Wind Shear over Forested Areas

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Nomenclature

d = displacement distance
h = tree height
U = wind speed
U_{ref} = wind speed at reference measurement height
z = measurement height above ground
z_{ref} = reference measurement height
z_0 = surface roughness

I. Abstract

THE installation of wind turbines within forested areas presents many problems. These include correctly characterizing the hub height wind resource and wind shear, determining the energy production from a wind turbine and estimating the level of turbulence and associated loads. This paper adds to the knowledge-base regarding wind shear in forested areas as it affects resource assessment. SODAR data from a forested island offshore of Maine are used to estimate mean shear characteristics and wind turbine power production and to evaluate shear models over forested areas. The mean shear and power production estimates show that shear at this site is much different than might be expected and that it has a significant effect on power production estimates. The best-fit parameters for three models are used to determine if and when they might be generally applicable to forest canopy shear flows. The result show that all of the models can be used to characterize 10-minute averaged wind shear at this site, but that none of the three models result in a consistent set of parameters that could be used to predict wind shear if the appropriate parameters for the site are unknown. Further investigation shows that the model parameters at this site are a function of time of day, wind speed and wind direction.

II. Introduction

The Renewable Energy Research Laboratory at the University of Massachusetts has been collecting data at a meteorological tower on the island of Vinalhaven, offshore of Maine[1] (see Fig. 1). The tower sits on a low forested hill in the middle of the small island. Data at 40 m at the meteorological tower indicate significantly lower wind speeds than expected, based on previously collected data at more exposed sites and on projections from wind maps. Wind maps indicate a significant wind resource offshore of the island and an adequate resource over the island. Nevertheless, projections to higher elevations using standard shear models did not indicate that the wind resource at the site was very good. It was decided to use the UMass SODAR to explore the shear over the island in more detail.

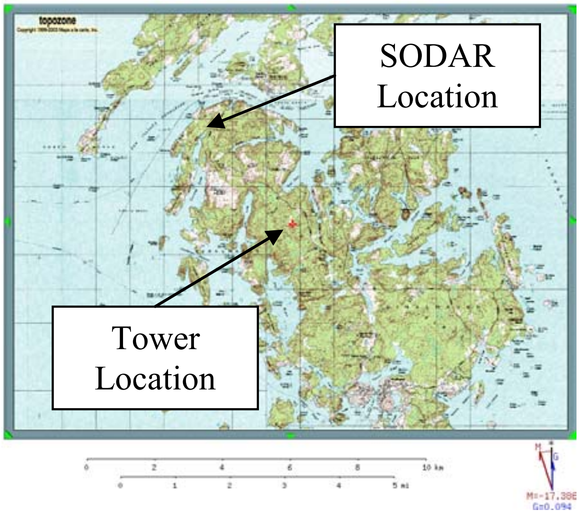

Figure 1. Map of sites on Vinalhaven.

The SODAR data has been used to investigate the shear over the forest at Vinalhaven and to explore often-used models for shear over forests. Numerous researchers have considered aspects of the details of atmospheric boundary layer meteorology above forests[2,3,4]. Research has included issues related to both turbulence[3] and shear[4] models. Nevertheless, there is enough uncertainty with respect

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to modeling wind shear and turbulence over forested areas that the British Wind Energy Association convened a Workshop on the Influence of Trees on Wind Farm Energy Yields in March 2004. At that workshop Rafferty[4] discussed validation of five different models for wind shear over forests, concluding that none were adequate and that measurements were needed for siting wind turbines in forests.

Data have been collected at two sites on the island of Vinalhaven offshore of the U.S. state of Maine. At the first site, wind speed and wind direction data are being collected with anemometers 40 m above the ground. The site is on a hill, with an elevation of 55 m, surrounded by forests. At the second site, the SODAR has been used to collect data up to 200 m above the ground. This site is about 1.5 km NW of the tower site, also in a forested area. The elevation of the nearby terrain surrounding the SODAR varies from about 5 m to 30 m above sea level. At both sites with distance from the shore is a function of direction. At the tower site, the distance from the water varies from 1 km in the northerly direction to over 15 km in the southerly direction. The SODAR is 17 km from the water in the SE direction, but less than 1 km in the NE direction. Figure 1 shows the location of the two sites on a topographic map. The height of the forest is consistently about 20 m in the area of the data collection. The forest is continuous in all directions, except for a few clearings for houses, an occasional rock ledge and the ocean beyond the coast.

