Dennis: SODAR-Based Wind Resource Assessment

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Executive Summary

This report summarizes the wind data collected at the Department of Public Works grounds in the town of Dennis, Massachusetts using one of the Wind Energy Center's three SODAR (Sonic Detection and Ranging) units for the purpose of wind resource assessment.

From December 5th, 2009 to December 31st, 2010, wind speed and direction were measured at a site in Dennis, Massachusetts, 41°41'33.10"N, 70° 8'10.30"W (NAD83). The data obtained from this site were analyzed and compared to 50 m anemometer data collected at Yarmouth, Massachusetts (41.66215º N, 70.22458º W). Based on the comparison between the SODAR site and the tower data, the validity of the SODAR data was confirmed.

Wind data collected at the BUZM3 buoy in Buzzards Bay since 1997 was used as a reference site and a Measure-Correlate-Predict (MCP) algorithm was used to predict long-term wind speeds at the Dennis site. The buoy is located at 41°23'48" N 71°2'0" W and the anemometer is mounted at 24.8 m.

After conducting the MCP analysis, the predicted wind speeds were adjusted to account for the bias in the SODAR data caused by vector averaging effects as well as by volume averaging effects. Long-term average wind speeds were predicted at a range of heights (30 m to 160 m). The following table shows the predicted wind speeds and the expected range of uncertainty from 50 m to 100 m at Dennis.

Height [m]	Predicted wind speed [m/s]	Min [m/s]	Max [m/s]	P90 wind speed [m/s]
50	5.77	5.31	6.24	5.18
60	6.13	5.69	6.56	5.56
70	6.47	6.03	6.90	5.90
80	6.74	6.30	7.17	6.18
90	6.97	6.55	7.39	6.43
100	7.22	6.80	7.64	6.69

Capacity factors were estimated at hub heights between 49 m and 80 m, using a few representative power curves. The following table shows the predicted capacity factors:

Turbine	Rated Power [kW]	Hub Height [m]	Capacity Factor		Capacity Factor with losses	
			Predicted wind speed	P90 wind speed	Predicted wind speed	P90 wind speed
Fuhrlaender	250	50	0.21	0.16	0.19	0.15
Vestas V52	850	49	0.21	0.16	0.19	0.15
Siemens/Bonus	1000	60	0.23	0.18	0.20	0.16
GE 1.5 xle	1500	80	0.35	0.30	0.32	0.27
GE 1.5 xle	1500	100	0.40	0.35	0.36	0.32

An uncertainty analysis was conducted and each source of significant error was quantified and accounted for. These sources of errors included the error of the SODAR, the uncertainty of the MCP analysis and inter-annual variability. The uncertainty ranges stated above include all of the significant sources of uncertainty.

Introduction

As electricity prices continue to increase and with growing concerns of global warming, renewable energy sources are steadily burgeoning in popularity. Currently, the most economical renewable source for electricity generation is wind energy. Since Eastern Massachusetts is home to an abundant source of wind, many towns and communities are actively pursuing the installation of wind turbines. When evaluating the viability of a wind turbine installation, one of the most important parameters is the wind resource at the site. This report summarizes the wind resource assessment carried out by the Wind Energy Center (WEC) at the University of Massachusetts, Amherst for the town of Dennis, MA.

The traditional method of collecting wind data is through the use of cup anemometers mounted on meteorological (met) towers. The maximum height for a typical met tower is 50 m. Therefore the estimated wind speeds must be extrapolated up to higher heights when estimating the wind resource at heights of interest for wind energy. With the increasing size of modern wind turbines and higher hub heights, this traditional method leads to an increase in uncertainty and is therefore becoming less desirable.

SODAR (Sonic Detection and Ranging) offers an alternative approach to estimating wind speed. As will be explained in a subsequent section, SODAR measures wind speed by emitting high frequency acoustic waves and recording the Doppler shift of the reflected signal. The wind speed is calculated at a range of heights (from 30 m to 160 m). SODAR can therefore provide more information about the wind resource at a site than a typical met tower assembly.

From December 3rd 2009 WEC's SODAR console unit collected wind data at the Department of Public Works in Dennis, MA. The SODAR experienced power supply problems for some part of the year and data was not collected during those periods. This report presents the measured data that was obtained during this time and the results of the data analysis. Anemometer wind data measured at Yarmouth, MA were used to validate the SODAR data and the data collected on the BUZM3 buoys in Buzzards Bay was used with the SODAR data to estimate the long-term wind speed at a range of heights (30 m to 160 m).

Outline of Report

Prior to discussing the data collected at Dennis, an overview of SODAR operation is given. The basic functionality of SODAR is discussed and the filters used to determine valid data are presented. Also, some of the limitations of SODAR are identified. These include the effects of echoes caused by ground clutter (i.e. trees, buildings, etc.) and the inability to measure wind speed during precipitation.

Following this, the data analysis methodology is explained. Since ground clutter may contaminate SODAR readings, near-by anemometer data must be used to validate or to

discredit the SODAR data at each height. Also, since gaps will exist in the SODAR data, due to data filtering and precipitation, anemometer data must be used in conjunction with Measure-Correlate-Predict (MCP) to determine average wind speeds at the SODAR site over a range of heights.

After the methodology has been presented, the location and duration of data collection at Dennis is discussed. The data is presented and is compared to the near-by anemometer data at Yarmouth. Based on the correlation and average ratio between the SODAR and tower data, valid height ranges are determined.

The results from the MCP analysis using the valid SODAR data and the long-term data are then presented. The long-term predictions are adjusted to account for vector and volume averaging effects. An uncertainty analysis is also conducted. All significant sources of errors are discussed and included in the overall uncertainty of the predicted wind speeds. Next, capacity factors based on a number of power curves are estimated for hub heights between 49 m and 80 m. Finally, a summary and discussion of the results are given as well as some concluding remarks.

Overview of SODAR Operation and Data Filtering

SODAR Operation

The SODAR console unit owned by RERL is an ART Model VT-1. This is described as a monostatic (it emits and receives the signal from the same location) phased-array SODAR. High frequency acoustic waves (~4500 Hz) are emitted from the SODAR in three consecutive directions: one in the vertical direction (W) and two in orthogonal directions approximately 17 degrees from vertical. The horizontal wind speed components, U and V, are calculated from the two orthogonal tilted beams. After each signal is emitted, a portion of the acoustic energy is backscattered due to fluctuations of the refractive index of air and is returned to the SODAR at some shifted frequency. The SODAR measures the reflected signal and calculates the shifted frequency at each height (from 30 m to 160 m at 10 m intervals). This shift in frequency is called the Doppler shift.

The Doppler shift refers to the change in frequency from a moving source as measured by a fixed observer. The amount of this apparent frequency shift is directly related to the velocity of the moving source (i.e. wind speed). Therefore, after every chirp, the SODAR calculates the wind speed in the direction of the beam at each specified height (range gate). The default range gate heights are from 30 m to 160 m at 10 m increments. The wind speeds are then averaged in each direction (U, V and W) over a ten-minute interval and the average vector wind speed and wind direction are determined at each range gate.

$$Note: Vector\ Wind\ Speed = \sqrt{(U\ Speed)^2 + (V\ Speed)^2}$$

$where\ U\ Speed\ and\ V\ Speed\ are\ corrected\ for\ Vertical\ Speed\ (W)$

It should be noted that the SODAR measurement differs slightly from an anemometer measurement. The SODAR measures the instantaneous wind speed components and then averages them to determine the vector wind speed. Anemometers measure the instantaneous wind speed (i.e. U and V components are indistinguishable) and the average scalar wind speed is calculated. The scalar wind speed is typically $1 - 2\ \%$ higher than the vector wind speed. The difference between the scalar average and the vector average is a function of the turbulence intensity. A relationship has been developed that relates the turbulence intensity to the difference between vector and scalar averages (6). The long-term predicted wind speeds will therefore be adjusted to reflect an equivalent scalar wind speed based on the turbulence intensity at the _____ site.

