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Turbulence Intensity Measurements with WindCube® Nacelle

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Vaisala WindCube® Nacelle (WCN, formerly named *WindIris*) is a *Nacelle-Mounted Lidar* (NML) that provides reliable wind data at multiple distances in front of a Wind Turbine Generator (WTG) to achieve quick and accurate Power Performance Tests (PPT), at low operational costs and in conformity with industry best practices.

WCN is quick and easy to deploy and operate to provide accurate and complete wind information to suggest explanations for wind turbine energy production underperformances and reasons for unexpected failures, such as nacelle yaw misalignment, or abnormal shears and high turbulence intensities.

Turbulence Intensity (TI) is one of the most important wind-related parameters, and is widely used in many applications, such as the verification of PPT, the load estimation of WTG, and the assessment of turbine micro-siting. The IEC 61400-50-3 standard was released in early 2022, which provides important guidance for the wind industry for the use of NML and standardizes the PPT procedure.

Currently, several works and results evaluate the accuracy of TI measurement by wind lidar. But comprehensive and summary reports are still lacking, especially for NML. This white paper summarizes the results on TI of NML from two measurement approaches by several field campaigns, which can prove TI measurement accuracy and add value to TI-related topics in research and industrial applications.

1 Technology

Lidar principle

Today, wind LiDAR (Light Detection and Ranging) is widely used in the wind energy industry for wind measurement. Ground-Based LiDAR (GBL) and NML are the most popular wind profiling lidars, and both provide plenty of useful information and measurements to evaluate the accuracy of TI measurements with wind lidar. For the measurement of Radial Wind Speed (RWS), GBL and NML use very similar lidar technology. The main difference is that GBL uses vertical laser beams, while NML uses horizontal laser beams.

GBL has many uses for Wind Resource Assessment (WRA) due to its portability and easy deployment, and NML has an advantage for direct TI measurements by Line of Sight (LOS). There are several studies on TI evaluation by field measurement[1-3].

Table. 1 summarizes several results of field measurements by GBL and NML. Some investigations discuss that wind lidar tends to underestimate the wind speed variance because of two effects: probe volume and wind projection[4].

Lidar Type	Author	Year	r_2	slope	Information
GML	Bonin TA[1]	2017	0.78	0.95	Met Tower: 300m height
	Sathe A[2]	2015	0.91~0.96	0.69~0.90	ABL condition : neutral
			0.80~0.84	0.66~0.87	ABL condition : unstable
	Sathe A[3]	2015	0.87~0.90	1.12~1.16	Complex terrain
NML	Penã A[5]	2017	0.74~0.77	0.91, 1.14	Flat terrain

Table 1: Summary for TI measurement results for GBL and MNL in several field campaigns

Fig. 1 Photo of WCN installation (left: WCN on onshore WTG, right: WCN on offshore WTG)

Fig. 1 is one on-site photo, in which the WCN is installed on top of the WTG nacelle and measures the wind in front of the rotor. Fig. 1 (left) is the installation on one onshore WTG in a complex terrain. Fig. 1 (right) is on one offshore WTG close to the shore. Given the high financial costs of building a met mast offshore, NML is a natural solution for PPT as NML can be easily deployed on wind turbines and provide highly accurate wind measurements.

WCN geometry

Fig. 2 shows the spatial geometry of four laser beams. The horizontal angle of two beams at each height (the upper height or the lower height) is 30° (Fig. 2a) and the vertical angle is 10° (Fig. 2b). The spatial positions of the four measurement points at one measurement distance are shown in Fig. 2c. WCN can measure along the horizontal distance from 50 m to 700 m in front of WTG, with up to a maximum of 20 measurement points and an accuracy of 0.1 m/s for wind speed and of 0.5° for wind direction. A calibration study conducted by the Technical University of Denmark shows that the uncertainty of its wind speed measurement was in the range of 2% to 3.5% comparing with the anemometer tower[6].

TI general definition

Turbulence can manifest as gusts, eddies, and fluctuations in wind speed. TI is a basic measure and a common description of atmosphere turbulence[7]. TI can be calculated by the below formula[1].

$$TI = \frac{S}{V} \qquad (1)$$

Here, S is the standard deviation of horizontal wind speed in 10 min, V is the averaged horizontal wind speed in 10 min.

