Triton Remote Sensing Systems: Comparing Accuracy with Collocated Met Towers

Abstract

Using a large dataset of 30 Triton remote sensing wind profilers and collocated met towers deployed around the globe, Vaisala has conducted a unique validation experiment that reflects the performance that real commercial users of Triton can expect in the field, under conditions of limited terrain complexity and modest precipitation frequency.When the mean wind speed differences for all measurement pairs are aggregated, the average relative difference is +0.09%, and the percent root mean-square of the differences is 1.27%.

This is consistent with an estimated uncertainty of the Triton of approximately 1%, if the met tower measurement uncertainty is assumed to be independent and approximately 1% as well, a reasonable assumption for a large set of met towers maintained by many different Triton users. It was also found that filling in unrecovered data with wind speeds extrapolated using Triton-derived shear values improves the wind estimates from the Triton in two ways: First, the uncertainty in mean wind speed estimates incurred by a bias in the speed at unrecovered times can be reduced to a root mean-square value of 0.47%, with no degradation in the accuracy of the Triton mean wind speed at recovered times. Second, mean wind estimates based on Triton measurements, when filled in using Triton-estimated shear, exhibit an uncertainty less than half that of estimates sheared up from met towers — a reduction from 2.7% to 1.3%. These findings support the use of Triton as a stand-alone wind measurement device for use in wind energy resource assessment measurement campaigns.

Figure 1. Map showing geographical distribution of Triton/met tower pair locations. Each numbered circle indicates the number of pairs that were located in that general region. Exact locations and provider names cannot be shown here, to honor confidentiality agreements with the providers.

Motivation

As the wind industry continues to mature, development of new wind energy projects requires wind resource measurements that are cost-effective, rapidly deployable to remote locations, and reliably accurate across the rotor plane of modern utility-scale wind turbines.

The Vaisala Triton Wind Profiler is a sodar-based technology that fills these needs, and is becoming a measurement system of choice for wind energy developers across the globe. In fact, a sufficiently large number of users have owned and operated Triton Wind Profilers over the past several years such that a unique opportunity now exists to validate the measurement capabilities of the Triton in diverse, real-world conditions.

Many of these Triton users have placed their devices in close proximity to a met tower with anemometry and wind vanes at multiple heights, for the purpose of comparison of the remotely sensed and in situ–measured wind speeds and directions. A subset of these users has shared their "Triton/met pair" measurements with Vaisala. In addition Vaisala maintains a smaller set of Triton/met pairs itself. As a result, we now possess a dataset sufficient to perform a statistically meaningful global validation of the Triton Wind Profiler.

Many research and industry groups have conducted focused validation studies of remote sensing devices, usually with a carefully controlled deployment of one device and one met tower [e.g., Crescenti 1997 (references therein); Kindler et al. 2009; Verhoef et al. 2009; Scott et al. 2010; Lang and McKeogh 2011; Yi et al. 2012]. A more challenging validation is one in which a large fleet of remote sensing devices, along with collocated met towers, are deployed by a broad and diverse user community in different locations across the globe. These deployments, and the associated differences in measured wind speed and direction, more accurately reflect what a typical user will experience with a Triton deployed in a variety of possible locations.This purpose of this white paper is to present results of Vaisala's validation analysis of a set of 30 Triton/met pairs gathered by a number of Triton users over the past 6 years. The analysis presented here will address two specific questions:

1. Can the Triton Wind Profiler essentially act as a met tower, in simple terrain with typical meteorological conditions? Stated another way, is the Triton as good as a met tower, in terms of measuring wind speed and direction accurately at the heights typically represented by met towers?

2. Can the Triton Wind Profiler improve uncertainty of the wind resource at hub height and above, compared to extrapolation from lower heights on a met tower? This question can be answered with the subset of Triton/met pairs in which the met tower has multiple sensor heights spanning a wide height range, from which lower heights can be used to extrapolate wind speeds upward, to be compared with tower-measured and Triton-measured winds at the upper sensor heights.

The answers to these questions will provide additional assurance to the wind energy industry that wind profiling sodar technology is beneficial to a wind measurement campaign, not just as a supplement to extensive met tower deployments, but as an alternative to them.

The dataset

Over the course of the past six years, Vaisala has acquired data samples from deployments of Triton Wind Profilers in close proximity to met towers (hereafter referred to as Triton/met pairs). Roughly two thirds of these Triton/met pairs were provided by customers, either in response to Vaisala requests for data, or in connection with customer inquiries about Triton behavior that required investigation by the Triton developers. The other approximately one third of the pairs were associated with either internal or external R&D efforts to validate Triton measurements or to test technology upgrades. Thirty of these pairs were selected for this study based on the following criteria:

- Limited terrain complexity
- An environment not dominated by frequent heavy rain
- An absence of major technical problems with the Triton hardware or firmware that have since been corrected
- Well-designed siting such that noise artifacts are minimized
- At least four weeks of overlapping usable data from the Triton and met tower

The pairs are well distributed geographically (see Fig. 1), with approximately even distribution between North and South America, and a smaller number of sites in Europe and southern Africa. To enhance the diversity of the dataset, it is also important that the pairs do not all come from one provider. The 30 pairs were provided by 11 different Triton users, most of whom provided only one pair, but four of whom provided from 2 to 9 pairs. The 30 pairs employed 24 different Triton units. In cases where the same Triton unit was used for multiple pairs, the Triton either: was moved to adjoin different met towers; adjoined a single met tower, but we used two different time periods separated by at least 2 months to introduce seasonal variability; or adjoined a single met tower, but we used time periods in which two different speaker array technologies were installed in the Triton. Each pair gathered simultaneous, nearly continuous 10-minute wind measurements for periods ranging in length from 4 to 25 weeks. The measurement periods occurred throughout the six years of Triton's commercial deployment history, from mid-2009 to mid-2015.

The separation distances between the Triton and met tower ranged from 70 to 220 m, with a mean separation distance of 134 m. As stated above, the dataset was filtered to areas of limited terrain complexity. Although most of the sites would be described as flat terrain, three were in slightly rolling terrain, and one was 300 m from a mesa edge. In all cases, though, the terrain within approximately 200 m of the Triton and met tower was relatively uncurved (i.e., neither convex nor concave in shape), to avoid a violation of the geometric assumptions made in the vector retrieval of the wind. The intervening terrain was permitted to have a slight slope, but to ensure a valid comparison, sites were chosen that had only modest elevation differences between the Triton and met tower, with most elevation differences being less than 2 m, and all within 6 m.