In addition to wind data, the SODAR also records the ambient temperature, the precipitation and the wind speed as measured by an anemometer mounted on a ~3 m-high pole.

SODAR Data Filters and Data Quality Checks

The next section describes the SODAR data filtering that was applied to the data at both the pre-processed and post-processed stages. The main function of these filters was to remove spurious data caused by high levels of ambient or electrical noise and to ensure good quality data.

Pre-processing SODAR Filtering

When the SODAR collects data, there are four initial criteria that must be met in order for the data to be considered valid. First, the signal-to-noise ratio (SNR) is calculated at each height and if it is found to be below the user-defined minimum then the data is discarded. Next, the amplitude of the signal is calculated and the data is removed if it is below the minimum allowed amplitude.

The third criterion is called the consensus check. Once the ten-minute interval is complete, there will be ~150 data samples (Doppler shifts) in each direction. The average Doppler shift is calculated in each direction and if, over that time interval, a data sample has a Doppler shift beyond the range of the average Doppler shift plus or minus the "consensus" (default = 100 Hz), then the data point is removed.

Finally, if, over the ten-minute interval, there is less than the minimum percent of valid data points (default = 15%) then the data for that ten-minute interval is considered invalid and is removed from the data set (5).

Echo Rejection Algorithm

In addition to the pre-processing SODAR data filtering described above, the manufacturer has included an optional echo rejection algorithm which is designed to minimize the effect of echoes caused by ground clutter. This option was enabled throughout the SODAR operation at Dennis.

Ground clutter is defined as trees, buildings, bushes or any stationary object surrounding the SODAR that could reflect the signal at a zero Doppler shift. When echoes occur in this way, the measured wind speed is biased low since the SODAR will interpret the zero Doppler shift as zero wind speed. Echoes from ground clutter impact the lower range gates more significantly than the higher range gates.

Ideally, the SODAR should be situated in an area void of ground clutter. When this is not possible, however, there are several steps that can be taken to minimize the effect of ground clutter. First, if the SODAR is oriented in such a way to direct the SODAR beams away from the ground clutter, the degree of echo contamination is lessened. Also, it has been found that if the SODAR can be raised to a higher elevation (for example, to the roof of a building) then the echoes have less of an impact. Finally, if ART's echo rejection algorithm is employed then the negative bias caused by echoes is greatly reduced.

The echo rejection option is a built-in function in the ART Model VT-1s and can be enabled at the user's discretion. The algorithm works by comparing the amount of spectral energy at the zero Doppler shift to spectral energy at other frequencies. If there is sufficient energy at a frequency other than the zero-shift, then the wind speed is calculated at this frequency and the energy at the zero-shift is ignored. It has been found in previous data sets that the echo rejection option is very effective at lessening the effects of ground clutter contamination.

The SODAR is located in a clearing with the closest tree line being about 25 m away. The trees were approximately 15 m tall at its highest. The echo rejection algorithm were enabled in this instance.

Post-processing SODAR Filtering

Once the wind speeds had been measured by the SODAR, additional filters were applied to the data. These filters were designed by comparing SODAR measurements to anemometer readings and determining appropriate cut-offs for removing erroneous data. These filters included the following:
- Maximum W turbulence intensity (W speed / Vector Wind Speed)
- Maximum U and V turbulence intensity (U or V speed / Vector Wind Speed)
- Minimum and maximum W wind speed (normalized by vector wind speed)
- Noise filter
- Shear filter

Turbulence Intensity Filters

The **maximum W turbulence intensity used in the filtering was 0.4** and the **maximum U and V turbulence intensity applied was 0.9**. These values have shown to remove invalid measurements while retaining the majority of good data.

Vertical (W) Wind Speed filter

Minimum and maximum normalized W wind speeds were also defined based on comparisons between SODAR and anemometry data. The **minimum and maximum values used in the filtering algorithm were –0.12 and 0.16**, respectively.

Noise filter

At past sites, there have been occurrences of extraneous noise entering the system which can contaminate the SODAR signal. The noise filter was designed to remove these erroneous data averages. Mention whether sources of extraneous noise were insignificant at the site.

The noise algorithm compares the calculated wind speed at each height to the wind speed measured by the anemometer (mounted on a 3 m pole). At each time step, the average difference between the SODAR (at each height) and the anemometer are calculated using the measured differences from the most recent five time steps. If the difference, at that time step, is greater than the average difference plus 4 m/s, then the data is discarded. Mention whether or not this filter had an impact on the data.

$$\left(Avg\ Difference\right)_{height} = \left(\frac{\left(Diff_{t-5} + Diff_{t-4} + Diff_{t-3} + Diff_{t-2} + Diff_{t-1}\right)}{5}\right)_{height}$$

$$If\ \left(Diff_t\right)_{height} > \left(Avg\ Difference + 4\right)_{height}\ Then\ Discard$$

Shear filter

Finally, a shear filter was applied to the data. This filter was developed after it was observed that, even after applying the other filters, a significant amount of scatter existed when plotting SODAR versus anemometer data. It has been found that at sites where ground clutter is present, echoes tend to contaminate the signal and bias the wind speed low, particularly at lower range gate heights. It has also been observed that at higher heights, the returning signal has a lower amplitude and it becomes increasingly difficult for the SODAR to accurately distinguish signal from noise. Finally, when comparing SODAR to tower data, the highest correlation coefficients are typically found at SODAR heights between 40 m and 80 m.

Based on these observations, the shear filter was designed with the following algorithm:
1) The average wind speed is calculated at 70 m, using wind speeds at 60, 70 and 80 m. This is called the true wind speed at 70 m.
2) It then compares the wind speed at every height to the true 70 m wind speed.

3) The shear power law exponent, alpha, is calculated at each height using the 70 m wind speed as the datum. The following equation shows the wind shear power law expression where U is wind speed [m/s], z is height, z_r is the reference height and α is the power law exponent.

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

4) If alpha is greater than the user-defined maximum shear exponent then the data point is removed
5) If alpha is less than the user-defined minimum shear exponent then the data point is removed.
6) If the 60 m or 80 m data point had been deleted due to shear, then the 70 m data point is also removed.

When designing this filter, it had to be decided what alpha limits should be specified. To answer this question, several tall tower data sets were analyzed. The power law exponent, alpha, was calculated at each ten minute interval between the lower and upper height for each of the tall tower data sets. For each data set, day and night histograms were calculated and the minimum alphas were selected such that 2.5% of the alphas were less than the minimum. The maximum alphas were defined at an alpha where approximately 2.5% of the alphas were greater. Table 1 lists the five tall tower sets and the range of acceptable alphas. As shown, for more complex and forested terrain, the range of acceptable alphas are relatively wide. Conversely, the range of acceptable alphas is much narrower for the offshore tower (Cape Wind). This trend is logical since more wind shear will be present (i.e. higher alpha) when more obstacles are present to slow down the wind. For the Dennis data set, the alpha limits based on the Hull WBZ tall tower were used in the shear filter since the site has similar characteristics.