WCN TI algorithm

The overall algorithm on the TI calculation used by WCN can be summarized in the four steps below:

Step 1: Compute 10 minutes averaged wind speed and Standard Deviation (SD) for each four beams using 1Hz data, the status variable is used here to consider data availability:

$$dRWS_i = \sqrt{\frac{\sum (RWS_i - \overline{RWS_i})^2 * Status_i}{\sum Status_i}} \qquad (2)$$

$$\overline{RWS_i} = \frac{\sum (RWS_i * Status_i)}{\sum Status_i} \qquad (3)$$

Step 2: Divide SD by LOS mean wind speed to calculate the TI for each beam:

$$TI_{LOS} = TI_i = \frac{dWS_i}{\overline{WS_i}} = \frac{dRWS_i}{\overline{RWS_i}} \qquad (4)$$

Step 3: Compute TI+ and TI- using the mean TI from the two upper and lower beams:

$$TI_+ = \frac{TI_0 + TI_1}{2} \qquad (5)$$

$$TI_- = \frac{TI_2 + TI_3}{2} \qquad (6)$$

Step 4: Compute TI at hub height from TI+ and TI- by a logarithmic interpolation law:

$$TI_{gain} = \frac{TI_+ - TI_-}{ln(H_-) - ln(H_+)} \qquad (7)$$

$$TI_{Huser} = TI_+ + TI_{gain} . (ln(H_+) - ln(H_{user})) \qquad (8)$$

A new filtering method is added in Step 1 that removes the wind speed outliers for the SD calculation. This filtering method significantly improves TI measurement accuracy.

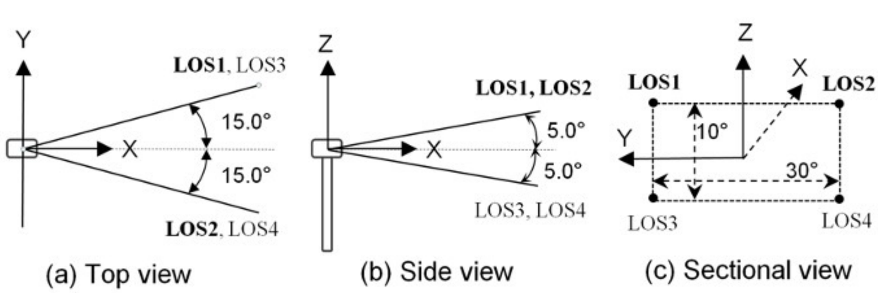

Fig. 2 Laser beam geometry of Nacelle-Mounted Lidar

2 Comparison method

The field measurement is an important and straightforward way to understand the capability and accuracy of TI by wind lidar. There are two types of uncertainties for wind measurement: one is coming from the laser measurement, while other is coming from the TI algorithm. The laser measurement is the intermediate value of laser TI measurement before the algorithm, which is the foundation to the TI accuracy to wind lidar.

There are two typical approaches to compare the measurement with wind sensor: White Box Comparison (WBC) and Black Box Comparison (BBC), which are demonstrated by Fig. 3. WBC can be used to evaluate the direct capability of TI measurement of the laser itself, while BBC provides the final accuracy of TI after the reconstruction algorithm. For wind energy applications, the 10-min averaged wind speed and TI are widely used.

White Box Comparison

For WBC, WCN measures wind speed and TI at Line of Sight (TI LOS). When the WCN beam points directly to a met mast anemometer it is possible to directly compare TI LOS with a reference TI from the anemometer. The measurement at LOS is the lidar raw data, and this comparison can exclude uncertainty from the reconstruction algorithm.

This approach can provide more information and TI could be calculated by formula (4)[8].

Black Box Comparison

For BBC, TI is reconstructed at hub height by the measurement of LOS. The NML is usually facing the wind direction, if the angle between LOS and wind direction is not too big, the TI of horizontal wind speed could be equal to the TI at LOS. For the comparison of reconstructed TI at hub height, NML should measure towards the reference wind measuring device, such as an IEC met mast, and then compare TI with the reference TI. For the four beams, the TI Hub is reconstructed by four TI LOS: TI0, TI1, TI2 and TI3.

