WIND DATA REPORT

Plymouth

December 1, 2007 – February 29, 2008

Prepared for

Massachusetts Technology Collaborative
75 North Drive
Westborough, MA 01581

by

Tom Langelier
James F. Manwell
Utama Abdulwahid
Anthony F. Ellis

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Renewable **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.

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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 in Plymouth in May 2007. The base of the 50m meteorological tower is installed 41m above sea level. Anemometers and wind direction vanes are installed at 38 and 50 m (125 and 164 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 winter of 2007, between December 2007 and February 2008. The mean recorded wind speed was 5.93 m/s (13.27 mph) at 50m and the prevailing wind direction was from the west. The average wind shear exponent was 0.39. The average turbulence intensity at 50m was 0.18.

The gross data recovery percentage (the actual percentage of expected data received) was 98.20% and the net data recovery percentage (the percentage of expected data which passed all of the quality assurance tests) was 95.58%.

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 Plymouth monitoring tower is located in a cornfield owned by the Plymouth County Sherriff's Office, and is used by the nearby Plymouth County Correctional Facility. The 50 m (164 ft) tower is located at 41°-56'-10.69" North, 70°-39'-02.46" West, shown below in Figure 1. The tower base is 41 m (135 ft) above sea level.

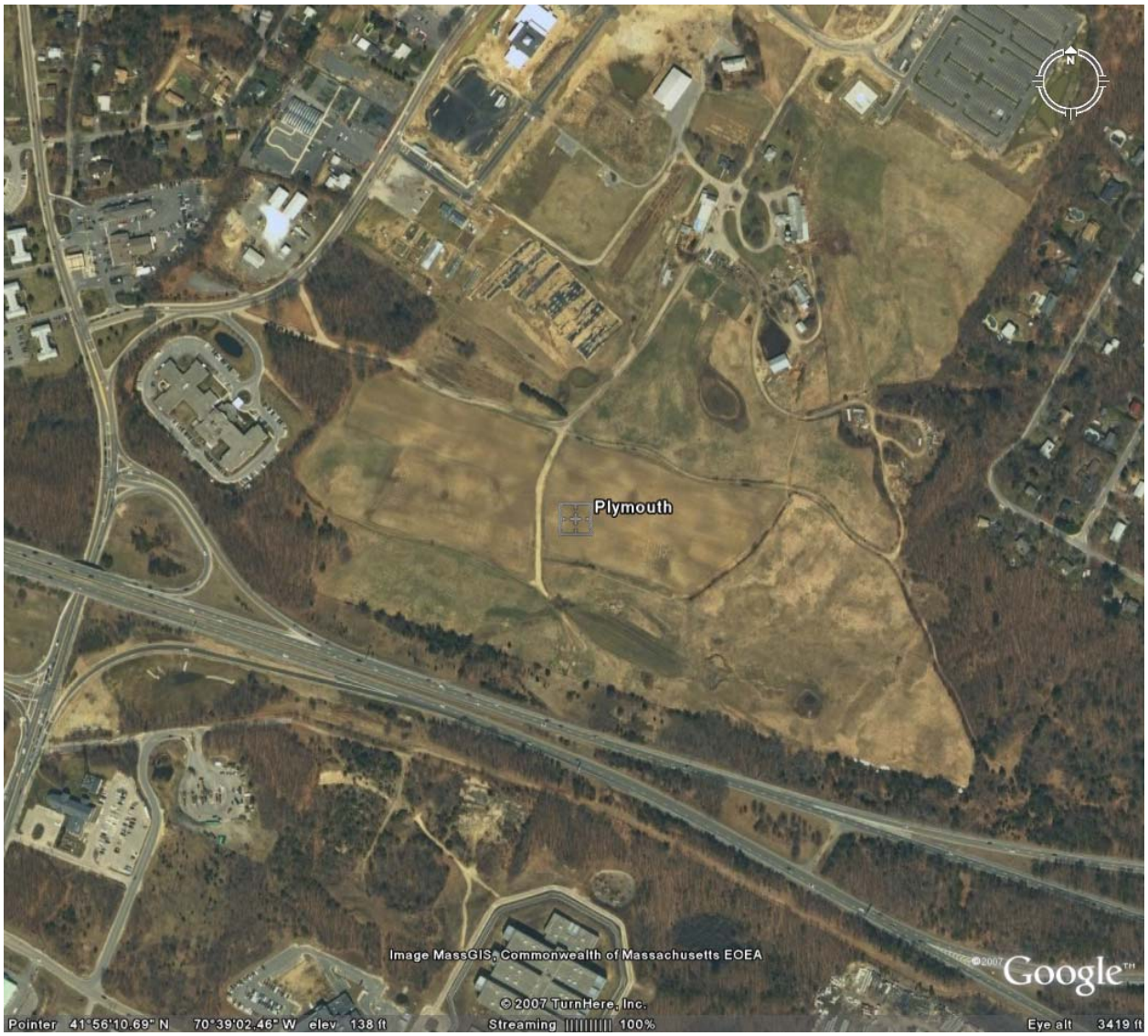

Figure 1 – Site Location

SECTION 2 - Instrumentation and Equipment

