Sodar and Extrapolated Tower Wind Shear Profile Comparison in Various Topographic Conditions

Elizabeth Walls, Niels LaWhite

Second Wind Inc, 366 Summer St., Somerville, MA, USA, 02144
liz.walls@secondwind.com

Summary

At four sites across the U.S., wind data was collected with both Second Wind's Triton SODAR and an adjacent met tower. At each site, excellent agreement was found between the tower and Triton data in terms of both correlation ($R_{avg} = 0.975$) and average wind speed. The power law exponent, alpha, was estimated at each site using both the tower and Triton data. These exponents were then used to extrapolate the tower wind speeds and the resulting wind speed profiles were compared. For a range of rotor radii and hub heights, the equivalent wind speed was found for each extrapolated wind speed profile. The difference in theoretical power available in the wind was then compared for various rotor sizes and hub heights.

It was found that extrapolating wind speeds, based solely on tower data, can lead to either an under or over estimation of wind speeds at higher heights. At each site, the equivalent hub height wind speeds were calculated, using both the extrapolated wind speed profiles. It was found that as the rotor radius and hub height increased so did the difference in the estimated equivalent hub height wind speed. Since $P \alpha U^3$, the increasing difference in equivalent wind speed then translated to an increasing difference in the theoretical power. With a 100 m hub height and a 40 m rotor radius, the extrapolation based on tower data led to an underestimation of theoretical power of –16.4% at one site while the tower extrapolation produced an overestimation of 9.3% at another.

Introduction and Background

When conducting a wind resource assessment at a potential wind turbine site, the accuracy of the measured wind speed can be critical to the economics of the project. Currently, the standard method of acquiring wind data is by measuring the wind speeds with cup anemometers mounted on meteorological (met) towers. Since met towers typically do not exceed 60 m in height [1] and the standard hub height of modern wind turbines are 80 m and higher, the measured wind speeds have to be extrapolated up to hub height. Either the power law or logarithmic law shear profile are typically used to extrapolate the measured wind speeds and, in doing so, a certain amount of error can be introduced. This error in the extrapolated hub height wind speed may lead to either an under or overestimation in the expected power production of a wind turbine.

Remote sensing devices, such as SODAR (Sonic Detection and Ranging), can measure wind speeds across the span of a wind turbine and therefore offer an alternative to the standard method of wind data collection. These types of devices are becoming more widely accepted in the wind industry as a reliable method of wind data collection. Not only do SODARs offer a more complete picture of a potential site, they also facilitate the opportunity to validate or discredit methodologies typically used for wind speed extrapolation.

Second Wind commercialized their Triton Sonic Profiler in early 2008, which is a low-power (7 W) monostatic, phased-array SODAR. Over the last year or so, many Tritons have been installed around the world in various topographic conditions. At many sites, there have also been met towers with which to compare and validate the Triton's performance. After observing very high correlations between the tower and Triton data at several different sites, questions were raised as to how the extrapolated tower wind shear profile would compare to the wind shear profile measured by the Triton.

The following paper investigates how well wind speed extrapolation based on tower data compares to the wind shear profile obtained based on Triton data. Data will be presented from four sites of varying topography where a Triton collected wind speed data adjacent to a met tower. After demonstrating the strong agreement between the Triton and tower data at the uppermost anemometer level, the wind shear exponent, alpha, will be calculated based on both the Triton and tower data. The tower wind speed data will be extrapolated using both estimated shear exponents and the resulting wind speed profiles will be compared. The relative differences in the extrapolated wind shear profiles will then be compared in terms of the difference in theoretical power available in the wind.

Second Wind's Triton SODAR Functionality

Before explaining the experimental set-up and subsequent results of the study, a brief description of SODAR functionality will be given in the following section. SODARs measure wind speed and direction by emitting high frequency acoustic pulses into the atmosphere. As the acoustic pulse travels through the air, a portion of the energy will be backscattered due to changes in the refractive index of air. After transmitting the pulse, the SODAR switches to receive mode and records the backscattered signal. The frequency content of the returned signal is then analyzed and the frequency shift (i.e. Doppler shift) is determined at a range of heights. The Doppler shift is directly proportional to the wind speed along the direction of the transmitted beam. [2, 3]

For wind resource applications, the maximum SODAR measurement height is typically 200 m. To measure data up to this height, SODARs (with three beam directions) will transmit a total of approximately 260 pulses over a ten-minute interval. At the end of every ten-minute interval, the average radial wind speed along each beam direction is calculated. With the average radial wind speeds, the horizontal and vertical wind speeds and wind direction can then be determined.