Table 1: Summary of Tall Tower Alpha Limits

Site	Site Description	Day Alpha Minimum	Day Alpha Maximum	Night Alpha Minimum	Night Alpha Maximum
Nantucket, MA	Coastal	-0.2	0.7	-0.3	0.8
Hull WBZ, MA	Coastal / Complex terrain	-0.5	0.8	-0.3	0.9
Hatfield, MN	Onshore: flat with no trees	-0.5	0.9	-0.5	1.1
Isabella, MN	Onshore: forested	-0.3	1	-0.5	1.2
Cape Wind site, MA	Offshore	-0.2	0.6	-0.2	0.6

SODAR Operation during times of precipitation

Since the SODAR measures the speed of moving volumes encountered in the atmosphere, precipitation will usually lead to incorrect wind speed measurements. The effect of precipitation is most evident in the W (vertical) direction, since precipitation obviously falls in this direction. A precipitation gauge was mounted on the SODAR unit and the data acquisition control system ensured that **SODAR data was not collected during times of precipitation**.

Data Analysis Methodology

The following section outlines the approach taken in analyzing the Dennis SODAR data. Since the SODAR data alone was not sufficient to predict long-term wind speeds due to the limited data collection period and gaps in the data, an MCP algorithm was used with long-term anemometer data from the BUZM3 buoy in Buzzards Bay to develop an estimate of the expected wind resource. Also, tower data from Yarmouth, MA was used to validate the SODAR data. The steps taken in analyzing the Dennis data are described below.

1) **SODAR data was analyzed and compared to 50 m anemometer data collected at Yarmouth, MA.**

   The correlation coefficient, average ratio and standard deviation of the ratio of SODAR to anemometer data were determined at each range gate.

2) **Based on the comparison between the SODAR data and anemometer data, the valid range gates for the SODAR data set were determined.**

   After examining the correlation coefficient and ratio between the SODAR and anemometer data, a range of heights at which the data is valid was determined. This approach was taken because, as mentioned, if ground clutter is present, data at lower height can be contaminated which can lead to incorrect estimations of wind shear. Also, at higher heights, the reflected strength of the SODAR signal can become weaker and it becomes increasingly difficult for the SODAR to distinguish between signal and noise. The near-by tower data served as a guide in selecting the valid height ranges of the SODAR data.

3) **The MCP algorithm was used with wind data from BUZM3 as the reference site to predict long-term wind speeds.**

   Measure-Correlate-Predict (MCP) is a technique used to predict the wind resource at a target site using long-term data at a reference site. The method used in this report is discussed in Reference 4. The site at Dennis was the target site and the anemometer data measured on the BUZM3 buoy was used as the reference site. A relationship was developed between the target and reference site based on the ratio of the wind speed standard deviations. Based on this relationship, a predicted long-term wind speed at a range of heights at Dennis was found.

4) **The predicted long-term wind speeds were adjusted to account for the low-bias due to volume and vector averaging.**

   SODAR measurements tend to be lower than those of an anemometer and two main reasons for this are: vector averaging and volume averaging. These will be explained in more detail later in the report. After MCP, the predicted wind speeds at all heights were adjusted to reflect the bias.

Summary of Data Collection

Location and Duration of Data Collection Site

On December 3rd 2009, WEC brought its SODAR console unit to the site in Dennis, MA with coordinates of 41°41'33.10"N, 70° 8'10.30"W (NAD83) and began collecting data. The SODAR experienced power supply problems during its stay at this location causing periods in which data is unavailable. The total data collected, however, is sufficient to conduct the analysis presented in this report.
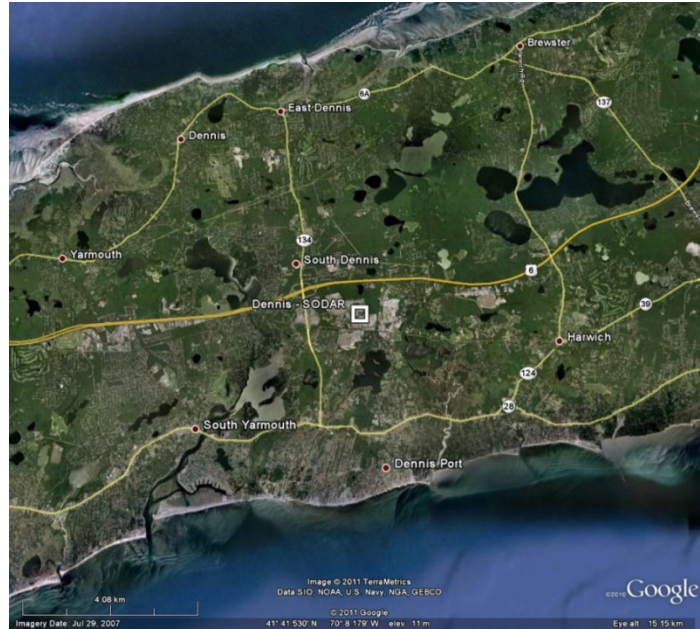

Figure 1: Map of Dennis SODAR Site

Figure 2: Map of the Dennis SODAR Site (zoomed)

Once the SODAR data was collected, its validity had to be checked by comparing it to near-by anemometer data. A met tower was in operation for some overlapping period with the SODAR at Yarmouth, MA. The data collected at this tower was used to validate the SODAR data. Figure 3 shows a map of the Dennis SODAR site relative to the tower site. The distance between the Dennis SODAR and Yarmouth Met Tower sites was 5 miles (8 km).

Figure 3: Map of Dennis SODAR and Yarmouth Tower site

After the SODAR data was validated, an MCP algorithm was used to estimate the long-term wind speed. The long-term data set used as the reference site was from a NOAA buoy in Buzzards Bay (BUZM3) and wind data collected since 1997 was used in the MCP analysis. The distance from the Dennis site to the buoy was 42 miles (68 km). Figure 4 shows a map of the Dennis site relative to the buoy location.
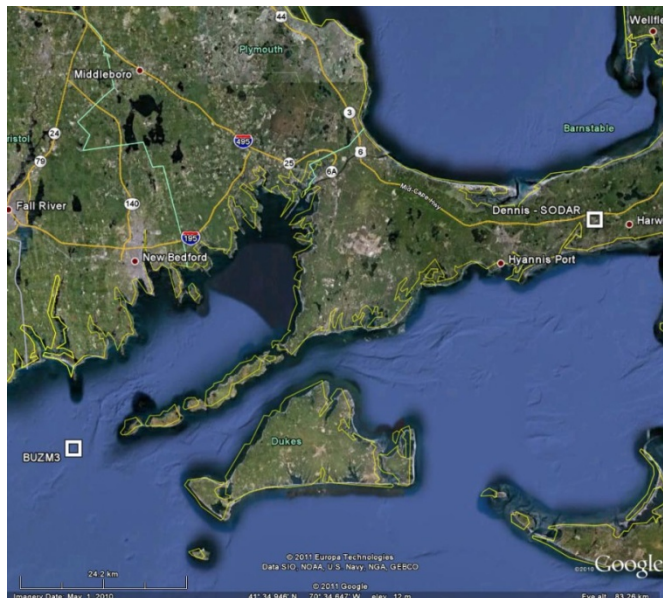

Figure 4: Map of the Dennis SODAR and BUZM3 Buoy Location

Determining Range of Valid SODAR data

The following section presents the results of the SODAR data analysis, which was conducted to determine the valid data that would be used in the MCP algorithm. The validity of lower heights can be compromised due to echo contamination, resonance or noise. At upper heights, the returning signal is less strong and it sometimes becomes difficult for the SODAR to distinguish between signal and noise. The SODAR data was therefore compared to the Yarmouth tower data and the range of valid SODAR data was determined.