The 50 m (164 ft) monitoring tower is supplied by SecondWind, the sensors and logger are supplied by NRG systems. The wind speed and direction were measured at both 38 and 50 m height. The monitoring equipment consists of the following items:

- Symphony Data Logger, serial #3204
- SecondWind 50m tower
- 4-#40 Anemometers, standard calibration (Slope 0.765, Offset 0.350)
- 2-#200P Wind direction vanes (Slope 1.0, Offset 0.0)
- #110S Temperature sensor (Slope 0.138, Offset -86.383)
- 4- Sensor booms for anemometers, 54" length
- 2- Sensor booms for vanes, 44" length
- Lightning rod and grounding cable
- Shielded sensor wire

The logger samples data from the sensors once every two seconds. These samples are combined into 10-minute averages and are put into a binary file along with the standard deviation for each 10-minute interval. These binary files are stored on a data card that is mailed to the University of Massachusetts, Amherst on a regular basis. Using the NRG software BaseStation®, the binary files are converted into ASCII text files.

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	**50 m [m/s]**	**50 m [m/s]**	**50 m [-]**	**38 m [m/s]**	**38 m [m/s]**	**38 m [-]**
Dec 2007	5.58	16.20	W	5.07	15.00	W
Jan 2008	6.14	18.40	SW	5.56	16.8	SW
Feb 2008	6.06	20.50	W	5.50	19.10	W
Dec 2007-Feb 2008	**5.93**	**20.50**	**W**	**5.38**	**19.10**	**W**

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 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 Height Units	Turbulence Intensity at 10 m/s 50 m [-]	Turbulence Intensity at 10 m/s 38 m [-]	Mean Wind Shear Coefficient, α Between 50 m and 38 m [-]
Dec 2007	0.19	0.21	0.38
Jan 2008	0.17	0.20	0.39
Feb 2008	0.18	0.22	0.39
Dec 2007-Feb 2008	**0.18**	**0.21**	**0.39**

SECTION 4- 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.
- 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

