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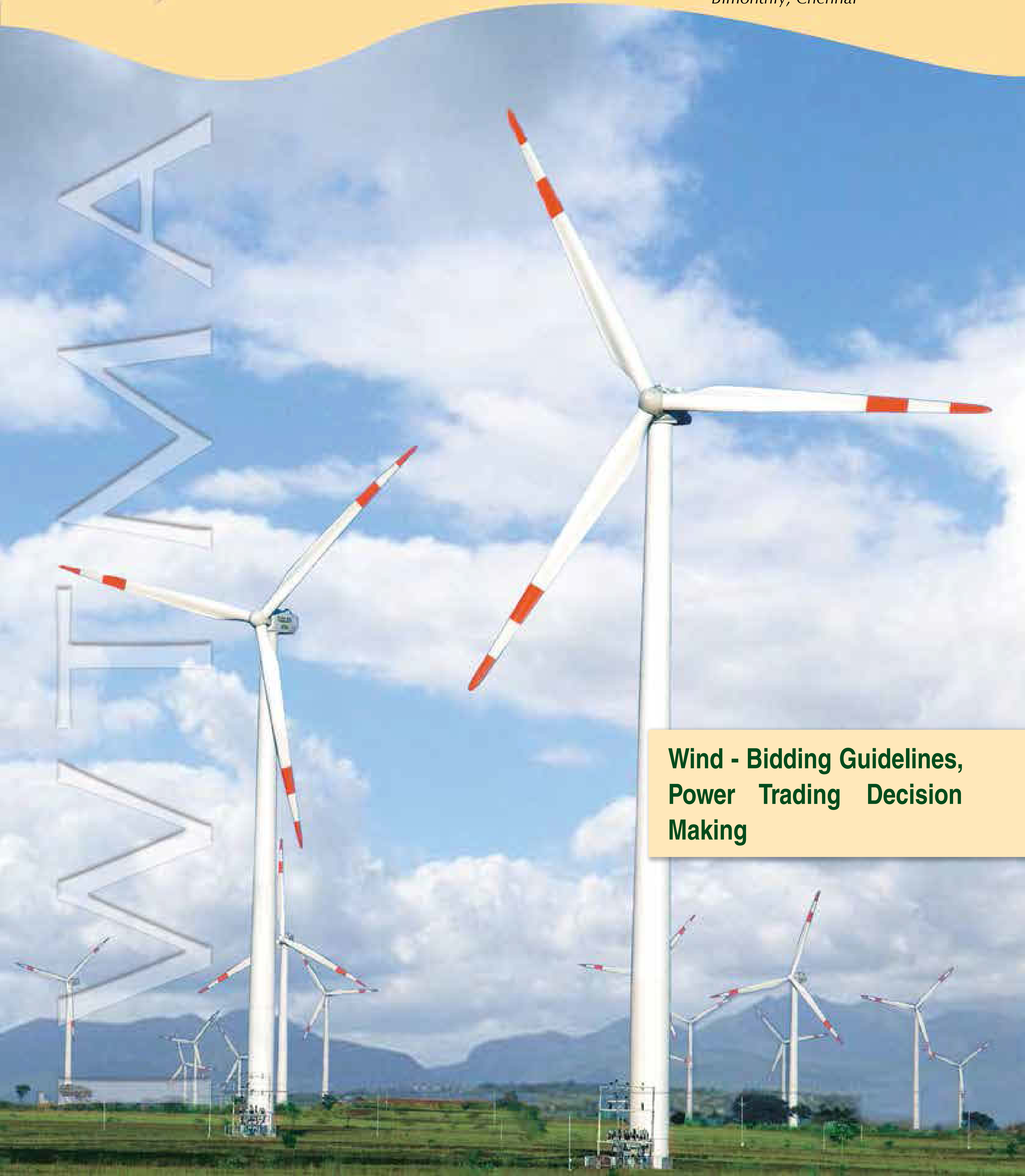
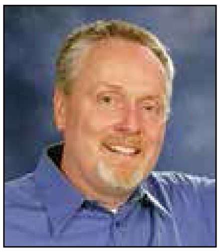