The wind data was analyzed by plotting:
- Time series of SODAR data at 30 m, 60 m and 90 m
- Percent of valid data versus height
- Time series of SODAR (at 50 m) and tower data (at 50 m)
- Cross-correlation between the SODAR and tower data (at 50 m) versus height
- Average Ratio of SODAR to tower data (at 50 m) versus height
- Standard deviation of ratio of SODAR to tower data (at 50 m) versus height

Summary of Dennis data

The SODAR was placed at the Dennis site beginning from December 3rd, 2009. Data collected at the site up to December 31st, 2010 was used in this analysis. Figure 6 shows the time series of the SODAR data at 30 m, 60 m and 90 m for the time period. The large gaps in the data was where the power supply problem occurred.
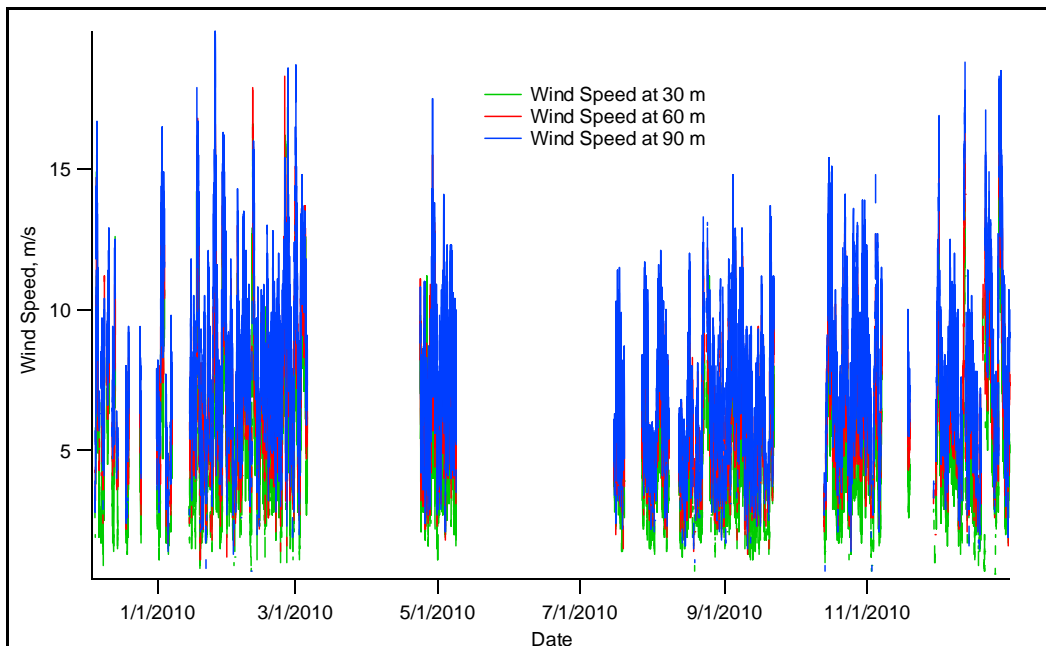

Figure 5: Dennis Time Series

Figure 7 depicts the percent valid data collected during this time after applying all filters for the duration of the whole period and also for the duration that the SODAR was

collecting data. Table 3 lists these percentages, the percentage of data filtered by the
SODAR algorithm, post-processing code and the total data filtered from the collected
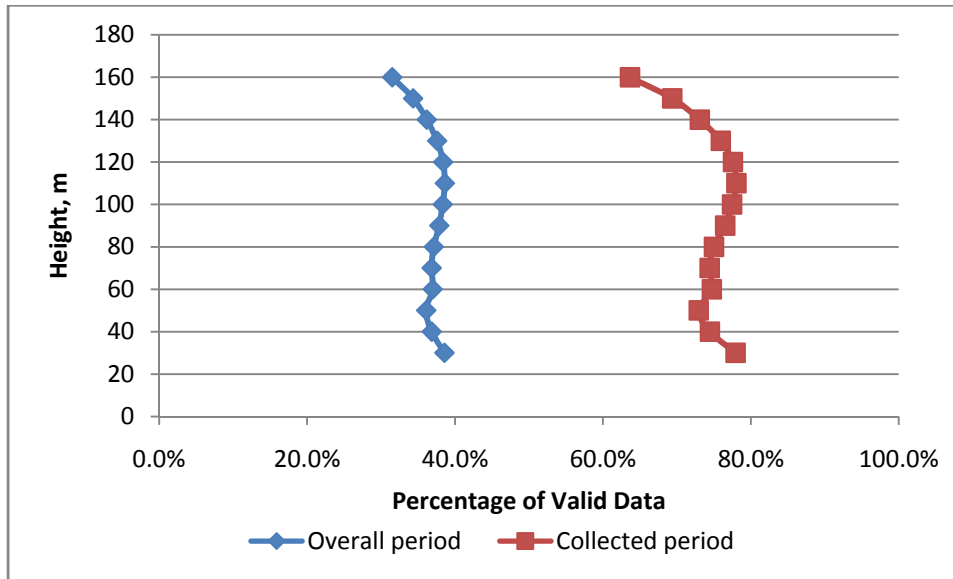period.

Figure 6: Percent Valid Data

Table 2: Percentage of data removed by filters

Height [m]	Percentage of valid data		Percentage of data filtered over collected period		
	Overall period	Collected period	by Post-Processor Code	by SODAR	Total
30	38.6%	77.9%	21.7%	0.3%	22.1%
40	36.9%	74.5%	25.5%	0.1%	25.5%
50	36.1%	73.0%	27.0%	0.0%	27.0%
60	37.0%	74.7%	25.0%	0.3%	25.3%
70	36.8%	74.4%	25.0%	0.6%	25.6%
80	37.1%	75.0%	24.2%	0.7%	25.0%
90	37.9%	76.5%	22.3%	1.2%	23.5%
100	38.3%	77.5%	20.0%	2.5%	22.5%
110	38.6%	78.1%	17.0%	4.9%	21.9%
120	38.4%	77.6%	15.0%	7.4%	22.4%
130	37.6%	75.9%	14.0%	10.0%	24.1%
140	36.2%	73.1%	13.4%	13.5%	26.9%
150	34.3%	69.4%	12.2%	18.4%	30.6%
160	31.5%	63.6%	11.4%	25.0%	36.4%

Next, a sampling of data from the SODAR at 50 m was plotted in Figure 8 with the
Yarmouth tower data (at 50 m) versus time. The graph indicates a very good correlation
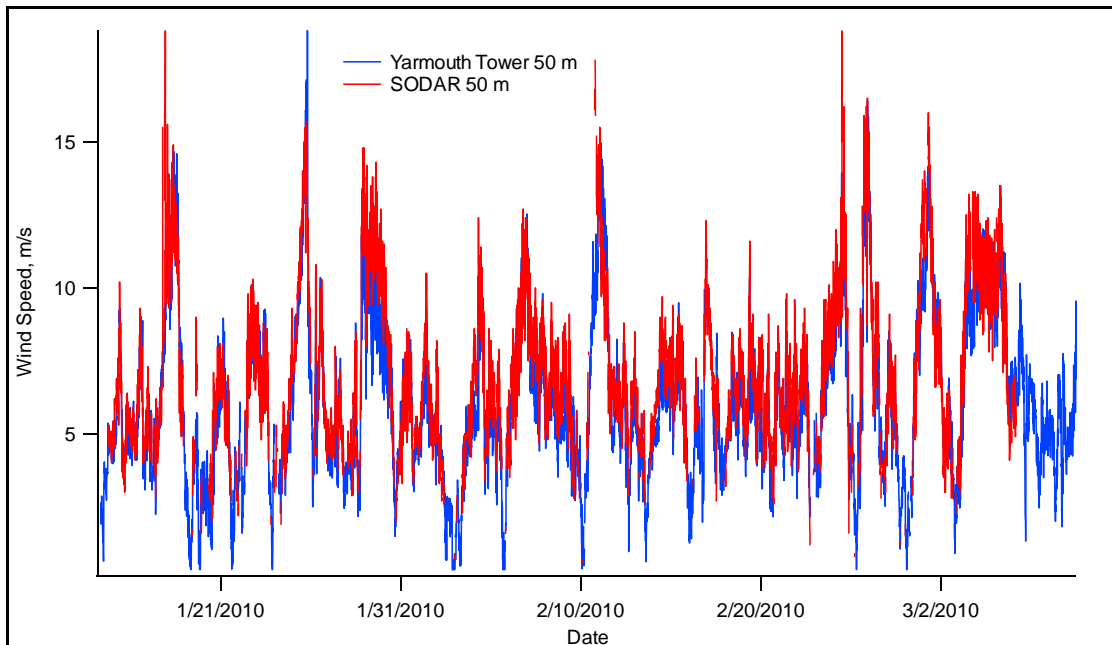between the two sites.

