TI measurement by WindCube Nacelle

WindCube Nacelle

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Outline

Introduction of TI

Method

Result (a): White box comparison

Result (b): Black box comparison

Conclusions

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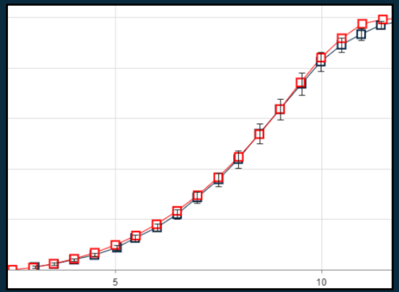
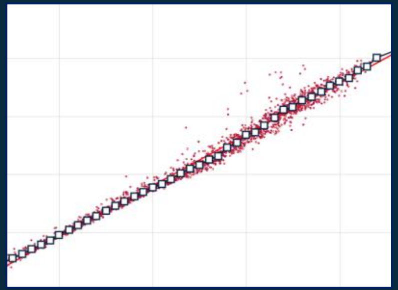
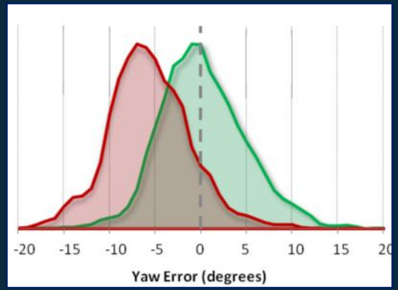
Applications:

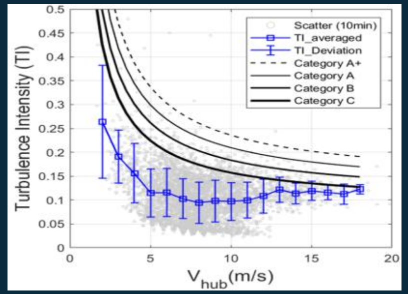

Power Curve Verification


Turbine Control

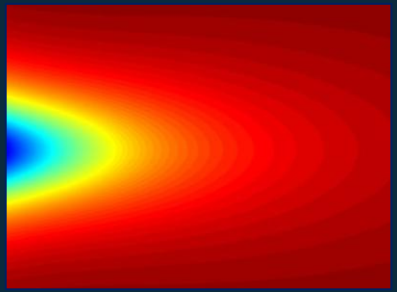

Transfer Function



Yaw Misalignment



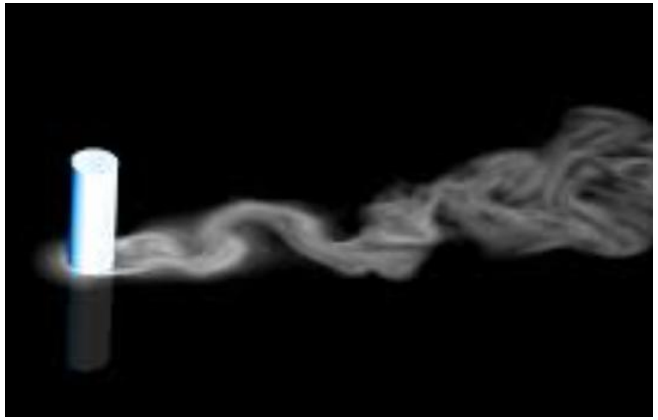
Turbulence Intensity


Research Projects

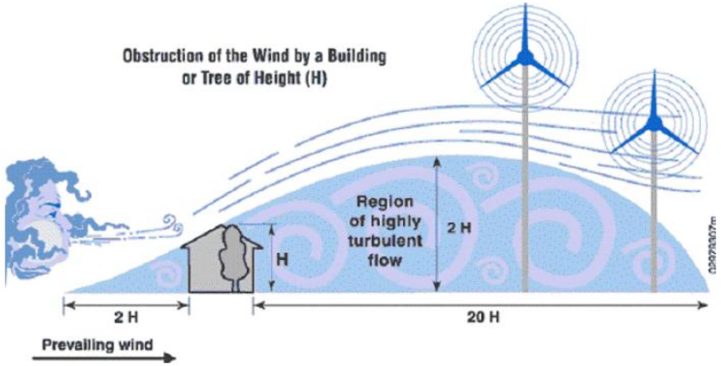
Turbulence is common and important!