Wind - Bidding Guidelines, Power Trading Decision Making

Paving the Way for Remote Sensing Adoption in India



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Introduction

A key question in developing and financing a wind project is how much energy will it produce? This depends on wind – a variable resource that dramatically affects the cash flow of a wind project. Wind resources vary from night to day, from day to day, from month to month, and from year to year. An accurate estimate of both the mean wind speed, and the variations around that mean are crucial to understanding the potential risks and rewards of developing a wind project.

For over 30 years, the primary wind measurement tool has been a meteorological mast (or "met tower") equipped with anemometers, vanes, and data loggers that record wind speed and direction. Every modern wind energy project, in contributing to an industry worth billions of dollars, has been cost-justified based on this technology. Ideally, a met tower would be tall enough to gather measurements throughout the entire height range of the rotor, but this is impractical, especially with the ever-increasing hub heights of modern wind turbines (Figure 1). In practice, due to costs, permitting, and other constraints, most met masts don't reach higher than 80-100 meters. To quantify the winds at higher hub heights and throughout the depth of the rotor plane, wind developers, independent engineers and investors must extrapolate the measured values upward, using wind shear values derived from lower heights. However, this process is prone to error (as much as 10-15%), increasing the uncertainty of the energy estimate. This uncertainty will only worsen as average turbine heights continue to extend beyond 100 meters.

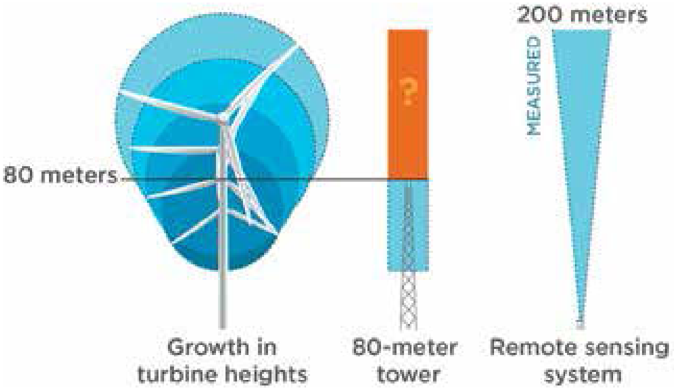

Figure 1: Value of Remote Sensing as Turbine Hub Heights Grow

Today, ground-based remote sensing technology supplements towers, measuring wind speed and direction at much higher heights than met masts (up to 200 m; Figure 1).

One particular remote sensing technology is SoDAR (SOnic Detection And Ranging). As with other remote sensing technologies (LiDAR, radar), SoDAR wind profilers collect measurements of horizontal wind speed and direction at heights up to ~200 m above ground, significantly extending past the height range of met towers. They do this by measuring the Doppler frequency shift of energy pulses that are sent upward, reflect off of turbulent eddies within the air, and return to the device, where the Doppler shifts are recorded and converted to wind vectors. SoDAR uses sound pulses, whereas LiDAR uses infrared light (scattered off of aerosols) and radar uses microwaves (scattered off of turbulence or precipitation). Each of these technologies have their unique advantages and challenges. The characteristics of SoDAR that is attractive for wind resource assessment include: its consistent accuracy without the need for periodic calibration; its portability; its low power requirement; and its rugged ability to withstand long, unattended, self-powered deployments in remote and diverse locations, under harsh weather conditions (Figure 2).