Figure 7: Dennis SODAR and Yamouth Tower Time Series

The cross-correlation coefficients between the SODAR and the tower data and between the SODAR and the Yarmouth tower were calculated at each height and are shown in Figure 9. The highest correlation occurs at about the tower height as expected.

When determining the heights of valid data, the correlation coefficient was used as an indicator of ground clutter contamination. In Figure 9, one would expect a high correlation between the SODAR and the tower at lower heights (i.e. closer to the anemometer height of 50 m). One would also expect the correlation coefficient to decrease at higher heights as the distance between the SODAR and anemometer measurement was increased.

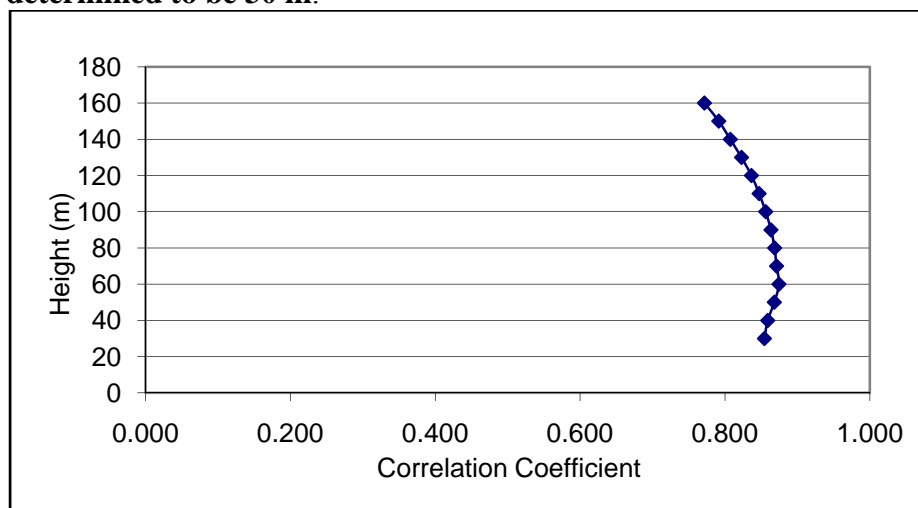Based on the correlation coefficient, **the minimum height of valid data was determined to be 30 m**.

Figure 8: Dennis and 50 m Tower Correlations with Height

Next, the ratio between the SODAR data and the Yarmouth tower data was examined. Figure 10 shows the ratio of SODAR data at 50 m to the Yarmouth tower data. If the two sites were perfectly correlated and had the same average wind speed, one would expect very little scatter and the majority of the points should lay around 1.0. If echo contamination was an issue, one would observe a significant amount of data points with very low ratios, particularly at lower wind speeds.
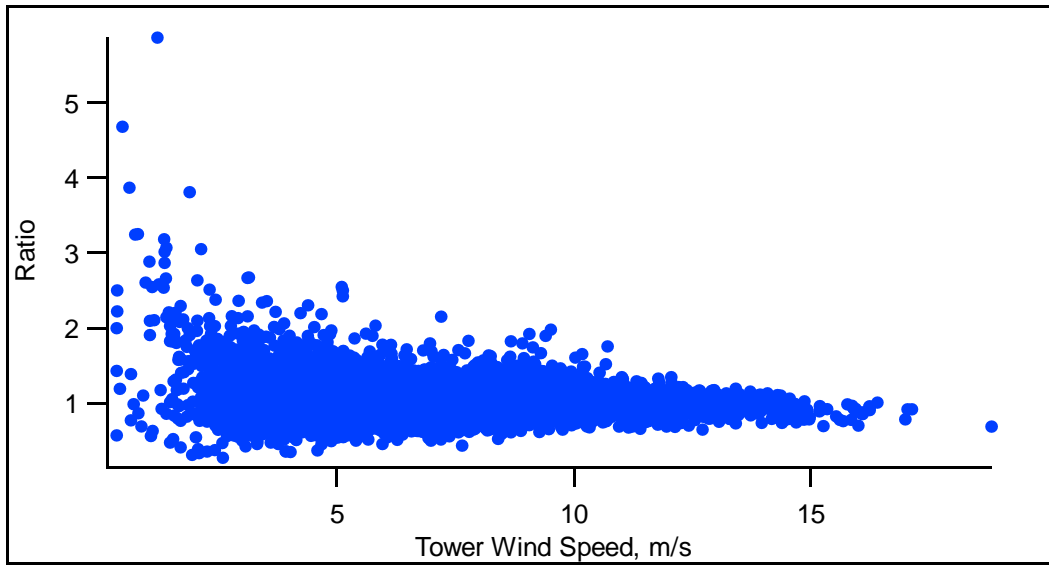
Figure 9: Ratio of the SODAR at 50 m to Yarmouth Tower at 50 m

The average ratios and the standard deviation of the ratios were then calculated at each height and are plotted in Figure 11 and Figure 12. The average ratio plot illustrates how the average wind speed at the Dennis site, at a range of heights, compared to the average wind speed at Yarmouth at 50 m. As expected, the average ratio increased with height.

The standard deviation plot shows how much scatter was present in the ratio plots for each height. One would expect a larger standard deviation at heights away from the tower height, since the distance between the measurement points becomes larger. Figure 12 shows the standard deviation increasing as it moves away from 50 m. There is a slightly larger than expected standard deviation at the 110 m station but it is determined to be an acceptable value. Based on this analysis, **the maximum height of valid data was determined to be 160 m**.
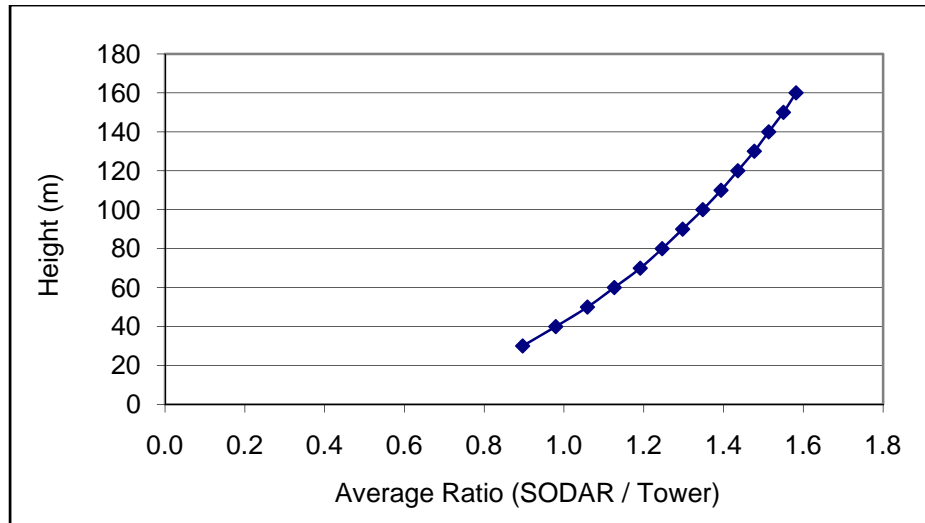
Figure 10: Average Ratio of Dennis SODAR to Yarmouth Tower (50 m)
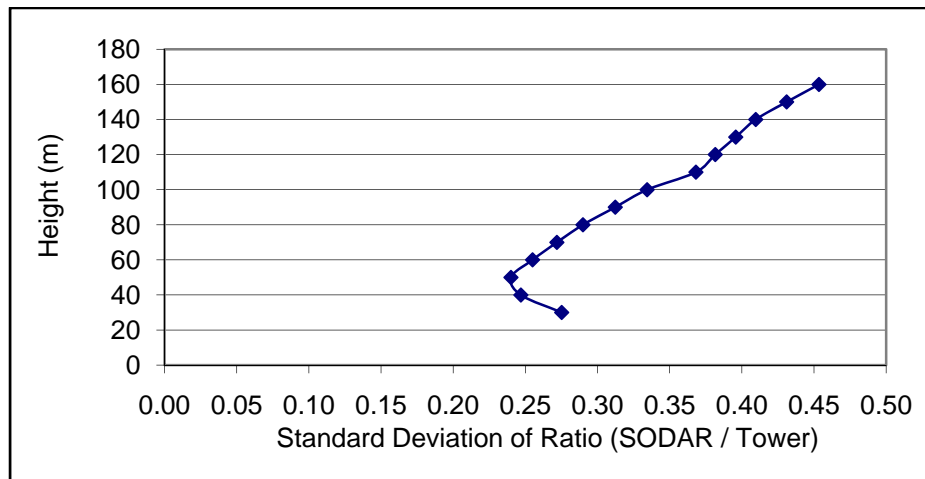
Figure 11: Standard Deviation of Ratio of Dennis SODAR to Yarmouth Tower