(1) Turbulence in water flow

(2) Turbulence in air flow



(a) Turbulence generated by obstacle/surface

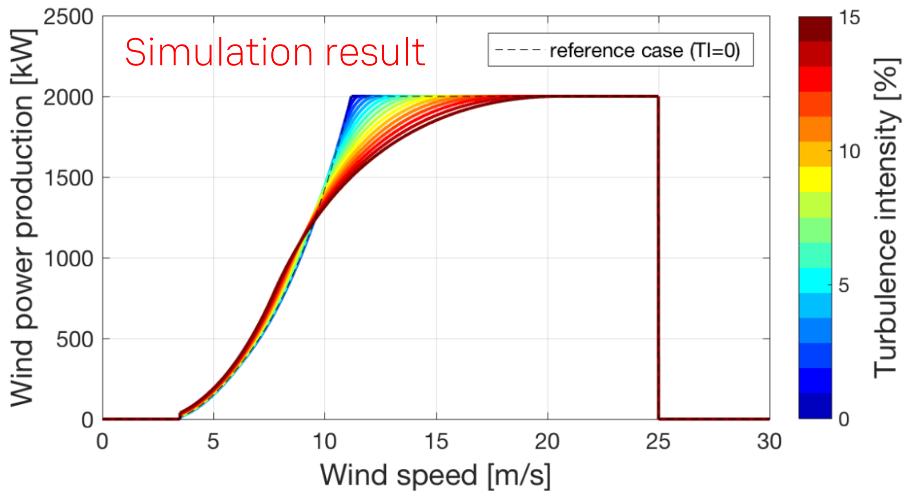


(b) Turbulence generated by turbine wake

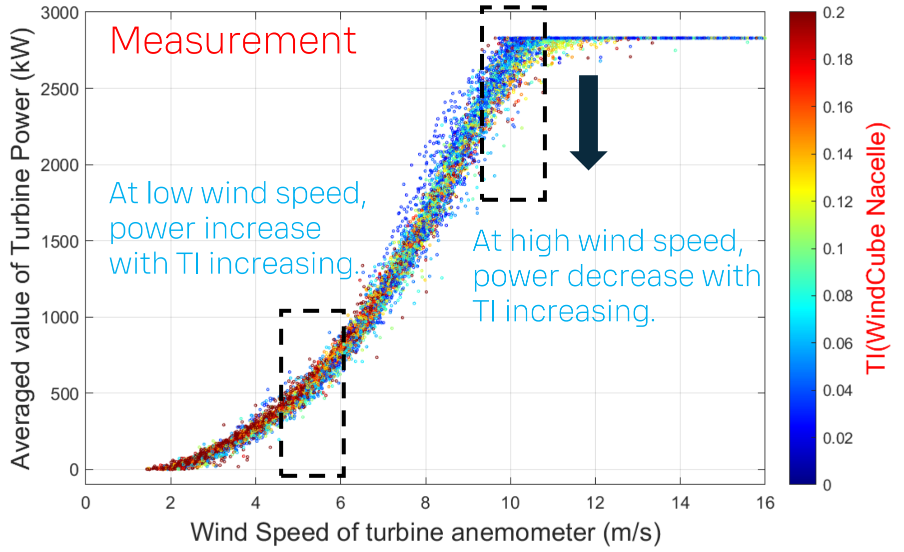
Importance of TI for wind turbine

- TI affects significantly:
  - (1) Power Performance Testing (PPT)
  - (2) Turbine load estimation (Load)
  - (3) Annual Energy Production (AEP)
- TI on Power Performance Testing:
  - TI reduces turbine power at high wind speed.
  - TI increases turbine power at low wind speed.

- Two open publications on TI of WindCube Nacelle
  - Field Study of Turbulence Intensity measurement by Nacelle Mounted Lidar. (TORQUE 2022). Journal of Physics: Conference Series. https://iopscience.iop.org/article/10.1088/1742-6596/2265/2/022104
  - Turbulence Intensity Measurements with WindCube® Nacelle. Vaisala product white paper. https://www.vaisala.com/sites/default/files/documents/WEA-ERG-WhitePaper-TurbulenceIntensityMeasurements-B212723EN.pdf