Second Wind's Triton Sonic Profiler is a monostatic, phased array SODAR and was commercialized in 2008. The Triton's power requirement is 7 W and it is powered via two solar panels and deep-cycle batteries. It transmits three beams at approximately 4500 Hz with a pulse length of 70 ms, at a tilt angle of 11.4° and with the beams spaced by 120°. In addition to reporting the horizontal and vertical wind speed and wind direction, the Triton also provides a quality factor for each measurement height at each ten-minute interval. The quality factor is used to rate the quality of the data point and to then filter out any noisy data that may have been acquired. The quality is a function of signal-to-noise ratio (SNR) and the number of valid samples that were collected over the ten-minute interval. As will be shown in subsequent sections, a minimum quality of 90% is typically used to filter Triton data.

Site and Data Set Descriptions

For this study, Triton and tower data from four sites are compared and analyzed. The length of each data set is approximately two months. These sites vary in their topographic description and are spread across the U.S. The four sites include the following:

1) Cranberry Bog in Massachusetts
2) Open Field in Kansas
3) Ridgeline in Washington State
4) Wind farm in Washington State

The following section gives a brief description of each site and of the data collected.

Site 1: Cranberry Bog (Trees, Complex)

This first site is located in a cranberry bog in southeastern Massachusetts. There is a 60 m met tower installed at this location with cup anemometers mounted at 40, 50 and 60 m. The site is surrounded by trees and the terrain is flat.

Triton data collection began at this site in early 2008. For this study, data collected from May 15th, 2008 to July 15th, 2008 are included in the analysis. Figure 1 shows a photo taken at this site.

Figure 1: Cranberry Bog in MA

Site 2: Open Field in KS

The next site is situated in a flat, open field in Kansas. There are no trees or any other stationary objects to be sources of fixed echoes. Similar to the cranberry bog, there is a 60 m met tower with cup anemometers stationed at 30, 45 and 60 m.

Data acquired from September 1st, 2008 to November 1st, 2008 are included in this study. A photo of the Triton at this site is shown in Figure 2.

Figure 2: Open Field in KS

Site 3: Ridgeline in WA

The next site is located on a ridgeline in Washington State. The terrain at this site is much more complex than the first two sites. It is very hilly and there is a steep drop off to a river at the bottom of a gorge. There is a 50 m met tower at this site and it has cup anemometers mounted at 30, 40 and 50 m.

Data collected at this site from August 15th, 2008 to October 15th, 2008 are included in this study. Figure 3 shows a photo of the Triton at this site.

Figure 3: Ridgeline in WA

Site 4: Wind Farm in WA

The last site included in this study is at a wind farm in Washington State. The surrounding terrain is hilly and the near-by wind turbines affect the wind flow field in certain wind direction sectors. A 60 m met tower is installed at this site and it has cup anemometers at 40, 50 and 60 m.

The length of data included in the study from this site is approximately 1.5 months. Data measured from September 1st, 2008 to October 17th, 2008 are used in this study.

Figure 4: Wind Farm in WA

Triton vs Tower data: Validation

Before beginning the comparison of the Triton-measured wind shear profile to that of the extrapolated tower profile, the Triton data from each site is validated. For each data set, the Triton data is compared to the near-by anemometer data. First, a correlation study is conducted followed by an average wind speed comparison. For the two types of comparisons, various filters are applied to the Triton and tower data.

Data Filtering for Correlation Study

For each of the four data sets, a correlation coefficient is calculated between the Triton and tower data at the uppermost anemometer height. Before calculating this parameter, however, the data needs to be filtered to remove noisy or erroneous data points.

For every ten-minute interval, the Triton measures a quality factor for each measurement height. The quality is a function of the signal-to-noise ratio (SNR) as well as the number of valid data points collected during the ten-minute average. A minimum quality of 90% is used and all Triton data with a quality less than this is removed from the data set.

Next, the Triton data is filtered based on vertical wind speed. The main purpose of this filter is to remove data that have been affected by precipitation. During times of precipitation, the Triton can mistakenly interpret the reflections from falling raindrops as a strong, downward vertical wind speed. To remove rain-affected data and to eliminate other instances of erroneous data, only Triton data with a vertical wind speed between +/- 1.5 m/s are kept in the data set.

At the uppermost height of the met towers at all four sites, there are two cup anemometers. It is well known that the wind speeds measured by cup anemometers can be affected by tower shadow. For this reason, the maximum of the two anemometer readings, for every ten-minute interval, is used in the correlation study. While it is true that using the maximum of the two anemometers can introduce a high bias, the mean wind speed is not included in the correlation coefficient calculation and this approach is therefore deemed appropriate.