III. SODAR Description

The UMass ART VT-1 SODAR measures wind speed and direction at multiple heights using an acoustic signal. Separate acoustic signals are broadcast in different directions every two seconds to measure the vertical, longitudinal and lateral wind speeds at heights from 30 to 200 m in 10 m increments. These signals are reflected from density variations in the atmosphere and received by the SODAR. The frequency and time delay of the received sounds are used to determine wind speeds at each height. SODAR has been shown to provide reliable measurements at multiple heights without a tower, usually from much higher elevations than typical anemometry[5,6]. The UMass ART VT-1 SODAR reports vector averaged wind speeds and direction. These are then corrected for systematic calibration errors and the effects to turbulence, resulting in approximately equivalent scalar wind speed averages.

IV. Data Description and Characterization

The data at the tower site have been collected continuously since August 2002.

Wind speed data were collected at the SODAR site for five months, from February 26, 2004 until July 28, 2004. This period covers a range of temperatures, wind speeds and wind directions and periods during which the trees around the site had no leaves and periods after which the leaves appeared. There were two predominant wind directions, NW to NE and SSW. The data are therefore useful for investigating the effects of time of day (due to changing atmospheric stability), distance from shore, wind speed and the presence of foliage. A 42 hour sample of the data is shown in Fig. 2.

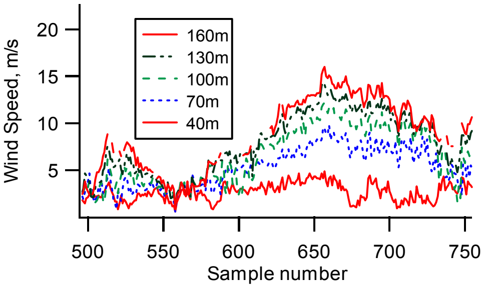

Figure 2. Sample SODAR data from Vinalhaven.

The data at the SODAR site include a variety of wind conditions, but, overall, indicate relatively low wind speeds at typical measurement heights. Figure 3 illustrates the mean wind shear at the site during the entire five month measurement period, which is remarkably linear, the commonly used 1/7th power law profile and two log law profiles for comparison. A roughness length, z_0, of 0.5 m is often recommended for forests[7]. The roughness length of 22.5 m represents a roughness length that provides a reasonable fit to the data and, perhaps coincidently, is about the local tree height. It can be seen that the shear at the SODAR site is significantly greater than might be anticipated, using standard shear models.

V. Projected Power Production

The power production at the tower site from a Vestas 660 kW wind turbine was estimated based on the anemometer data, using a standard shear model and the mean shear found at the SODAR site (z_0 = 22.5 m). The average annual wind speed over the period from September 2002 until August 2003 at 40 m was 5.37 m/s at the tower site. Using the standard log law and a roughness length of 0.5 m, the mean annual wind speed and capacity factor of a Vestas V47 wind turbine on a 65 m tower would be 5.91 m/s and 0.22. On an 80 m tower they would be 6.23 m/s and 0.25. If the roughness length of 22.5 m were assumed at the site, then the mean annual wind speed and capacity factor at 65 m would be 9.88 m/s and 0.50. On the 80 m tower they would be 11.81 m/s and 0.54. Clearly, these estimates are very different. Obviously, the correct determination of wind shear at the site is very important!

VI. Shear Models

The SODAR data have been analyzed to determine if any of three shear models might be shown to adequately represent the data and under what conditions. If so, then the shear models determined to be adequate might be tested at other forested sites. Each model was fit to each of 18215 10-minute averaged shear profiles and two criteria were used to evaluate the success of the models:

1. The distribution of model parameters in general and under a variety of conditions
2. The closeness of the model fit as judged by RMS prediction errors over the heights used for the parameter fits.

The three different shear models are 1) the standard Log Law model used in the wind industry, 2) a modified Log Law model and 3) a linear model.

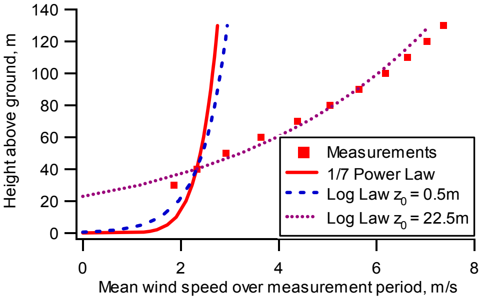

Figure 3. Mean wind shear at Vinalhaven SODAR site

The standard log law model[7] that is used to characterize wind shear has the form:

$$U = U_{ref}\left[\ln\left(\frac{z}{z_0}\right)\bigg/\ln\left(\frac{z_{ref}}{z_0}\right)\right] \tag{1}$$