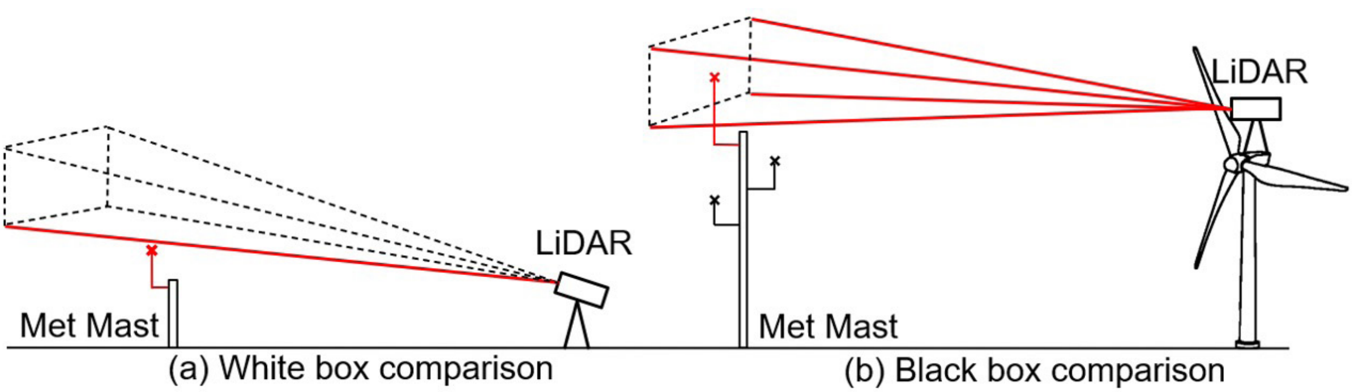

Fig. 3 Schematic diagram: (a) white box test; (b) black box test

3 Measurement and result by WBC

WBC setup

FThe project for WBC has been conducted in one verification site for wind lidar in the north of Germany, and the detailed information of the measurement setup is shown in Fig. 4. The site has: (1) two met masts of 30-meter height as the reference for wind speed (T-MM-N and T-MM-S in Fig. 4); (2) one platform at the 30-meter height on the top a lattice tower for the WCN installation (FW-MM in Fig. 4).

Both met masts are equipped with the calibrated reference sensors: wind cup and wind vane. To reduce measurement duration, two laser beams at the same height (two upper beams