Data quality control and alignment

Both the met tower and Triton data in each pair were quality controlled prior to inclusion in the validation analysis. Additionally, data from the two sources had to be aligned in time and interpolated in height in order to provide a common basis for comparison. The specific procedures of the quality control and alignment processes are described in the Appendices A and B, respectively.

Triton data recovery

Before proceeding to the comparisons between the Triton and met tower measurements, we address the data recovery rate, a topic of significant interest to users of remote sensing devices, as the uncertainty of the mean wind speed estimate is related to the data recovery rate. Both lidar and sodar are subject to periods of inability to measure winds due to environmental conditions or technical problems. We calculated the data recovery rate as a function of height for each of the 30 Triton deployments as follows. At each Triton data height level, we counted the number of times within the period of record that the Triton reported a wind speed that met the Quality Factor and Vertical Velocity thresholds and that did not occur during a period of intentional experimentation (see Appendix B). We divided this by the total number of 10-minute time steps within the period of record, minus the number of times excluded for intentional experimentation. The resulting fraction (or percentage) is the data recovery at that height, for that Triton deployment. We then averaged the data recovery rate across all 30 Triton deployments, at each height level. The resulting overall data recovery as a function of height is shown in Fig. 2. Not surprisingly, the pattern exhibits high recovery (≥ 90%) up to 80 m, and above that, a steady drop-off with increasing height.

Triton's hardware and firmware have been upgraded periodically over the six years since the first commercial deployments, resulting in improvements in measurement accuracy and data recovery. In particular, the introduction of the Triton Performance Upgrade (TPU) speaker array has yielded a significant boost in performance since 2013. We performed the data recovery analysis separately for the set of Tritons using the original speaker array design (18 of the 30 Triton/met pairs), and the TPU Tritons that used the enhanced speaker array design (12 of the 30 Triton/met pairs). The improvement in data recovery is considerable for the TPU units: 17% higher than original units at 100 m, 47% higher at 140 m, and 106% higher at 180 m.

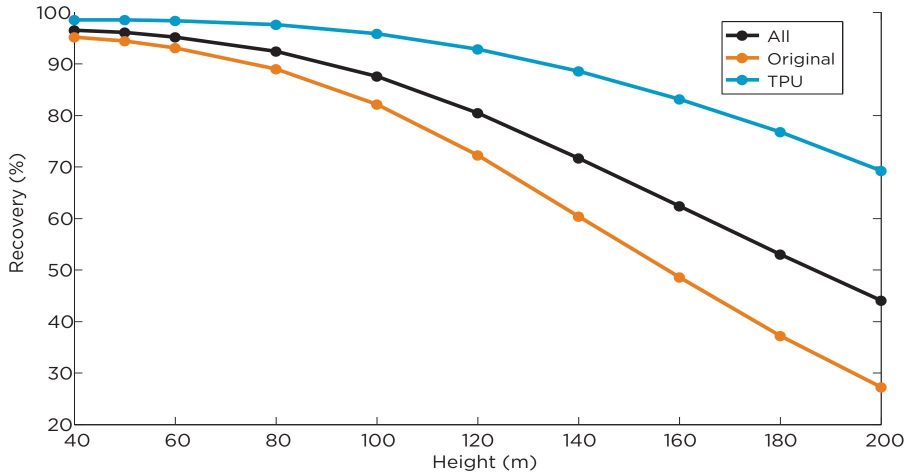

Figure 2. Average Triton data recovery rate as a function of height. Separate curves for Tritons employing the original or newer TPU speaker array are indicated as shown in the legend.

Sample comparison at a single Triton/met pair

With the data QC'd and arranged onto a common set of time points and height levels, it is straightforward to perform comparisons within individual Triton/met pairs. As an example, three scatter plots are shown for a Triton/met pair located in southern Africa, with measurements taken over a period of approximately 2 months. The top panel of Fig. 3 is a scatter plot of 10-minute wind speeds at 81 m height from the Triton (*y*–axis) versus the met tower (*x*–axis). Correlation and mean difference values are listed within the figure. The middle panel of Fig. 3 shows a similar scatter plot for wind direction at 81 m, and the bottom panel shows shear parameter, estimated as described in Appendix B. In all three plots, the data line up quite closely to the 1-to-1 line, although this is not the case with every pair. The larger scatter in the shear parameter comparison is not surprising, as it is subject to the compounding effects of independent speed errors at multiple heights that contribute to the shear calculation, for both the met tower and the Triton. Also calculated, but not shown for this individual example, are additional statistical metrics, which are described below in the aggregate results.

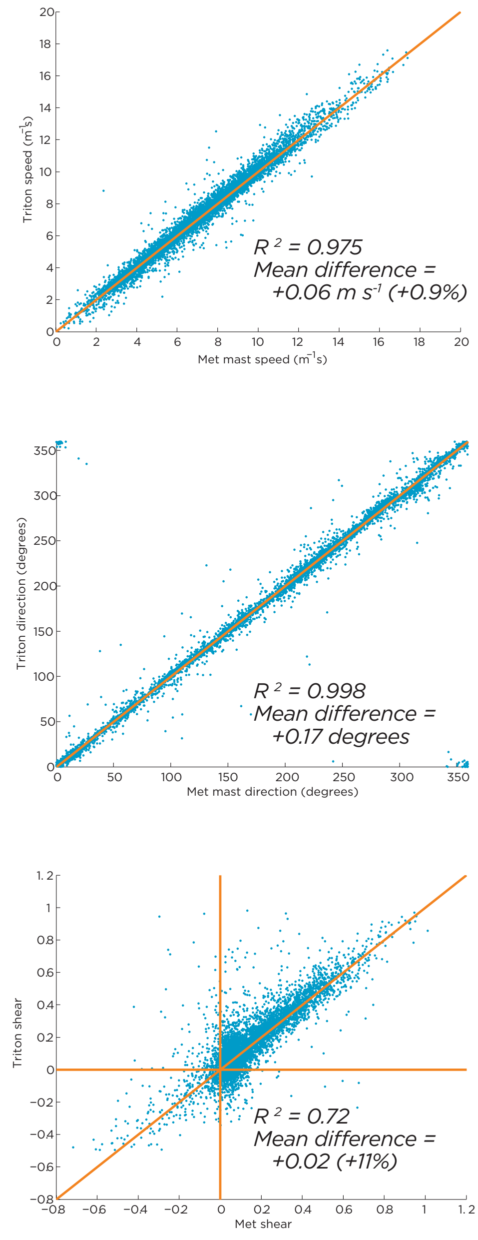

Figure 3. Scatter plots comparing 10-minute Triton and met tower data at one of the sites in the validation study, located in southern Africa. *Top panel*: 81-m wind speed (m s^{-1}); *middle panel*: 81-m wind direction (degrees); *bottom panel*: wind shear exponent. 10-minute R^2 and mean difference values are annotated in each panel. In each panel, 10-minute R^2 and mean difference values are annotated, and 1-to-1 line is shown in orange.