Table 4 summarizes the data analysis when comparing the Dennis SODAR to the Yarmouth 50 m tower:

Table 3: Summary of SODAR Comparison to Yarmouth Tower

Height	30	40	50	60	70	80	90
Averages	0.897	0.979	1.059	1.126	1.191	1.246	1.297
Stdev of Ratio	0.275	0.247	0.240	0.255	0.272	0.290	0.312
CorrCoeff	0.854	0.859	0.868	0.875	0.871	0.86858	0.864

Height	100	110	120	130	140	150	160
Averages	1.348	1.394	1.436	1.477	1.513	1.550	1.582
Stdev of Ratio	0.334	0.368	0.382	0.396	0.410	0.431	0.453
CorrCoeff	0.856	0.847	0.837	0.823	0.807	0.792	0.772

Based on this comparison between the SODAR data and the Yarmouth data, **the valid height range of SODAR data was found to be from 30 m to 160 m**.

MCP Prediction for Dennis Using BUZM3 Data

Once the valid height ranges had been selected, the MCP algorithm was carried out. Since the tower that were used as a comparison to the SODAR data had about a year of data, another long-term reference site was needed as an input into the MCP algorithm. The reference site used was from the BUZM3 buoy located in Buzzards Bay (41°23'48" N 71°2'0" W). An anemometer is mounted at a height of 24.8 m and historical wind data since 1997 is used. When conducting an MCP analysis, it is best to use full-years of long-term data therefore data from May 13th 1997 to May 13th 2007 were used. Wind data from BUZM3 shows the same gross trends as SODAR measurements at Dennis and Figure 13 shows the spread between the two sites are bounded relatively well.
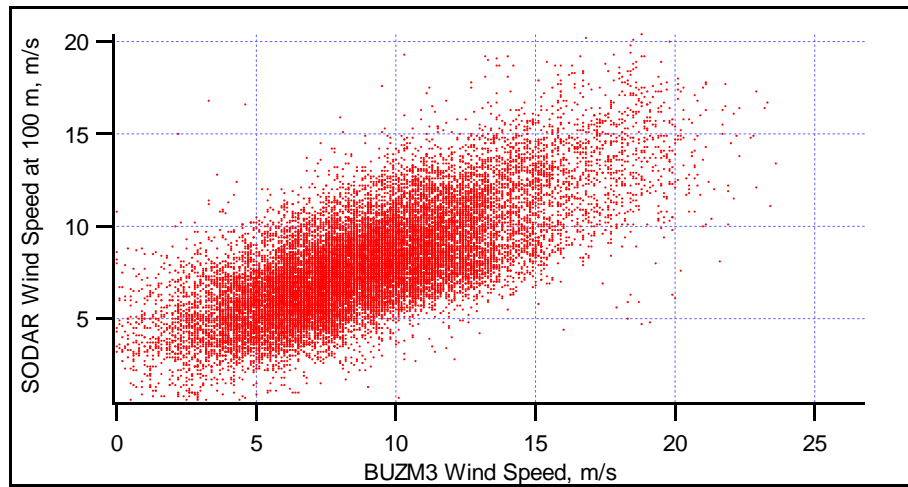
Figure 12: Scatter Plot of SODAR at 100 m and BUZM3 data

After conducting the MCP analysis, the predicted wind speeds were adjusted to account for bias due to both volume averaging and vector averaging. Volume averaging means that the SODAR measures wind speed over a volume for every height of interest (range gate). If the wind speeds vary significantly within that volume then the predicted wind speed can be skewed. This is of particular importance at sites with high wind shear. At such sites, the predicted wind speed will be biased low by a SODAR. The extent of the underprediction is a function of height and of the power law shear exponent, alpha. At Yarmouth, the average alpha exponent was found to be 0.21. Using an in-house program coded in Visual Basic, the percent error was found at each range gate as shown in Table 5 below.

Table 4: Volume Average Percent Error

Height, m	Volume Average Bias
30	-3.21%
40	-1.68%
50	-1.04%
60	-0.71%
70	-0.52%
80	-0.39%
90	-0.31%
100	-0.25%
110	-0.21%
120	-0.17%
130	-0.15%
140	-0.13%
150	-0.11%
160	-0.10%

As previously mentioned, the SODAR measures a vector averaged wind speed where as an anemometer measures a scalar averaged wind speed. The scalar average will always be greater than the vector average (typically $1 - 2$ % higher) and the difference between the two is a function of the turbulence intensity. A relationship was developed that relates the ratio of the scalar and vector wind speeds to the turbulence intensity and is shown in Figure 14 below (6) where U/U_a = Vector Wind Speed / Scalar Wind Speed.
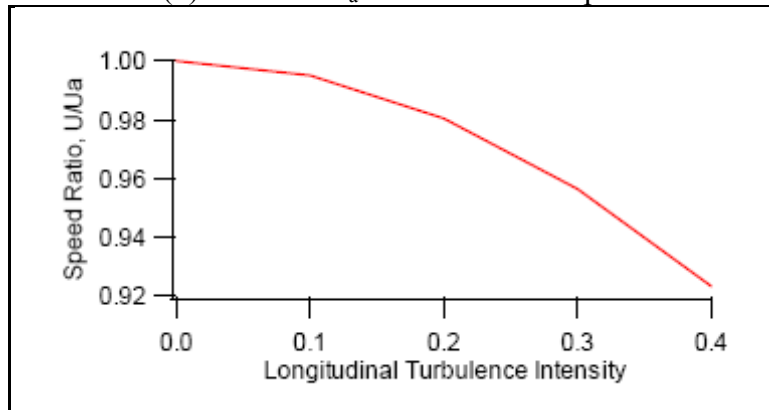
Figure 13: Effect of vector averaging on wind speed ratio, U/U_a, as a function of turbulence intensity

Longitudinal turbulence intensity is measured by anemometers and is defined as the standard deviation of the horizontal wind speed divided by the average horizontal wind speed over a ten minute period. Based on the Yarmouth Tower data, the average turbulence intensity at Dennis was assumed to be 0.21. A speed ratio of 0.98 corresponding to a turbulence intensity of approximately 0.21 is shown in Figure 14. This translates into a 2 % low bias due to vector averaging.