Figure 2: Triton Wind Profiler in Diverse Environments

However, as relative newcomers, remote sensing technologies face a high bar for acceptance by the wind resource measurement community, which has vast experience and a high comfort level with met towers and cup anemometry. To work toward acceptance, remote sensing manufacturers, their customers, and third-party consultants have conducted a number of comparison studies between remote sensing devices and collocated met towers. Vaisala, in partnership with various customers and consultants, has conducted a number of such studies on the Triton Wind Profiler, a SoDAR-based remote sensing device. This article will summarize results from our global Triton validation study [1]. At the time that study was conducted, there were insufficient data sets from collocated Triton and met tower pairs in India, but several are now available, and so we present specific results from two Indian Triton/met tower collocations. Of particular interest to the Indian market is the question of how well the Triton performs in the monsoon season, not just because it is by far the windiest time of year, but also because SoDAR measurements are complicated by heavy rainfall, so there is a concern that data recovery in the monsoon season using SoDAR might be challenging.

The Global Triton Validation Study

In 2015, we conducted a global validation study in which it compared 30 Triton/met tower pairs across the globe. The purpose of this study was to quantify customer-experienced accuracy of commercially deployed Tritons in a variety of geographic and meteorological conditions, with a sample size that was large enough to generate meaningful statistical results. Characteristics of the study are summarized in Table 1, and the approximate geographic distribution of the pairs is shown in Figure 3. The study attempted to address two key questions that a potential remote sensing user would likely ask:

1. Will the device recover a sufficient amount of data to give confidence that it is capturing the actual wind distribution at the site?
2. What is the accuracy of the device compared to a met tower, primarily in terms of measuring the mean wind speed over an extended period of time?

Table 1: Details of Global Triton Validation Study	
Number of Triton/met tower pairs	30
Number of tower sensor heights compared	100
Range of tower heights	34 – 120m
Range of distances from met tower to Triton	70 – 220m (average: 134m)
Elevation differences between met and Triton	< 6m (mostly < 2m)
Number of Tritons with original/upgraded speaker array	18 / 12
Periods of measurement	4 – 25 weeks
Customers / Users providing data	11
Terrain	Mostly flat
Frequency of rain occurrence	Low to moderate

To address the first question, we examined the data recovery rate averaged across the 12 Triton units used in the study that employed the latest version of the Triton speaker array (known as the "Triton Performance Upgrade", or TPU). The recovery rate is defined as the percentage of time that the device yields a valid measurement at a particular height, where "valid" means that the measurement has passed some standard quality control (QC) procedure. Those results are shown in the upper panel of Figure 4. Even at heights up to 100 m, the recovery rate remains above 95%, only slightly lower than typical data recovery rates for met towers.

Figure 3: Sites included in Global Validation Study

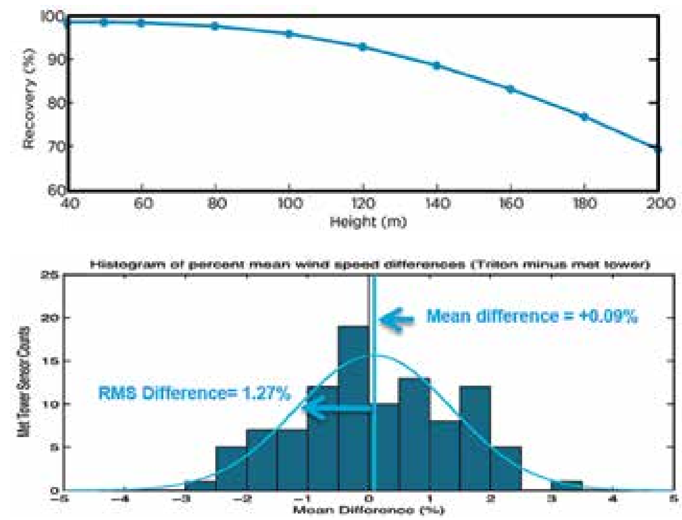

Figure 4: Validation Study Results - Top: Data Recovery Versus Height Bottom: Histogram of Mean Wind Speed Differences.