The roughness length, z_0, determines the rate of change of the wind speed with height:

$$\frac{d\left(U/U_{ref}\right)}{dz} = \left[\frac{1}{z}\bigg/\ln\left(\frac{z_{ref}}{z_0}\right)\right] \tag{2}$$

and the elevation at which the wind speed is determined to drop to zero:

$$z_{U=0} = z_0 \tag{3}$$

Finally, for the function to be defined,

$$z_0 > 0 \tag{4}$$

A modified log profile that is sometimes used to model wind shear above a forest canopy. Reference 8, for example, assumes a displacement height of d and a roughness length that may be different than that if one assumes that $d = 0$. The shear is determined from:

$$U = U_{ref}\left[\ln\left(\frac{z-d}{z_0}\right)\bigg/\ln\left(\frac{z_{ref}-d}{z_0}\right)\right] \tag{5}$$

In this model, both the roughness length, z_0, and displacement height, d, determine the rate of change of the wind speed with height:

$$\frac{d\left(U/U_{ref}\right)}{dz} = \left[\frac{1}{z-d}\bigg/\ln\left(\frac{z_{ref}-d}{z_0}\right)\right] \tag{6}$$

and the elevation at which the wind speed is determined to drop to zero:

$$z_{U=0} = z_0 + d \tag{7}$$

From a mathematical point of view, there is no reason why d cannot be less than zero and this possibility was explored, as described below.

There is also no mathematical reason why z_0 cannot be less than zero in this model. Nevertheless, for all modeling done for this work, z_0 is assumed to greater than zero. Values less than zero require that d be greater than any z of interest and result in a decrease in wind speed with height. For positive z_0, the function is only defined for:

$$0 < z_{ref} - d \tag{8}$$

Non-negative wind speeds require that:

$$z_0 < z_{ref} - d \tag{9}$$

The data from 40 m to 100 m were used to determine the best fit for d, z_0 and U_{ref} which minimized the RMS prediction error over the 40 m to 100 m interval. For this analysis, if any of the data points were flagged, the fit was not calculated. The search space for the best fit was:

$$-80 \le d \le z_{ref} \tag{10}$$

$$0.001 \le z_0 < z_{ref} - d \tag{11}$$

$$U_{40} - 1 \le Uref \le U_{40} + 1 \tag{12}$$

Where U_{40} is the measured wind speed at 40 m. This may result in negative displacement distances and roughness lengths that are greater than the height of the lowest anemometer.

Many of the individual 10-minute wind shear profiles show a significantly linear behavior up to between 80 and 120 m, above which the wind shear decreases. Given the linear nature of many of the shear profiles below about 100 m, a linear model was also investigated. Linear regression was used to determine the appropriate slope, and offset, for the model:

$$U = \frac{dU}{dz} z + U_0 \tag{13}$$

The slope is normalized for comparison with the slope of the log law:

$$\frac{d\left(U/U_{40}\right)}{dz} \tag{14}$$

Figures 4 to 6 show samples of the measured data and the best-fit modified log model and the linear model. The standard log law model is omitted to avoid clutter, but parameters are provided in the caption.

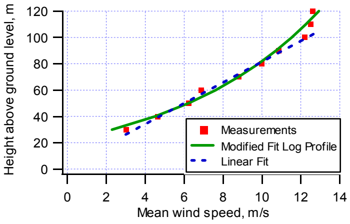

Figure 4. Sample shear, ten-minute sample number N=69, mod. log law: d= -77.0 m, z0=90.0 m, log law: , z0=22.75 m.

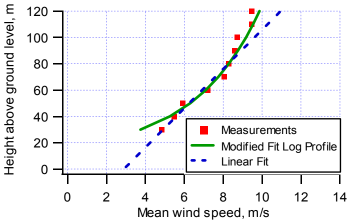

Figure 6. Sample shear, ten-minute sample number N=1406, mod. log law d = -7.0 m, z0=14 m, log law z0=10.25 m.

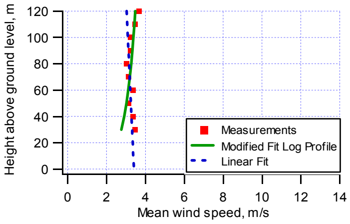

Figure 5. Sample shear, ten-minute sample number N=6003, mod. log law: d = -80.0 m, z0 = 0.0001 m, log law: z0 = 0.0001 m.

