CFARS Site Suitability Initiative:

An Open Source Approach to Evaluate the Performance of Remote Sensing Device (RSD) Turbulence Intensity Measurements & Accelerate Industry Adoption of RSDs for Turbine Suitability Assessment

Revision history

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CFARS SCIENCE

CFARS GUIDANCE

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Industry Support for CFARS

“UL strongly supports the activity of CFARS and in particular the work done to produce this significant and useful suitability white paper. We feel that this is a very valuable industry initiative that will support a deeper understanding of the applicability of remote sensing by the careful and detailed analysis of a large number of high quality data sets. The results CFARS presents in this white paper will help to create a common understanding and foster a great acceptance by stakeholders across the whole wind industry.”
Dr Chris Ziesler, Director Advisory Services, North America, UL

“CFARS is pushing the boundary of wind resource science. Their work increases our confidence in remote sensing data, including for applications like climate suitability that previously relied nearly exclusively on meteorological mast data. CFARS’s work helps WSP provide the best possible advice to our clients, minimizing risk and maximizing project performance.“
Matthew Breakey, Team Lead, Renewable Energy Assessment, WSP

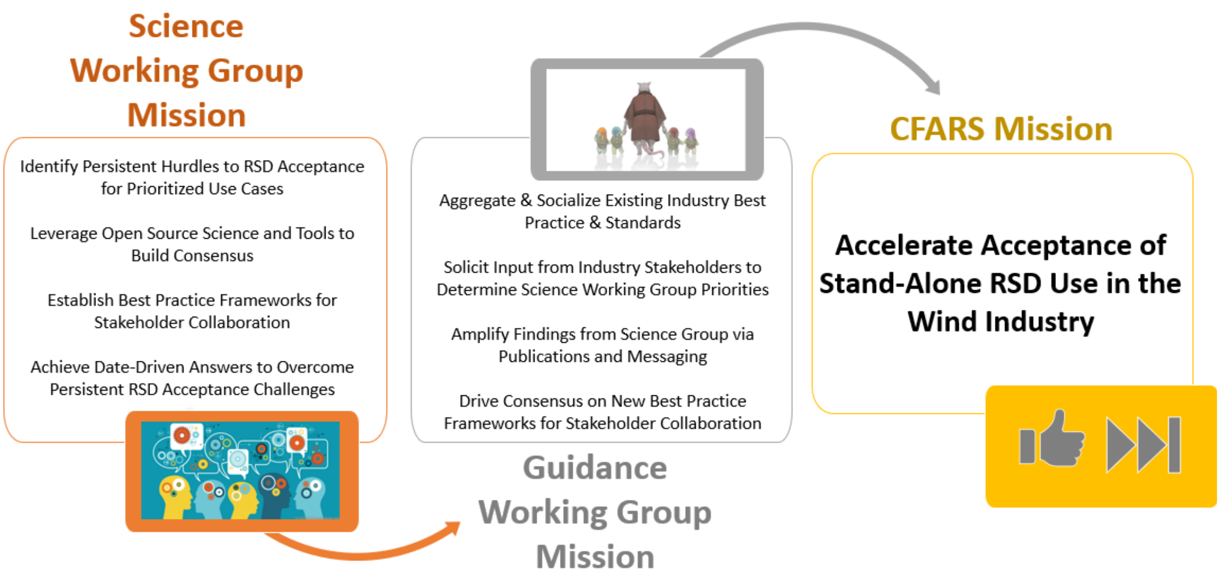
“Natural Power places great value in the work undertaken by the CFARS participants, and is pleased to be involved in the on-going effort to best leverage RSD technology in the wind industry. In this white paper, through common vision, collaboration, and intelligence sharing, the site suitability working group has brought us a step closer to realizing the potential that RSDs have to inform site conditions by defining a framework to characterize RSD turbulence behavior as compared to traditional anemometry.”
Taurin Spalding, Global Validation & Methods Manager, Natural Power

“The interest of applying lidars for measurements of site wind characteristics have increased exponentially over the last 5-10 years. DNV believe lidars will serve a role in future projects and run internal projects as well as a joint industry project with the aim to write a Recommended Practice about lidar TI measurements. DNV is one of the partners in CFARS, and we see this CFARS whitepaper as an important development in making lidar TI measurements certifiable. The open-source tool TACT will be very beneficial and will enable different stakeholders to create more reliable lidar TI data.”
Johan Olaison, Principal Specialist, DNV Renewables Certification

1 Introduction

In 2017 the industry consortium, Consortium for Advancing Remote Sensing (CFARS), launched to as an open platform for key wind stakeholders to collaborate on projects that advance the understanding of the accuracy and reliability of RSD measurements. CFARS is comprised of nearly 30 diverse wind energy stakeholders, including developers, consultants, turbine manufacturers, RSD manufacturers, and research institutions. CFARS is dedicated to bringing together wind industry stakeholders with a shared interest in closing persistent knowledge gaps that impede acceptance of RSD use. The mission of CFARS is to unlock opportunities for the wind industry to take more advantage of RSD measurement benefits and accelerate widespread adoption of RSDs for a variety of use cases throughout the wind plant lifecycle.

CFARS operates within two workstreams; the *Science* and *Guidance* working groups. The Science working group identifies open questions regarding RSD acceptance for prioritized use cases and leverages open source science and tool to advance understanding and build consensus on the best approach to achieve acceptance. The Science working group's mission is to establish best practice frameworks for stakeholder collaboration to achieve data-driven answers to overcome RSD acceptance challenges. The Guidance working group aggregates and socializes existing industry best practice and standards and solicits input from industry stakeholders, via surveys and forums, to determine the priority use cases for Science Working Group focus. In addition, the Guidance working group amplifies the findings from the Science group via publications and messaging, further driving consensus on best practice approach for accelerating RSD acceptance.



There are many benefits of RSDs underpinning the desire for greater use of RSD for wind industry applications, including safety, cost, efficiency and wind production estimate accuracy given capacity to measure at higher heights and more complex boundary layer parameters (e.g., Turbulence Kinetic Energy). Therefore, as the industry seeks to deploy RSDs in greater numbers, in more varied flow conditions, and for a wider variety of use cases, it is important that the measurements obtained from these devices are well understood and appropriate for the intended purpose(s). One important use case for wind data is that of site suitability analysis, determining the most optimal turbine for the given site conditions. One of the key variables in any site suitability analysis is turbulence intensity.

Today, a majority of the industry's understanding, along with tools deployed for modelling the relationship between turbulence and turbine fatigue loads, are derived from meteorological mast mounted cup anemometer measurements of turbulence. It is well known that RSD turbulence intensity measurements differ from cup anemometers given inherent differences in measurement principles. Therefore, until the industry forms a consensus regarding the relationship between RSD derived turbulence intensity and turbine fatigue loads directly, RSD measurements should be adjusted to produce similar results to anemometers, to avoid installation of potentially suboptimal turbines for the given site conditions.

Ideally, a TI adjustment method would be developed that permits the use of RSDs, not only in conjunction with an onsite meteorological mast, but also in the absence of any supplemental onsite measurements. Within CFARS, the **Site Suitability Subgroup (the Subgroup)** formed with the **mission to share knowledge, increase confidence, and build consensus on best practice use of ground based, vertically profiling, RSDs for onshore site suitability assessment**, both as a collocated and a standalone[1] device.

In this white paper, the results from the Subgroup's **first benchmarking analysis** of ***unadjusted* RSD to cup anemometer turbulence intensity (TI) and reference cup-to-redundant cup measurement differences are presented**. The Subgroup chose to benchmark these collocated measurements first to establish a 1) baseline understanding of the unadjusted RSD to cup measurement differences and 2) proof-of-concept for successful industry collaboration using a closed data and open method approach. Eight organizations participated in the benchmarking activity, contributing a total of 35 datasets.

Further, **this document introduces the Subgroup's forthcoming analysis**, examining the performance of *adjusted* RSD TI measurements compared to cup anemometry. The second analysis expands on the closed data and open method approach and will create the **industry's first open source tool for comparing the performance of disparate RSD TI measurements and cup anemometry, the TI Adjustment Comparison Tool (TACT).** TACT incorporates stakeholders' views on best practices for RSD TI adjustment methods, consisting of more than 15 techniques ranging from simple to advanced in complexity and cover both site-specific to global application. The Subgroup does not intend to develop new RSD TI adjustment methods and designed TACT flexible enough to input proprietary RSD TI correction methods for performance benchmarking. Further, TACT performs statistical analyses on the measurement differences and reports key TI comparison evaluation metrics that its contributors deem appropriate for informing decisions on acceptable TI bias for turbine load models. Preliminary results from this benchmarking activity using TACT will be released to the industry in the Spring 2022 and summarized in detail in a forthcoming peer-reviewed article.

Finally, to ensure the delivery of commercial value to open source science and tools generated in the Subgroup, **a best practice collaboration framework to connect RSD TI benchmarking activities with RSD TI acceptance decision-making** for site suitability assessment is introduced herein. The CFARS best practice framework *does not attempt to establish adjusted RSD TI acceptance threshold criteria*, but rather provide a platform that enables more-informed, data-driven decisions, on acceptable loads bias thresholds in a commercial setting. The **framework encourages industry stakeholders to collaborate to further refine TACT, leverage the tool to advance industry understanding of the sensitivity of turbine fatigue load models to varying TI measurements and therefore de-risks the use of adjusted RSD measurements in site suitability assessment.**

[1] Standalone means there is no onsite meteorological mast

CFARS

The CFARS Site Suitability Subgroup

$$TI\ [\%] = \frac{WS_{stdev}}{WS_{avg}}$$

The Site Suitability Subgroup (the Subgroup) aims to increase the acceptance of RSDs for turbine site suitability assessment, with a focus on turbulence intensity (TI) measurements. The classic definition of (horizontal) turbulence intensity is derived from the measurement strategy of a cup and sonic anemometer which deliver a time series of wind speed values. The TI metric used in site suitability assessment today describes how much the observed wind speed at a given height varies over a 10-minute period for a given wind speed bin.