Aggregate results

While results from a single Triton/met pair illustrate the details of the correlation between 10-minute measurements from the two sources, the true value of this study is in the aggregate results across all Triton/met pairs, because it is the aggregate results that provide insight into the uncertainty of the wind climate estimated from Triton Wind Profilers in general. To this end, the quantities listed in the scatter plots in Fig. 3 were calculated for every Triton/met pair. In addition, other metrics commonly used to quantify the relationship between remotely sensed and in-situ measured parameters were calculated.

Wind speed

For wind speed, the slope and offset (or *y*–intercept) of the best-fit line through the scatter plot, as well as the root mean-squared difference (RMSD) of the 10-minute data were also calculated. The distributions of all of these wind speed metrics among the 30 Triton met pairs are shown in Fig. 4. Both the individual data points and box-and-whisker summaries of the distributions are shown. For this analysis, each anemometer height level of each met tower was treated as a separate validation point, so there are 100 points shown, instead of 30. It can be seen that the slopes and offsets distribute closely around the values of 1 and 0, respectively, which are the values expected if the Triton and met towers are perfectly matched. The vast majority of Triton/met sensor pairs have 10-minute R^2 values greater than 0.96 and RMSD of the 10-minute values less than 0.6 m s^{-1}. **When the mean differences at all 100 qualifying anemometer measurement heights within the 30 Triton/met tower pairs are aggregated, the average mean difference in wind speed is +0.09%, and the percent RMSD (PRMSD) of mean wind speeds is 1.27%.**

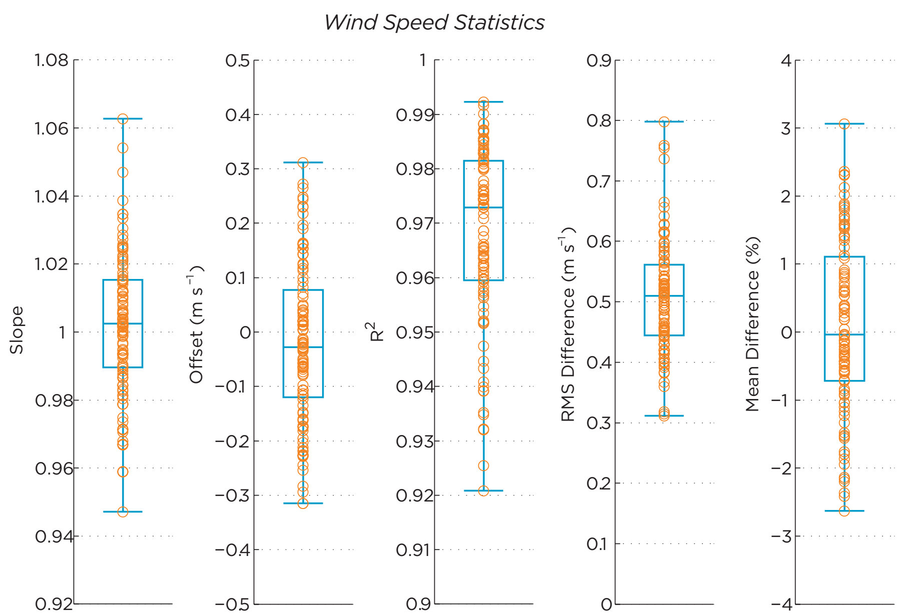

Figure 4. Wind speed statistics derived from comparisons of data samples for all 100 different sensor heights on the towers in the 30 different Triton/met tower pairs used in the study. From left to right, slope of the best fit line to a scatter plot of Triton versus met tower 10-minute wind speeds; offset (or *y*-intercept) of that same best-fit line; squared correlation coefficient of Triton versus met tower 10-minute wind speeds; root mean-squared value of Triton minus met tower 10-minute wind speeds; and mean of Triton minus met tower 10-minute wind speeds.

Wind shear

Figure 5 presents similar metrics for the wind shear parameter. There are far fewer data points for wind shear than for wind speed and direction, because all heights at a met tower are used to produce an single value of wind shear at the met tower, rather than treating each height as a separate data point. Additionally, not all towers had qualifying height levels for an accurate shear parameter estimate (as described in Appendix B). The R^2 and RMSD of the 10-minute values indicate substantial scatter in the shear parameter estimate, which is not surprising, considering it is a derivative of multiple wind speed measurements, each containing independent errors. However, there is considerable value in the Triton shear estimate, as demonstrated in later sections describing recovered speed bias and shear extrapolation. **When all 100 measurement heights within the 30 Triton/met tower pairs are aggregated, the average mean difference in shear is +0.002, and the RMSD in mean shear is 0.013.**

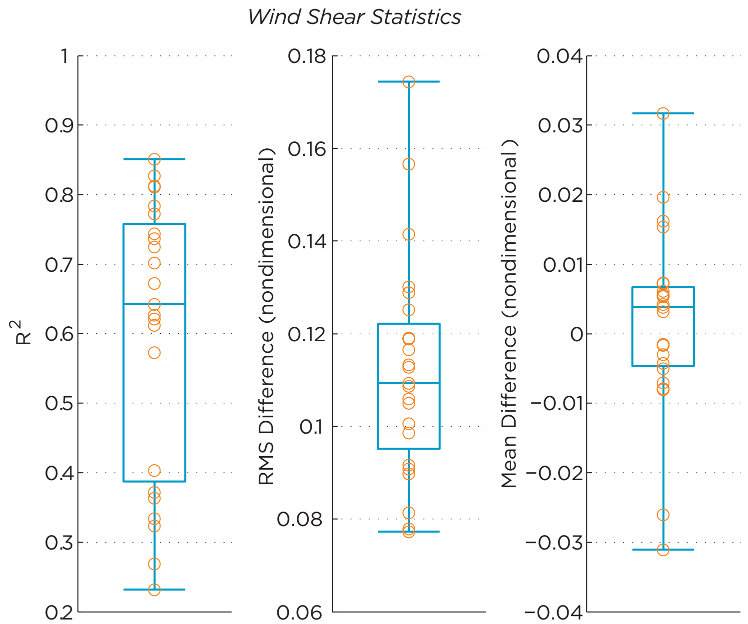

Figure 5. Wind shear exponent statistics derived from comparisons of data samples for all 30 Triton/met tower pairs used in the study. From left to right, squared correlation coefficient of Triton versus met tower 10-minute wind shears; root mean-squared value of Triton minus met tower 10-minute wind shears; and mean of Triton minus met tower 10-minute wind shears.