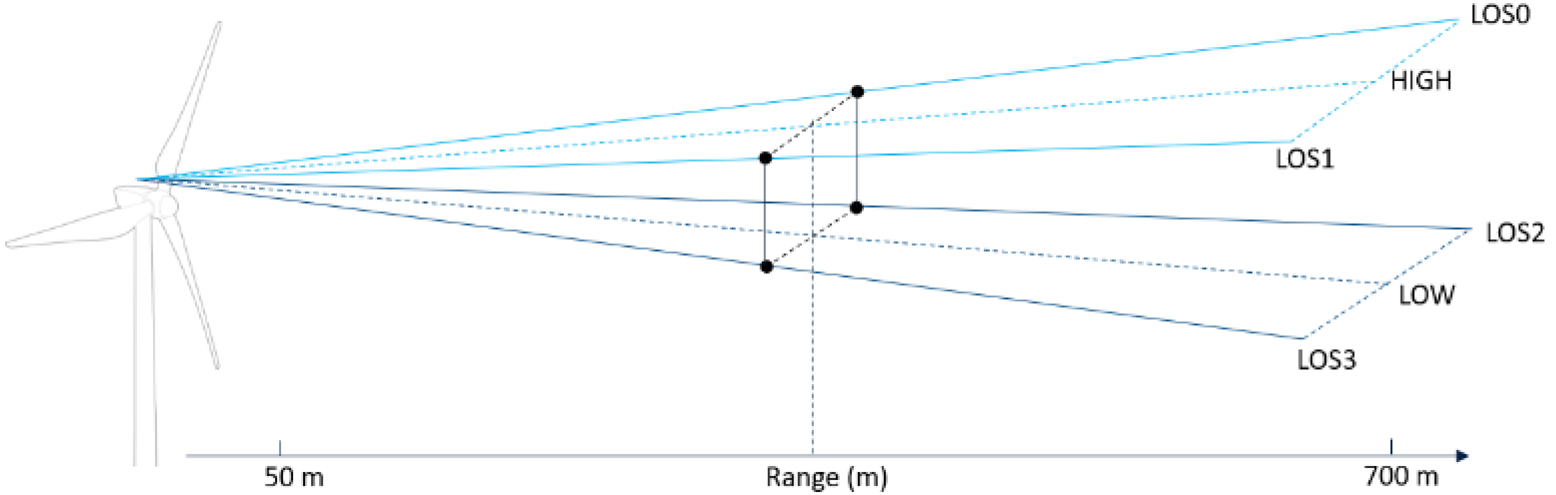


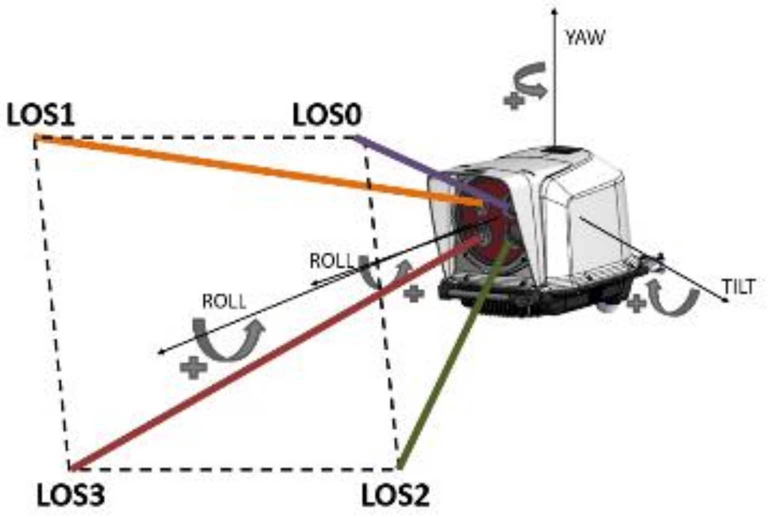
Saint-Drenan(2020). A parametric model for wind turbine power curves incorporating environmental conditions.

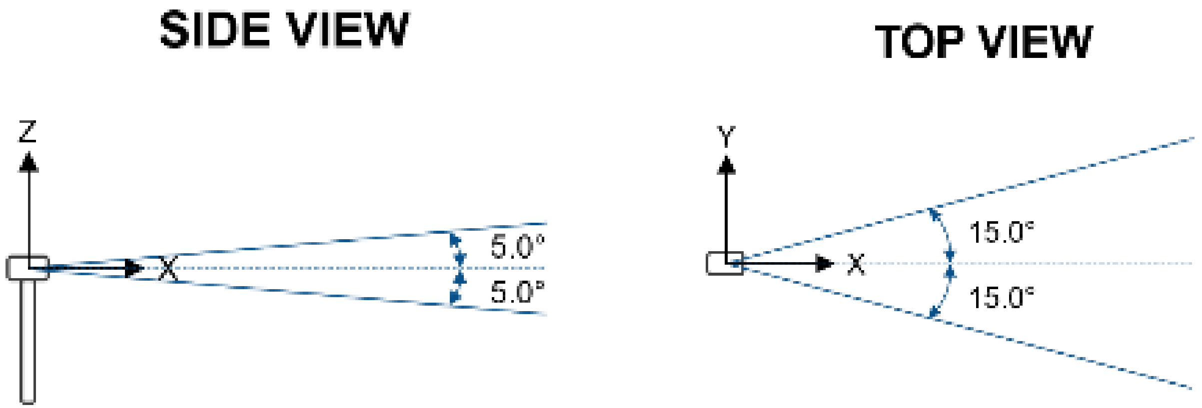


Wind algorithm: beam geometry

Measurement specifications	
Range	50m to 450m/700m (depending on version)
Ranges	10/20 user defined distances, simultaneously measured