High turbulence can generate excessive fatigue loads on major components in a turbine. This is a problem because it reduces turbine performance and energy yield, increases operation and maintenance costs related to unanticipated repairs, and potentially decreases the turbine's overall lifespan. Therefore, it is imperative that a project site's TI conditions during a pre-construction site suitability assessment are accurately measured and understood to make sure we are choosing a suitable turbine — a turbine that will not endure disproportionate fatigue loads once operational. Reliable measurements of TI are required, not only for selecting an appropriate turbine, but also to enable site suitability modelling to ensure an appropriate operating strategy for the selected turbine. This is increasingly pertinent as the industry seeks to extend and maximize turbine lifetimes.

Today, a majority of the industry's understanding, methodology, and modelling strategies for turbine site suitability assessment originate from meteorological mast mounted cup anemometer measurements of wind speed. While trusted cup anemometry remains invaluable, the familiarity and reliance on cup anemometry have been barriers to wide-spread use of RSDs. However, the growing demand to meet new market requirements, coupled with more than a decade of proven RSD wind measurements, is motivating broad industry desire and momentum towards integrating more agile and advanced measurement techniques from RSDs into many elements of wind project development and operation, including site suitability assessment. Further, in addition to measuring the traditional horizontal TI metric described above, RSDs can measure a wealth of parameters across the line-of-sight beams and spectral analysis may be helpful to characterize atmospheric flow beyond what a cup or sonic anemometer can measure.

Wind turbine hub heights and blade lengths have increased dramatically over the last decades, a trend widely expected to continue. These taller turbines increase the cost to install and maintain hub height meteorological masts to gather the required wind measurements for wind energy development and operations. RSDs are proven devices that can reliably and accurately [1-2] make measurements for these high hub heights and heights across the whole turbine rotor.

Another important industry motivation is that of safety. Safety is critical to the wind power industry. It should no longer be acceptable to use a higher risk method of wind measurements (meteorological mast) as standard, when a safer, lower risk, method (RSD) can also give technically acceptable results.

Specifically, in relation to site suitability, there are a number of relevant considerations for turbine safety, and certification:

1. Wind turbines are often operated close to the site-specific conditions. Thus, uncertainty and bias originating from a site suitability analysis based on RSD TI measurements could lead inadvertently to the breaching of fatigue load design limits of a wind turbine generator (WTG) and thus component damage and increased failure rates, jeopardizing the WTG's structural integrity and thus resulting in safety issues.
2. Turbines are developed, designed, and verified (prototype wind and load measurements) against anemometer turbulence intensity measurements and the loads calculated based upon these

turbulence measurements. Any change in measurement technology and differences in turbulence intensity could lead to a 'misalignment' or bias in the design load calculations which are the basis for a turbine certification.

3. There could be a misalignment in turbulence intensity assumptions on a project level. Turbines are designed and certified against anemometer TI. If, as part of a wind farm certification or due diligence, on-site RSD TI data are being used, the TI prediction method needs to be sufficiently precise to produce a TI level comparable with the measurement technology (anemometers) used in the actual design of the turbine.

Therefore, while it is currently not broadly accepted to deploy standalone RSD for all sites or for all measurement purposes, the mission of CFARS remains: to increase the acceptance of RSDs, by demonstrating their validity across the full life cycle of wind project development and specifically, in the case of this whitepaper, for site suitability.

Nonetheless, two compounding challenges lie ahead on the road to RSD derived turbine site suitability decisions. The first challenge is the fundamental difference between cup anemometer and RSD wind measurement principles. The RSD measures across a *volume of air* (assuming homogenous flow through this measurement volume and can therefore be adversely affected by complex flows), while cups measure at a single point. As a result, cup anemometer and RSD TI measurements will inevitably vary, even when collocated. Therefore, while both cup anemometer and RSDs indicate TI, the measured turbulence fundamentally differs hence the direct comparison between the two observations requires more care. The inherent differences between these two instrument types also highlights some advantages for remote sensing devices. Although both cup anemometers and RSDs are influenced by vertical wind speed, an RSD can isolate this component from the TI measurement, while a cup anemometer cannot decompose velocity vectors.

The second, perhaps more formidable challenge, is centered on *what the industry does about the inherent cup to RSD TI measurement differences*. One solution to this challenge is to adjust RSD reported TI values to fit well to the ones reported by a cup or sonic anemometer. Another possible way forward would be to advance understanding of the relationship between RSD volumetric TI and turbine design parameters/ suitability, which in turn, would enable refinement of current turbine fatigue models to receive RSD measurements directly. The Subgroup agreed to begin by **tackling open questions regarding best practice RSD TI adjustments for onshore site suitability assessments from ground based, vertically profiling RSDs first, both as co-located and standalone devices, since it is a low-hanging fruit approach that the industry has already suggested as acceptable.**

Finally, the Subgroup continues to work closely with other industry site suitability workstreams, such as the IEA Task 32 and the DNV Joint Industry Project (JIP) Lidar Measured TI, to ensure the learnings amongst all entities are shared and that maximum value is generated towards the common objective to advance understanding of RSD use for site suitability.

2 Methods

2.1 Data Collection

To benchmark the TI differences, 35 datasets were collected from 8 organizations. Of these 35 datasets, 29 consisted of 10-minute data from two anemometers and an RSD measurement, all collocated at the same height. The remaining 6 datasets had data from two anemometers only. Each organization filtered their own datasets for RSD measurement quality, sensor plausibility, icing, and met tower shading.

The Subgroup's first iterations of an open source tool[2] allowed each member to locally process their own filtered, collocated datasets. For this analysis the tool enabled the computation of binned error statistics between different TI measurements with a consistent analysis methodology and a standardized output. The Subgroup results were generated by aggregating each organization's output.

The group datasets include:

- 4 anemometer types, 2 lidar types, and 1 sodar
- Concurrent measurement heights ranging from 30 m to 139 m
- Met tower to RSD collocation distances ranging from 0 m to 130 m
- Simple, moderate, and complex terrain classes[3]
- 8 regions in North America and 3 locations in Europe
- **Unadjusted lidar and sodar measurements** directly output from the device (i.e., no post-processed adjustment methods applied to any measurements)

Subgroup data providers are at liberty to provide any dataset for analysis, although it was highly encouraged to have at least 3 months of collocated measurements. The datasets used for this analysis included a variety of anemometer model types and mast configurations. For each dataset a set of metadata was also provided in order to understand the likely quality of the datasets provided and the potential for additional bias. The metadata includes information on IEC mounting compliance, the anemometer model, the anemometer class and data filtering actions taken. This information made it possible to determine the sensitivity of the results to these and several other factors. In short, only those datasets that met IEC compliance were used to generate the results described herein.

There remains a need for more data to evaluate RSD TI adjustment techniques in the full range of wind energy site conditions. In particular, the sodar datasets are too small to draw definitive benchmarking conclusions in this report.

Finally, over the past two years, the Subgroup adopted an iterative approach to its analyses, in which learnings from initial tests motivated new research questions and evolved its testing strategy. Details on the Subgroup's upcoming second benchmarking exercise investigating the sensitivity of a generic turbine loads model output to *adjusted* RSD TI compared to cup anemometers and is presented in more detail in Section 4.

[2] https://github.com/CFARS/site_suitability_tool

[3] The classification of sites can be subjective and a different, data-based, approach to site classification will be used in the Subgroup's second benchmarking exercise and presented in a forthcoming white paper.

2.2 Analysis

The methodologies and metrics used in the benchmarking tests for all 35 project datasets are described in this section with reference to and the plotting of an example dataset ("the example dataset") for illustrative purposes. The example dataset contains wind speed measurements from 2 cup anemometers and 1 RSD at the same measurement height and concurrent in time. The example dataset is comprised of filtered 10-minute data over a period of 4 months. This dataset has 10 channels as shown in Figure 1 below. The first cup anemometer in each dataset, as in this example dataset, is defined as the reference anemometer i.e., the truth measurement (WS_Cup1_Avg). Each wind speed measurement source (Cup 1, Cup 2, RSD) has an associated attribute for wind speed average, wind speed standard deviation, and calculated TI as depicted in the column header in Figure 1.

Figure 1: Timeseries Subset of the Example Dataset

Timestamp	WD_Avg	WS_Cup1_Avg	WS_Cup1_Std	TI_Cup1	WS_Cup2_Avg	WS_Cup2_Std	TI_Cup2	WS_RSD_Avg	WS_RSD_Std	TI_RSD
2/12/2018 10:10	256.7	7.03	1.09	15.5%	6.91	1.10	15.8%	7.12	1.25	17.6%
2/12/2018 10:20	257.3	6.61	1.29	19.5%	6.65	1.23	18.5%	7.19	1.47	20.4%
2/12/2018 10:30	258.3	7.12	1.20	16.9%	7.12	1.20	16.8%	7.14	1.57	22.0%
2/12/2018 10:40	260.0	7.11	1.08	15.2%	7.13	1.03	14.5%	6.95	1.33	19.1%
2/12/2018 10:50	256.9	7.01	1.34	19.2%	6.97	1.34	19.2%	7.02	1.52	21.7%
2/12/2018 11:00	259.7	6.90	1.23	17.8%	6.93	1.21	17.5%	7.08	1.41	19.9%

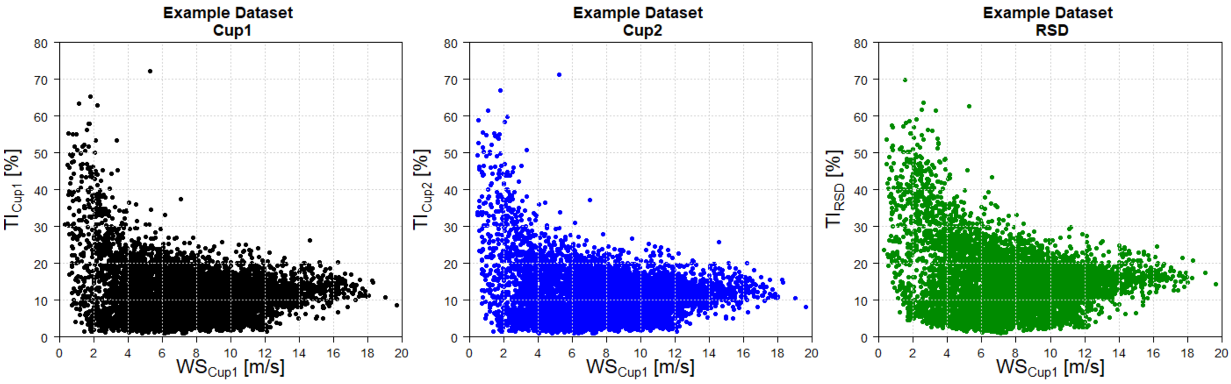
The TI for each 10-minute timestamp is calculated by

$$TI\ [\%] = \frac{WS_{stdev}}{WS_{avg}} \quad (1)$$

where TI is expressed as a percent, its most common form.