Long-term wind speed predictions were made at every height between 30 m and 160 m

(at 10 m intervals) and were adjusted to account for vector averaging and volume averaging. Table 6 shows the predicted long-term wind speeds. The predicted Weibull parameters, k and c, are presented and their significance will be explained later in this section. The uncertainty of the MCP analysis is also shown in the table. This uncertainty is associated only with the MCP portion of the analysis and is not the overall uncertainty of the wind speed.

Table 5: Dennis Long-term Wind Speed Prediction Results

Height [m]	Corrected estimated wind speed [m/s]	Uncertainty of MCP [m/s]	Estimated k	Estimated c
30	4.88	0.36	2.03	5.22
40	5.32	0.35	2.15	5.79
50	5.77	0.35	2.32	6.32
60	6.13	0.32	2.45	6.72
70	6.47	0.32	2.53	7.10
80	6.74	0.31	2.56	7.41
90	6.97	0.29	2.54	7.67
100	7.22	0.28	2.55	7.96
110	7.46	0.27	2.54	8.21
120	7.67	0.25	2.54	8.46
130	7.87	0.26	2.51	8.68
140	8.07	0.28	2.49	8.91
150	8.28	0.32	2.45	9.14
160	8.51	0.33	2.40	9.40

The predicted wind speed is shown for each height as well as the estimated standard deviation. The Weibull probability density function (PDF) parameters, k and c, were also estimated at each height. A PDF provides a statistical representation of the wind resource at a site. The *k* parameter is referred to as the shape factor and the *c* parameter is called the scale factor. The shape factor determines the shape of the peak in the PDF and the scale factor is related to the average mean speed. A typical value for the shape factor is 2.0 and a higher value implies that there is less variation in the wind speeds at the site.

$$Weibull\ PDF : P(U) = \left(\frac{k}{c}\right)\left(\frac{U}{c}\right)^{k-1} \exp\left[-\left(\frac{U}{c}\right)^{k}\right]$$

Dennis Uncertainty Analysis

Throughout the process of estimating long-term wind speeds, several sources of error were introduced and must be accounted for. The following section describes each source of significant error, how the error was quantified and then compiled to determine the expected range of uncertainty. The end result is a range of wind speeds around the

predicted mean wind speed that can be expected at Dennis. The percentage uncertainty values are the standard deviation divided by the mean value. In other words, the uncertainty range is representative of the expected standard deviation surrounding the predicted mean wind speed. Also, a P90 wind speed is given which represents the minimum average wind speed that can be expected at Dennis with 90% confidence.

The significant sources of uncertainty in this analysis included:
1) Uncertainty of SODAR Wind Speed, δU_1
2) Uncertainty of MCP Analysis, δU_2
3) Inter-annual Variability Uncertainty of Long-term Data, δU_3

All the error sources (%) were combined into one equivalent uncertainty using the following equation:

$$\delta U = \sqrt{\delta U_1^2 + \delta U_2^2 + \delta U_3^2}$$

Uncertainty of SODAR Measurement (δU_1)

The first source of error that was considered was the uncertainty of the SODAR. The manufacturer of the SODAR claims that the horizontal wind speed measurements have an accuracy of ± 0.25 m/s and the vertical wind speed is accurate to ± 0.04 m/s (5). Based on the relationship between the horizontal and vertical wind speed components, the overall uncertainty in the SODAR measurement is ± 0.282 m/s. At each range gate, the SODAR wind speed uncertainty of ± 0.282 m/s was converted to a percentage uncertainty (i.e. % uncertainty = (0.282 / Mean Wind Speed) x 100).

Uncertainty of MCP Analysis (δU_2)

The MCP algorithm estimates the long-term wind speed at a target site based on the relationship of the wind speeds at the target site and a reference site. In this case, the target site was the Dennis SODAR and the reference site was the BUZM3 buoy. In the algorithm, a standard deviation was determined which quantified the uncertainty in the predicted long-term wind speed at the target site. An uncertainty was determined at each height at the Dennis site and this was representative of the uncertainty in the MCP analysis (3).

Inter-annual Variability Uncertainty of Long-term Data (δU_3)

The next source of uncertainty is the inter-annual variability uncertainty, which arises since the wind speed at a given site will vary from year to year. Typically, 20 years of data is considered to be sufficient to capture all inter-annual variability. With a shorter data set, there is uncertainty about whether the predicted wind speed is in fact representative of the long-term wind speed at that site. To quantify this error, the following equation can be used (1):

$$\delta U = \frac{6\%}{\sqrt{N}}$$

$where : N = Length\ of\ Data\ Set\ in\ Years$

Since 12 years of data from the buoy was used in this analysis, the inter-annual variability uncertainty is 1.73 %.

Summary of Uncertainty Analysis

Table 10 shows the predicted wind speeds at the site at Dennis along with the range of expected wind speeds incorporating all the error sources. The predicted P90 wind speed is also shown at each height which represents the minimum average wind speed that can be expected with 90% confidence.

Table 6: Predicted Wind Speeds, Expected Ranges and Expected P90 Wind Speed

Height	Predicted wind speed	Total uncertainty		Min	Max	P90 wind speed
[m]	[m/s]	[%]	[m/s]	[m/s]	[m/s]	[m/s]
30	4.88	9.49	0.46	4.42	5.34	4.29
40	5.32	8.66	0.46	4.86	5.78	4.73
50	5.77	8.04	0.46	5.31	6.24	5.18
60	6.13	7.17	0.44	5.69	6.56	5.56
70	6.47	6.78	0.44	6.03	6.90	5.90
80	6.74	6.42	0.43	6.30	7.17	6.18
90	6.97	6.05	0.42	6.55	7.39	6.43
100	7.22	5.80	0.42	6.80	7.64	6.69
110	7.46	5.52	0.41	7.04	7.87	6.93
120	7.67	5.23	0.40	7.27	8.07	7.16
130	7.87	5.19	0.41	7.46	8.28	7.35
140	8.07	5.25	0.42	7.65	8.50	7.53
150	8.28	5.45	0.45	7.83	8.73	7.70
160	8.51	5.42	0.46	8.04	8.97	7.91