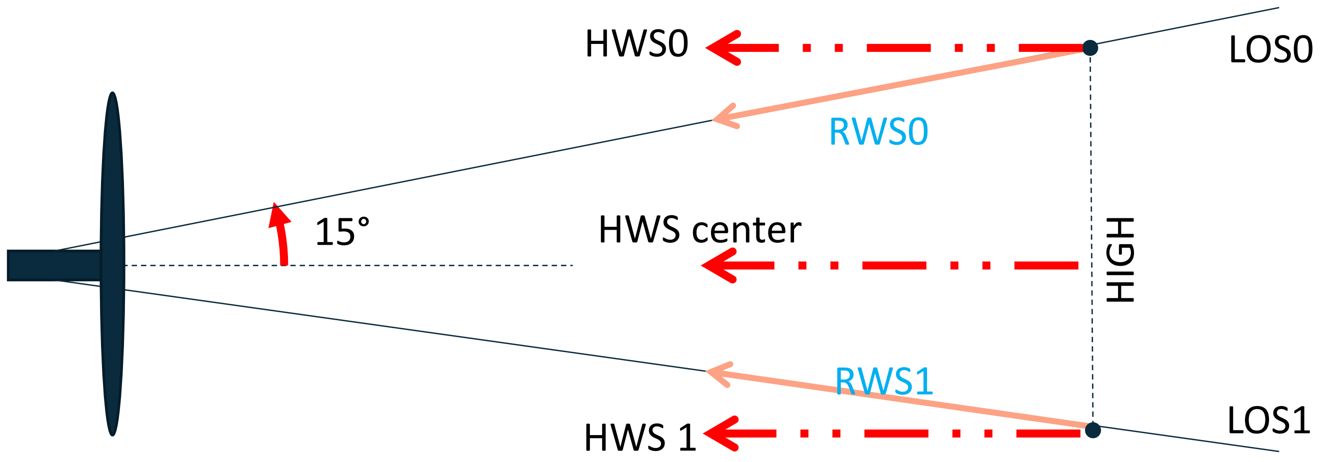




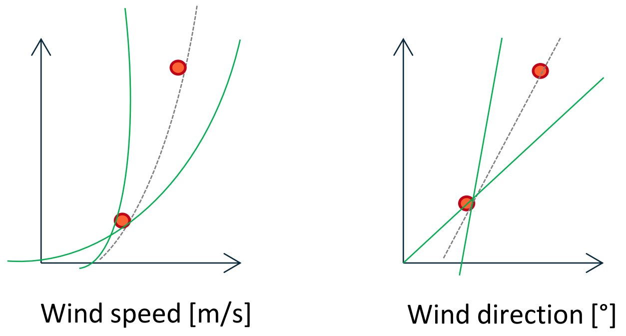


Wind algorithm: Hub height wind speed

- For each range gate, two wind vectors are reconstructed at two heights
  - 10mn averaged RWS from lower pair of beams provides HWS at lower height
  - 10mn averaged RWS from upper pair of beams provides HWS at upper height
- Extrapolation coefficient are calculated based on upper and lower HWS
  - Wind shear is calculated using a shear profile assumption : power law
  - Wind veer is calculated using a veer profile assumption: linear



- Wind vector is retrieved at any height
  - For each range gate, based on the extrapolation coefficients, HWS is reconstructed at hub height
  - (or any height configured by the user)



Main assumption of wind field reconstruction:

- Horizontal homogeneity
- No inflow angle
- Assumption on shear and veer profile (power law/linear)

Wind algorithm: TI for WindCube Nacelle

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- Step(1): To compute the averaged value for Radial Wind Speed(RWS) at each beam *i* in 10 minutes using 1Hz data

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

- Step(2): To compute Standard Deviation for Radial Wind Speed(RWS) at each beam *i* in 10 minutes using 1Hz data

$$dRWS_i = \sqrt{\frac{\sum\left((RWS_i - \overline{RWS_i})^2 \cdot Status_i\right)}{\sum Status_i}}$$

  - *Here, $Status_i$ is the quality flag(1Hz) given by spectrum data*

- Step(3): Divide SD by LOS mean wind speed to calculate the TI for each beam

$$TI_{\mathrm{LOS}} = \frac{dRWS_i}{\overline{RWS_i}}$$

- Step(4): To compute TI at upper and lower heights

$$TI_+ = \frac{TI_0 + TI_1}{2}$$

$$TI_- = \frac{TI_2 + TI_3}{2}$$

- Step(5): To compute vertical factor by the interpolation law

$$A = \frac{TI_+ - TI_-}{ln(H_-) - ln(H_+)}$$

- Step(6): To compute TI at hub height by vertical interpolation

$$TI_{hub} = TI_+ + A \times (ln(H_+) - ln(H_{hub}))$$

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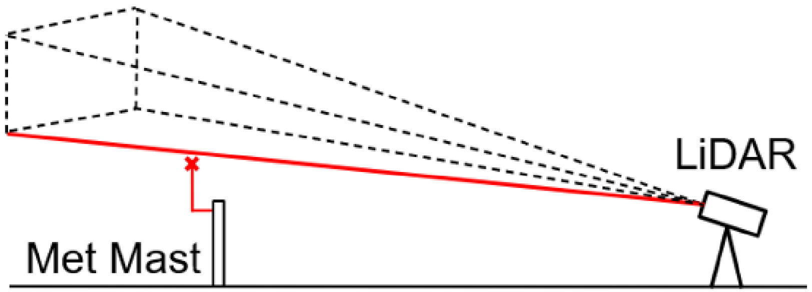
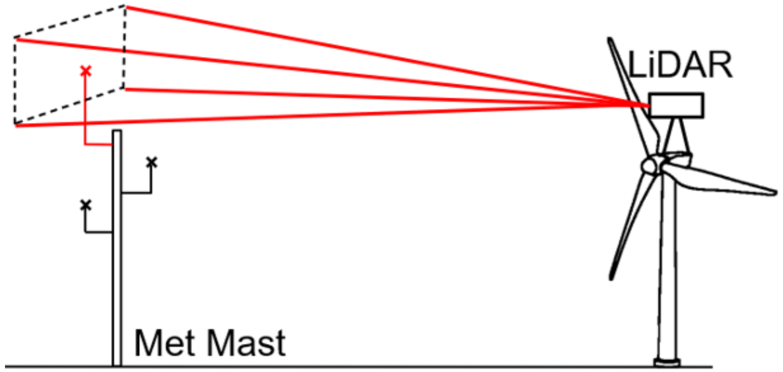
Method: TI evaluation

- Two methods for TI comparison between WCN and Met Mast:



(a) White box comparison

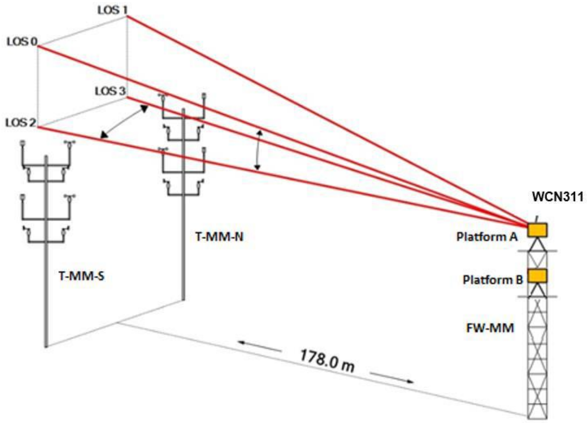


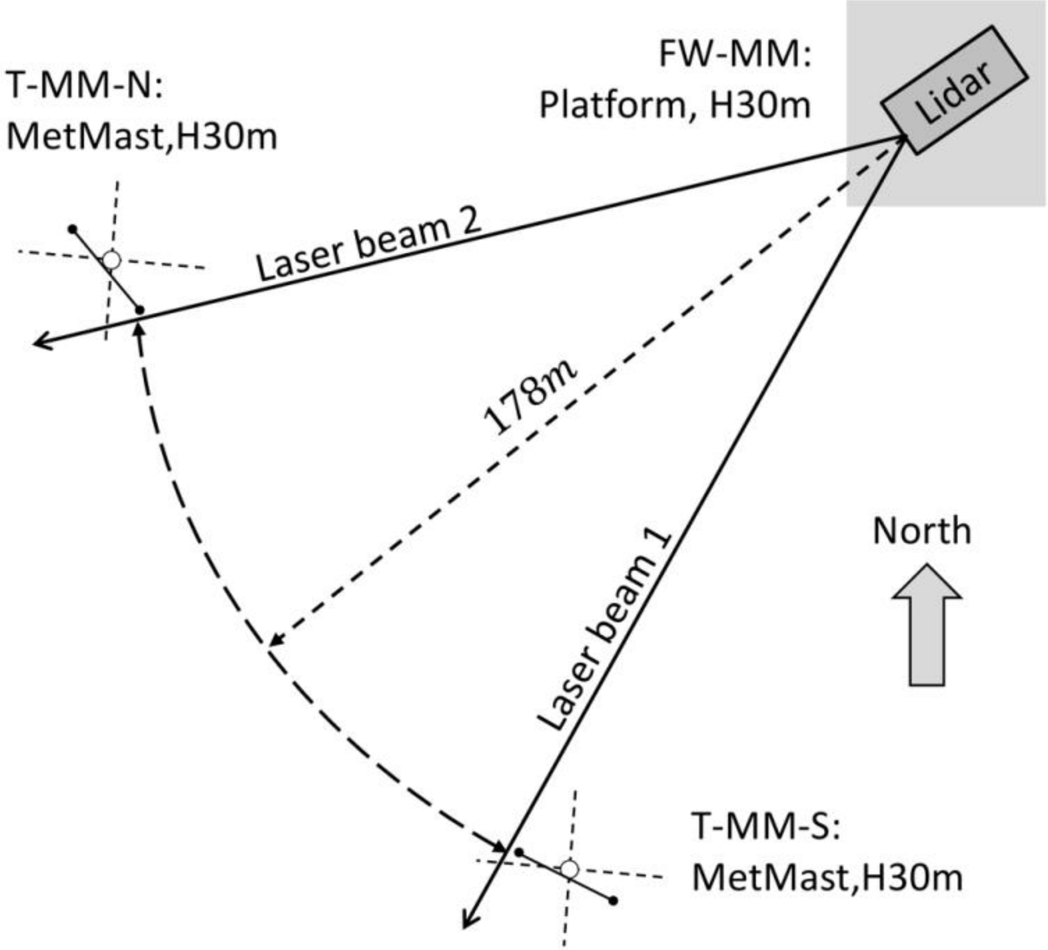
(b) Black box comparison

- White box comparison:
  - (1) direct measurement of TI by laser beam
  - (2) TI at the range gate of laser beam
  - (3) normally at verification site
  - (4) same technology for pulse wind lidars
- Black box comparison:
  - (1) final data of TI for many applications
  - (2) TI at hub height
  - (3) normally at the measurement campaign
  - (4) results from 4 Laser Beams

Measurement: White Box Comparison

- Lidar: WindCube Nacelle
- Serial number: WIPO0100311
- Measurement period:
  - LOS2&3: 21/02/2021 to 19/05/2021: 5 months
  - LOS0&1: 19/05/2021 to 22/10/2021: 6 months
- WindCube Nacelle is installed at fixed platform, the platform height is 30 meter.
- Two IEC met masts are the reference of wind speed, the height of met mast is 30 meter.