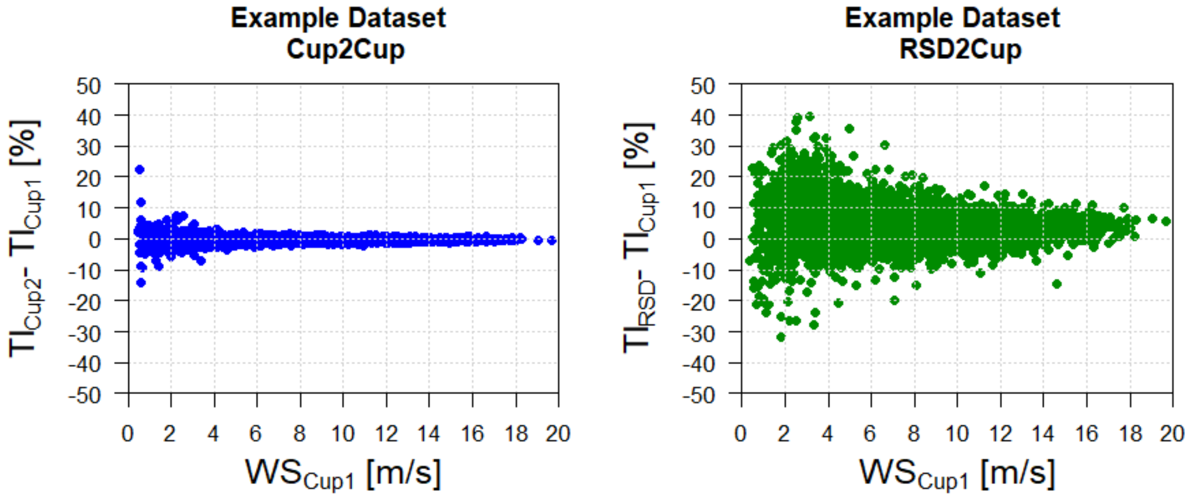
A common visualization of the example data, showing TI from the three measurements as a function of the reference wind speed is displayed in Figure 2 (Cup1).

Figure 2: Scatter plot of TI Data for the Example Dataset



More informative however, is the direct *comparison of various TI measurements*. The simplest metric for this comparison is **TI difference**. The reference wind speed (Cup1) is considered our baseline, so using the data shown in Figure 2, we can calculate the difference between TI observed by Cup 2 and by Cup 1 (TI_{Cup2} - TI_{Cup1}, labelled “Cup2Cup”) and the difference between TI observed by the RSD and by Cup 1 (TI_{RSD} - TI_{Cup1}, labelled “RSD2Cup”) for every 10-minute timestamp.

Figure 3: Scatter plot of TI Data for the Example Dataset



From Figure 3 it is evident that for this example dataset, the RSD-to-cup TI differences are greater than the cup-to-cup differences with RSD-to-cup comparison results showing a more pronounced deviation from zero within each wind speed bin; nonetheless both sets of TI differences are non-zero, although the mean TI difference across all wind speed bins is consistently positive for RSD-to-cup comparison (3.2 %) and closer to zero for the cup-to-cup comparison (-0.2 %).

Finally, a dynamic bin count threshold was used, based on the IEC 12-1 recommended sensitivity analysis bin threshold formula, to determine the minimum number of data points required for a bin to be included in the analysis and calculated for each project. Essentially, the formula requires that the minimum number of samples per bin are 50% of the number that represents an even distribution of all samples over all bins.

A dynamic sample size threshold (n_i) was calculated as:

$$n_i = N / 2n_b \quad (2)$$

where,

n_i is the minimum number of samples required per bin for a given data set

N is the total number of data points

n_b is the number of bins according to the distinct wind speed range available in each project data set

2.2.1 Mean Bias Error (Accuracy) and Root Mean Square Error (Precision)

A key aim of this work is to benchmark the difference between unadjusted RSD and cup TI measurements. The Subgroup chose two basic statistical metrics to support this goal. First, ***binned*** **TI Mean Bias Error** (MBE), hereafter referred to as TI MBE, is used to measure the *average TI difference between two datasets*, which gives overall bias or systematic error. When using MBE, the error direction, indicating an over prediction versus an underprediction, is preserved but muted in the process of averaging. MBE can be described as a measure of *accuracy* (i.e. representative of closeness to the truth). Figure 4a shows an example of high accuracy results (i.e., MBE close to 0) and Figure 4b shows an example of low accuracy results (i.e., MBE farther from 0), despite both panels having the same precision (spread of the observed data).

Figure 4:

Figure 4a Higher Accuracy = Mean is close to truth

(i.e., MBE close to 0)

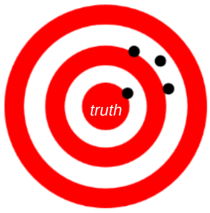


Figure 4b Lower Accuracy = Mean is farther from truth

(i.e., MBE far from 0)

The equation for MBE is shown below. In this analysis, a value of zero for MBE at a given wind speed bin indicates that on average, the two TI measurements are indistinguishable. Oftentimes, MBE is a single number, though due to the importance of resolving the results of this analysis by wind speed bin, TI MBE is calculated for each wind speed bin i such that:

$$TI\ MBE_i\ [\%] = \frac{1}{N_i} \sum_{n=1}^{N_i} TI_{comp,n,i} - TI_{ref,n,i} \tag{3}$$

where,

TI_{comp} is the comparison quantity (TI_{Cup2} or TI_{RSD})

TI_{ref} is the reference quantity (TI_{Cup1})

i is the wind speed bin (wind speed bin is center averaged with a size of 1 m/s)

n is the individual datapoint (timestamp)

N is the total number of data points in wind speed bin i

Next, the **TI Root Mean Square Error (RMSE)** is used in this study to measure the *average TI precision* between two datasets, where the direction of the error is not considered. Strictly speaking, precision refers to the repeatability of data measurement. Herein, because in a broad scale, we are comparing datasets with different methodologies under different measurement conditions, precision in this study represents the random error or the statistical variability between instruments, which can be described by the spread of the TI errors (i.e., RMSE). Figure 5a shows an example of high precision (i.e., low RMSE) and Figure 5b shows an example of low precision (i.e., high RMSE), despite both figures illustrating the same average accuracy.

Figure 5:

Figure 5a Higher Precision = Lower Spread

(i.e., lower RMSE)

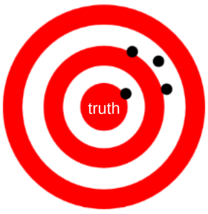


Figure 5b Lower Precision = Higher Spread

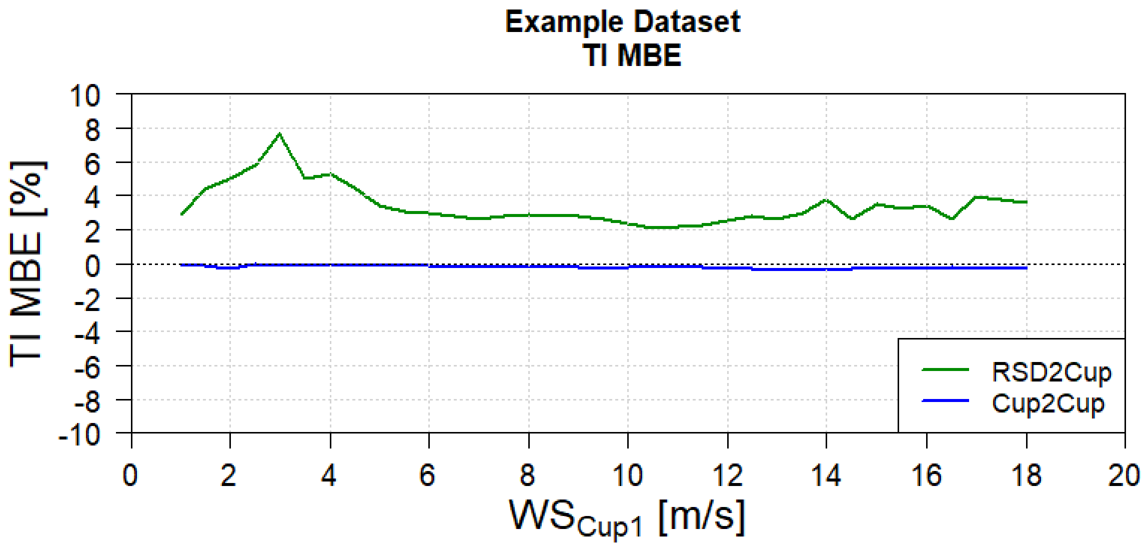
(i.e., higher RMSE)

The equation for TI RMSE is shown below, where we calculate TI RMSE for every wind speed bin i following:

$$TI\ RMSE_i\ [\%] = \sqrt{\frac{1}{N_i}\sum_{n=1}^{N_i}\left(TI_{comp,n,i} - TI_{ref,n,i}\right)^2} \quad (4)$$