Data Filtering for Average Wind Speed Comparison

When comparing the average wind speeds between the Triton and tower data, a more intensive set of filters is implemented. The Triton data is first filtered based on a minimum quality factor of 95%. In an effort to reduce any noise in the data, the minimum quality factor is slightly higher than the threshold used in the correlation study. Next, any Triton data with a vertical wind speed beyond +/- 1 m/s is removed from the data set. The range for allowable vertical wind speeds is narrower for this comparison since the horizontal wind speeds recorded by anemometers can be skewed during periods of significant vertical wind speeds.

In the correlation comparison, the maximum of the two anemometers is used however this approach is not appropriate when comparing the average wind speeds as measured by the Triton and tower. Instead the average of the two anemometers is used along with filters designed to remove tower shadow effects.

First, the tower data is filtered based on the ratio of the anemometer readings. If the wind speeds measured by the anemometers differ by more than 2% then the data point is omitted from the data set. Next, anemometer wind speeds less than 2 m/s are removed from the data set. Finally, the anemometer data is filtered based on direction. To avoid tower effects, only direction sectors that are 45° from the booms (with a width of 30°) are used in the comparison. Figure 5 shows a configuration with booms in a N-S orientation and the shaded green areas depict the direction sectors that should be unaffected by tower shadow and are therefore included in the analysis.

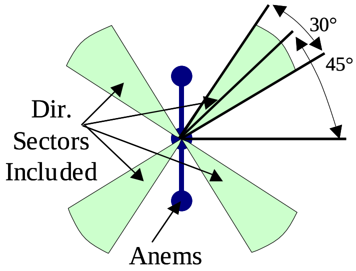

Figure 5: Direction Sector Filtering

Results of Triton versus Tower Validation

The filters described in the previous section were applied to all four data sets and the comparisons were made. The following section presents the results of the correlation study and average wind speed comparison at each site. The operation uptime of the Triton and the percent of valid Triton data are also shown for each site.

Results from Cranberry Bog in Massachusetts

Data collected from May 15th to July 15th, 2008 was included in this comparison. During this time interval, the Triton was operational and collecting data 98.4% of the time. Also, during this time, 99.5 % of the Triton data collected at 60 m had a quality greater than 90%. In other words, 99.5% of the 60 m Triton data was considered valid.

Figure 6 shows a scatterplot of the 60 m wind speed measured by the Triton compared to the 60 m anemometer data. The correlation coefficient calculated for this data set was found to be 0.968.

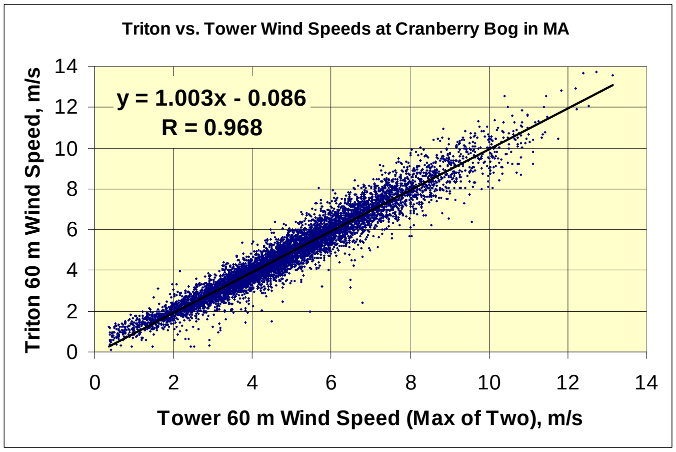

Figure 6: Triton vs. Tower Data (Cranberry Bog)

After applying the aforementioned filters, the average wind speeds measured by the Triton and tower were compared. The percent difference between the Triton and tower data was found to be –1.1%.

Results from Open Field in Kansas

The same type of analysis was conducted for the data collected at the second site: the open field in Kansas. Recall that data collected from September 1st to November 1st, 2008 was included in this study. The operational uptime of the Triton at this site was 99.3%. The percent of valid data (i.e. with Q > 90%) measured at 60 m was 94.5%.

The wind speeds measured at 60 m by the Triton are plotted against the tower measurements in Figure 7. There is some scatter however the overall correlation coefficient was found to be very high at 0.976.