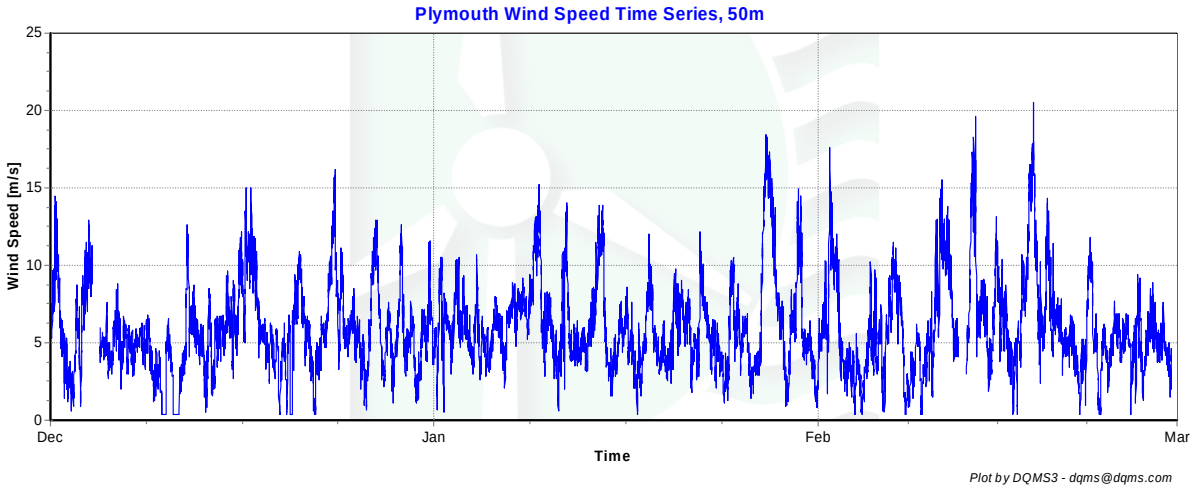

Figure 2 – Wind Speed Time Series, December 2007 – February 2008

Wind Speed Distributions

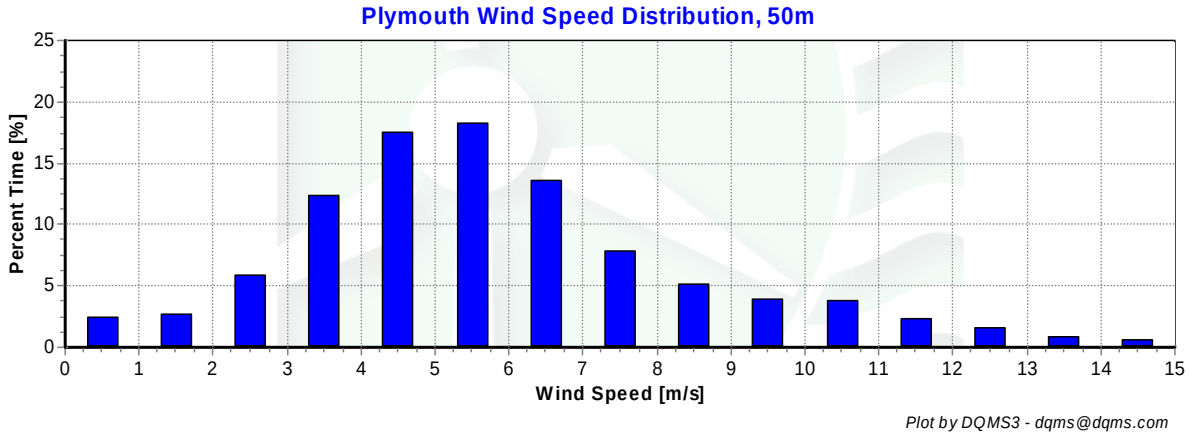

Figure 3 – Wind Speed Distribution, December 2007 – February 2008

Monthly Average Wind Speeds

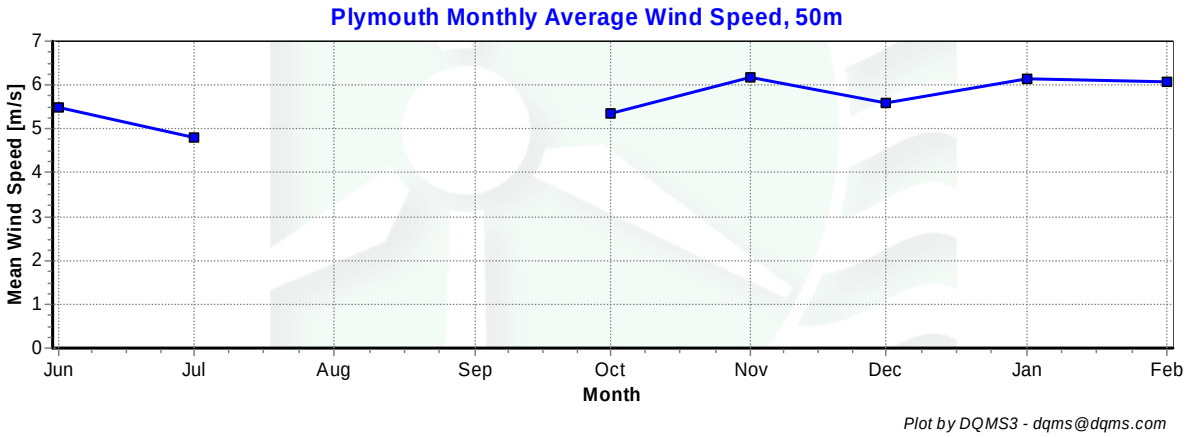

Figure 4 – Monthly Average Wind Speed, December 2007 – February 2008

Diurnal Average Wind Speeds

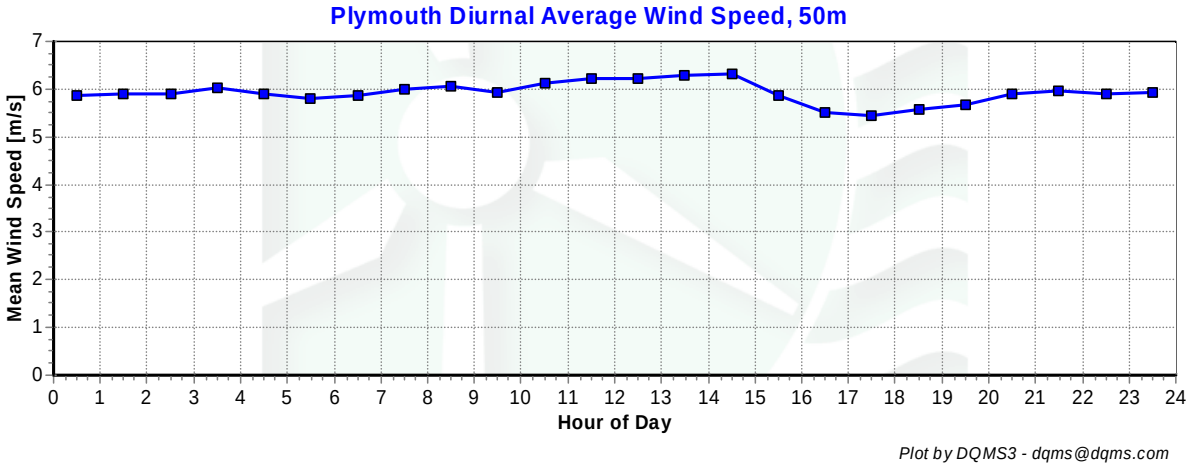

Figure 5 – Diurnal Average Wind Speed, December 2007 – February 2008

Turbulence Intensities

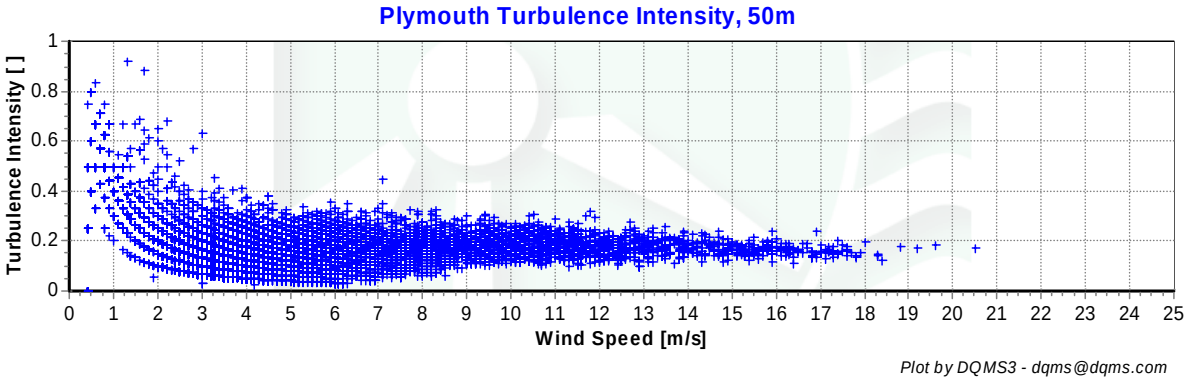

Figure 6 – Turbulence Intensity, December 2007 – February 2008

Wind Roses

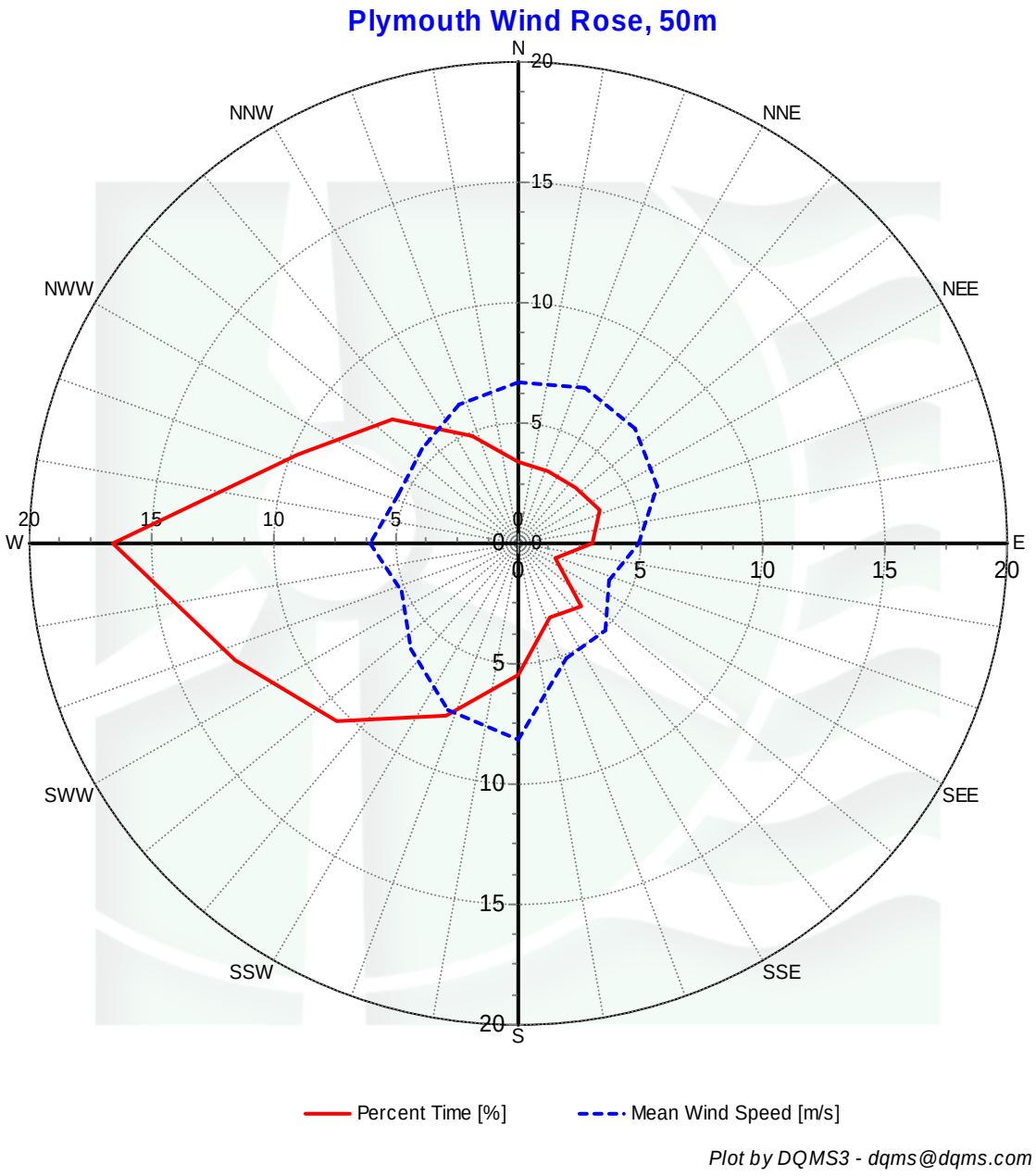

Figure 7 – Wind Rose, December 2007 – February 2008

SECTION 5 - Significant Meteorological Events