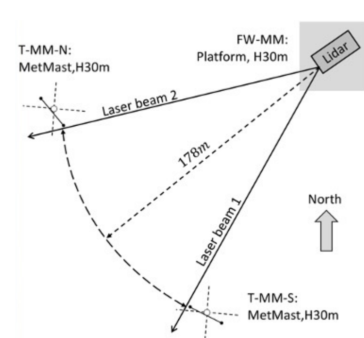

Fig. 4 Overview of test site by top view

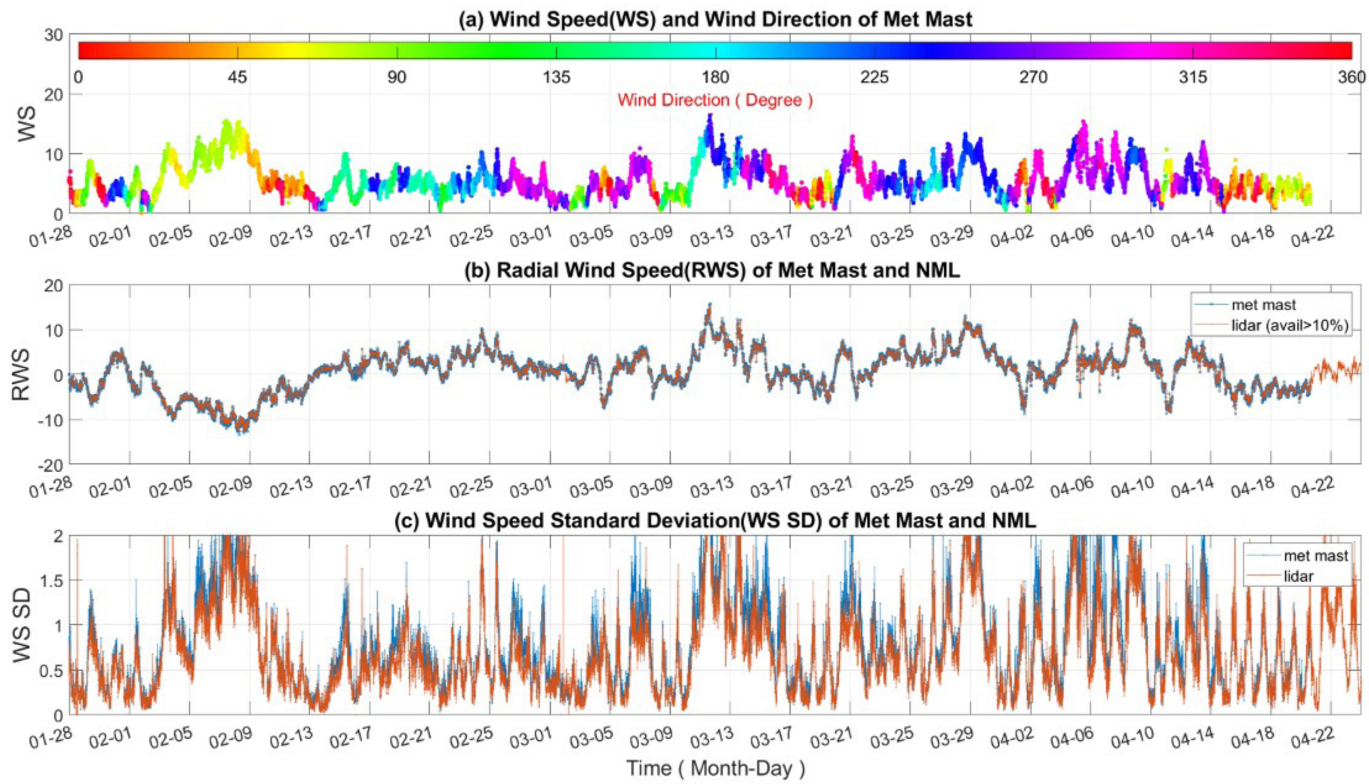

Fig. 5 Time series comparison of met mast and NML

or two lower beams) are verified simultaneously. In the verification of two beam (Laser beam 1 and Laser beam 2), the beam 1 is pointed at the south met mast (T-MM-S) and the beam 2 is pointed at the north met mast (T-MM-N). Therefore, beam 1 and beam 2 are verified at one period to reduce the measurement time. The interval width of the wind sector is selected 20 degrees.

The project was defined in 2020, and measurement started in February 2021, using a 4-beam WCN. IEC-compliant calibrations were performed at this test site for 11 months. The data analysis shows the accurate results of WCN measurement.

WBC raw data

Fig. 5 shows the raw data comparison of 10-min averaged value between met mast and WCN in the verification site[9]. The time series of wind speed and wind direction of the met mast is shown in Fig. 5a: Y-axis is the wind speed, and the color of scattered points is the wind direction. The wind direction of the measurement period is mainly from the west and northeast: 1) the blue and purple scattered points are the wind direction from west; 2) the red and yellow scattered points are the wind direction from northeast. Fig. 5b shows the RWS: the orange line is the direct RWS measurement by WCN, while the blue line is the one calculated from the met mast (by projecting the wind speed to the direction of the laser beam using the wind direction). Fig. 5c shows the time series of the wind speed SD, the orange line is from WCN, and the blue line is from the met mast.

The wind speed SD is the numerator of TI, and the blue and orange lines vary very consistently, which indicates good capability of NML on TI measurement. The HWS SD of the met mast (the blue line) is slightly higher than the RWS SD of NML (the orange line). This is expected because RWS is only one component of the wind direction (compared to HWS SD). Therefore, to evaluate more accurately the TI measurement capability of NML, data filtering on wind direction is needed. The comparison results are shown in Fig. 6.

WBC comparison

Fig. 6 shows the comparisons at LOS2 for the intermediate measurement between WCN and met mast: RWS, TI, and Total Kinetic Energy (TKE). Fig. 6a is the RWS comparison between WCN and the met mast: the blue scattered points are the 10-minute averaged wind speed: Y-axis is the direct RWS measurement by WCN, while X-axis is the computed RWS from the met mast. Fig. 6b shows the TI comparison at LOS2 direction and Fig. 6c shows the TKE comparison. For the turbulence comparison between the met mast and NML, the TKE has a better correlation than TI.

The three bottom figures, Fig. 6d, Fig. 6e and Fig. 6f, are the bin-averaged comparisons. Some applications mainly use the bin averaged value of TI, so the results are also given here. The bin-averaged results are better than 10-min results.