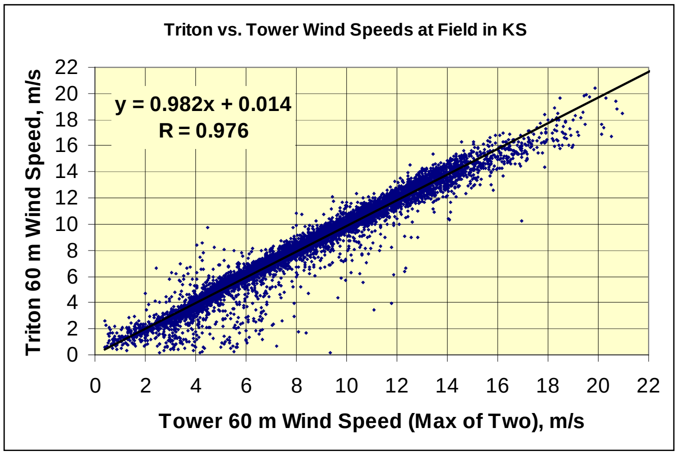

Figure 7: Triton vs. Tower Data (Open Field)

Finally, the average wind speed measured at 60 m by the Triton was compared to that measured by the anemometers at 60 m. The average wind speeds measured by the two devices differed by –0.55%.

Results from Ridgeline in WA

Next, the results of the analysis conducted for the data collected at the ridgeline site in Washington State is presented. From August 15th to October 15th, 2008, the Triton was powered and collecting data 94.9% of the time. During this time interval, 91.1% of the data collected at 50 m (i.e. height of the tower) was deemed valid.

Figure 8 shows the 50 m wind speeds measured by the Triton compared to the 50 m anemometer data. The scatterplot shows a tight distribution and a very high correlation coefficient of 0.988 was calculated.

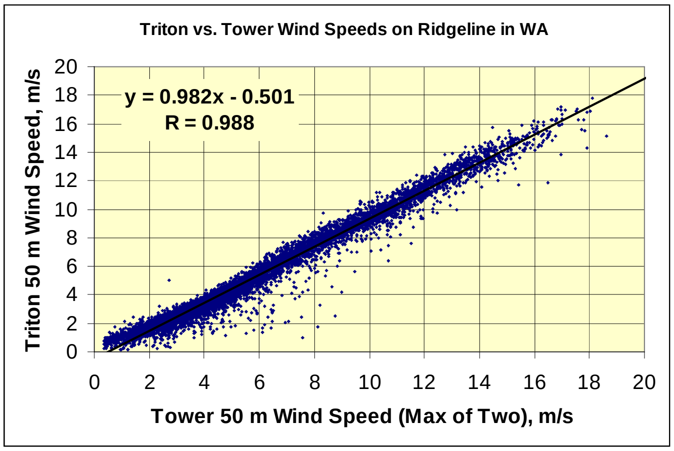

Figure 8: Triton vs Tower Data (Ridgeline)

The average wind speeds were compared and it was found that the Triton measured an average wind speed that was 7.6% lower than that measured by the tower. It is expected that the complex terrain and distance from the Triton to tower location both contributed to the difference in average wind speed.

Results from Wind Farm in WA

Finally, the validation results from the fourth site are presented. The data interval included in this study ranged from September 1st to October 17th, 2008. During this time, the operational uptime of the Triton was 99.8%. The percent of valid data collected at 60 m (i.e. with a Q > 90%) was found to be 97.4%.

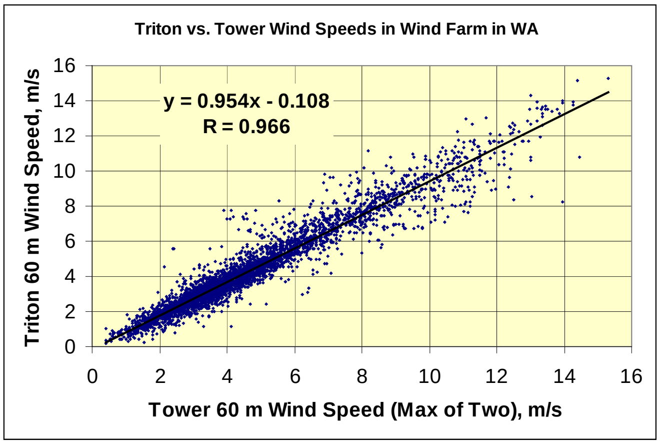

Figure 9: Triton vs. Tower Data (Wind Farm)

A scatterplot of the wind speeds measured by the Triton and near-by met tower at 60 m is shown in Figure 9. There is some scatter in the plot that may be explained by the complex flow field induced by the surrounding wind turbines. The correlation coefficient was found to be 0.966.

The average wind speeds were compared and it was found that the Triton and tower average wind speeds differed by only –0.6%.

Summary of Validation Study

Table 1 below summarizes the results obtained from the validation study conducted at each of the four sites. The table includes the percent of operational uptime, the percent of valid data measured by the Triton at the uppermost anemometer height, the correlation coefficient found between the Triton and tower data and the percent difference in average wind speed as measured by the Triton and tower.