Results: White Box Comparison

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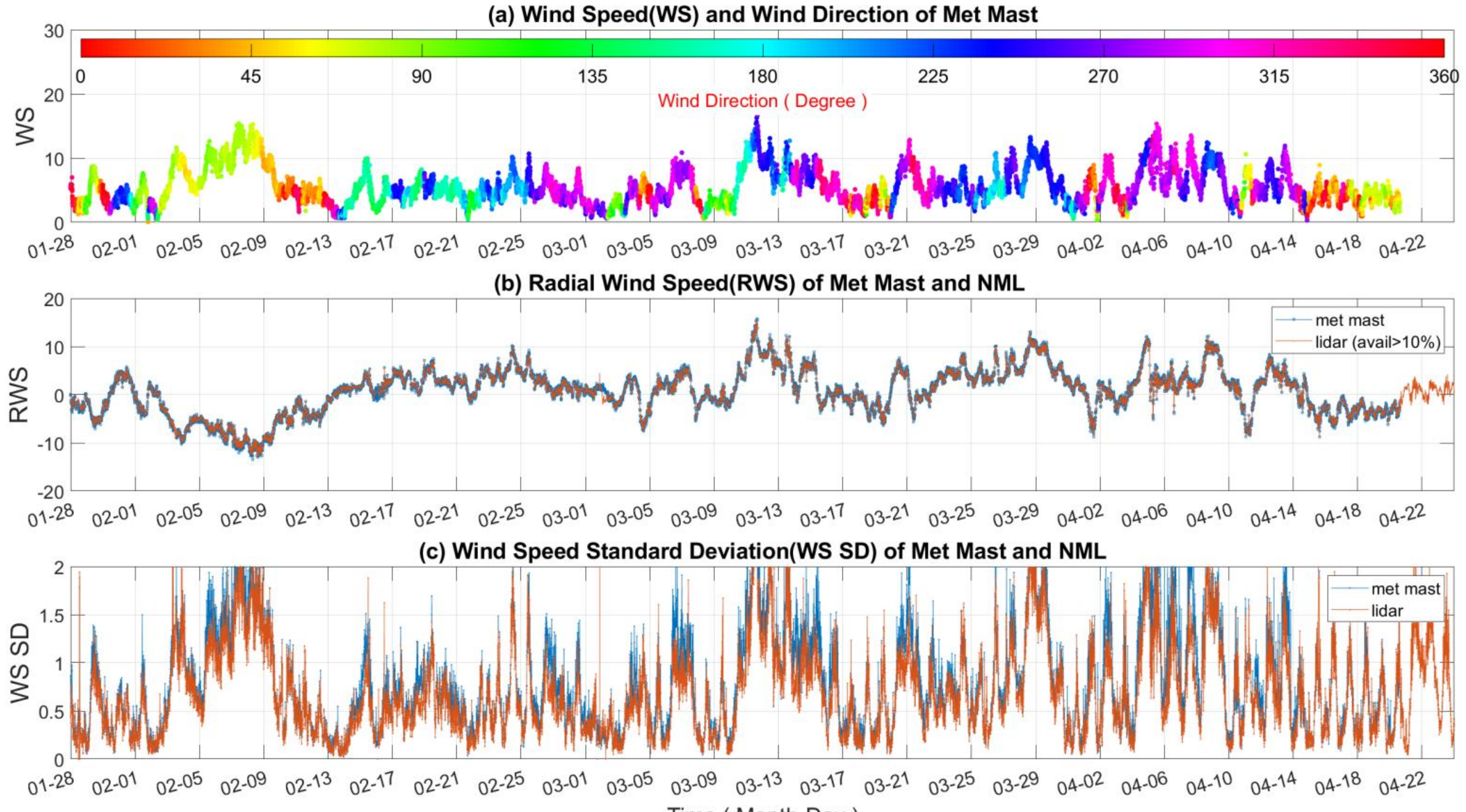
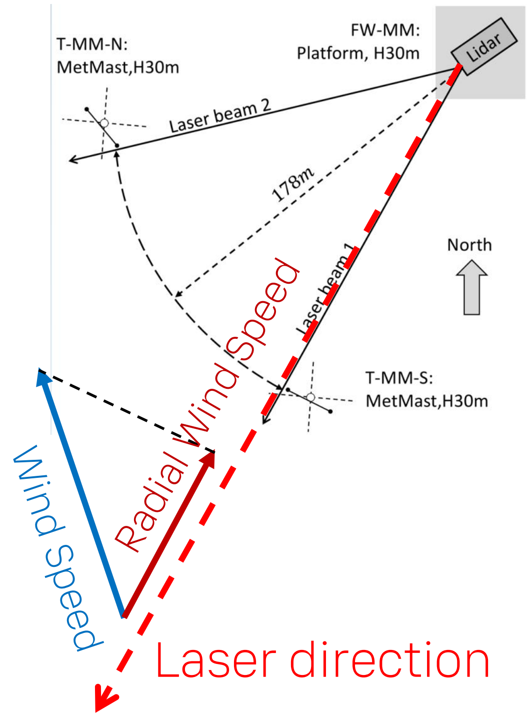


Duration: 3 month



Met Mast SD: $\frac{1}{n}\sqrt{\sum(WS_i - \overline{WS_i})^2}$

Lidar LOS SD: $\frac{1}{n}\sqrt{\sum(RWS_i - \overline{RWS_i})^2}$

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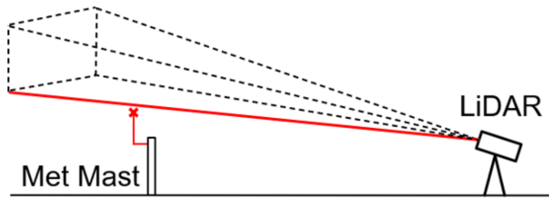
Field Study of Turbulence Intensity measurement by Nacelle Mounted Lidar.
https://iopscience.iop.org/article/10.1088/1742-6596/2265/2/022104