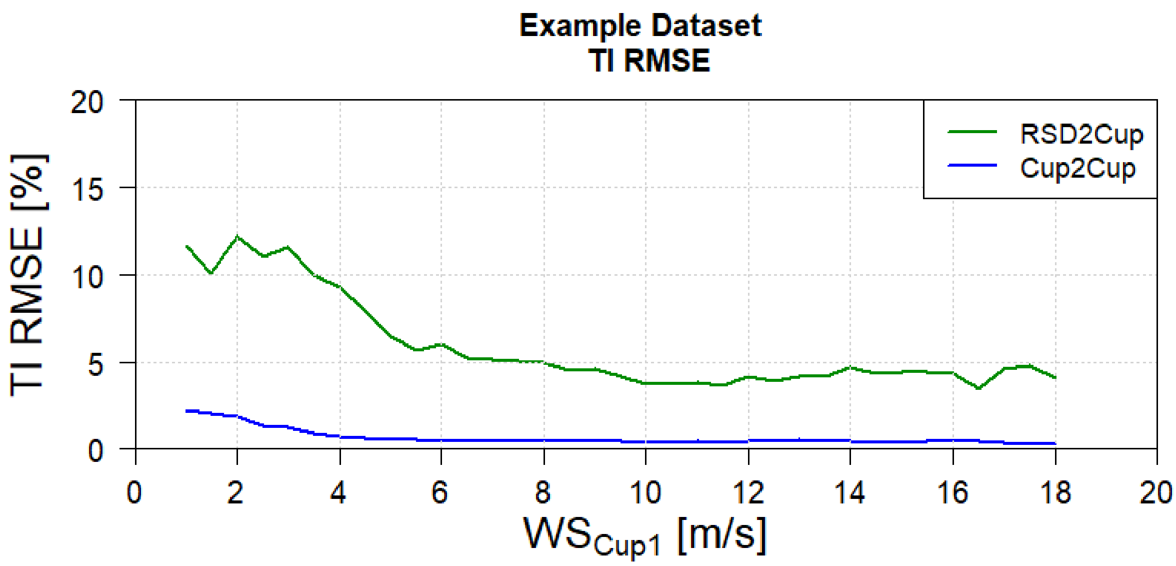
Considering again the example dataset, **TI MBE** is calculated by binning the data from the scatter plot shown in Figure 2. TI MBE results for the example dataset demonstrate higher accuracy for the cup-to-cup results (near-zero MBE) compared to RSD-to-cup results (larger MBE, further from zero) (Figure 6). Recall that Cup 1 is always considered the reference measurement in this study, and either Cup 2, lidar, or sodar are the comparison measurement. It is also worth noting that the RSD-to-cup MBE in the Figure 6 example is positive across all wind speeds, meaning there is a consistent overestimation in TI bias compared to the reference cup.

Figure 6: TI Mean Bias Error (MBE) for the Example Dataset



The **TI RMSE** results from the example dataset demonstrate higher precision for the cup-to-cup results (lower RMSE) compared to RSD-to-cup (higher RMSE) (Figure 7).

Figure 7: Root Mean Square Error (RMSE) for the example Dataset



It is helpful to analyse MBE and RMSE together because they illustrate different, yet complementary, information about TI measurement comparisons. MBE depicts the closeness to the truth on average (Figure 8a), and RMSE represents the average closeness of the results to each other and to the truth (Figure 8b). For instance, in a dataset of TI error, half of the data are above the mean and half of the data are below the mean. In this case, the dataset is highly accurate on average (i.e., MBE = 0), but the spread of the data indicates noticeable statistical variability (i.e., RMSE > 0). Depending on how the analysis is presented and interpreted, these features in the data could lead to a higher uncertainty or lower confidence in the dataset overall.

The goal is to target both low MBE and low RMSE (i.e. adequate accuracy and adequate precision as shown in Figure 8c)

Figure 8:

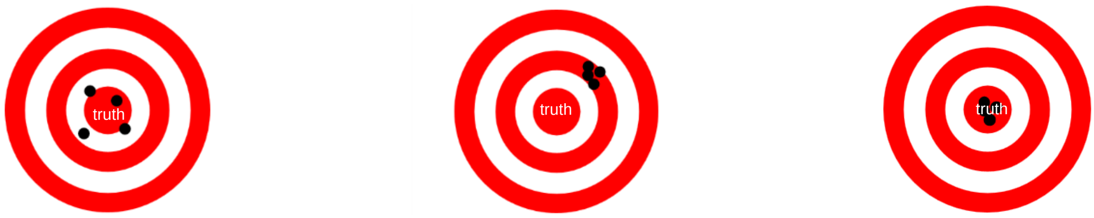


Figure 8a Low MBE and High RMSE **Figure 8b High MBE and Low RMSE** **Figure 8c Low MBE, Low RMSE**

2.2.2 Representative TI

In addition to quantifying the concurrent TI measurements' accuracy and precision, the Subgroup is interested in understanding the magnitude of differences in Representative TI as it is used explicitly in making decisions regarding turbine suitability at a given site. Representative TI is defined as the value that marks the approximate 90th percentile of the TI distribution. In other words, there is a 90% probability that the measured TI will be less than or equal to the representative TI.

Returning to our example dataset, consider now the wind speed and TI data that has been binned by WS_Cup1. For each wind speed measurement (Cup 1, Cup 2 and RSD), we have WS_Avg, WS_Std, TI_Avg, and TI_Std. A sample binned data set is shown in the Table 1 below.

Table 1: Binned Results of the Example Dataset

		Cup 1				Cup 2				RSD			
WS_bin	BinCount	WS_Avg	WS_Std	TI_Avg	TI_Std	WS_Avg	WS_Std	TI_Avg	TI_Std	WS_Avg	WS_Std	TI_Avg	TI_Std
3.5	28	3.62	0.07	12.79	4.76	3.65	0.10	11.46	4.95	3.74	0.14	12.71	5.38
4.0	63	4.00	0.14	11.86	4.87	4.04	0.17	10.79	4.92	4.12	0.21	11.71	5.73
4.5	80	4.51	0.14	12.40	5.77	4.54	0.16	11.74	5.94	4.63	0.18	12.51	6.38
5.0	91	4.98	0.14	12.76	5.84	4.99	0.14	12.36	6.25	5.08	0.20	13.30	6.84
5.5	93	5.49	0.13	12.54	6.19	5.51	0.14	12.35	6.65	5.59	0.22	13.51	7.20
6.0	59	5.96	0.13	13.76	6.03	5.99	0.16	13.41	6.18	6.08	0.23	14.44	6.72
6.5	62	6.46	0.14	15.63	5.60	6.44	0.15	15.73	5.78	6.57	0.20	16.89	6.70

From the binned data for an individual project, we can easily calculate **representative TI** [3], by combining the binned TI_Avg and TI_Std data using:

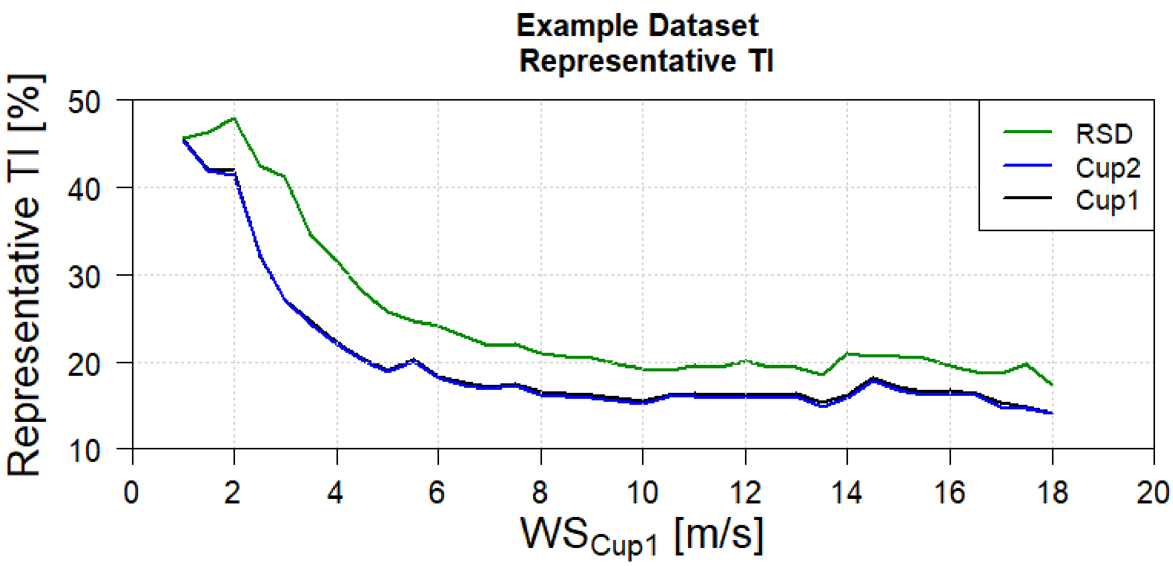
$$Representative\ TI_i\ [\%] = TI_{avg,i} + 1.28 \cdot TI_{std,i} \quad (5)$$

where i is the wind speed bin.

Representative TI can be defined in this way as the turbulence intensity measurements within each wind speed bin are assumed to be normally distributed.