Table 1: Summary of Validation Results

Site	Operational Uptime	% Valid data at Anem. Height	Correlation Coefficient	Average Wind Speed
Cranberry Bog in MA	98.4%	99.5%	0.968	-1.10%
Open Field in KS	99.3%	94.5%	0.976	-0.55%
Ridgeline in WA	94.9%	91.1%	0.988	-7.60%
Wind Farm in WA	99.8%	99.8%	0.966	-0.60%

At all four sites, the correlation measured between the Triton and tower data was found to be very high with an average correlation coefficient of 0.975. Also, for each data set, the average wind speeds, as measured by the Triton and tower, were found to agree very well and differed by less than 1.5% except at the Ridgeline site where terrain and spatial differences attributed to a larger difference in average wind speed. Now that the Triton data has been validated at all four sites, the shear exponents as determined by the Triton and tower data can now be compared.

Shear Measurement Using SODAR data

In this next section, a simple method to estimate the power law shear exponent using SODAR data will be presented. The power law is used to approximate observed wind shear profiles and it is defined in Equation 1 where U_z is the wind speed at height, z; U_{zr} is the wind speed at the reference height, z_r and α (alpha) is the power law exponent. [4]

Equation 1: Power Law

$$\frac{U_Z}{U_{Z_R}} = \left(\frac{z}{z_R}\right)^{\alpha}$$

The exponent, alpha, describes the shape of the wind shear profile. A low alpha implies very little shear where the wind speed does not drastically change with height while a high alpha is indicative of large increases in wind speed as a function of height.

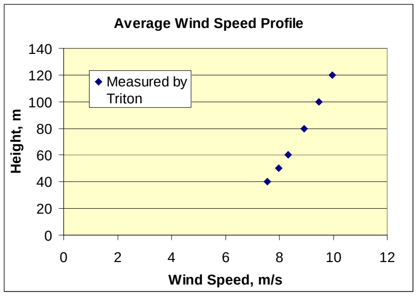

Figure 10: Average Wind Speed Profile

When using met towers with cup anemometers, it is common to measure the wind speed at two heights, determine alpha and then extrapolate up to hub height. With SODAR data, however, wind speeds are measured across the rotor diameter and alpha can therefore be estimated using several data points instead of only two.

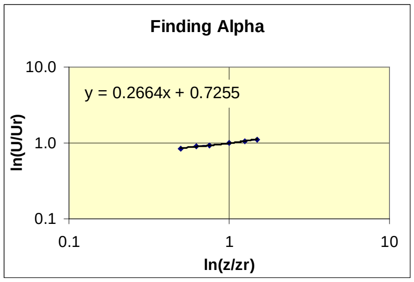

Figure 11: Finding Alpha

To estimate alpha from SODAR data, first the average wind speeds are calculated from 40 m to 120 m (only using data where valid data was recorded up to 120 m such that the same number of data points are included in each average). An example of average wind speeds measured by a SODAR from 40 m to 120 m is shown in Figure 10. Next, $\ln(U_z/U_{zr})$ is plotted against $\ln(z/z_r)$ and the slope of the line of best fit is alpha. Figure 11 shows an example of this where alpha was found to be 0.2664. Figure 12 shows the same data as Figure 10 but with the power law profile (with alpha = 0.266).

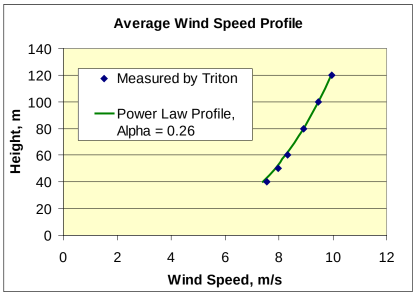

Figure 12: Fitted Power Law Profile

The above method was used to approximate alpha from Triton data collected at the four sites included in the study.

Comparison of Estimated Wind Shear Exponents

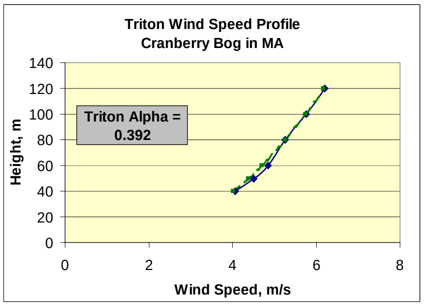

Figure 13: Wind Speed Profile (Cranberry Bog)