A. Performance of Modified Log Law Model

The distribution of the displacement distance for the complete data set is illustrated in Fig. 7. The resulting best-fit displacement distances range from -80 to 40, with somewhat more numerous occurrences of displacement distances above 0 m and about 45% of the displacement distances between -80 and -79 (not shown on the graph due to the scale choice).

The resulting roughness lengths span 120 m. The distribution of the roughness length for the complete data set is illustrated in Fig. 8. Roughness lengths greater than 80 m occur more frequently than any others and 21% of the data have roughness lengths between 0 and 1 (not seen on the graph).

Large negative values of displacement distance and large positive values of roughness length are associated with high wind shear.

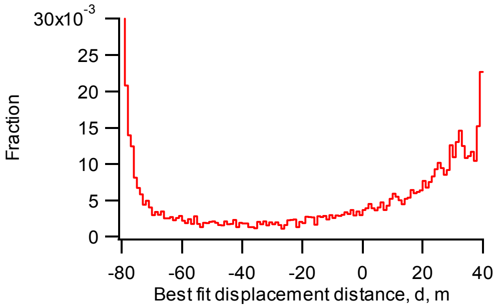

Figure 7. Displacement distance distribution from modified log law.

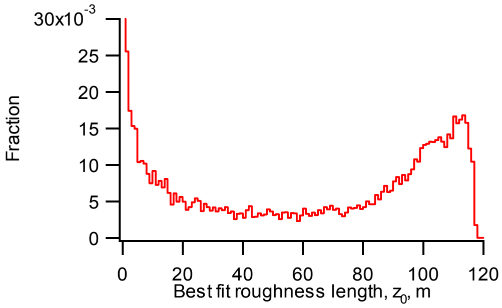

Figure 8. Roughness length distribution from modified log law.

Models for shear over forests have been proposed[4] with a variety of values for z_0 and d. These range from $d = 0$ and $z_0 = h/30$, where h is the tree height, to models with large values of d and small values of z_0 ($d = h - 0.86\ z_0$ and $z_0 = h/30$, $d = h - 0.86\ z_0$ and $z_0 = 0.30$, $d = 2/3\ h$ and $z_0 = h/90$) and models with small values for d and large values for z_0 ($d = 0.076\ h$ and $z_0 = 0.78\ h$). The methods of determining z_0 and d for the six models discussed in Reference 4 are shown in Table 1. The predicted parameter values for each of these models for the SODAR site on Vinalhaven (where h is assumed to be equal to 20 m) are also shown in Table 1.

Table 1. Model and predicted parameters for SODAR site.

Model Parameters			SODAR site	
	z_0	d	z_0	d
1	$h/30$	0	0.67	0
2	$h/30$	h-0.86 z_0	0.67	19.4
3	0.30	h-0.86 z_0	0.30	19.7
4	$h/90$	$(2/3)h$	0.22	13.3
5	$0.78h$	$0.076h$	15.6	1.5

It is apparent that none of the models for estimating z_0 and d discussed by Raferty can adequately predict the average wind shear observed at Vinalhaven, although that denoted as Model 5 comes the closest.

On the other hand, examination of the observed profiles shows that, when the parameters are adjusted by appropriate fitting techniques, there are numerous combinations of these that do a reasonable job of representing the data in the framework of the modified log law or a linear fit. The fits using a wider range of possible parameters are only a very slight improvement over those when displacement distances are constrained to positive or zero values or to values that ensure that the predicted wind speed reaches zero at or above the ground.

A number of conclusions can be drawn from the results so far.

- The modified log law model can be used in many cases to represent the 10-minute averaged forest canopy shear data quite well.
- There is no ideal roughness length nor displacement distance that can be used to characterize this data set.
- Because there are no well defined parameters to use, shear prediction in the absence of measured data is not possible at this site and with this model
- Numerous possible sets of parameters model the shear data approximately as well as others.
- Often the more negative the displacement distance, the better the model represents linear shear.

Nevertheless, if shear data is available, the modified log law model can be used to analyze the flow above the forest canopy. For example the height at which the wind speed is zero can be estimated using the best fit parameters and Eqn. 7. Some of those data are illustrated below in Fig. 9.

The distribution of the zero wind speed height for all of the data (Fig. 10) shows that, often, the wind speed is approximately zero in the canopy between 20 and 40 m above the ground.