Wind direction

Statistics for wind direction are shown in Fig. 6. For wind direction, we calculated only the R^2, RMSD, and mean difference metrics, using all times when Triton-measured wind speed exceeded 3.0 m s^{-1}. The R^2 values are generally very close to 1.0, with nearly all exceeding 0.95. The RMSD of the 10-minute values and the mean differences show several large deviations exceeding 5 degrees. This is attributed to difficulties with precise alignment of the instruments relative to true north, and this difficulty is likely coming into play for both the tower-mounted wind vanes and the Triton Wind Profilers. These results underscore the importance of taking care to align the instrument as accurately as possible to true north. **When all 100 measurement heights within the 30 Triton/met tower pairs are aggregated, the average mean difference in wind direction is +1.7 degrees, and the RMS of mean wind direction differences is 7.5 degrees.**

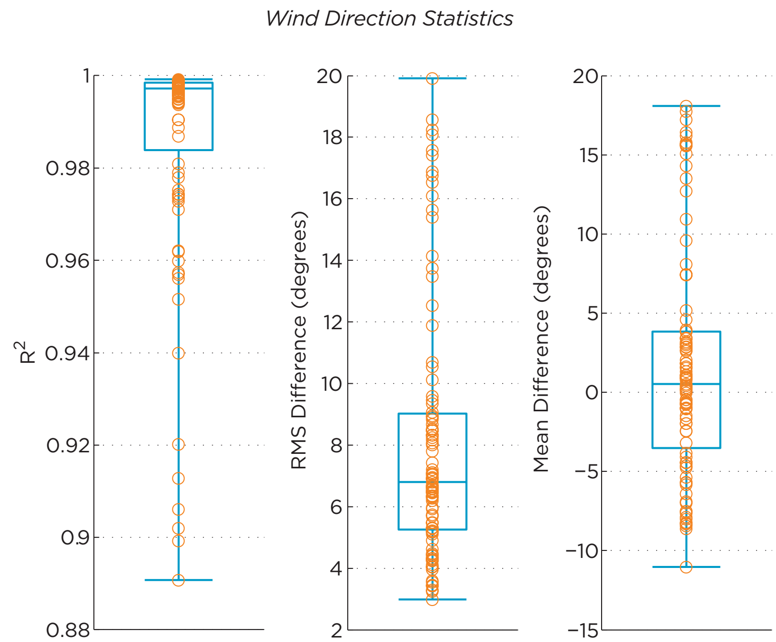

Figure 6. Wind direction statistics derived from comparisons of data samples for all 100 different sensor heights on the towers in the 30 different Triton/met tower pairs used in the study. From left to right, squared correlation coefficient of Triton versus met tower 10-minute wind directions; root mean-squared value of Triton minus met tower 10-minute wind directions; and mean of Triton minus met tower 10-minute wind directions.

Wind speed differences versus errors

It is important to bear in mind that the differences between the mean wind speeds measured by Tritons and nearby tower-mounted sensors, as seen in the right-most panel of Fig. 4, should not be interpreted solely as errors in the Triton measurements. They include contributions from errors with respect to "truth" in both measurement techniques. Determination of the error distribution with respect to "truth" of either measurement requires knowledge of the error distribution in the other measurement, which is unknown.

Considering the distinctly different technologies used in sodar versus tower-mounted sensors, it is reasonable to assume that the errors of the mean wind speed measured by Tritons and met towers are independent, in which case the percent RMS errors (PRMSE) of mean wind speed from Tritons and met towers across a fleet of pairs should add in a summed-squares manner to the percent RMS differences (PRMSD) between them: $PRMSD^2 = PRMSE_{Met}^{\ 2} + PRMSE_{Triton}^{\ 2}$. This can be depicted graphically as in Fig. 7. Any combination of met tower and Triton error must fall along a circular curve of radius equal to the observed PRMSD value of 1.27% (the solid curve). Due to the limited sample size (100 separate pairs, from each of the included sensor heights at the 30 towers), there is a possibility of a "lucky draw", such that the true error pair lies outside the solid curve, but the sample error pair lies on it. We performed a Monte Carlo simulation with 1 million randomly chosen pairs of "true" PRMSE values for Tritons and met towers. For each of those 1 million error combinations, we created 100 individual pairs of error randomly and normally distributed using the "true" value as a standard deviation; calculated a sample PRMSE