To address the second question, we compared the mean wind speed measured by the Triton to that measured by the met tower at the exact same set of valid time points, over the entire period of measurement for each pair (ranging from 4-25 weeks). The distribution of the differences in mean wind speed (Triton minus met tower), as a percent of the met tower-measured mean wind speed, at all 100 sensor heights on the 30 met towers, is shown in the lower panel of Figure 4. The distribution is approximately normal, with the mean of the distribution very close to zero, meaning that the Triton is, on average, unbiased with respect to met tower-mounted cup anemometers. The width of the distribution, as represented by the root mean square of the differences (RMSD), is 1.27%.

It is important to realize that these errors arise from inaccuracies in both the met towers and Tritons. If the met tower accuracy with respect to "truth" (expressed as a root mean-squared error, or RMSE) is around 1.0%, which is a reasonable assumption, then a RMSD of 1.27% is consistent with the Triton also having a RMSE of around 1.0%, assuming independent errors of the Tritons and their collocated met towers. Thus, these results show that in terms of mean wind speed, the uncertainty of Triton SoDARs (around 1%) is about the same as that of well-constructed met towers.

The Triton in India

The Indian wind energy industry is taking a keen interest in remote sensing technology, and, in particular, in the advantages offered by SoDAR technology (as described above). As with other regional markets that have explored the use of SoDAR, the same questions regarding data recovery and accuracy are frequently raised. Of particular concern is whether the SoDAR performs well during India's windiest season, the southwest monsoon, when rainfall is also maximized.

We obtained data for two collocated Tritons and met towers, one in Tamil Nadu (hereafter "Triton A"), with a 120m collocated met tower, and measurements during all of 2015; and one in Maharashtra (hereafter "Triton B"), with an 85m collocated met tower, and measurements from July-August 2017. To illustrate the behavior of the Triton measurements and the relative ease of the QC process, Figure 5 shows scatter plots of the Triton speed measurement (y-axis) versus the met tower speed measurement (x-axis), at sensor heights of 90 and 85m, respectively, for Triton A (left) and B (right). Regardless of the strength or quality of a particular 10-minute Triton measurement, a derived wind speed and direction are always recorded (except in rare instances of hardware or communication issues). The top row shows the scatter between the Triton and tower when no Triton QC is performed, i.e., when all Triton data is included regardless of quality. Particularly for Triton A, there are clearly many outliers in the 10-minute wind speeds that have not undergone QC. Some outliers (though not as many) also appear in the Triton B scatter plot with no QC. Table 2 shows statistical results, and again it is clear that Triton A's result is adversely affected by low-quality data, with a high bias and low R^2.

Triton's wind measurements are accompanied by other variables and parameters that can be used to filter the data with simple threshold algorithms. One parameter is appropriately named the "quality factor" (QF), ranging from 0 to 100, and is self-assessed by the Triton firmware, based on signal-to-noise ratio and the detection of background sound interference. We recommend removing all data for which QF < 90. Another such parameter is the measured Doppler vertical velocity (VV), which indicates likely rainfall if it is large and negative. Large positive values also indicate a poor wind retrieval. We recommend removing all data for which $|VV| > 1.5$ m s^{-1}. These two filters comprise the most common method of carrying out QC for the Triton data.