The long-term expected wind speed at the Dennis site at 60 m was found to be 6.13 ± 0.44 m/s. At 80 m, the long-term wind speed is predicted at 6.74 ± 0.43 m/s. Figure 15 shows the predicted wind shear profile at the Dennis site along with the expected range of uncertainty. The error bars represent a 68 % uncertainty (i.e. one standard deviation of a normal distribution). One can then estimate with 68 % confidence that the long-term wind speed at a given height will fall within the error bars.
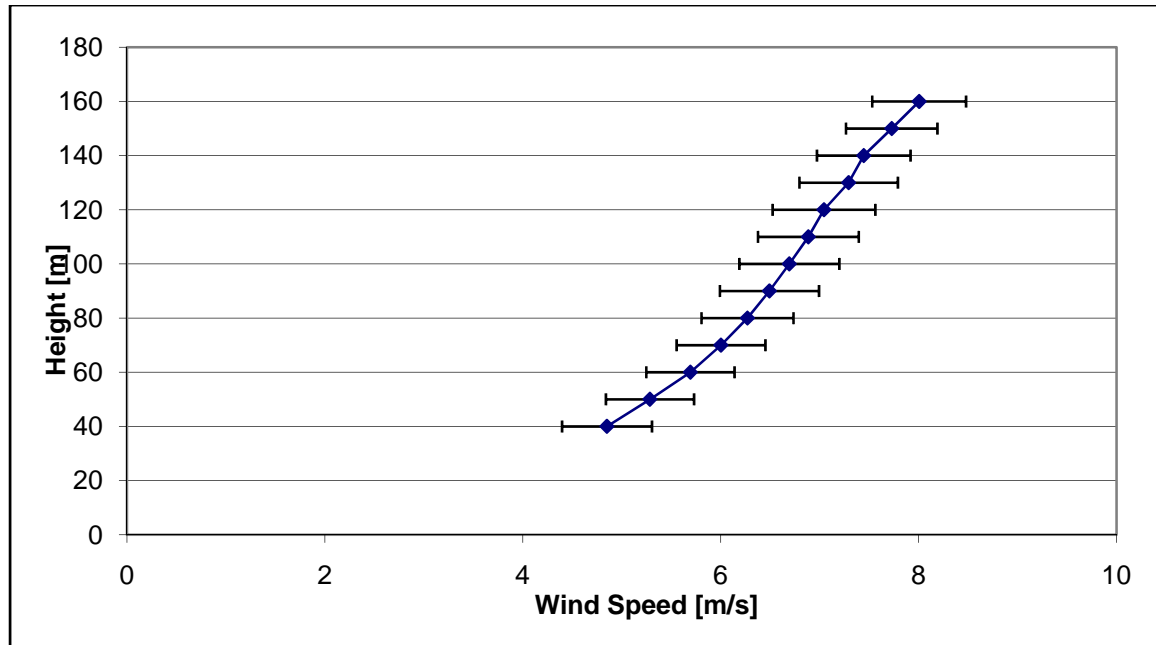
Figure 14: Wind Shear Profile with Uncertainty Range

Capacity Factor Calculation

Finally, using the predicted mean wind speeds, the expected capacity factor was calculated for a few turbines of different rated power at their respective representative hub heights. The capacity factor is defined as the actual annual wind energy output divided by the rated wind turbine output.

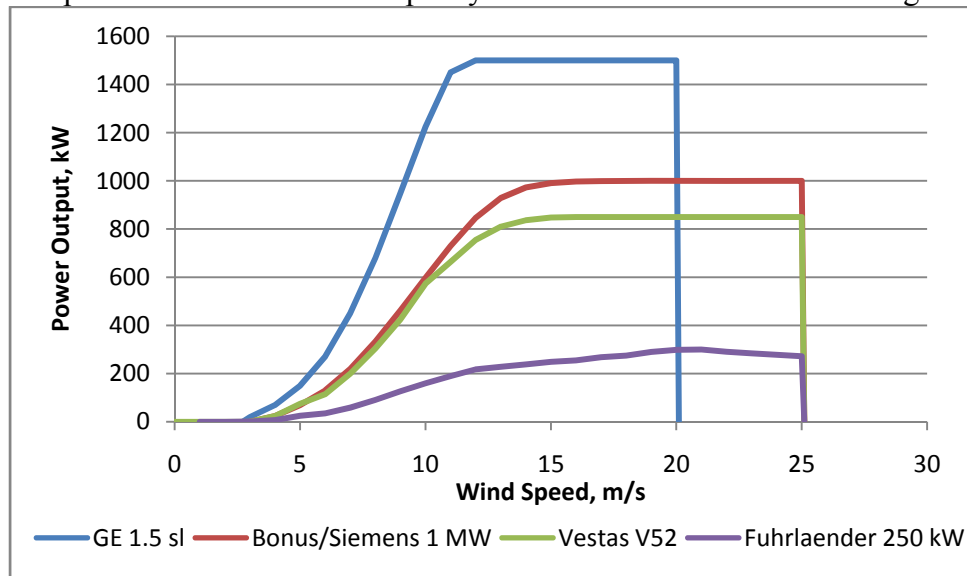The power curve used in the capacity factor calculation is shown in Figure 15.

Figure 15: Vestas V80 Power Curve

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. 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 the turbines and hub heights as listed in Table 5 below together with the predicted long term mean wind speed as calculated previously. 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 predicted power production was then multiplied by the expected losses that account for maintenance and icing. It was assumed that the loss factors due to maintenance and icing were each 0.95 and the combined loss factor was therefore 0.9025 (i.e. 0.95^2). Finally, the capacity factor is then calculated from:

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

where P_{rated} is the rated capacity of the turbine.

Table 9 shows the predicted capacity factors at the respective hub heights for each of the turbines.

Table 7: Dennis Capacity Factor Prediction

Turbine	Rated Power [kW]	Hub Height [m]	Capacity Factor		Capacity Factor with losses	
			Predicted wind speed	P90 wind speed	Predicted wind speed	P90 wind speed
Fuhrlaender	250	50	0.21	0.16	0.19	0.15
Vestas V52	850	49	0.21	0.16	0.19	0.15
Siemens/Bonus	1000	60	0.23	0.18	0.20	0.16
GE 1.5 xle	1500	80	0.35	0.30	0.32	0.27
GE 1.5 xle	1500	100	0.40	0.35	0.36	0.32

Summary and Discussion of Results

One of RERL's SODARs was brought to Dennis, MA on December 3rd, 2009. Data collected at this location up to December 31st, 2010 was used in the analysis presented in this report. Power supply problems during the duration caused some period in which data was unavailable.

The data collected at Dennis was compared to the Yarmouth tower data and the valid heights of SODAR data were found to be between 30 m to 160 m. Long-term wind speed data collected at the BUZM3 buoy in Buzzards Bay was then used as the reference data in MCP. The long-term wind speed was then estimated and adjusted to account for vector and volume averaging effects at each height.

An uncertainty analysis was conducted and the expected range of long-term wind speeds was determined at each height. The estimated long-term wind speeds are shown in Table 10, along with the expected range of uncertainty and the P90 wind speed.

Table 8: Predicted Wind Speeds and Ranges of Uncertainty

Height [m]	Predicted wind speed [m/s]	Min [m/s]	Max [m/s]	P90 wind speed [m/s]
30	4.88	4.42	5.34	4.29
40	5.32	4.86	5.78	4.73
50	5.77	5.31	6.24	5.18
60	6.13	5.69	6.56	5.56
70	6.47	6.03	6.90	5.90
80	6.74	6.30	7.17	6.18
90	6.97	6.55	7.39	6.43
100	7.22	6.80	7.64	6.69
110	7.46	7.04	7.87	6.93
120	7.67	7.27	8.07	7.16
130	7.87	7.46	8.28	7.35
140	8.07	7.65	8.50	7.53
150	8.28	7.83	8.73	7.70
160	8.51	8.04	8.97	7.91

The expected wind speed at Dennis at 80 m is 6.74 m/s and there is a 68% level of confidence that the average wind speed will be between 6.30 and 7.17 m/s.

Finally, using four representative turbines and their power curves, along with the predicted wind distribution, capacity factors were estimated at their respective hub heights. The capacity factor is defined as the actual annual wind energy output divided by the rated wind turbine output. Table 11 summarizes the predicted capacity factors at the turbine hub heights.

Table 9: Summary of Estimated Capacity Factors at Dennis

Turbine	Rated Power [kW]	Hub Height [m]	Capacity Factor		Capacity Factor with losses	
			Predicted wind speed	P90 wind speed	Predicted wind speed	P90 wind speed
Fuhrlaender	250	50	0.21	0.16	0.19	0.15
Vestas V52	850	49	0.21	0.16	0.19	0.15
Siemens/Bonus	1000	60	0.23	0.18	0.20	0.16
GE 1.5 xle	1500	80	0.35	0.30	0.32	0.27
GE 1.5 xle	1500	100	0.40	0.35	0.36	0.32

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2) M. Ray, A. Rogers and J. Manwell, "Accuracy of Wind Shear Models for Estimating the Wind Resource in Massachusetts," 2005.
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