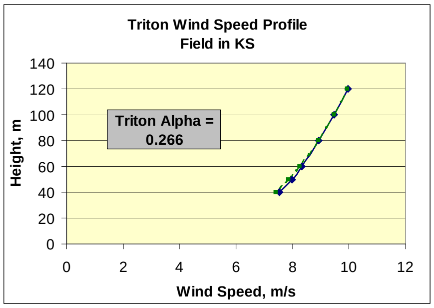

Figure 14: Wind Speed Profile (Open Field)

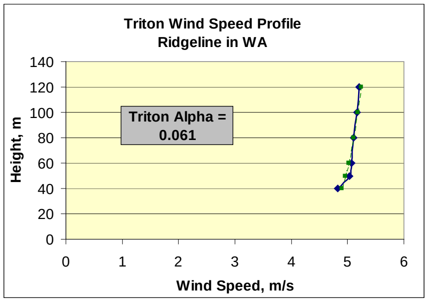

Figure 15: Wind Speed Profile (Ridgeline)

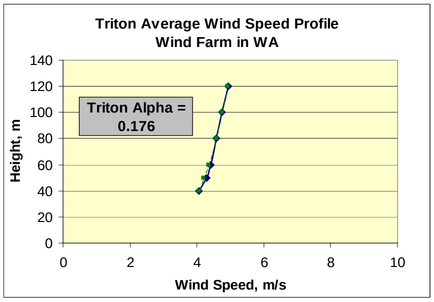

Figure 16: Wind Speed Profile (Wind Farm)

Using the method described in the previous section, alpha was estimated at each site using the Triton data. Alpha was also estimated at each site using the near-by tower data. As mentioned, at each site, there are 3 heights on the towers with anemometers. To reduce the uncertainty in alpha estimation, the anemometers with the largest vertical separation were used. [1]

In this study, it is the overall shear exponent that is being estimated and compared as opposed to examining diurnal and directional variability. It should be noted, however, that large variations in diurnal (i.e. night vs. day) wind shear are often observed. [5] Also, wind shear is very often a function of wind direction due to variability in the surrounding terrain. To keep a level of simplicity, however, only overall wind shear exponents between Triton and tower data are compared.

Figures 13 – 16 show the average wind speeds measured by the Triton from 40 m – 120 m along with the fitted power law profile for each of the four sites. The estimated alphas vary considerably from site-to-site. The lowest alpha was measured at the Ridgeline site where alpha = 0.06 whereas the highest alpha of 0.392 was measured at the Cranberry Bog site.

Alpha was also calculated using the tower data and Table 2 below compares the alpha as found from the Triton and tower data at each site along with the percent difference between the two estimates. As shown, the percent difference in the estimated alpha differed by as much as 61%.

Table 2: Summary of Estimated Power Law Exponents

Site	Triton Alpha	Tower Alpha	% Difference
Cranberry Bog in MA	0.392	0.443	13.0%
Open Field in KS	0.165	0.266	61.2%
Ridgeline in WA	0.061	0.044	-27.9%
Wind Farm in WA	0.176	0.148	-15.9%

The power law exponents were estimated with both the Triton and tower data and the extrapolated wind shear profiles, using either alphas, are now compared. Figures 17 - 20 show the average wind speeds measured by the tower and then show the extrapolated wind shear profile using alpha as estimated from the Triton data and from the tower data. As shown, the difference in the extrapolated profiles increases with height. The most significant difference was observed at Site 2: Open Field in Kansas. In this case, the tower significantly underpredicted the wind speed at the upper heights. At Site 1: Cranberry Bog in MA, the trend was the opposite where it was found that extrapolating using tower data lead to an overprediction in wind speeds above 60 m. For the last two sites, the alphas found using the Triton and tower data were quite similar and, as a result, the extrapolated wind shear profiles do not deviate as much as the first two sites.

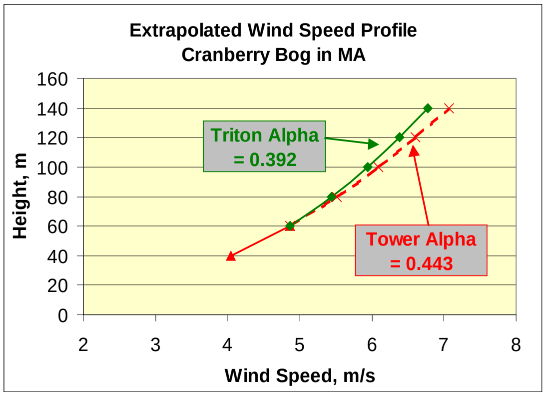

Figure 17: Extrapolation Comparison (Cranberry Bog)