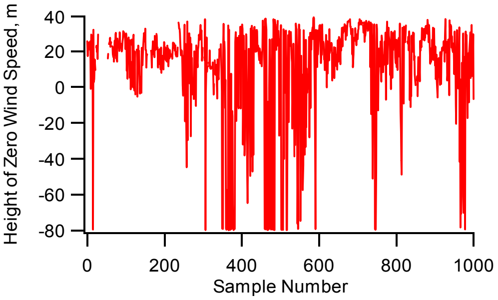

Figure 9. Sample zero wind speed height data.

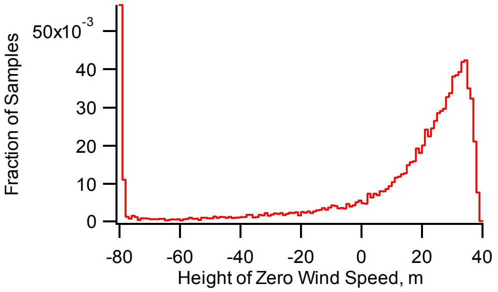

Figure 10. Distribution of heights of zero wind speed.

B. Performance of Linear Model

The linear model has also been investigated as a model to represent the shear data above the forest canopy. Examples of the normalized slope and offset, as determined by linear regression are illustrated in Figs. 11 and 12. Distributions of the normalized slope and offset over the data set are shown in Figs. 13 and 14.

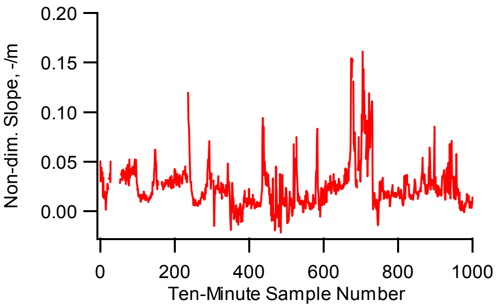

Figure 11. Time series of normalized slope from linear model.

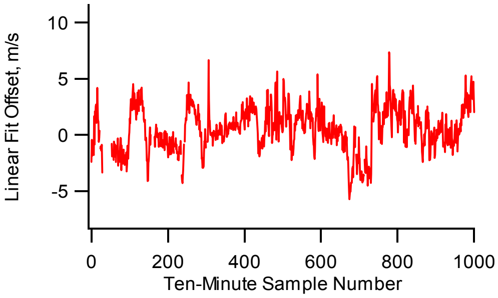

Figure 12. Time series of offset from linear model.

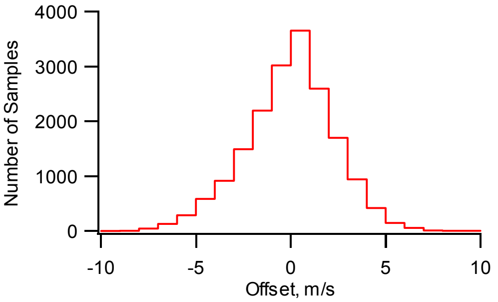

Figure 13. Distribution of offset from linear model.

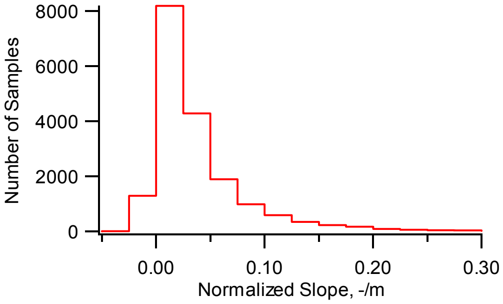

Figure 14. Distribution of normalized slope from linear model.

The linear model provides a much more consistent set of parameters (the offset clusters around 0.5 and the normalized slope clusters around 0.25) than does the modified log law, but there is still a range of offsets found and slopes that vary by an order of magnitude.

C. Performance of Standard Log Law

Finally, the standard log law was also considered for characterizing the shear characteristics at the site.

The distribution of the resulting roughness lengths (here, by definition, $d = 0$) are illustrated in Fig. 15. These results indicate a tendency toward roughness lengths between 20 and 40 m, but no characteristic roughness length. In addition, 12% of the data fall between 0 and 1. Using this model, the elevation at which U=0 is the same as the roughness length.