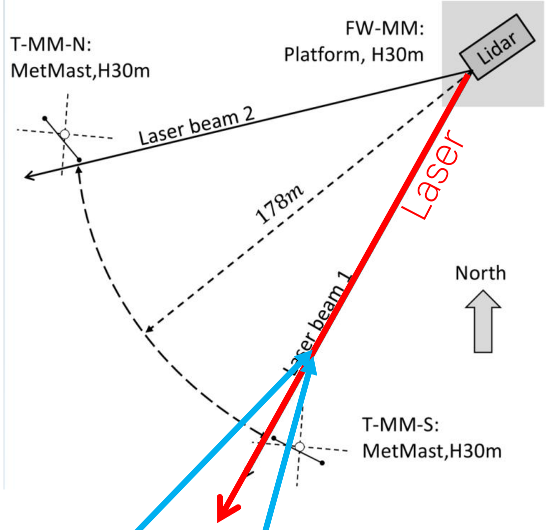
Measurement: White Box Comparison

(1) Verification at DNV site: drawing and photo



(a) White box comparison

(2) Wind sector for data analysis:

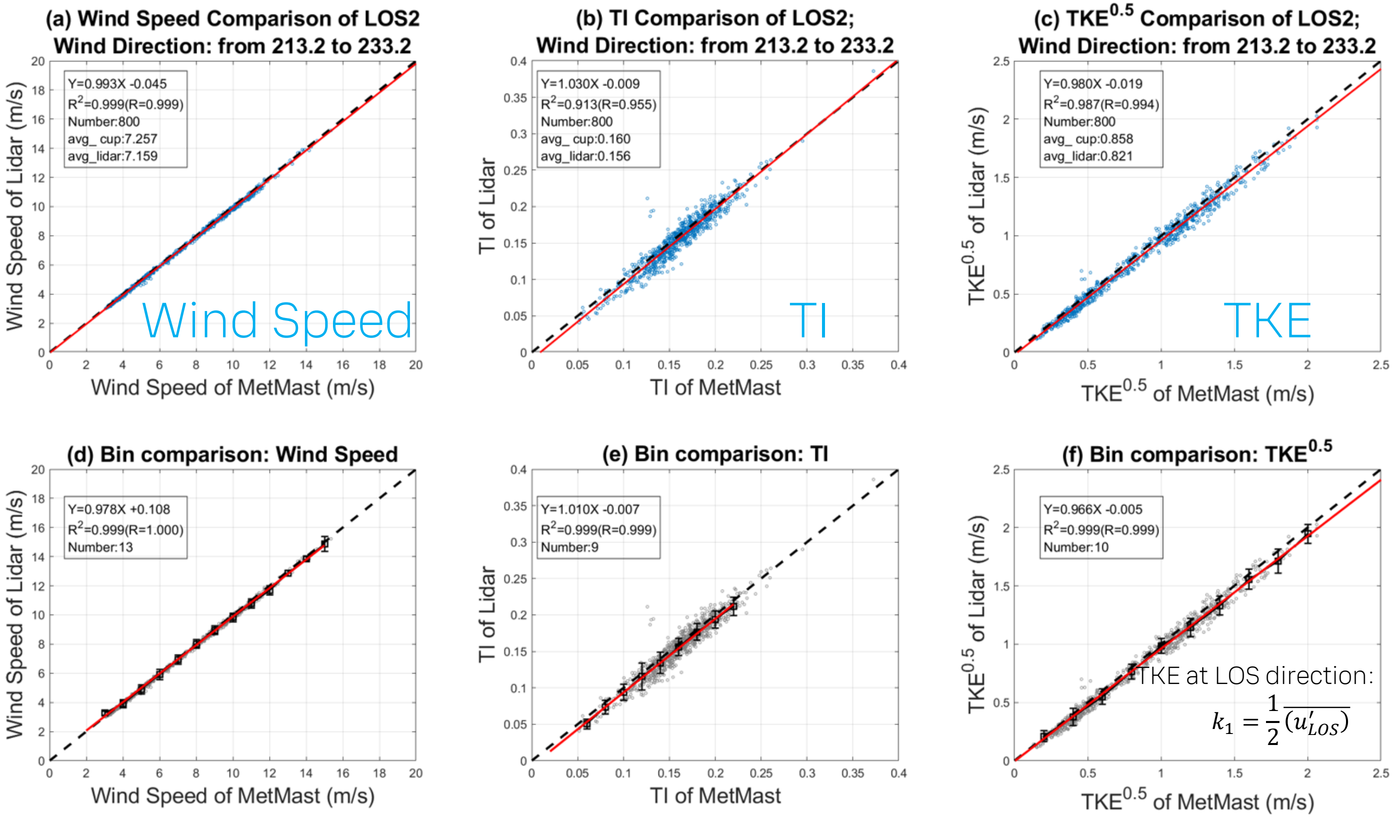


233°

213°

Wind direction is selected:
from 213° to 233°

(3) Figures: comparison between WindCube Nacelle and Met Mast



Field Study of Turbulence Intensity measurement by Nacelle Mounted Lidar.
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Measurement: Black Box Comparison