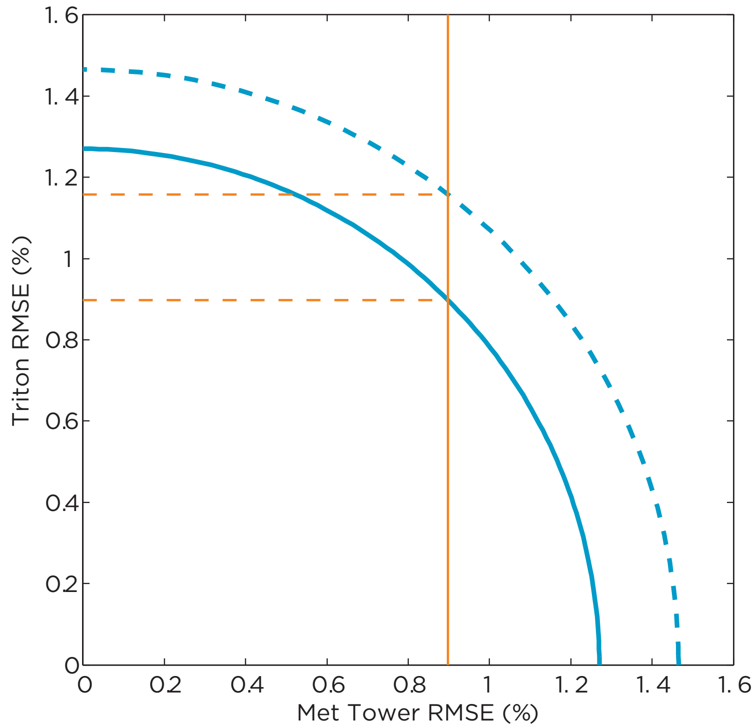

Figure 7. Curve (solid teal color) illustrating the relationship between the PRMSE of Triton and met tower mean wind speed measurements, consistent with the observed PRMSD between the mean wind speeds measured by Tritons and met towers of 1.27%. Dashed curve: outer bound (95% confidence) for the true PRMSE of the two measurement techniques, based on Monte Carlo test. Orange line: Met tower PRMSE = 0.90%. Dashed orange lines: Locations where the solid orange line crosses the PRMSD = 1.27% curve (Triton PRMSE = 0.90%) and the 95% outer bound curve (Triton PRMSE = 1.16%).

(for Triton and met) and PRMSD between them; selected all pairs that produced a sample PRMSD within a very close tolerance of our observed PRMSD of 1.27%; and then within that subgroup, determined the PRMSD threshold that encompassed 95% of the true PRMSD values of the samples. That PRMSD threshold is 1.47%, and is represented by the dashed curve in Fig. 7. Thus, for example, if we assume the met tower measurements across the entire fleet have a PRMSE of 0.90% (the thin orange line in Fig. 7), the most likely value of the Triton PRMSE is also 0.90% (where the orange line crosses the solid blue line), and with 95% confidence we can say that the Triton PRMSE is less than 1.16% (where the orange line crosses the dashed blue line).

Of course, we do not know the PRMSE of the met tower measurements. Errors in tower-mounted anemometer measurements of wind speed arise from many sources, including:

- Sensor calibration uncertainty
- Imperfect sensor response to turbulence and off-horizontal flow
- Sensor degradation not detected by QC process
- Tower flow distortion effects not detected by QC process

Some of these uncertainties can be reduced by using high-quality sensors, mounting the sensors following industry standards, using redundant pairs of sensors, frequently maintaining the tower, and carefully QC'ing the data. However, across a large fleet of towers from many sources, it is likely that the PRMSE of the tower-measured mean wind speeds is around 1%. It is unlikely to be much less than that, considering the uncertainty of a new calibrated sensor in undistorted flow is at least 0.5%. It is unlikely to be much greater than that, as anything approaching 1.5% would be assigning nearly all the PRMSD of 1.51% to the met tower and none to the Triton. A PRMSE of 1% for the met towers is consistent with a PRMSE of Triton-measured mean wind speeds also being around 1%, or in other words, the errors in mean wind speed measured by tower-mounted anemometers and by Triton Wind Profilers are indistinguishable from each other, and probably both around 1%.

Recovered speed bias

It was stated above that data recovery is a topic of significant interest to users of remote sensing devices, and the data recovery characteristics of the Triton were shown in Fig. 2. Reduced data recovery is of particular concern if there is a systematic bias, either upward or downward, to the unrecovered wind speeds compared to the wind speeds at all times. If there is a such a bias, the recovered winds will be biased in the opposite direction, and wind resource assessments based on the measured data will likely inherit some or all of that bias (although it is possible to recover some of the missing winds with a well-correlated off-site or synthetic long-term reference time series).

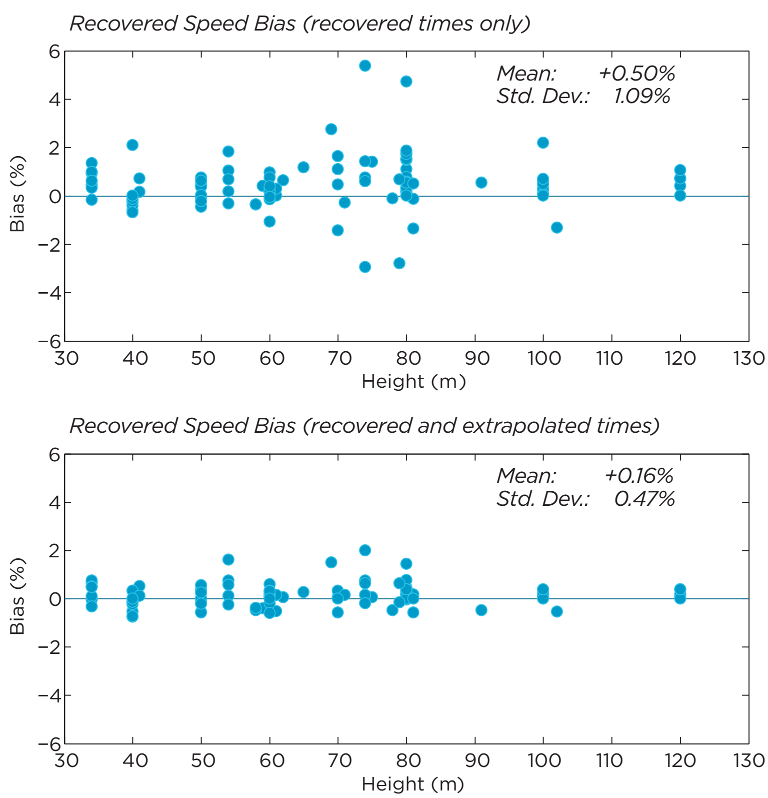

Figure 8. Recovered wind speed bias, as a function of height, for all 100 sensor heights in all 30 Triton/met tower pairs. Top panel: Bias computed using only actually recovered times. Bottom panel: Bias computed using both recovered times and times at which it was possible to extrapolate the Triton data to the desired height. In both panels, mean and standard deviation of the recovered speed bias are shown in upper right.