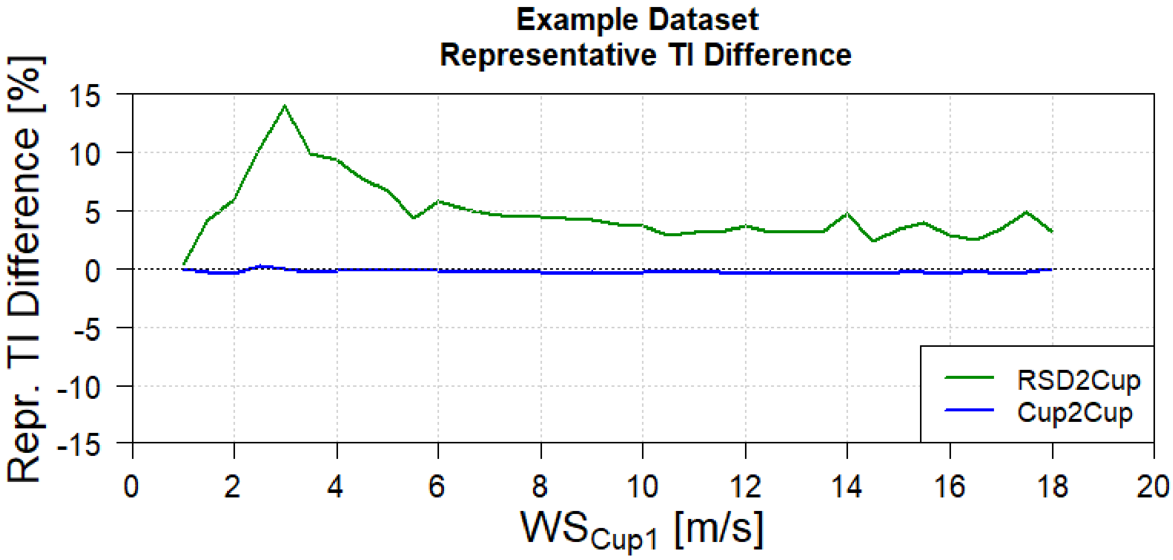
The representative TI curves for the three wind speed measurements from the example dataset (Cup 1, Cup 2, RSD) are displayed in Figure 9. These results show that the two cup anemometers measure very similar representative TI, while the RSD reports a higher representative TI across all wind speed bins. Since the data are from the same site and the dataset is concurrent, we can conclude that the measured representative TI is dependent on wind speed measurement device. It is important to calculate and evaluate representative TI across wind speeds because it is one of the direct inputs to loads models.

Figure 9: Representative TI Curves for Cup 1, Cup 2, and RSD for the Example Dataset



In addition, it is important to evaluate the difference in concurrent cup and RSD representative TI curves. The difference between the representative TI value in each bin for the example dataset, again using Cup 1 as the reference measurement, is shown in Figure 10.

Figure 10: Representative TI Difference for the Example Dataset



3 Benchmarking Cup and *Unadjusted* RSD TI Measurement Differences

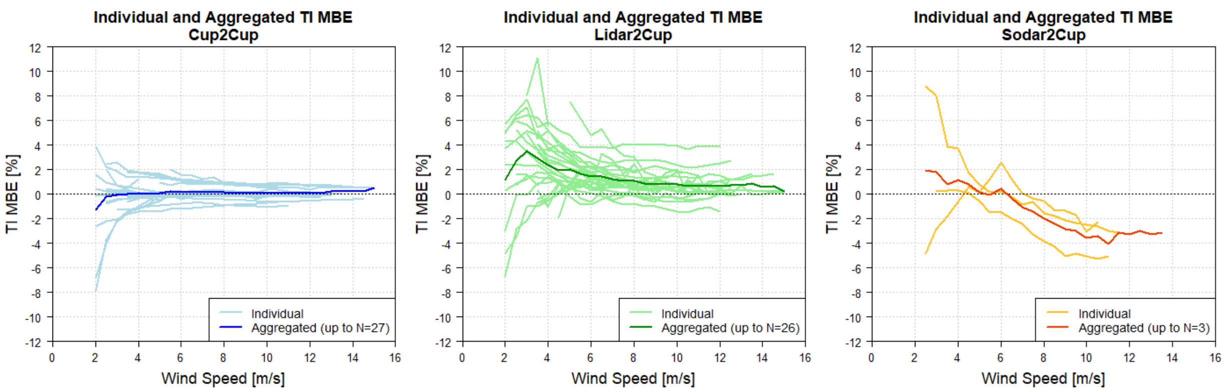
The difference in turbulence intensity measurements between two sensors or two discrete representations of TI (i.e., adjusted vs. unadjusted) manifests as a difference in the characterization of turbulence intensity mean and standard deviation in each windspeed bin at a given project site. Because a loads model ingests these binned statistics, the model output from two different TI distributions as input will vary based on the magnitude of bias between the two TI distributions in each bin. It is also important to note that differences in TI within each wind speed bin can impact loads differently depending on both the project site and specific turbine model. Therefore, the definitive acceptance of TI measurements relies on an evaluation based on a specific turbine model and the statistical representation of the TI distribution coupled with the site wind speed distribution as input to a specific load model. For example, for one turbine, a relatively high TI bias in a low wind speed bin may lead to a higher error in the overall loads than another turbine with a lower percentage of overall power production in that wind speed bin.

3.1 Aggregated TI MBE Results

For the comprehensive results of the benchmarking exercise, all 35 datasets compiled by the Subgroup were leveraged to understand the *magnitude* of concurrent TI measurements' MBE (i.e., difference or accuracy), and RMSE (i.e., precision or repeatability) and the dependence of these metrics on sensor type. Each project has an associated TI MBE curve for the cup-to-cup comparison, and all but six projects have an associated TI MBE curve for the RSD-to-cup comparison.

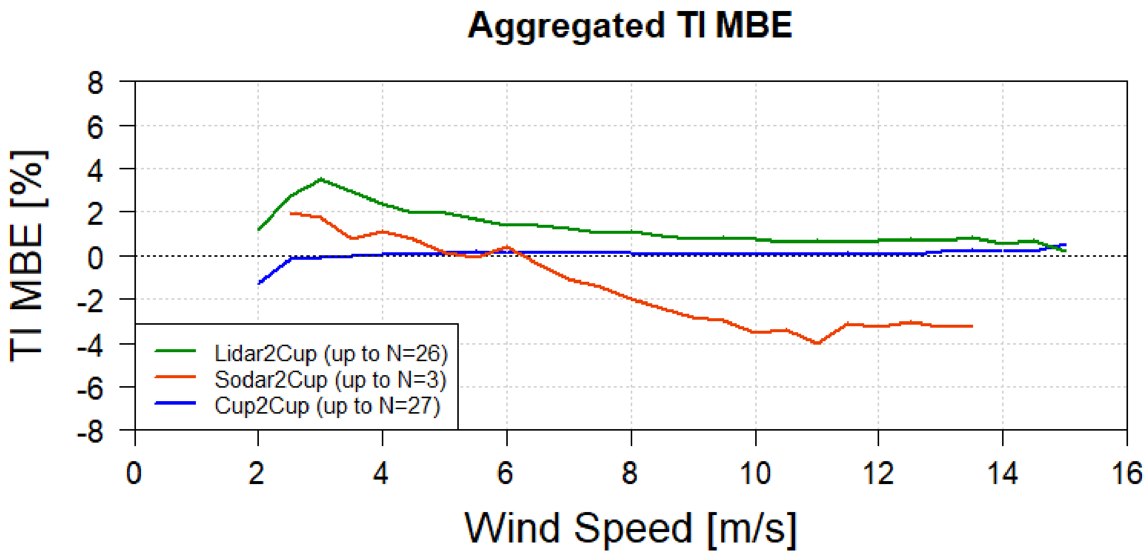
Individual project TI MBE and the binned average TI MBE across the entire CFARS dataset (i.e., **Aggregated TI MBE**) are compared in Figure 11. Because not all projects have data for every wind speed bin, the project count included in the average for the aggregated result varies by wind speed. In other words, the Aggregated TI MBE is calculated as the average across all projects *with available data in that bin*.

Figure 11: Individual Project and Aggregated TI MBE for cup-to-cup, lidar-to-cup, and sodar-to-cup. The example dataset presented earlier would represents just one of the individual light-coloured lines.



The same aggregated results as above are shown in Figure 12, now on the same axis. This plot shows the first *summary of key results from the benchmarking exercise*.

Figure 12: Aggregated TI MBE



Aggregated TI MBE for cup-to-cup, lidar-to-cup, and sodar-to-cup. Note that there are only 3 sodar datasets, all for a single sodar model (Triton). *RSD measurements are unadjusted.* Given the small sample size, the fact datasets were cleaned based on each participants' best practices and represent a mix of simple to complex terrain, broad conclusions from the results within should not be drawn.

Focusing on the more important wind speed bins for energy capture, 4-12 m/s, the aggregated cup-to-cup MBE is near-zero at 0.04-0.20% across the wind speed range (Table 2). Because the result is consistently positive, this means Cup 2 slightly overestimates the TI compared to Cup 1. For the full set of aggregated results by wind speed bin, see **Error! Reference source not found.** in the Appendix.

Table 2: Aggregated TI MBE for comparison at the 4-12m/s bin range. RSD measurements are unadjusted.

Range of Aggregated TI MBE for 4-12 m/s			
	Cup2Cup	Lidar2Cup	Sodar2Cup
Min	0.04	0.65	-4.03
Max	0.20	2.40	1.13

The cup-to-cup comparison includes mostly sites with two different cup anemometer models (23 out of 27), which results in anticipated anemometer to anemometer differences. The MBE is in some instances higher for individual projects (up to 2%) than the aggregate values (Figure 11).

The lidar-to-cup MBE is between 0.65-2.40% for the same wind speed range (demonstrating lidar TI overestimation), with a trend of improving accuracy as wind speeds increase. The sodar-to-cup MBE has a different trend, with positive MBE up to 1.13% for wind speeds less than 6 m/s and negative MBE up to - 4.0% for wind speeds above 6 m/s.