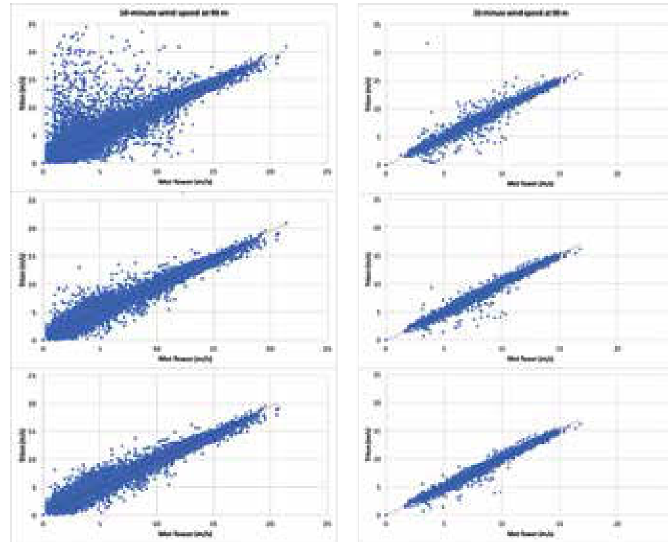

Figure 5: Comparison of two Tritons in India with Collocated Met Towers, with Three Different Levels of QC on Triton Data:

Top: No QC. Middle: Quality Factor and Vertical Velocity Threshold QC. Bottom: QF, VV, and 10-minute Ramp Threshold QC.

Triton A Quality Control	10-minute R^2	Bias (%)	Data Recovery (%)
No QC	0.88	+2.0	99.0
QF Threshold and Vertical Velocity Threshold	0.96	+0.2	90.6
QF and VV Thresholds, and Ramp Threshold	0.97	+0.2	90.0

Triton B Quality Control	10-minute R^2	Bias (%)	Data Recovery (%)
No QC	0.95	+0.6	99.9
QF Threshold and Vertical Velocity Threshold	0.97	+0.6	96.6
QF and VV Thresholds, and Ramp Threshold	0.98	+0.6	95.1

Table 2: Statistical results for each level of Triton data QC shown in Figure 5

The second row in Figure 5 shows scatter plots after the QF and VV thresholding is applied. For Triton A, most of the bias disappears, and the R^2 value increases substantially (0.88 to 0.96). There is a loss of data, of course, and in the case of Triton A, the data recovery drops to 90.6%, lower than the global average for 90m height in Fig. 5, but still a highly useful percentage of recovered data. For Triton B, the R^2 with no QC is already quite high (0.95), but increases even more (to 0.97) with standard thresholding, with very little loss of data recovery (still at 96.6%). Bias was small and remains so after thresholding. Note that Triton B's measurement period is entirely during the monsoon, so the occurrence of rainfall was either infrequent enough, or light enough in intensity, or both, as to not significantly reduce data recovery.

The third row explores one of several lesser used, but still easy to apply and potentially helpful QC methods. Here, consecutive Triton time points are compared, and if the difference (or "wind ramp") is larger in magnitude than some threshold (we used 5 m/s for Triton A, and 3 m/s for Triton B), then both time points are flagged for removal. This filtering removes single time step spikes in data that are not accurate. The lower row of scatter plots shows that this additional filtering "cleans up" the data even more compared to the met tower, with even better statistics, but at some cost to data recovery. In general, we recommend the QF/VV filters described above, but users are provided with flexibility to filter with different methods and/or thresholds to achieve their own level of comfort with the data, weighed against the value of data recovery.

Upper-Level Wind Shear

An attractive aspect of remote sensing is its ability to "see" winds at much higher altitudes than the heights of typical met towers. This is important because typical industry-standard assessment methodologies involve extrapolation of met tower measurements up to hub height (or rotor tip height). In so doing, one assumes that the wind shear profile measured over the range covered by the tower continues above the tower, but this is often not the case. Remote sensing can potentially reduce the uncertainty incurred by vertical extrapolation. The met tower collocated with Triton A is 120m in height, so this Triton/met tower pair can be used to explore two questions. First, at this site, is the shear above a typical tower height (which we'll take to be 90m) the same as the shear below that height? And, second, if they are not the same, does the Triton accurately capture this difference?