Winter of 2007 experienced, on average, normal winds and precipitation, though February broke a 114 year record for precipitation. Over the period there was a total of approximately 90 hours of icing events resulting in data loss, though no events were long enough to affect statistical accuracy.

Source: http://www.ncdc.noaa.gov/oa/climate/research/cag3/cag3.html.

SECTION 6 - Data Collection and Maintenance

There were no maintenance/equipment problems during the report period, and no maintenance performed.

SECTION 7- 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 [%]	98.20
Net Data Recovered [%]	95.58

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.

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

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

TestOrder	TestField1	TestField2	TestField3	CalcField1	CalcField2	CalcField3	TestType	Relation	Factor1	Factor2	Factor3	Factor4
1							TimeTest Insert					
4	Etmp2aDEGC						MinMax		-30	60		
5	EtmpSD2aDEGC						MinMax		-30	60		
10	Anem50aMS						MinMax		0	90		
11	Anem50bMS						MinMax		0	90		
12	Anem38aMS						MinMax		0	90		
13	Anem38bMS						MinMax		0	90		
14	Anem50yMS						MinMax		0	90		
15	Anem38yMS						MinMax		0	90		
20	AnemSD50aMS						MinMax		0	4		
21	AnemSD50bMS						MinMax		0	4		
22	AnemSD38aMS						MinMax		0	4		
23	AnemSD38bMS						MinMax		0	4		
24	AnemSD50yMS						MinMax		0	4		
25	AnemSD38yMS						MinMax		0	4		
30	Vane50aDEG						MinMax		0	359.9		
31	Vane38aDEG						MinMax		0	359.9		
50	Turb50zNONE						MinMax		0	2		
51	Turb38zNONE						MinMax		0	2		
60	Wshr0zNONE						MinMax		-100	100		
70	Pwrd50zWMC						MinMax		0	5000		
71	Pwrd38zWMC						MinMax		0	5000		
200	VaneSD50aDEG	Anem50yMS					MinMaxT		0	100	100	10
201	VaneSD38aDEG	Anem38yMS					MinMaxT		0	100	100	10