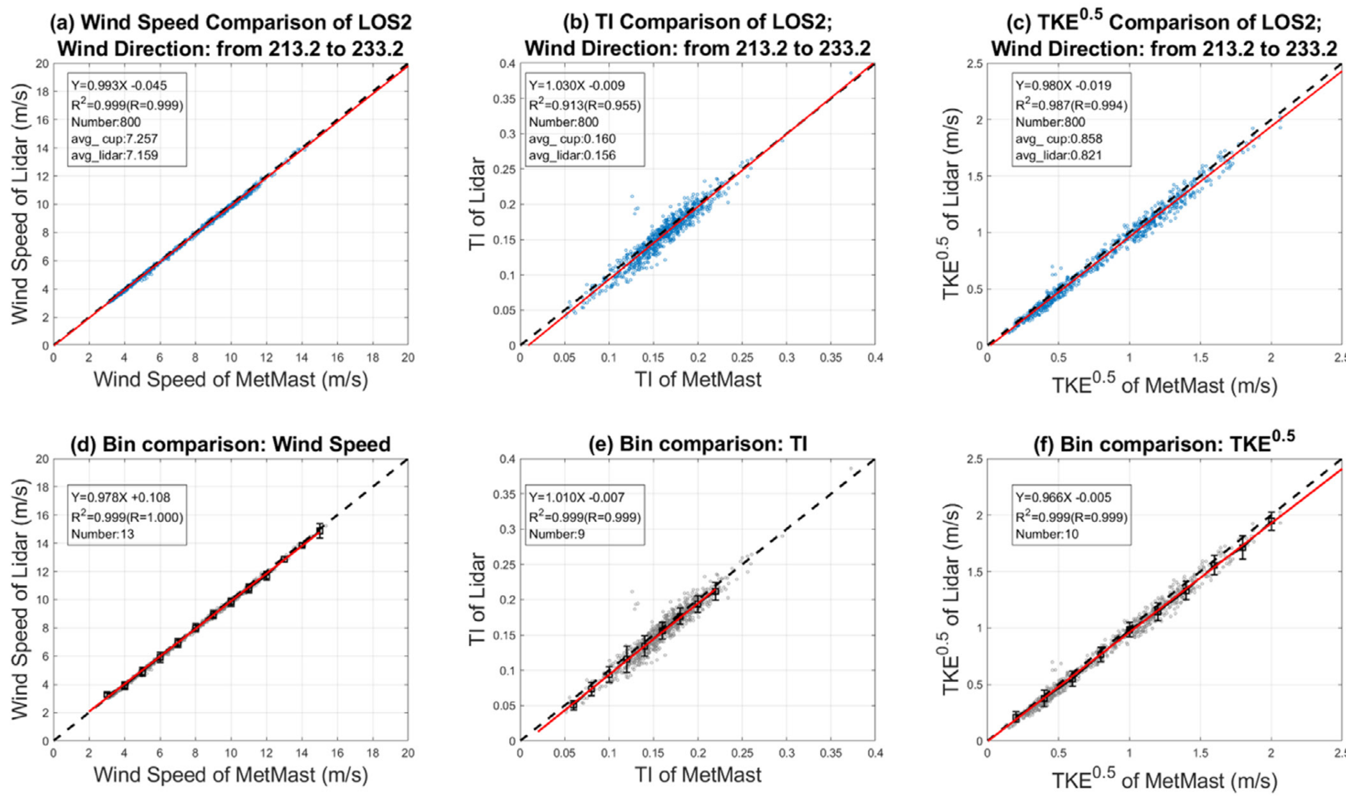

Fig. 6 Comparison of met mast and NML (LOS2): left wind speed; middle: TI; right: TKE (Three top figures: 10min comparison; three button figures: bin comparison)

WBC conclusion

The result of TI LOS shows that: 1) comparing the 10min averaged data, coefficient of determination r2 of TI is 0.913 with slope of 1.030 and the coefficient of determination r2 of √TKE is 0.987 with slope of 0.980; 2) comparing bin-averaged data, coefficient of determination r2 of TI is 0.999 with slope of 1.01 and the coefficient of determination r2 of √TKE is 0.999 with slope of 0.966.

To our best knowledge, the results of turbulence by WCN are quite promising. The WCN measures wind speed and turbulence along the LOS and could provide 1Hz data, which has more information for the spatial and temporal structure of the atmosphere turbulence. This might be the possible research direction for NML to investigate the turbulence structure in the Atmospheric Boundary Layer (ABL) at low attitude.