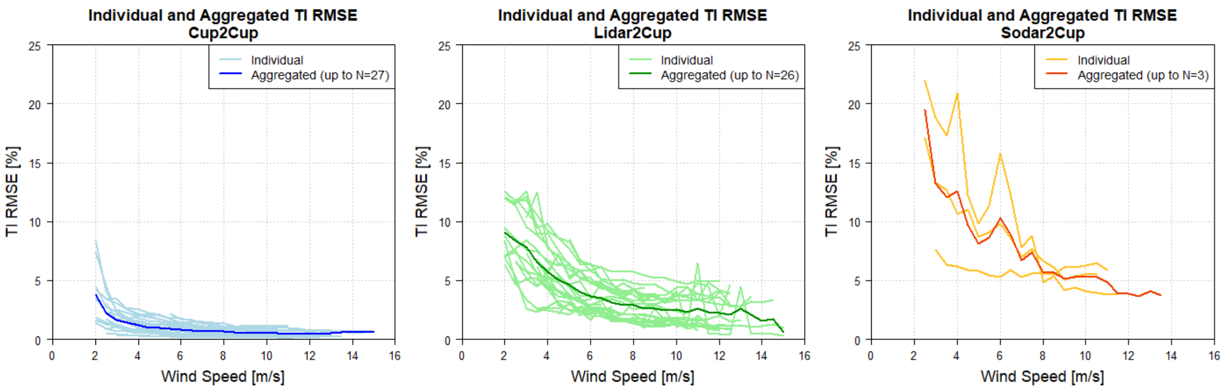
It was expected that the MBE would be higher for the lidar-to-cup and sodar-to-cup comparisons due to inherent differences in measurement principles.

Both lidar and sodar tend to strongly overestimate TI at low wind speeds and sodar tends to strongly underestimate TI at high wind speeds. Tests were conducted with only 3 sodar (Triton) datasets, so strong conclusions cannot be drawn from the small sample size.

3.2 Aggregated TI RMSE Results

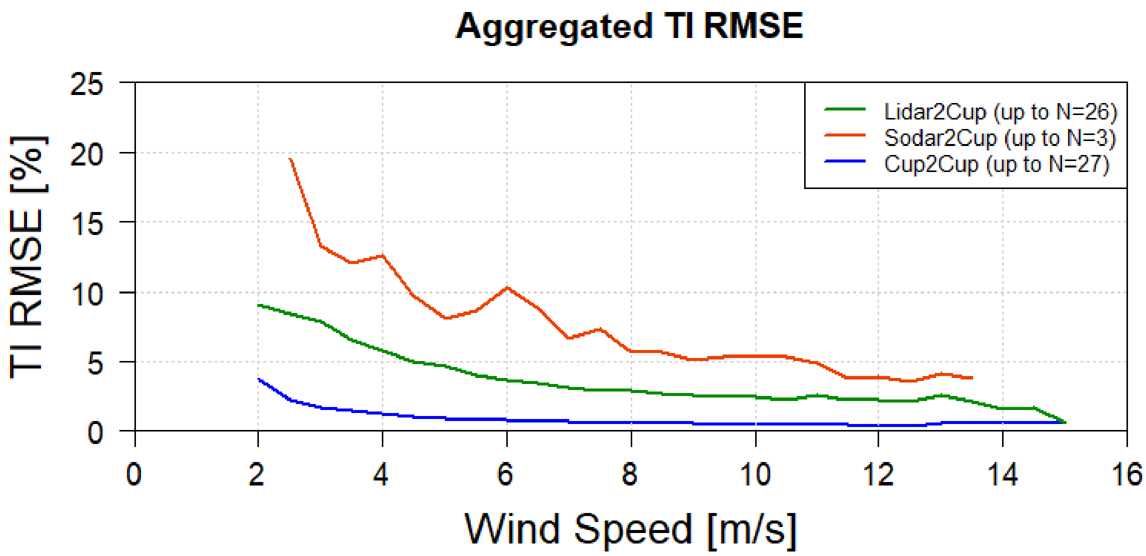
Figures 13 and 14 are structured the same way as Figures 11 and 12 for TI MBE, but instead show the Individual and Aggregated TI RMSE metric.

Figure 13: Individual Project and Aggregated TI RMSE for cup-to-cup, lidar-to-cup, and sodar-to-cup. *RSD measurements are unadjusted.*



This plot shows the second key result from the benchmarking.

Figure 14: Aggregated TI MRSE for cup-to-cup, lidar-to-cup, and sodar-to-cup. *RSD measurements are unadjusted.*



Again, focusing on the wind speed range 4-12 m/s, the aggregated cup-to-cup RMSE result is again quite low (favorable precision) at 0.43-1.23% across the wind speed range (Table 3). The lidar-to-cup RMSE is larger, between 2.21-5.77% for the same wind speed range, and the sodar-to-cup RMSE is largest, between 3.85-12.59%. All comparisons have a trend of improving precision as wind speeds increase. Nonetheless, given the small sample size, the fact datasets were cleaned based on each participants' best practices and represent a mix of simple to complex terrain, broad conclusions from the results within should not be drawn.

Table 3: Aggregated TI RMSE for comparison at the 4-12 m/s bin range. RSD measurements are unadjusted.

Range of Aggregated TI RMSE for 4-12 m/s			
	Cup2Cup	Lidar2Cup	Sodar2Cup
Min	0.43	2.21	3.85
Max	1.23	5.77	12.59

3.3 Representative TI Results

Figure 15 and Figure 16 below show the representative TI results, as defined in section 2.2.2, now aggregated across all projects.

Figure 15: Individual Project and Aggregated Representative TI for cup-to-cup, lidar-to-cup, and sodar-to-cup. *RSD measurements are unadjusted.*

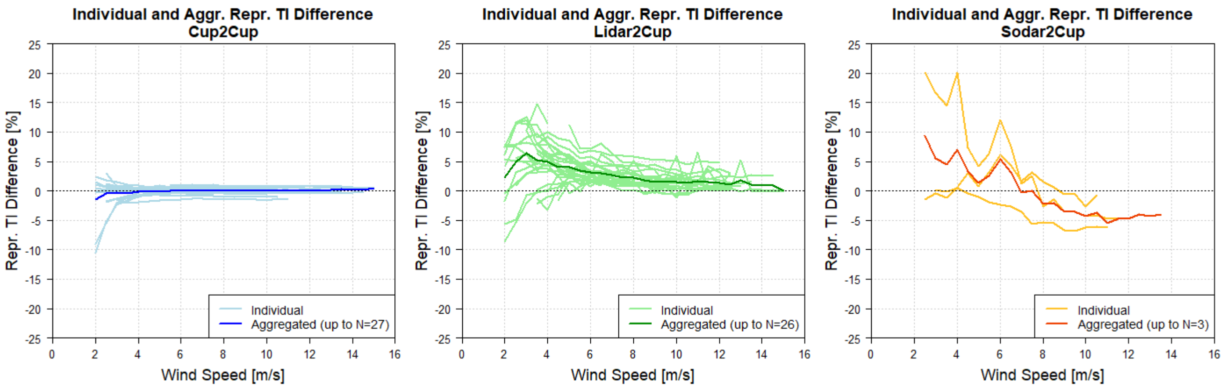
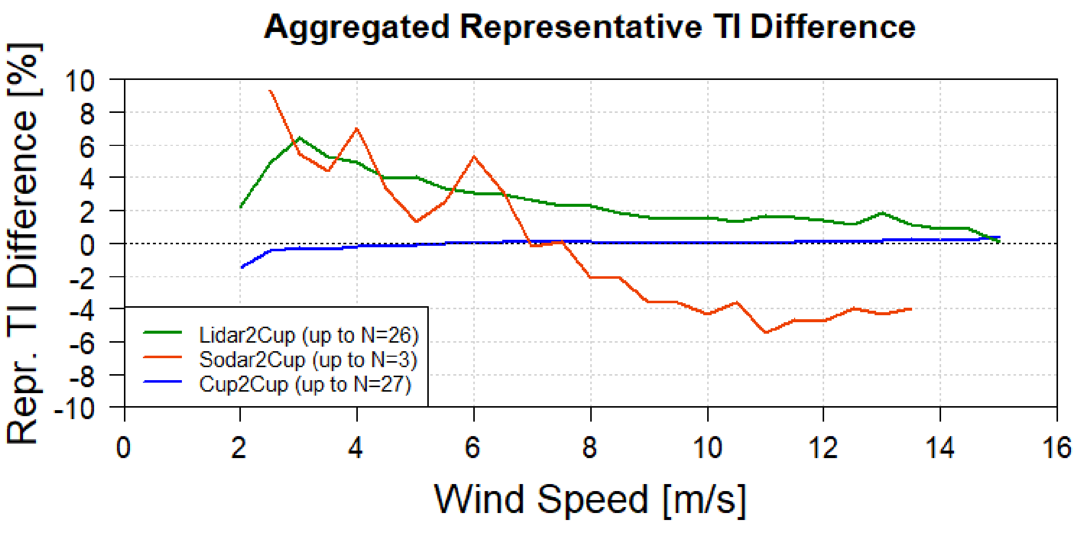


Figure 16: Aggregated Representative TI Difference for cup-to-cup, lidar-to-cup, and sodar-to-cup. *RSD measurements are unadjusted*.



Within wind speed range 4-12 m/s, cup-to-cup aggregated representative TI difference ranges from -0.18 to 0.10% while aggregated representative TI difference for lidar-to-cup and sodar-to-cup exhibit larger differences (Table 4). The lidar-to-cup aggregated representative TI difference is positive across all wind speed bins while the sodar-to-cup aggregated representative TI difference switches from positive to negative as wind speed surpasses 7 m/s.

Table 4: Aggregated Representative TI Difference for comparison at the 4-12 m/s range. RSD measurements are unadjusted.