300	Anem50aMS	AnemSD50aMS	Vane50aDEG	VaneSD50aDEG	Etmp2aDEGC		Icing		0.5	1	2	4
301	Anem50bMS	AnemSD50bMS	Vane50aDEG	VaneSD50aDEG	Etmp2aDEGC		Icing		0.5	1	2	4
302	Anem38aMS	AnemSD38aMS	Vane38aDEG	VaneSD38aDEG	Etmp2aDEGC		Icing		0.5	1	2	4
303	Anem38bMS	AnemSD38bMS	Vane38aDEG	VaneSD38aDEG	Etmp2aDEGC		Icing		0.5	1	2	4
400	Anem50aMS	Anem50bMS					CompareSensors		1	0.25	3	0
401	Anem38aMS	Anem38bMS					CompareSensors		1	0.25	3	0
500	Amax50aMS						MinMax		0	90		
501	Amin50aMS						MinMax		0	90		
502	Amax50bMS						MinMax		0	90		
503	Amin50bMS						MinMax		0	90		
504	Amax38aMS						MinMax		0	90		
505	Amin38aMS						MinMax		0	90		
506	Amax38bMS						MinMax		0	90		
507	Amin38bMS						MinMax		0	90		
508	Vmax50aDEG						MinMax		0	359.9		
509	Vmin50aDEG						MinMax		0	359.9		
510	Vmax38aDEG						MinMax		0	359.9		
511	Vmin38aDEG						MinMax		0	359.9		
512	Etmx2aDEGC						MinMax		-30	60		