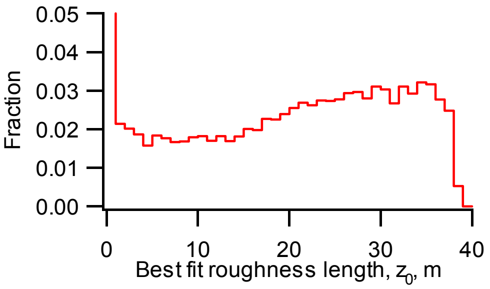

Figure 15 Distribution of roughness length from standard log law model

VII. COMPARISON OF MODEL FITS

One measure of the appropriateness of these models is the distribution of the RMS prediction error between 40 m and 100 m. This is illustrated in Fig. 16. The data shows that both the modified log law and the linear models represent the data about equally well, with the linear model having, overall, only slightly greater RMS errors. The one parameter standard log law also has comparable, but slightly greater, RMS prediction errors than the other two models. Figure 16 also includes RMS prediction errors for the modified log law when the parameters are constrained to ensure that the wind speed goes to zero above the ground ("realistic shear") and errors of the models listed in Table 1. Constraining the values of d and z_0, results in similar, but slightly higher, RMS errors than without constraints. In contrast, the RMS prediction errors of the models in Table 1 are significantly greater than when the model parameters are fitted to the data.

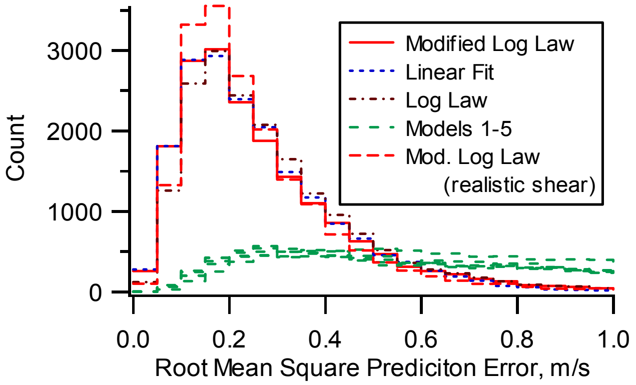

Figure 16 Distribution of RMS prediction errors for the modified log law, the modified log law with realistic shear, the log law, the linear model and the five models discussed in Ref. 4 and Table 1.

In summary, all of the models provide equally good fits to the data, but none of the three models serve well as a predictive tool due to the ambiguity over which parameter to use to correctly model the forest canopy flow.

VIII. DAILY EFFECTS ON WIND SHEAR

On the other hand, the model results can be used to look at the effects of a variety of factors on the forest canopy shear.

The graph of the linear model offset versus time of day, illustrated in Fig. 17, shows that the shear characteristics at this site change significantly over the day. The offset of the linear model is the wind speed that the model determines would occur at the ground. More negative offsets, depending on the slope, indicate a greater height at which the wind speed is zero.

The distributions of offsets for different hours of the day are illustrated in Fig. 18. The data show a significantly different behavior in the middle of the day as opposed to in the early morning or late afternoon. In the middle of the day the linear offsets are much greater. There are also a greater number of high zero-wind-speed heights in the morning and the evening (Fig. 19) and fewer in the night and at midday.

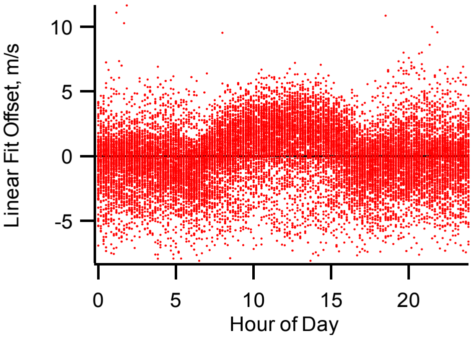

Figure 17. Linear offset versus time of day.

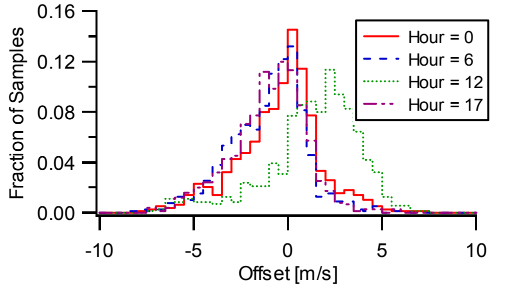

Figure 18. Linear offset versus time of day.

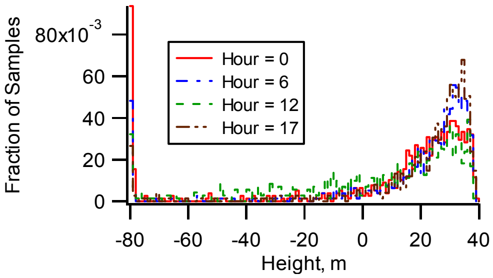

Figure 19. Distribution of zero wind speed height versus time of day.