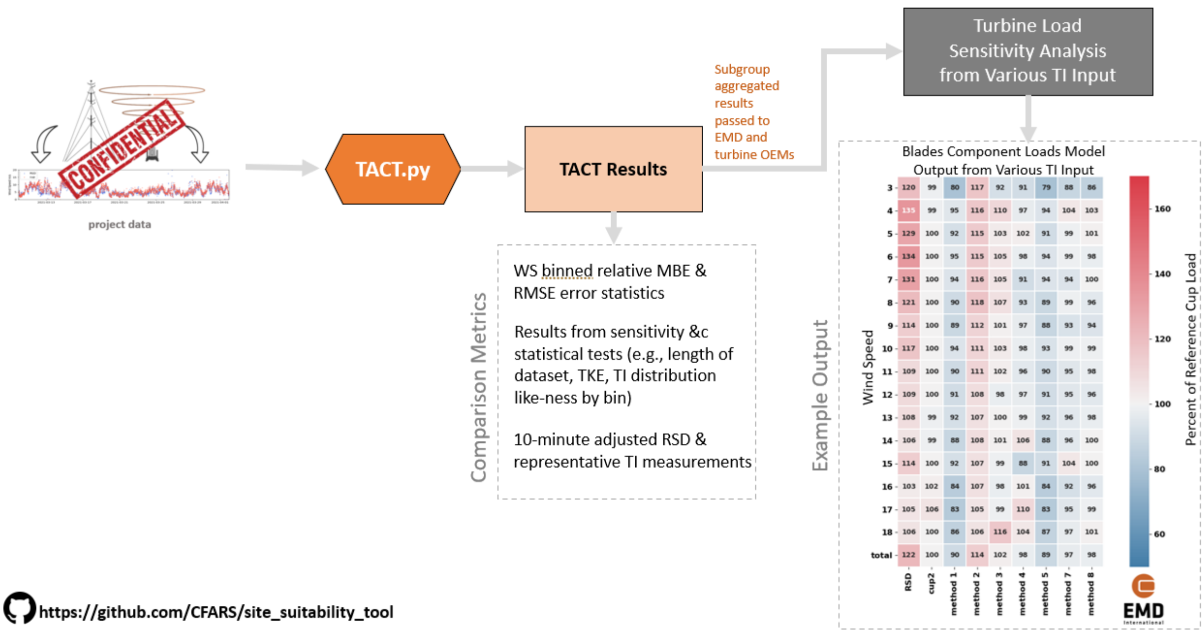
Range of Aggregated Representative TI Difference for 4-12 m/s			
	Cup2Cup	Lidar2Cup	Sodar2Cup
Min	-0.18	1.30	-5.43
Max	0.10	4.92	7.06

While differences between cup and unadjusted RSD TI measurements are expected, benchmarking the magnitude of the variation is a helpful starting point when considering the possible impact on turbine fatigue load model output and the performance targets of RSD TI adjustment methods.

4 Upcoming Analysis: Benchmarking Cup and Adjusted RSD TI Measurement Differences with Open Source TACT

As a complementary next step to the results presented herein, the Subgroup will generate **aggregated statistics on the magnitude of *adjusted* RSD-to-cup TI differences** using the **industry's first open source tool** for comparing the performance of disparate RSD TI measurements and cup anemometry, the TI Adjustment Comparison Tool (TACT). This analysis will utilize an expanded global dataset of over 40 collocated RSD and cup measurement datasets derived in simple to complex terrain. Users can run TACT on their local computer by downloading the source code from the GitHub repository and completing a configuration template that allows the script to understand the user's unique dataset.

Figure 17: Schematic of the Subgroup's upcoming analysis using TACT.



TACT incorporates more than 15 RSD TI adjustment methods, based on stakeholders' feedback on best practice. The RSD TI adjustment methods included range from simple to advanced, such as slope and offset adjustments, machine learning models, and raw 1 Hz physical and spectral based corrections. TACT also allows users to input their proprietary RSD TI correction methods for performance benchmarking compared to the other 'common' techniques. The Subgroup does not intend to develop new RSD TI adjustment methods and so designed TACT. Nonetheless, the Subgroup welcomes industry collaboration to advance or optimize a viable RSD TI adjustment method. For example, learnings within the group led to the incorporation of a less widely used lidar TI adjustment method into TACT that leverages lidars' 1Hz measurements and the formulation of Turbulent Kinetic Energy (TKE).

TACT Output

TACT reports TI comparison evaluation metrics that its contributors' deem appropriate for informing decisions on acceptable TI bias for turbine load models; such as wind speed binned *relative* MBE and *relative* RMSE for unadjusted and adjusted RSD TI and representative TI measurements compared to cup TI, as well as comparing error statistics between adjusted RSD TI to extrapolated cup TI. TI distribution similarity tests by wind speed bin are also performed.

Further, TACT performs sensitivity analyses on each dataset's temporal length and TKE stability class to understand if the performance of RSD TI adjustments may be classified by such conditions. This would allow analysts to gauge the appropriateness of using adjusted RSD TI measurements after early assessment of environmental parameters and therefore decide if additional measures need to be taken to work with the data. In addition, a corresponding RSD measurement uncertainty framework could be developed, and uncertainty assigned based on conditions during deployment. In essence this would be a classification of the **TI measurement capabilities similar to the classification of the wind speed measurement capabilities of the RSD as presented in the Annex L of the IEC 61400-12-1**. Such a classification is likely to be required per RSD model and firmware version, and differences between continuous wave and pulsed lidars, and sodars would likely exist.

Finally, in the upcoming Subgroup analysis, the participants' **aggregated TACT output will be passed to EMD International to input into their generic turbine fatigue loads model. A loads-based sensitivity analysis from various TI input will be performed, with the aim to quantify load model bias as a function of adjusted RSD TI bias to cup (Figure 17).** Specifically, the impact of adjusted RSD TI bias on the blade and tower bending moments will be studied. The participants' aggregated TACT output will be shared with turbine OEMs, to increase understanding of TI adjustment methods on proprietary loads models as well. **This upcoming Subgroup analysis has the potential to significantly move-the-needle towards RSD TI acceptance consensus given the large dataset deployed in testing, broad range of RSD TI adjustment methods considered, and commitment from key industry players to share knowledge regarding loads model impact**. Preliminary results from this effort will be released in the Spring 2022 and summarized in detail in a forthcoming peer-reviewed article.

5 Best Practice Framework for Stakeholder Collaboration to Determine Acceptable Loads Bias Thresholds with Adjusted RSD TI

The Subgroup developed a best practice collaboration framework to elucidate an opportunity to connect RSD TI benchmarking activities with RSD TI acceptance decision-making for site suitability assessment (Figure 18). The **framework encourages industry stakeholders to continue collaborating to refine TACT, leverage the tool to advance industry understanding of the sensitivity of turbine fatigue load models to varying TI measurements and therefore de-risks the use of adjusted RSD measurements in site suitability assessment.** Specifically, the Subgroup's open source TACT and complementary best practice framework enables consensus on the following:

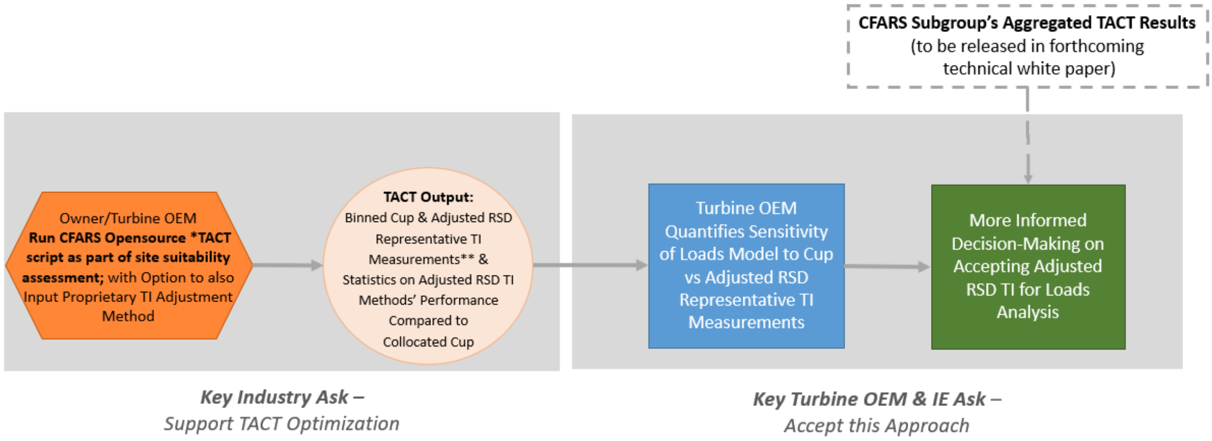
a) Important RSD parameter(s) that could be considered in TI adjustment methods
b) Relevant statistical analysis for comparing performance of TI adjustment methods to cup anemometers
c) Appropriate evaluation metrics and sensitivity analyses to define the target for RSD data validity
d) Advantages of adopting a load-based sensitivity approach when considering acceptability of load bias and uncertainty from adjusted RSD TI measurements

The first step of the evaluation framework recommends the owner or turbine OEM input RSD and cup measurements into TACT. As described in Section 4, TACT applies numerous simple and more complex correction methods to the RSD measurements and computes binned error metrics and sensitivity analyses regarding the performance of the adjusted TI methods compared with the collocated cup measurements for a given dataset. The tool is also adaptable to input a proprietary RSD TI adjustment method for comparison. While the TACT tool incorporates knowledge and best practices from a diverse group of industry stakeholders in the Subgroup, the tool would greatly benefit from broad industry review and refinement; a key "ask" from the Subgroup.

Next, the framework recommends turbine OEM's input TACT output of binned cup and adjusted RSD representative TI measurements into their specific fatigue load models. This would allow turbine OEMs, and IEs if appropriate, to directly compare the impact of various adjusted TI measurements on load model bias compared to a cup at a given site. In addition to generating these site-specific results, the Subgroup's aggregated results showing the sensitivity of a generic load model's response to various measurements may also be referred to for reference.

The CFARS best practice framework *does not attempt to establish distinct RSD TI acceptance threshold criteria*. Rather, the CFARS best practice framework described herein encourages the broader industry to further refine TACT and for turbine OEMs and IEs to leverage its output in a commercial setting so that **data-driven discussions around the sensitivity of load model output to adjusted RSD TI may ensue.** In turn, these discussions will advance understanding of suitability risks when using adjusted RSD TI measurements and **ultimately lead to more-informed decisions on accepting adjusted RSD TI for site suitability assessment.**

Figure 18: Schematic representing a CFARS recommend best practice framework from stakeholder collaboration to leverage TACT in determination of acceptable loads bias from RSDs. *TACT – TI Adjustment Comparison Tool. More information on TACT may be found here: https://github.com/CFARS/site_suitability_tool.



