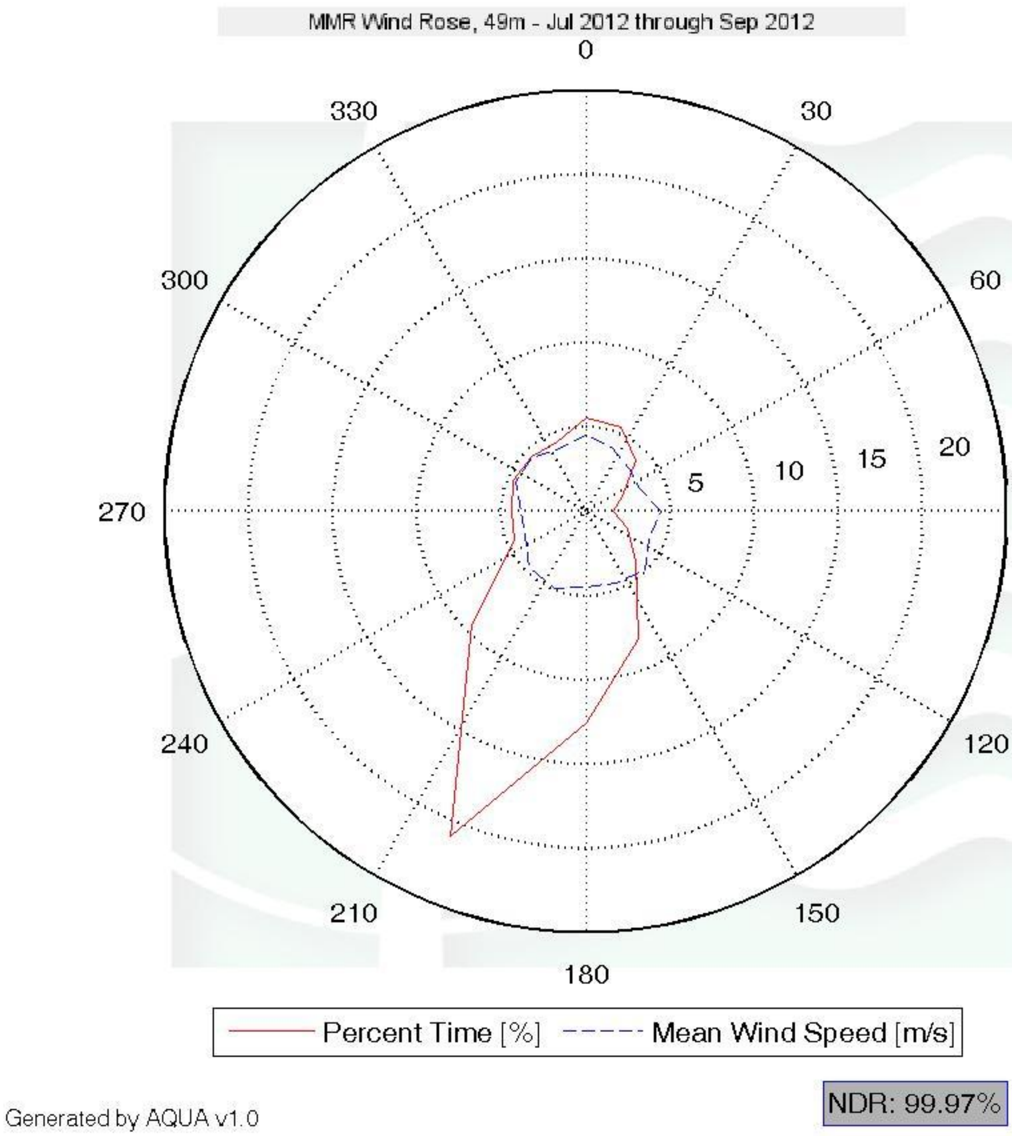

Figure 7 – MMR Wind Rose for July 1 to September 30, 2012

SECTION 6 - Significant Meteorological Events

No significant meteorological events were observed in this quarter.

SECTION 7 - Data Collection and Maintenance

No maintenance was required during this quarter. The second anemometer at 49 m is malfunctioning and will be replaced during refurbishment.

On June 26 and June 27 the sites stopped calling in and the problem was found to be that dial-up service is no longer supported by University computer systems. Verizon is also stopping new loggers from using current ipack logger setups, and will discontinue service beginning July of 2014 while migrating to 3G. Data from these sites for those last days were stored at the loggers on site and were recovered on July 26 2012. This revised report includes data for the whole of the period from May 2012 to the end of June 2012. Ipacks are being upgraded and will be swapped out as they become available.

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 [%]	81.28

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.