IX. EFFECTS OF WIND SPEED ON WIND SHEAR

Wind speed also has an effect on the wind shear characteristics. Figure 20 shows that at higher wind speeds the average slope of the shear profile between 40 and 100 m decreases and shows fewer occurrences of higher slopes. At low wind speeds there are still many occurrences of low slopes but also more spread in the slopes. Thus, high wind shear (greater dU/dz) occurs more frequently at lower wind speeds. Figure 21 shows the distribution of offsets for a variety of 70 m wind speeds. The distributions at higher wind speeds are fairly symmetrical, while that for 3 m/s has more offsets around 2 – 3 m/s and fewer offsets above 5 m/s.

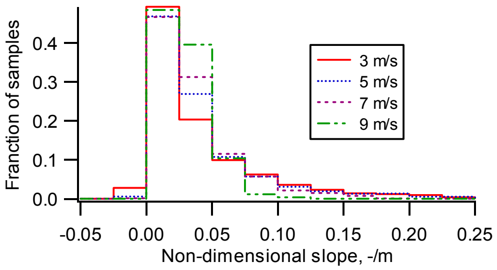

Figure 20. Distributions of slope at selected wind speeds.

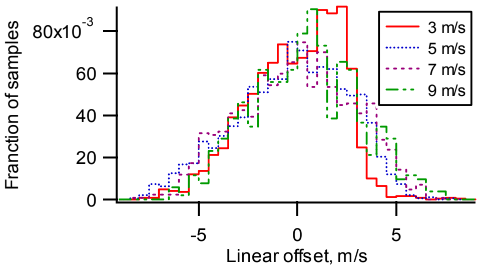

Figure 21. Distributions of offset at selected wind speeds.

X. EFFECTS OF WIND DIRECTION ON WIND SHEAR

Wind direction also has an effect on the shear behavior at this site. Sample distributions of shear slope and offset are illustrated in Figs. 22 and 23. The wind from the NW (310 degrees), the direction of the open ocean, shows a distinct concentration of slopes less than 0.1/m, while the winds from the NE (50 and 80 degrees) include a much wider range of shear. The NW winds also tend to have greater offsets than those from the NE. More analysis is required to determine to what extent terrain, flow transition effects and wind speed are a factor in these results.

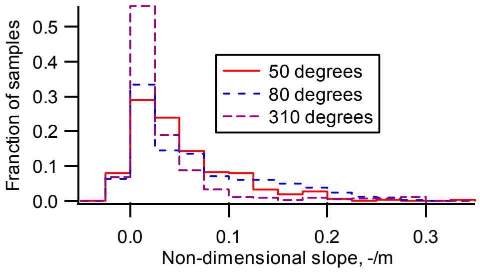

Figure 22. Distributions of normalized slope for selected directions.

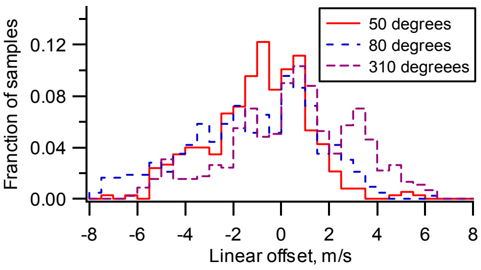

Figure 23. Distributions of offset for selected directions.

XI. FOLIAGE EFFECTS ON WIND SHEAR

Data collection started in late February and was completed at the end of July. The forest around the data collection site is a mixed evergreen and deciduous forest, with a preponderance of conifers. This means that the nature of the forest canopy changed during the data collection as the foliage appeared on the deciduous trees. The data were analyzed to identify any changes in the shear characteristics that might have been due to the changing foliage. April 15 was taken as the division point between the winter and the spring.

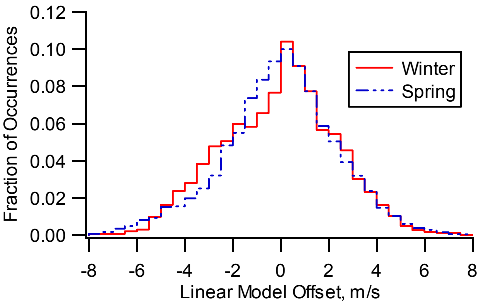

Figure 24. Distributions of offset in winter and spring.

The offset and normalized slope data seen in Figs. 24 and 25 do not indicate significantly varying seasonal behavior at this site. The zero height data from the log model (Fig. 26) also show no significant differences between seasons although there might be slightly more occurrences in the winter of higher heights at which the wind speed is zero.