To investigate the presence of a systematic bias, we define an "unrecovered speed bias", which is the difference between the mean wind speed at times not recovered by the Triton, and the mean wind speed at all times, expressed as a percent of the latter quantity. If this number is negative, for example, it means that the Triton tends to disproportionately miss low wind speeds. Because Triton-measured winds don't exist during unrecovered times, we can estimate the unrecovered speed bias by using the collocated met tower's measured winds as a surrogate. Therefore, the unrecovered speed bias is estimated as the difference between the mean wind measured by the tower only at Triton-recovered times and the mean wind measured by the tower at all times, expressed as a percent of the latter quantity. The tower winds must be used for both means so that the unrecovered speed bias does not include a spurious contribution from Triton-minus-met-tower differences. For the pairs of measurements at the 100 separate met tower sensor heights, the mean unrecovered speed bias was –10.3%, with a standard deviation of 19.7%. Thus, the Triton tends to disproportionately miss low wind speeds, although with considerable case-to-case variability.

These numbers seem large, but because they only apply to the winds when the Triton is not recovering data, they greatly overstate the uncertainty of using Triton wind measurements at recovered times as an estimate of the true mean wind. A quantity which better represents that uncertainty is the "recovered speed bias", defined similarly to the unrecovered speed bias except using recovered times instead of unrecovered times. This number is of opposite sign, and typically much lower than the unrecovered speed bias, because it is related to the unrecovered speed bias by the factor $-(1-R)/R$, where R is the data recovery rate. The average Triton recovery rate among the 100 met tower sensor heights was 94.6%, so this factor is, on average, 0.057, and the recovered speed biases should be roughly 18 times smaller than (and of opposite sign to) the unrecovered speed biases. The 100 values of recovered speed bias are shown versus height in the upper panel of Fig. 8. The mean and standard deviation of all the points in the figure are listed in the upper right corner. The standard deviation is of interest for two reasons. First, it allows for a statistical significance test that the mean value is different from 0.0% using the student's t distribution, and that test indicates that the mean of +0.50% is different from zero at the 95% confidence level. Second, while the mean difference could be removed by applying a simple bias correction, the standard deviation represents the random case-to-case uncertainty in the recovered mean speed compared to true mean speed. The value of 1.09% is comparable to the PRMSE of mean wind speed of around 1% estimated above from the Triton/met tower wind speed analysis, and represents an additional uncertainty that should be included in the overall uncertainty of the Triton measurement.

However, one can exploit the Triton's ability to measure winds, and thus shear, over a deep layer at times when data recovery is good, and use this shear information to fill in data at unrecovered times. Specifically, a diurnally varying mean shear parameter is calculated from Triton data when good recovery over a deep layer is achieved (see description of this diurnally varying shear parameter in Appendix B). This diurnally varying shear parameter is then used to extrapolate upward or downward from the nearest recovered height to times/heights when data was not recovered.

After doing this, the average data recovery for the 100 Triton/sensor pairs, when including the sheared-up values, increased from 94.6% to 97.3%.

The first thing to confirm is that by synthetically improving the Triton data recovery, we did not reduce its accuracy at estimating mean winds at recovered times. The results in the far right panel of Fig. 4 were recomputed for all towers, and the PRMSD of mean wind speeds went up only slightly, from 1.27% to 1.29%. However, by increasing the data recovery, the estimated recovered speed bias values now converge much more closely around the 0.0% line (Fig. 8, lower panel). The remaining mean recovered speed bias is reduced to 0.16%, which is still statistically different from 0.0% at the 95% confidence level, but is very small; and the standard deviation, representing the uncertainty contribution from the recovered data bias, is reduced to 0.47%, which is now half as small as the estimated uncertainty of the Triton's mean wind speed measurement of around 1%. The overall conclusion of this analysis is that the **Triton does have a tendency to miss lower wind speeds, biasing its recovered mean wind speed upward from the true mean wind speed; but by utilizing the Triton's own measured shear information to fill in unrecovered times, the additional uncertainty incurred by the recovered speed bias can be reduced to a root mean-square value of 0.47%, with no degradation in the accuracy of the Triton mean wind speed at recovered times.**

Shear extrapolation experiment

One advantage that is often stated for remote sensing devices compared to met towers is the ability of remote sensing devices to directly measure the winds at hub height and above; whereas met towers often do not extend to hub height and require extrapolation over a vertical distance of several tens of meters above the tower top, incurring additional uncertainty in the wind speed estimate at the target height. While this advantage is true in principle, there are factors that in reality could offset this advantage. First, the purported advantage requires that the shear between the top of the met tower and the target height differ significantly from that within the vertical extent of the tower, which may not be the case. Second, it requires that the remote sensing device be able to accurately measure winds at the height. Third, it requires that there not be a large uncertainty incurred by the remotely sensed measurements due to lower data recovery at the target height.

With the present data set, in which several of the towers among the Triton/met pairs have sensors at multiple, widely separated heights, we have an opportunity to directly measure this purported advantage. The procedure is as follows. For a particular tower, candidate target heights for extrapolation are selected, starting from the top-most speed sensor height and working downward. A candidate is considered a valid target height if:

- there are at least two source sensor heights (i.e., sensors from which the extrapolation will be made), below the candidate target height;
- the source sensor heights span a vertical distance of at least 15 m;
- the top source sensor height is at least 50 m above ground;
- the top source sensor height is at least 15 m below the candidate target height.

Among the dataset, there were 29 qualifying target-height measurements at 21 tall towers. The mean of the 29 target heights is 89 m (standard deviation of 17 m). The mean extrapolation distance is 22 m above the highest source height (standard deviation of 5 m).

A diurnally varying shear parameter was estimated from the source heights of the met tower, and that shear parameter was used to extrapolate winds upward to the target height sensors. Both the tower-extrapolated value and the Triton-measured value were compared to "truth", which is the tower measured value at the qualifying target height. The errors of these two estimates at the qualifying target heights are shown in Fig. 9.