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

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

TestOrder	TestField1	TestField2	TestField3	CalcField1	CalcField2	TestType	Factor1	Factor2	Factor3	Factor4
1	Temp>T_val					MinMax	-30	60	0	0
2	Anem38a>WS_val					MinMax	0	90	0	0
3	Anem38a>WS_SD					MinMax	0	4	0	0
4	Anem38b>WS_val					MinMax	0	90	0	0
5	Anem38b>WS_SD					MinMax	0	4	0	0
6	Vane38>WD_val					MinMax	0	359.9	0	0
7	Vane38>WD_SD					MinMax	0	100	0	0
8	Anem49a>WS_val					MinMax	0	90	0	0
9	Anem49a>WS_SD					MinMax	0	4	0	0
10	Anem49b>WS_val					MinMax	0	90	0	0
11	Anem49b>WS_SD					MinMax	0	4	0	0
12	Vane49>WD_val					MinMax	0	359.9	0	0
13	Vane49>WD_SD					MinMax	0	100	0	0
14	Anem38a>WS_val	Anem38b>WS_val				Comp Sens	1	0.25	3	0
15	Anem49a>WS_val	Anem49b>WS_val				Comp Sens	1	0.25	3	0
16	Anem38a>WS_val	Anem38a>WS_SD	Vane38>WD_val	Vane38>WD_SD	Temp>T_val	Icing	0.5	1	2	4
17	Anem38b>WS_val	Anem38b>WS_SD	Vane38>WD_val	Vane38>WD_SD	Temp>T_val	Icing	0.5	1	2	4
18	Anem49a>WS_val	Anem49a>WS_SD	Vane49>WD_val	Vane49>WD_SD	Temp>T_val	Icing	0.5	1	2	4
19	Anem49b>WS_val	Anem49b>WS_SD	Vane49>WD_val	Vane49>WD_SD	Temp>T_val	Icing	0.5	1	2	4

Sensor Statistics

	Expected Data Points	Actual Data Points	% Data Recovered	Hours Out of Range	Hours of Icing	Hours of Fault	%Data Good
Temp	13248	13248	100	741.833	0	0	66.402
Anem38a	13248	13248	100	0.167	0	5	99.766
Anem38b	13248	13248	100	0.167	0	3.333	99.841
Vane38	13248	13248	100	0.667	0	0	99.97
Anem49a	13248	13248	100	0.167	0	0	99.992
Anem49b	13248	13248	100	0.667	0	2141	3.004
Vane49	13248	13248	100	0.667	0	0	99.97
Total	**92736**	**92736**	**100**	**744.333**	**0**	**2149.333**	**81.278**

APPENDIX B - Plot Data

Wind Speed Distribution Data

Bin Center [m/s]	Percent Time [%]
0.5	0.87
1.5	4.18
2.5	12.66
3.5	23.35
4.5	25.31
5.5	17.02
6.5	8.88
7.5	4.01
8.5	2.34
9.5	0.77
10.5	0.38
11.5	0.2
12.5	0.04

Monthly Average Wind Speed Data

Month	Mean Wind Speed [[m/s]
Dec-09	6.93
Jan-10	6.13
Feb-10	6.08
Mar-10	6.67
Apr-10	5.41
May-10	5.19
Jun-10	4.95
Jul-10	4.69
Aug-10	5.07
Sep-10	5.63
Oct-10	6.28
Nov-10	6.25
Dec-10	6.62
Jan-11	5.21
Feb-11	6.25
Mar-11	6.09
Apr-11	6.20
May-11	5.17
Jun-11	4.63
Jul-11	4.74
Aug-11	4.94
Sep-11	4.86

Oct-11	5.81
Nov-11	6.32
Dec-11	5.69
Jan-12	6.07
Feb-12	5.43
Mar-12	5.99
Apr-12	5.48
May-12	4.38
Jun-12	5.05
Jul-12	3.98
Aug-12	3.99
Sep-12	4.45

Diurnal Average Wind Speed Data

Hour of Day	Mean Wind Speed [m/s]
0	4.54
1	4.59
2	4.47
3	4.27
4	4.36
5	4.12
6	3.82
7	3.85
8	4.03
9	4.24
10	4.38
11	4.55
12	4.69
13	4.86
14	4.98
15	4.96
16	4.83
17	4.43
18	4.36
19	4.55
20	4.74
21	4.71
22	4.64
23	4.65

Wind Rose Data

Bin Center [deg]	Percent Time [%]	Mean Wind Speed [m/s]
0	5.56	4.48
22.5	5.44	4.14
45	4.21	3.63
67.5	2.34	3.48
90	1.59	4.46
112.5	2.69	4.04
135	4.15	4.95
157.5	8.19	4.63
180	12.62	4.53
202.5	20.93	4.95
225	9.57	4.75
247.5	4.55	3.93
270	4.42	3.86
292.5	4.71	4.51
315	4.54	4.52
337.5	4.5	4.05