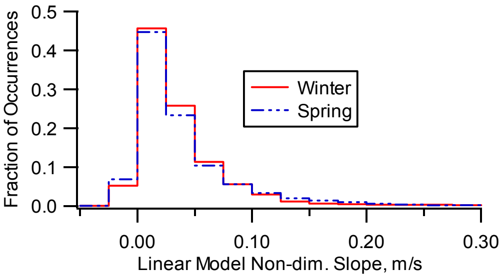

Figure 25. Distributions of slopes in winter and spring.

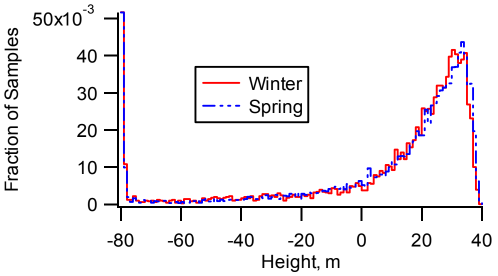

Figure 26. Height at which wind speed is zero in winter and spring.

XII. EFFECT OF CHANGE IN SURFACE ROUGHNESS ON WIND SHEAR

There is another factor which could affect the wind shear at Vinalhaven and which could make it somewhat unique among forested sites. This factor is change in surface roughness. Since the island is surrounded by ocean, wind approaching the island from any direction will experience a dramatic change in surface roughness ones it is over the land. The resultant effect has been known for some time. Reference 9, for example, discusses the effect of the change in roughness on the wind shear. They note that there may be a "transition height", above which the wind shear resembles that of the shear experienced over the original roughness, and below which the shear is influenced by the new roughness. This effect is illustrated in Fig. 27, which is taken from their report.

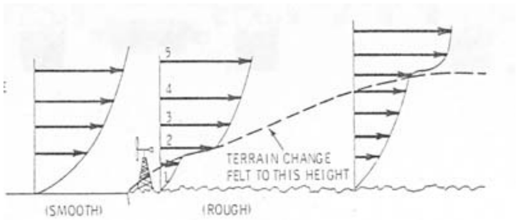

Figure 27. Transition from smooth to rough surface (from Ref. 9).

Reference 9 also attempts to relate the transition height to the distance from the change in roughness. For the conditions observed at Vinalhaven the transition height should be approximately 50 m at 0.5 km from the change. The transition height continues to increase with distance from the change, but less drastically. It is worth noting that in the case of Vinalhaven, above roughly 80-100 m, there is little wind shear, regardless of the direction of origin of the wind.

While some aspect of this phenomenon may be present at Vinalhaven, it is doubtful if it is the whole story. Perhaps the most significant difference between the profiles observed on Vinalhaven and those expected from Ref. 9 is that at lower heights, the wind shear is linear, and the transition height corresponds to a change from a steep linear shear to a much more gradual shear, rather than a drastic change from one conventionally appearing wind shear to another one.

XIII. SUMMARY AND CONCLUSIONS

A number of conclusions can be drawn from this work:

- There may be significantly more wind shear in forested terrain in height ranges of 40 to 100 m than conventional prediction models imply.
- The standard log law, a modified log law and a linear model can all be used to fit the observed profiles up to approximately 90 m above ground, but commonly used parameters in such models will not result in close matches to the observed results.
- There are no clear parameters that can be proposed for using either the modified log law, the log law, or a linear model as a predictive tool, based on this data. In particular, the values for d and z_0 do not consistently fit those of any specific model.
- A SODAR provides very useful information about wind shear at heights above those usually monitored with met towers.
- Energy capture predictions for wind turbines in forests require more accurate estimates of wind shear than are currently available.
- The wind resource at moderate heights (in the vicinity of 100 m) in forested terrain may be significantly greater than one might think, based on data from lower elevations and extrapolation using commonly applied methods.
- There can be very significant wind shear across a rotor above the forest at the SODAR site. Such shear could be a factor in the fatigue life and hence the design requirement of wind turbines to be used in such settings.
- Wind speed, time of day and wind direction all affect wind shear over forests.
- More analysis is needed to separate out the relative magnitudes of the effects of diurnal patterns, wind speeds and directions on the wind shear at Vinalhaven .
- The winds at Vinalhaven are fairly uniform above about 100 m elevation.
- The change in surface roughness accompanying the transition between the ocean surface and the forested terrain of Vinalhaven may significantly affect wind shear, and may affect the generality of the results reported here. Further work would be required to elucidate the expected shear over both land based and island forests.

Acknowledgments

The authors would like to thank the Massachusetts Technology Collaborative and the U.S. Department of Energy for their support related to this work.

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