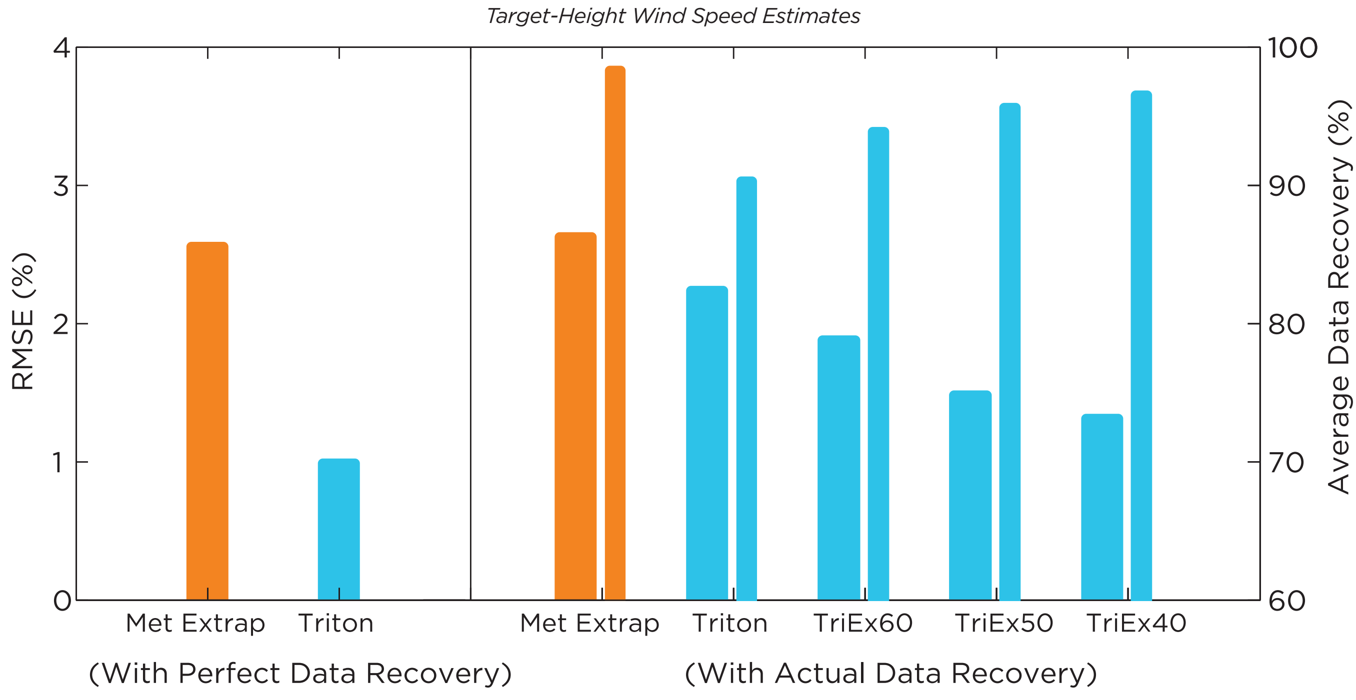

Figure 9. Root mean-squared errors of mean target-height wind speeds estimated by two methods: extrapolation upward from lower heights on a met tower (orange), and measured (or extrapolated upward) from Triton. *Left panel*: calculated AND validated only at times when both estimates are available (representing the "perfect data recovery" scenario). *Right panel*: calculated at times when each estimate is available, but validated against mean of target-height measurement at all times (representing the "true data recovery" scenario). Narrow bars in right panel indicate data recovery rate for each estimate (values on right axis). "TriEx60", "TriEx50", and "TriEx40" indicate Triton based estimates including upward extrapolation from as low as the indicated minimum height in meters, to fill in missing data.

First, the errors were calculated at all times that the met-tower extrapolated target-height wind, the Triton directly measured target-height wind, and the met-tower directly measured target-height wind, were all available. This is equivalent to comparing the extrapolated and Triton-measured mean winds under a scenario of “perfect data recovery” for both. It can be seen that under the perfect recovery scenario, the PRMSE of Triton mean target-height winds (1.0%) is less than half that of the extrapolated estimates (2.6%), suggesting the remote sensing advantage is real and significant.

However, in actual Triton deployments, data recovery averages 90% at the mean target height in this experiment (89 m), whereas the data recovery of a sheared-up value from met tower measurements is usually much closer to 100%. So a second analysis was performed, in which the mean of Triton target-height winds measured at recovered times was used as an estimate of the mean of met-tower target-height winds measured at all times; and the same was done separately for met tower sheared-up winds. These results are indicated by the orange and first teal-colored bar in the “actual data recovery” section of Fig. 9. The wide bar indicates the PRMSE (left axis), and the narrow bar indicates the corresponding average data recovery among the qualifying target height measurements (right axis). The PRMSE for met tower sheared-up estimates does not change significantly from the perfect recovery scenario, because data recovery is very high (99%). Meanwhile, the Triton’s lower data recovery at the target heights introduces additional uncertainty in the target-height wind estimate compared to the “perfect recovery” scenario. It is still lower than the uncertainty of the tower sheared-up estimate (2.3% compared to 2.7%), but not by as much as in the “perfect recovery” scenario. However, as was done for the recovered data speed analysis, one can exploit the Triton’s additional shear information above the met tower tops, gained at times when data is recovered (see description of this diurnally varying shear parameter in Appendix B), and fill in missing target-height data with values extrapolated up from lower Triton levels. This was done for three different minimum height levels from which we were willing to extrapolate upward to the target height: 60 m, 50 m, and 40 m. As the minimum height from which we’re willing to extrapolate is lowered, more data is “recovered” as indicated by the narrow bars, and uncertainty in the target-height estimate is reduced to 1.3%, not far from the value in the “perfect recovery” scenario. This result is a further demonstration of the added value of the Triton’s ability not only to directly measure winds at hub height and above, but also to fill in its own missing data using a climatology of upper-level shear measured at recovered times. **When incorporating the Triton’s own measured shear into the Triton estimate of wind speeds at high target heights (as is routinely done with met tower data), the uncertainty of mean wind speeds at those heights is substantially reduced, from 2.3% to 1.3%, and is less than half the uncertainty of extrapolated tower measurements (2.7%).**

Conclusions

Vaisala has accumulated a large dataset of measurements from collocated pairs of Triton Wind Profilers and met towers, deployed at diverse locations across the globe by the Triton user community. This dataset presents an opportunity to validate Triton's measurement capabilities as a stand-alone device under conditions of limited terrain complexity and modest precipitation, and provide guidance to users as to how it should be expected to perform in real-world deployments. Thirty Triton/met tower pairs were analyzed, yielding 100 separate anemometer records for validation. All Triton measurements were made by the instruments as shipped from the factory; in no case was any bias correction performed on the Triton data relative to the nearby met towers. Key results of the analysis are as follows:

- All Tritons (both original units and those with the upgraded speaker array, or "TPU" units) exhibit high data recovery (≥ 90%) up to 80 m. Data recovery for the newer TPU units is considerably improved compared to that of original units at higher heights: 17% higher at 100 m, 47% higher at 140 m, and 106% higher at 180 m.
- When the mean wind speed differences at all 100 qualifying anemometer measurement heights within the 30 Triton/met tower pairs are aggregated, the average relative difference is +0.09%, and the percent root mean-square of the differences is 1.27%. This is consistent with an estimated uncertainty of the Triton of approximately 1%, if the met tower measurement uncertainty is assumed to be independent and approximately 1% as well, a reasonable assumption for a large set of met towers maintained by many different Triton users.
- The wind speeds at unrecovered times are biased low, resulting in the Triton's mean wind speed estimate at recovered times having a high bias relative to the mean at all times. However, by utilizing the Triton's own measured shear information to fill in unrecovered times, the additional uncertainty incurred by the recovered speed bias can be reduced to a root mean-square value of 0.47%, with no degradation in the accuracy of the Triton mean wind speed at recovered times.
- When mean winds directly measured by Triton (under a perfect data recovery scenario), or filled-in with values based on Triton-measured shear (under a real data recovery scenario), are compared with estimates sheared up from lower met tower heights, the Triton mean wind speed estimates exhibit uncertainties less than half that of estimates sheared up from met towers. Under the real data recovery scenario, the reduction is from 2.7% uncertainty for met tower extrapolation down to 1.3% uncertainty for Triton measurement with filled-in values.

Appendix A: Data quality control and alignment

Both the met tower and Triton data in each pair were quality controlled prior to inclusion in the validation analysis.

The met tower data were reviewed for the following issues, and appropriate filters or adjustments were made:

- The functions to convert anemometer output to wind speed were inspected for reasonableness, if provided.
- Data recorded by malfunctioning sensors were excluded.
- Sensor data affected by the tower or surrounding structures were excluded.
- Periods of anemometer dragging were excluded.
- Periods of icing that affect the accuracy of wind speed and direction measurements were excluded.
- Sectors that were potentially waked by nearby turbines were excluded.
- Redundant anemometers at the same height were selectively averaged, meaning that at each time point, if both sensors provided a value that met the above QC criteria, their average was used; if only one sensor provided a QC'd value, it's value was used; and if neither provided a QC'd value, the value was set to missing.

The following QC and adjustment procedures were applied to the Triton data:

- The standard set of Triton height levels is every 10 m from 30 to 60 m, and then every 20 m from 60 to 200 m. However, the 30 m level is generally considered to be too short a distance to provide reliable data, and so it was excluded from this study.
- Triton measurement heights were adjusted to be relative to ground level at the met tower. This at least partially accounts for the reduced (or increased) wind speed the Triton would typically measure at the same height above ground level if it is at a lower (or higher) elevation than the met tower.
- Time periods when the Triton was known to be producing inaccurate or low-quality data due to intentional experimentation by Vaisala technicians were excluded from the Triton record.
- Finally, Triton data were filtered on the value of the Quality Flag (QF) and the Vertical Velocity (VV). This is a standard filtering procedure for all Triton Wind Profilers, not just for this study. The QF is calculated in Triton's firmware, independently for each time point and height level, and ranges from 0% to 100%. A high value indicates high confidence in the accuracy of the wind estimate at that height and time. Lower values

result from noise artifacts, insufficient turbulent targets, and other effects that reduce the quality or certainty of the wind estimate. The choice of QF threshold is somewhat arbitrary, but a reasonable compromise between data quality and data recovery is achieved at QF ≥ 90%, and that is what was used here. The VV is the vertical component of the Doppler velocity measured by the unit. Under non-precipitating conditions, VV is a measure of the vertical motion of the air itself, which is a necessary ingredient for the horizontal wind retrieval. Values are usually within the range 0.0±1.0 m s^{-1}. However, when it is raining, VV is dominated by the terminal fall speed of raindrops, which is usually several m s^{-1}, and the calculation of the horizontal wind speed is compromised. Therefore, raining periods are filtered out by excluding any time/height points when downward VV > 1.5 m s^{-1}.

- All Triton measurements were made by the instruments as shipped from the factory; other than the above-described QC procedures and adjustment based only on relative elevation, in no case was any bias correction performed on the Triton data relative to the nearby met tower.

Appendix B: Temporal alignment and vertical interpolation of data

To compare data from a met tower and a collocated Triton Wind Profiler, several steps must first be taken to put the two time series into a common framework. The first is to insure that they are properly synchronized in time. Mistakes in UTC offset are not uncommon in data logger records, so proper synchronization can be achieved by examining lag correlations between Triton and met tower wind speeds, and shifting the met tower time series to achieve maximum correlation at zero lag. The two time series are then bracketed in time so that they share the largest possible common period of record during which both have nearly continuous data.

The next step is to place all the data onto a common set of height levels. With the met tower serving as the “ground truth”, it is most sensible to preserve the met tower’s speed measurements in as original a form as possible, so the approach we used is to transfer Triton wind speeds to the met tower’s set of anemometer heights. For simplicity, we also transferred both the met tower and Triton wind direction measurements to the anemometer heights, so that all variables are on a common set of heights. Transfer of both met and Triton direction measurements to anemometer heights was by linear interpolation for anemometer heights that are between direction levels with non-missing data, or by nearest neighbor for anemometer heights that are outside of, but within 10 m of, direction levels with non-missing data. Transfer of Triton speed measurements to anemometer heights was by power-law interpolation for anemometer heights that are between Triton speed levels with non-missing data, or by power-law extrapolation for anemometer heights that are outside of, but within 10 m of, Triton speed levels with non-missing data. The power-law extrapolation uses a diurnally varying shear parameter, which is calculated uniquely for each Triton and for each 10-minute time of day, using a least-squares linear fit on a log-log plot of all Triton speed data versus height available during the period of record.

Because the Triton is relied upon to quantify the wind shear up through the rotor plane of typical turbines, an additional comparison was made of the shear parameter observed by the met tower and Triton. To make the comparison meaningful, we calculated the shear for both the met tower and Triton using data on the common set of anemometer heights, as described above.

At each 10-minute time during the period of record, a shear parameter was estimated for the met tower from all available met tower speed measurements, and then similarly for the Triton from all available speed values after transfer to the anemometer heights. The shear parameter was estimated using a least-squares linear fit to the speed data on a log-log plot with respect to height. In order to qualify for a shear calculation, the tower or Triton had to have at least two height levels with valid data above 30 m, of which the outermost levels had to be separated by at least 25 m.Valid data is any non-excluded wind speed measurement ≥ 3.0 m s^{-1}.

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