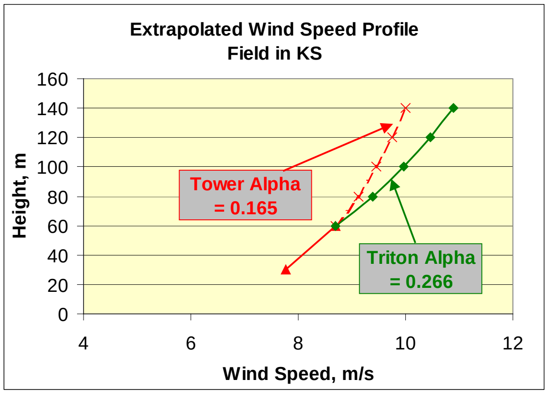

Figure 18: Extrapolation Comparison (Open Field)

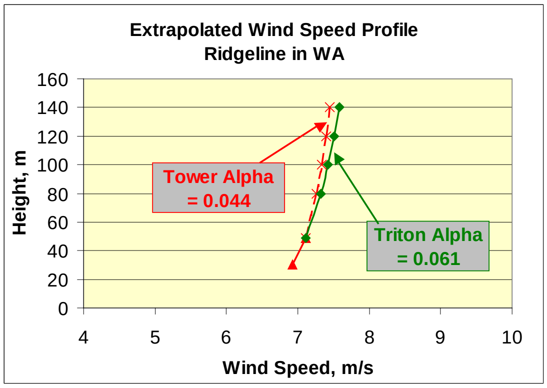

Figure 19: Extrapolation Comparison (Ridgeline)

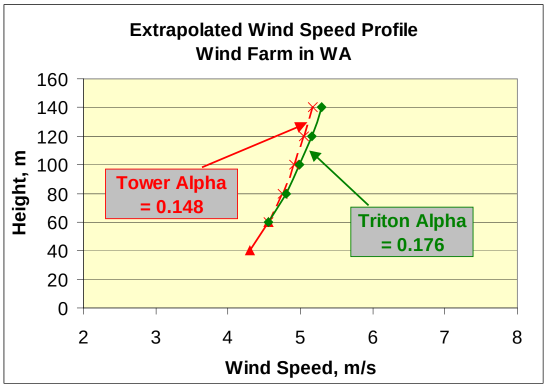

Figure 20: Extrapolation Comparison (Wind Farm)

Theoretical Power Output with Wind Shear Profiles based on SODAR vs Tower data

In the previous section, the extrapolated wind shear profiles were compared using the alphas estimated from both the Triton and tower data. It was shown that using tower data to extrapolate could lead to either an under- or over-estimation in wind speeds at heights above the met tower. It was also shown that, at two sites, the alpha found from tower data did not appear to significantly differ from the alpha found from the Triton data. With the estimated wind shear profiles at each site, the next question that arose was regarding how the theoretical power available in the wind would vary with the estimated wind shear profiles.

Equation 2: Theoretical Power Available in the Wind

$$P = C_P \eta \frac{1}{2} \rho \pi R^2 U^3$$

Equation 2 shows the theoretical power available in the wind where C_p is the power coefficient, η is the mechanical efficiency, ρ is the air density, R is the rotor radius and U is wind speed. [4]
For this analysis, it is assumed that all the parameters are constant except for the rotor radius and wind speed.

At each of the four sites, for a range of hub heights and rotor radii, the equivalent wind speed at hub height, U_{eq}, was found based on the extrapolated wind speed profiles as determined from both the tower and Triton estimated alphas. The equivalent wind speed is defined in Equation 3 where A is the total rotor area, U_h is the wind speed at height, h and A_h is the swept area of the rotor at height, h. [6]

Equation 3: Equivalent Wind Speed at Hub Height

$$U_{eq} = \frac{1}{A}\int U_h \cdot A_h \, dh$$

Equation 4: Percent Difference in Theoretical Power Available

$$\% \; Diff. = \frac{\left(Power_{\text{Based on Tower Alpha}} - Power_{\text{Based on Triton Alpha}}\right)}{Power_{\text{Based on Triton Alpha}}} \times 100$$

The first scenario that was considered was with a hub height of 80 m and a rotor radius of 40 m. The equivalent wind speed at hub height was calculated at each site using both extrapolated wind speed profiles. The difference in theoretical power available in the wind was then compared. The results of this comparison are shown in Table 3 below where the percent difference is defined by Equation 4. As shown, the largest difference occurred at Site 2: Open Field where the extrapolated wind speed profile based on tower data led to a 11% underprediction in theoretical power.