To answer these questions, we calculated the power-law shear parameter in the layers 60-90m, and 90-120m, from both the Triton and met tower measurements, at every 10-minute time point available for Triton A and its met tower. Histograms of those shear parameters are shown in Figure 6. The answer to the first question is clearly "no": looking first at only the met tower distributions (cyan-colored histograms), both the shapes of the shear distributions at the two heights, as well as the mean values, are different. The upper layer's distribution is wider and has a more pronounced double peak. It is also farther to the left, consistent with the lower mean shear (0.16 versus 0.23 in lower layer). Turning to the Triton-measured histograms (orange), these show that the answer to the second question is "yes": Triton is capturing the narrower, left-shifted, double-peaked upper layer distribution; and the two Triton-derived mean shear parameters of 0.16 and 0.22 are only slightly different than those derived from the met tower.

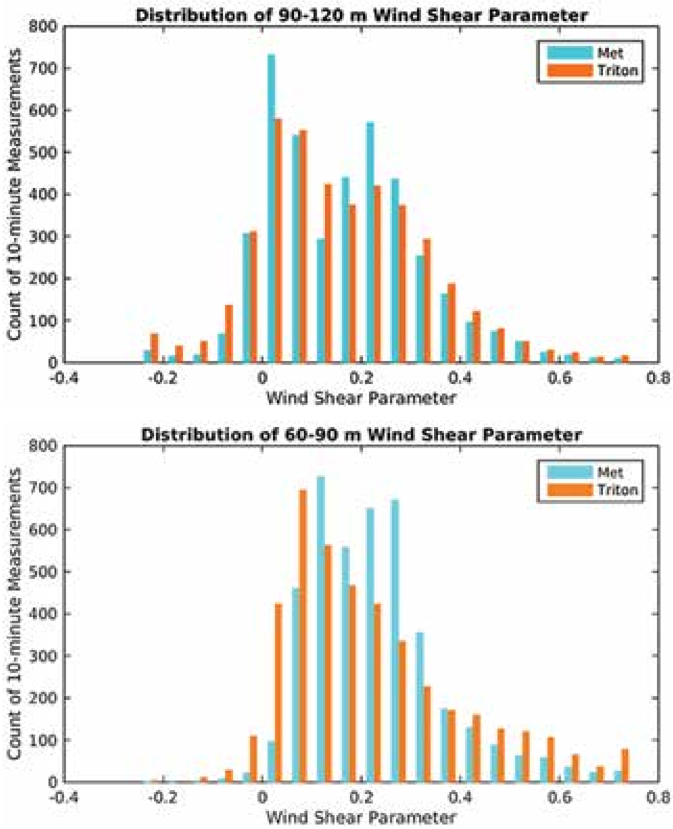

Figure 6: Distribution of 10-minute shear parameter measured by Triton A and the collocated met tower, for the lower layer (60-90 m, lower panel), and upper layer (90-120 m, upper panel)

Conclusions

The Triton Wind Profiler, a SoDAR-based remote sensing device that measures wind speed and direction up to 200 m above the ground level, has been validated in comparison to collocated met towers, both in India and across the globe.

The global validation study results indicated that, on average, Triton achieves very high data recovery at typical hub heights, and its accuracy in measuring the mean wind speed is around 1% root mean-squared error, comparable to well-constructed met towers. In addition, two Tritons deployed in India were studied in comparison to collocated met towers. The relative ease of quality controlling the Triton data was demonstrated, with significant effectiveness and improvement of statistical properties, at only a small cost in data recovery.

Furthermore, Triton performed very well during the southwest monsoon season. Data recovery seemed to suffer only very modestly from the rainfall that occurs in that season. Finally, comparisons of shear parameters measured at an upper and lower layer from both the tall tower in Tamil Nadu and the collocated Triton indicated that, at this site (and likely others as well), shear can change significantly at heights above typical met tower tops, and Triton performs well at capturing those different shear patterns at the upper heights. Overall, the results presented here engender confidence in the use of SoDAR-based remote sensing in the Indian wind industry, and should help pave the way for greater acceptance of this technology.

Reference

[1] Vaisala, 2015: Triton remote sensing systems: Comparing accuracy with collocated met towers. Vaisala white paper, available from www.vaisala.com/energy.