Sensor Statistics

Sensor	Expected Data Points	Actual Data Points	% Data Recovered	Hours Out of Range	Hours of Icing	Hours of Fault	% Data Good
Etmp2aDEGC	13105	12870	98.207	0	0	0	98.207
EtmpSD2aDEGC	13105	12870	98.207	0	0	0	98.207
Anem50aMS	13105	12870	98.207	0.167	69.333	5.5	94.773
AnemSD50aMS	13105	12870	98.207	0.167	69.333	5.5	94.773
Anem50bMS	13105	12870	98.207	0.167	73.833	0.333	94.804
AnemSD50bMS	13105	12870	98.207	0.167	73.833	0.333	94.804
Anem38aMS	13105	12870	98.207	0	86.5	24	93.148
AnemSD38aMS	13105	12870	98.207	0	86.5	24	93.148
Anem38bMS	13105	12870	98.207	0	89.167	1.5	94.056
AnemSD38bMS	13105	12870	98.207	0	89.167	1.5	94.056
Vane50aDEG	13105	12870	98.207	0	74.667	0	94.788
VaneSD50aDEG	13105	12870	98.207	0	74.667	0	94.788
Vane38aDEG	13105	12870	98.207	0.167	92.167	0	93.979
VaneSD38aDEG	13105	12870	98.207	0.167	92.167	0	93.979
Anem50yMS	13105	12870	98.207	0	0	0	98.207
AnemSD50yMS	13105	12870	98.207	0.167	0	0	98.199
Anem38yMS	13105	12870	98.207	0	0	0	98.207
AnemSD38yMS	13105	12870	98.207	0	0	0	98.207
Total	235890	231660	98.207	1.167	971.333	62.667	95.574

APPENDIX B - Plot Data

Wind Speed Distribution Data

Bin Center Wind Speed [m/s]	Percent of Time [%]
0.5	2.41
1.5	2.71
2.5	5.88
3.5	12.33
4.5	17.48
5.5	18.26
6.5	13.65
7.5	7.82
8.5	5.19
9.5	3.90
10.5	3.78
11.5	2.33
12.5	1.55
13.5	0.84
14.5	0.61
15.5	0.61
16.5	0.33
17.5	0.25
18.5	0.04
19.5	0.02
20.5	0.01
21.5	0.00
22.5	0.00
23.5	0.00
24.5	0.00

Monthly Average Wind Speed Data

Month	Average Wind Speed [m/s]
Sep	-
Oct	5.35
Nov	6.18
Dec	5.58
Jan	6.14
Feb	6.06

Diurnal Average Wind Speed Data

Bin Center Hour	Average Wind Speed [m/s]
0.5	5.86
1.5	5.88
2.5	5.91
3.5	6.04
4.5	5.91
5.5	5.82
6.5	5.88
7.5	6.00
8.5	6.05
9.5	5.94
10.5	6.13
11.5	6.21
12.5	6.22
13.5	6.29
14.5	6.33
15.5	5.88
16.5	5.52
17.5	5.45
18.5	5.57
19.5	5.67
20.5	5.90
21.5	5.95
22.5	5.91
23.5	5.95

Wind Rose Data

Direction	Percent Time [%]	Mean Wind Speed [m/s]
N	3.38	6.70
NNE	3.23	7.03
NE	3.29	6.72
ENE	3.59	6.16
E	3.07	4.96
ESE	1.66	3.98
SE	3.66	5.06
SSE	3.35	5.19
S	5.43	8.18
SSW	7.78	7.47
SW	10.47	6.23
WSW	12.58	5.15
W	16.62	6.04
WNW	9.75	5.29
NW	7.29	5.57
NNW	4.86	6.25