Table 3: Percent Difference in Theoretical Power with Hub Height = 80 m and Rotor Radius = 40 m

Cranberry Bog in MA	Open Field in KS	Ridgeline in WA	Wind Farm in WA
6.0%	-11.0%	-2.8%	-3.2%

The hub height was then held constant at 80 m, the rotor radius was varied from 20 – 60 m and the equivalent wind speed at hub height based on the two extrapolated wind speed profiles was found at each site. With the equivalent wind speeds, the theoretical power was then calculated and compared. As one would expect, as the rotor radius size increased, the difference in the equivalent hub height wind speeds went up and, consequently, the percent difference in theoretical power also increased. Figure 21 shows the results of the analysis. For Site 1: Cranberry Bog, the difference in the theoretical power increased from 5.2% to 6.7% as the rotor radius was increased from 20 – 60 m. Whereas, at Site 2: Open Field, the extrapolation based on tower data led to an underestimation of –9.8% to –12% as the rotor radius was varied from 20 to 60 m.

Next, the rotor radius was held constant at 40 m and the hub height was varied from 60 m to 100 m. Again, the equivalent wind speed at hub height was calculated at each site and with each of the extrapolated wind shear profiles. The results from this analysis are shown in Figure

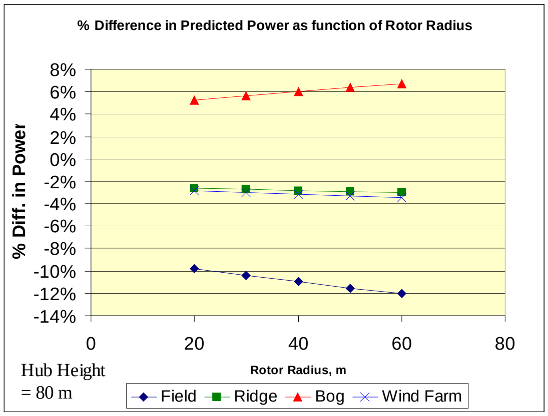

Figure 21: Percent Difference in Power with varying R

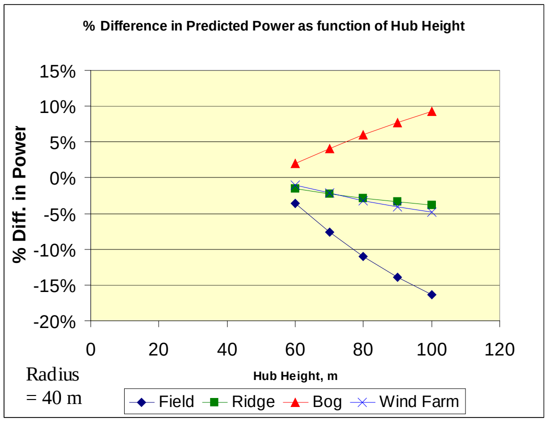

Figure 22: Percent Difference in Power with varying Hub Height

22. As shown, when the hub height was increased, the difference in the calculated theoretical power increased more drastically than when the rotor radius was varied. This can be explained based on the observations made from Figures 17 – 20. In these plots, the difference in the extrapolated wind shear profiles increased with height and this translates into a larger difference in the equivalent wind speed as the hub height is increased. With a hub height of 100 m, the theoretical power was overpredicted by 9.3% at Site 1: Cranberry Bog while, at Site 2: Open Field, the theoretical power was underpredicted by 16.4%.

Conclusions

In this shear study, Triton and tower data collected at four sites across the U.S. were analyzed and compared. At each site, excellent agreement was found between the tower and Triton data in terms of both correlation and average wind speed. The power law exponent, alpha, was estimated at each site using both the tower and Triton data. These exponents were then used to extrapolate the tower wind speeds and the resulting wind speed profiles were compared. For a range of rotor radii and hub heights, the equivalent wind speed was found for each extrapolated wind speed profile. The difference in theoretical power available in the wind was then compared for various rotor sizes and hub heights.

It was found that extrapolating wind speeds, based solely on tower data, can lead to either an under or over estimation of wind speeds at higher heights. At each site, the equivalent hub height wind speeds were calculated, using both the extrapolated wind speed profiles. It was found that as the rotor radius and hub height increased so did the difference in the estimated equivalent hub height wind speed. The increasing difference in equivalent wind speed then translated to an increasing difference in the theoretical power. With a 100 m hub height and a 40 m rotor radius, the extrapolation based on tower data led to an underestimation of theoretical power of –16.4% at one site while the tower extrapolation produced an overestimation of 9.3% at another.

SODARs and other remote sensing devices measure wind speeds across the rotor diameter. This allows for the wind shear exponent to be estimated based on data collected over the entire swept area. Using remote sensing to characterize a site reduces the uncertainty that may be introduced from extrapolated 60 m tower data.

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