6 Next Steps for Acceptance

Since its inception, the Subgroup has remained acutely aware of the need to advance the connection between RSD TI research and commercial implementation. As a first effort to accelerate TI adjustment research to operations, the Subgroup presents results from an industry-wide TI benchmarking activity involving eight organizations and 35 collocated RSD and cup datasets. Aggregated error statistics of MBE and RMSE between unadjusted RSD-to-cup and cup-to-cup are reported, as well as differences in Representative TI. Overall results demonstrate moderate to large error between unadjusted RSD-to-cup measurements compared to collocated cup-to-cup measurements, with the largest error associated with the few sodar datasets analysed.

As a complementary next step, the Subgroup will generate aggregated statistics on the magnitude of *adjusted* RSD-to-cup TI differences using the open source TACT, which comprises of over 15 RSD TI adjustment methods. Further, the Subgroup will perform a loads-based sensitivity analysis from various TI input to directly link loads model bias to adjusted RSD TI bias. Preliminary results from this benchmarking activity will be released to the industry in the Spring 2022 and summarized in detail in a forthcoming peer-reviewed article.

Finally, to ensure the Subgroup's research to business roll-out goal was achieved to pave the way forward for adjusted RSD TI acceptance for site suitability assessment, a best practice stakeholder collaboration framework was introduced to leverage the open source TACT and empower the industry to engage in data-driven discussions about load model sensitivity and acceptance of adjusted RSD TI bias in commercial setting. The DNV JIP [4] is working on adjusted RSD TI bias acceptance criteria for site suitability to be released in a DNV Recommended Practice document. After its release (expected for Summer 2022), the outcome will be included into the CFARS best practice framework to further accelerate decision-making on appropriate RSD deployment and use for site suitability assessment on a site-by-site basis.

Collectively, the Subgroup's success in benchmarking *unadjusted* RSD TI and creating the industry's first open source tool to adjust RSD TI measurements and compare to collocated cup anemometry are powerful examples of the technical and commercial advantages from adopting a forward-looking, collaborative, approach. Further, the Subgroup's upcoming TACT analysis **has the potential to significantly move-the-needle towards RSD TI acceptance consensus given the large dataset deployed in testing, broad range of RSD TI adjustment methods considered, and commitment from key industry players to share knowledge regarding loads model impact.** Finally, the best practice stakeholder collaboration framework introduced herein to leverage TACT in site suitability decision-making showcases how contributions of goodwill to share knowledge and innovate can bring stakeholders value in confidential, commercial, discussions as well.

CFARS' success in unifying the industry around the shared value of removing nuance and ambiguity in RSD best practice for site suitability is a testament to how open source collaboration can improve the industry's efficiency and accuracy across the wind plant lifecycle.

7 References

[1] Knoop, Steven, et al. "A 2-year intercomparison of continuous-wave focusing wind lidar and tall mast wind measurements at Cabauw." *Atmospheric Measurement Techniques* 14.3 (2021): 2219-2235.

[2] ZX300 Remote Sensing Device Type-specific Classification, DNV report GLGH-4275 18 14741 258-R-0003, Rev. D. https://www.nrgsystems.com/assets/resources/DNV-GL-Classification-of-ZX-300-M.PDF

[3] IEC 61400-1 (2005), International Standard : Wind turbines, Part 1: Design Requirements. Edition 3.0 Amendment 2010, International Electrotechnical Commission.

[4] DNV Joint Industry Project, Lidar Measured Turbulence Intensity. https://www.dnv.com/article/lidar-measured-turbulence-intensity-150071

8 Acknowledgements

The CFARS leadership committee would like to extend sincere gratitude to the following industry thought leaders for contributing to this document's content: Andrew Clifton (WindForS), Harald Mellinghoff and Chris Ziesler (UL), Taurin Spalding (Natural Power), Jason Fields (National Renewable Energy Laboratory).

Appendices

A Appendix 1

The tables below provide the Aggregated TI MBE, RMSE, and Representative TI results.

Table 1: Aggregated TI MBE Results

Wind Speed Bin	Cup2Cup		Lidar2Cup		Sodar2Cup	
	Project Count	Aggregated TI MBE	Project Count	Aggregated TI MBE	Project Count	Aggregated TI MBE
[m/s]	[-]	[%]	[-]	[%]	[-]	[%]
2.0	9	-1.25	10	1.19	--	--
2.5	15	-0.18	14	2.75	2	1.97
3.0	18	-0.08	16	3.52	3	1.78
3.5	24	0.00	23	2.96	3	0.79
4.0	24	0.06	23	2.40	3	1.13
4.5	24	0.04	23	1.93	3	0.80
5.0	25	0.11	24	1.98	3	0.14
5.5	27	0.20	26	1.69	3	-0.04
6.0	27	0.15	26	1.41	3	0.42
6.5	27	0.16	26	1.40	3	-0.32
7.0	26	0.16	25	1.25	3	-1.06
7.5	25	0.15	24	1.06	3	-1.42
8.0	26	0.15	25	1.11	3	-2.00
8.5	25	0.07	24	0.88	3	-2.43
9.0	23	0.08	22	0.79	3	-2.84
9.5	23	0.05	22	0.86	3	-2.96
10.0	23	0.05	22	0.78	3	-3.53
10.5	22	0.06	21	0.65	3	-3.39
11.0	20	0.06	20	0.68	2	-4.03
11.5	16	0.11	17	0.65	1	-3.13
12.0	16	0.08	16	0.69	1	-3.26
12.5	12	0.08	11	0.76	1	-3.00
13.0	6	0.21	5	0.71	1	-3.28
13.5	5	0.26	4	0.84	1	-3.16
14.0	3	0.22	3	0.59	--	--
14.5	3	0.21	3	0.67	--	--
15.0	2	0.54	2	0.21	--	--

Table 2: Aggregated TI RMSE Results

Wind Speed Bin	Cup2Cup		Lidar2Cup		Sodar2Cup	
	Project Count	Aggregated TI MBE	Project Count	Aggregated TI MBE	Project Count	Aggregated TI MBE
[m/s]	[-]	[%]	[-]	[%]	[-]	[%]
2.0	9	3.83	10	9.08	--	--
2.5	15	2.26	14	8.37	2	19.52
3.0	18	1.68	16	7.82	3	13.23
3.5	24	1.43	23	6.56	3	12.08
4.0	24	1.23	23	5.77	3	12.59
4.5	24	1.00	23	5.05	3	9.72
5.0	25	0.95	24	4.65	3	8.13
5.5	27	0.87	26	4.01	3	8.63
6.0	27	0.80	26	3.64	3	10.31
6.5	27	0.75	26	3.50	3	8.88
7.0	26	0.71	25	3.14	3	6.70
7.5	25	0.66	24	2.91	3	7.35
8.0	26	0.66	25	2.93	3	5.68
8.5	25	0.59	24	2.64	3	5.66
9.0	23	0.55	22	2.63	3	5.12
9.5	23	0.54	22	2.47	3	5.32
10.0	23	0.53	22	2.52	3	5.29
10.5	22	0.51	21	2.30	3	5.33
11.0	20	0.47	20	2.61	2	4.84
11.5	16	0.47	17	2.31	1	3.85
12.0	16	0.43	16	2.21	1	3.91
12.5	12	0.43	11	2.11	1	3.63
13.0	6	0.55	5	2.6	1	4.11
13.5	5	0.58	4	2.09	1	3.76
14.0	3	0.62	3	1.57	--	--
14.5	3	0.60	3	1.69	--	--
15.0	2	0.64	2	0.62	--	--

Table 3: Aggregated TI RMSE Results

Wind Speed Bin	Cup2Cup		Lidar2Cup		Sodar2Cup	
	Project Count	Aggregated Repr TI Diff	Project Count	Aggregated Repr TI Diff	Project Count	Aggregated Repr TI Diff
[m/s]	[-]	[%]	[-]	[%]	[-]	[%]
2.0	9	-1.49	10	2.23	--	--
2.5	15	-0.42	14	4.91	2	9.35
3.0	18	-0.29	16	6.42	3	5.46
3.5	24	-0.37	23	5.30	3	4.42
4.0	24	-0.18	23	4.92	3	7.06
4.5	24	-0.18	23	3.98	3	3.31
5.0	25	-0.08	24	4.07	3	1.31
5.5	27	0.03	26	3.38	3	2.55
6.0	27	-0.01	26	3.10	3	5.31
6.5	27	0.06	26	2.98	3	3.12
7.0	26	0.05	25	2.67	3	-0.20
7.5	25	0.04	24	2.27	3	0.06
8.0	26	0.10	25	2.31	3	-2.15
8.5	25	-0.02	24	1.83	3	-2.12
9.0	23	0.01	22	1.56	3	-3.61
9.5	23	-0.03	22	1.50	3	-3.59
10.0	23	0.03	22	1.55	3	-4.37
10.5	22	0.03	21	1.30	3	-3.66
11.0	20	0.00	20	1.62	2	-5.43
11.5	16	0.05	17	1.58	1	-4.71
12.0	16	0.04	16	1.39	1	-4.80
12.5	12	0.09	11	1.12	1	-3.97
13.0	6	0.20	5	1.87	1	-4.33
13.5	5	0.25	4	1.13	1	-3.93
14.0	3	0.20	3	0.89	--	--
14.5	3	0.16	3	0.86	--	--
15.0	2	0.46	2	0.09	--	--

About Us

CFARS was established in 2018 and initially comprised major North American wind project owners, developers, operators, 3rd party consultants and OEM / Technology providers. Working groups have been established to collaborate on projects promoting the acceptance and standardisation of Remote Sensing use.

Our work has attracted global interest and now CFARS represents hundreds of individuals and organisations and we seek to create consensus - industry consensus - and speak of Remote Sensing with a common voice.

We build bridges between industry players, research centres, standardisation bodies and task forces and other industry working groups to rapidly address short term projects.

CFARS gives access to a large pool of wind industry Remote Sensing data and jointly with our members help to validate the use of data. We jointly present compelling results to our industry peers.

Why? To act as a Consortium For Advancing Remote Sensing to enable and increase the competitiveness of the wind energy industry within the energy & power sector.

Our Members