4 Measurement and result by BBC

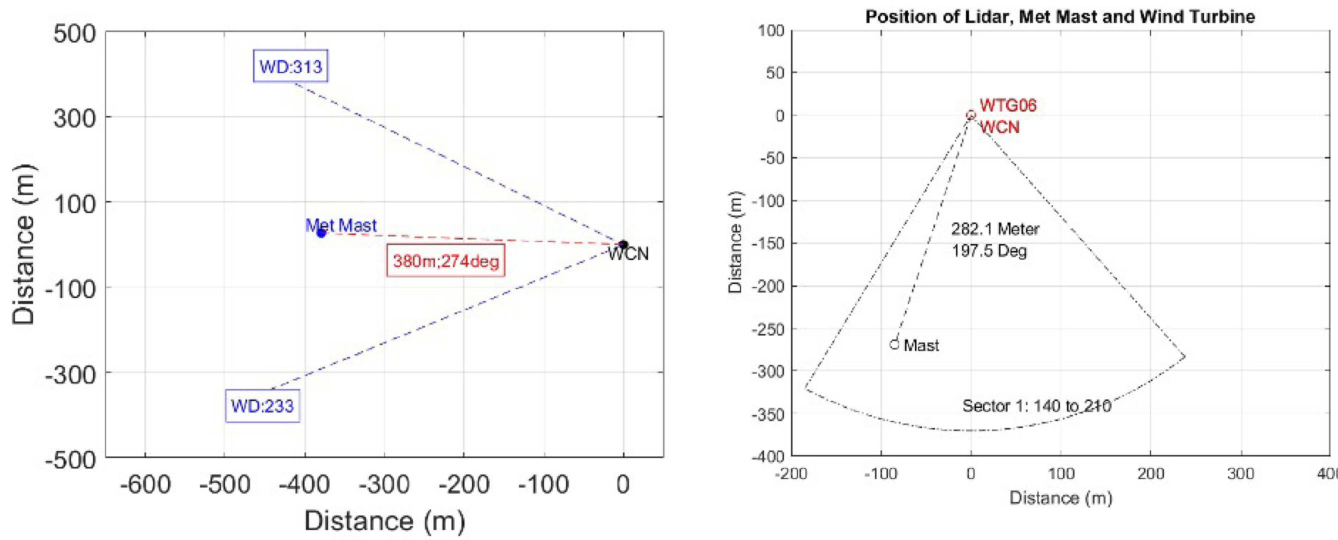

Fig. 7 Overview of test site by top view (left: project one; right: project two)

BBC setup

Turbulence Intensity at hub height (TI Hub) is the typical TI data for the applications for NML. Two projects are used to study the NML performance for TI Hub. Fig. 7 gives the information of the two-campaign setup and the relative position of the met mast with respect to WCN. The selected wind sector is also given by the dashed lines.

The test site of project one is a wind turbine test field in Denmark, shown in Fig. 7 (left). The measurement was taken between June 2019 and February 2020. A WindCube Nacelle Long-Range was installed on an 8 MW 167 m diameter, 120 m hub height offshore wind turbine and compared to a 120-meter IEC met mast and two WindCube GBLs placed respectively at three distances of 380m (2.27D, D is the Rotor Diameter of WTG), 395 m (2.36D) and 550 m (3.3D) from the WTG and aligned in the same direction as met mast. The validated wind sector is from 233 to 313 degrees. The met mast is located 380 meters in front of the wind turbine at the direction of 273 degrees.

The test site of project two is in an operational wind farm in the United States on flat, onshore terrain for a 3-month duration, showed in Fig. 7 (right). The target of this project is to gain experience with the technology and accelerate the acceptance and commercial application of NMLs for PPT. The WCN is installed on a wind turbine. One IEC met mast and a WindCube GBL are located closely at the distances of 282 m (2.2D) and 290 m (2.3D) in front of wind turbine at the wind direction of 197.5 degrees. The validated wind sector is from 140 to 210 degrees. The met mast is located 282.1 meters in front of the wind turbine at the direction of 197.5 degrees.

BBC comparison

Fig. 8 and Fig. 9 show the TI comparison result of BBC: The correlation coefficient is above 0.916, and the slope is 0.951~1.029. TI measurement by NML is very accurate and the bias is smaller than 4.9%. Two left figures of Fig. 8 and Fig. 9 are the comparisons using raw data without data filtering on NML and the raw data is already good for TI measurement.

The two right figures compare the TI with filtering out the data of NML by the data availability of 80% and the remaining data percentages in the two campaigns are 83.7% and 71.9% respectively for the measurement period, which is quite good for TI measurement and TI-related applications.

For TI comparison against a met mast, the data availability threshold of 80% is used. Here, we would like to highlight the good data coverage of valid TI. TI is very sensitive to wind speed outliers in high frequency data. In the past, the used threshold of data availability was 95%, which could remove 70% to 80% of data from the whole dataset. Now, the data coverage of valid TI reaches the same level as the one for wind speed.

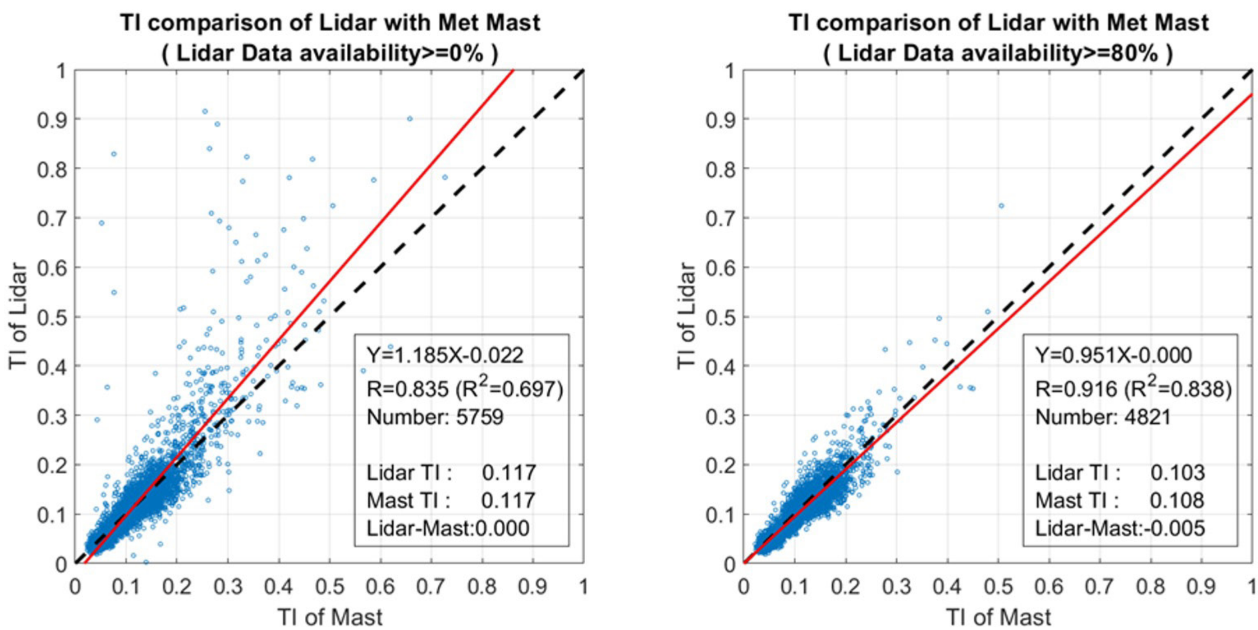

Fig. 8 The first measurement campaign: TI comparison for on-nacelle test

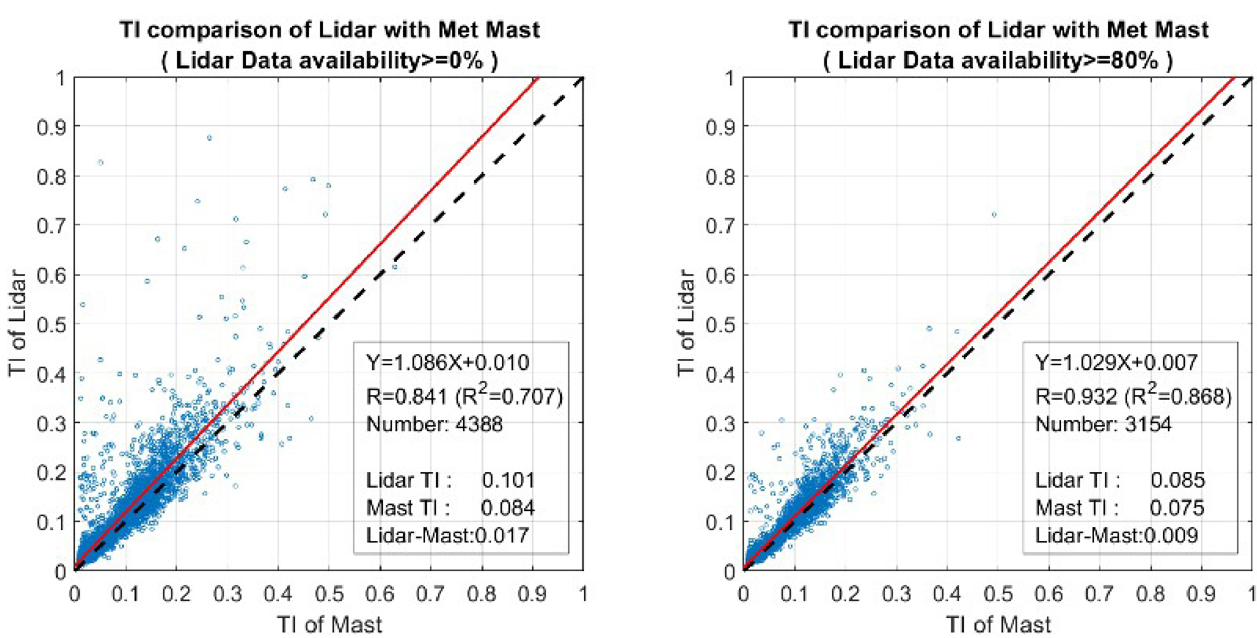

Fig. 9 The second measurement campaign: TI comparison for on-nacelle test

BBC conclusion

The result of TI Hub by BBC shows that: (1) the correlation coefficient is 0.916 and 0.932 with slopes of 0.951 and 1.029; (2) the data coverage percent of valid TI is high: 83.7% and 71.9%; (3) the global accuracy of TI measurements is high: bias is within 4.9%.

5 TI application on turbine class

A wind turbine shall be designed to safely withstand the wind conditions defined by the selected wind turbine class (IEC61400-1, 2019). WCN could be used to verify the safety of wind turbine class, especially at the whole wind direction, which is not easily be done by the Met Mast.

Fig. 10 shows the TI values at the first test site and TI categories (A+, A, B and C) are plotted by the black lines, which are defined by Normal Turbulence model (IEC61400-1, 2019). The TI values by Met Mast and WCN are compared: the blue line in Fig. 10a is the TI measurement by Met Mast; the red line in Fig. 10b is TI by WCN. From Fig. 10c, the TI measurement by WCN is very close to those by Met Mast, which indicts that the WCN has a good measurement capability to verify the safety of wind turbine class, which is decided at the preliminary stage of Wind Resource Assessment (WRA).

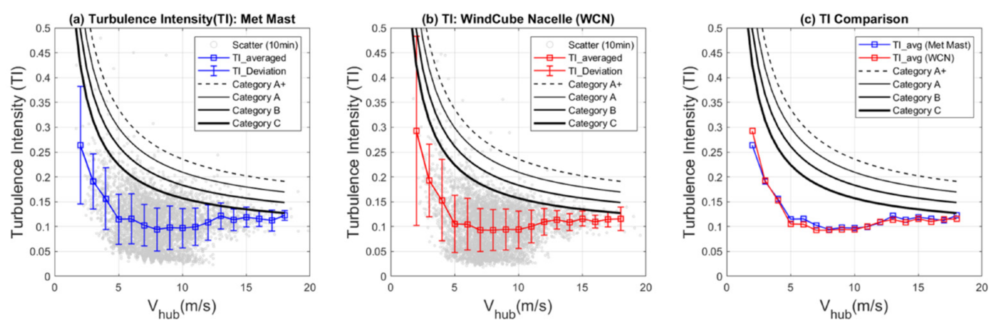

Fig. 10 The TI evaluation at first measurement campaign

Fig. 11 is the result for the second test site. The two test sites for Fig. 10 and Fig. 11 are the same test sites for Fig. 8 and Fig. 9. The data quality control and filtering are same for these figures, which is good for across comparisons.

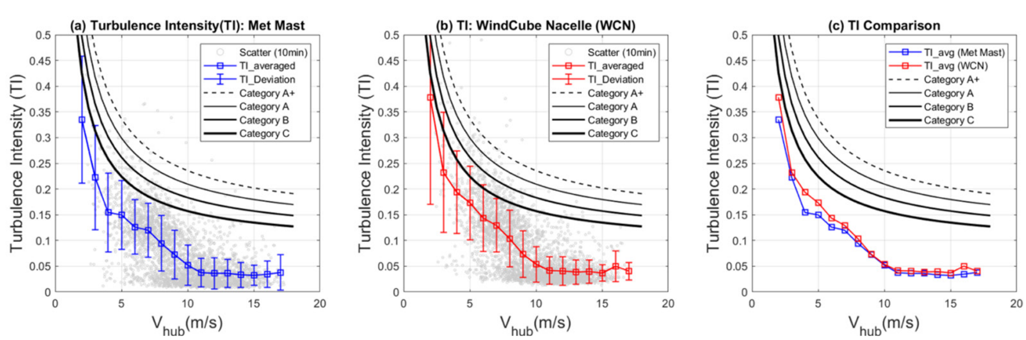

Fig. 11 The TI evaluation at second measurement campaign

6 Conclusion

This white paper summaries results using Vaisala WindCube Nacelle for the measurement of Turbulence Intensity and provides comprehensive and useful information to the wind energy industry. The results prove the accurate TI measurement of NML and could be the evidence base for further investigation.

Two approaches are used for TI evaluation: White Box Comparison (WBC) and Black box Comparison (BBC). For WBC, TI LOS is the direct measurement at each laser beam; for BBC, TI Hub is final data after Wind Field Reconstruction. This white paper mainly summaries the results from three field campaigns, and reaches the below conclusions:

(1) Results from WBC shows: (a) the correlation coefficient of TI LOS varies from 0.923 to 0.955; the slope of TI LOS varies from 0.978 to 1.030; (b) the correlation coefficient of TKE along LOS direction varies from 0.984 to 0.994; (c) the slope of TKE along LOS direction varies from 0.968 to 0.986.

(2) Results from BBC shows: (a) the correlation coefficient is 0.916 and 0.932 with slopes of 0.951 and 1.029; (b) the data coverage percent of valid TI is high: 83.7% and 71.9%; (c) the global accuracy of TI measurements is high: bias is within 4.9%.

The high measurement accuracy and data coverage of TI shows NML is ready for industrial applications. This white paper shows the improvement of TI measurement and provides contributions to improve the TI measurement of wind lidar plus further studies on the temporal-spatial structure of air turbulence in the low Atmospheric Boundary Layer.

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