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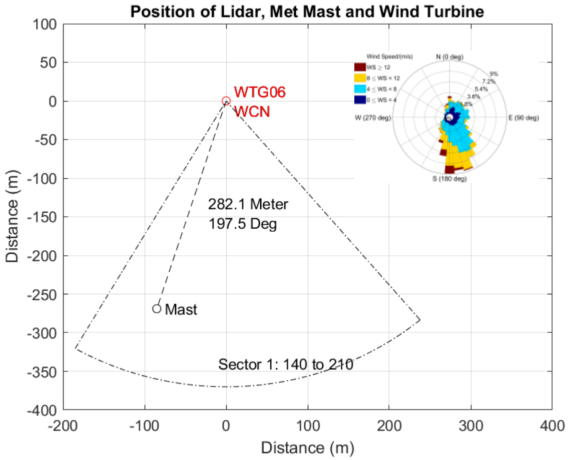
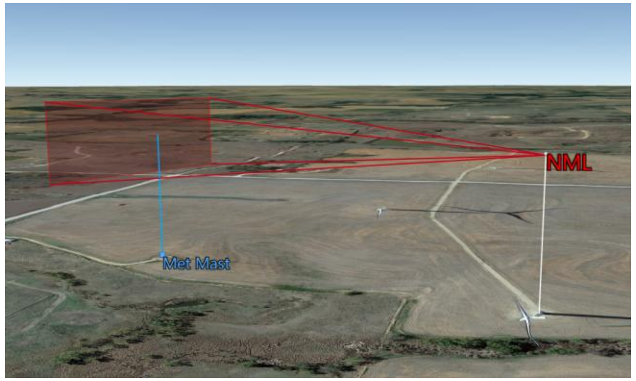
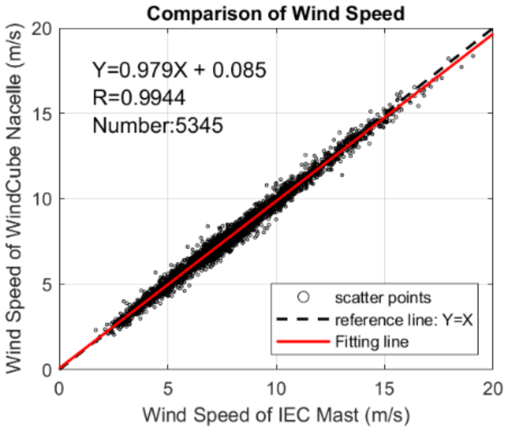
- Pilot project in U.S.
- Participations:
  - ENGIE North America, GE Renewable Energy, DNV and Vaisala
- Objective:
  - accelerate the acceptance of Nacelle-Mounted Lidar for Power Performance Testing

Instrumentation	Type	Measurement Height [m]	Distance from WTG [m]	Distance from WTG in [D]
Nacelle-mounted Lidar	WindCube Nacelle	89m	50m-700m	0.4D-5.5D
Met Mast	IEC compliant	32m-89m	282m	2.2D
Ground-based Lidar	WindCube	40m-200m	290m	2.3D





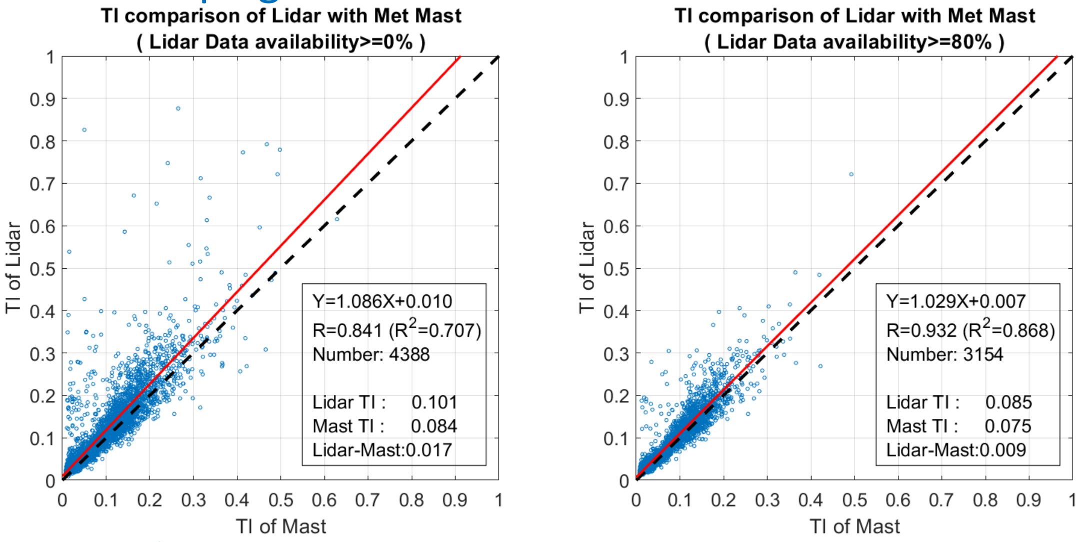


Results: Black Box Comparison

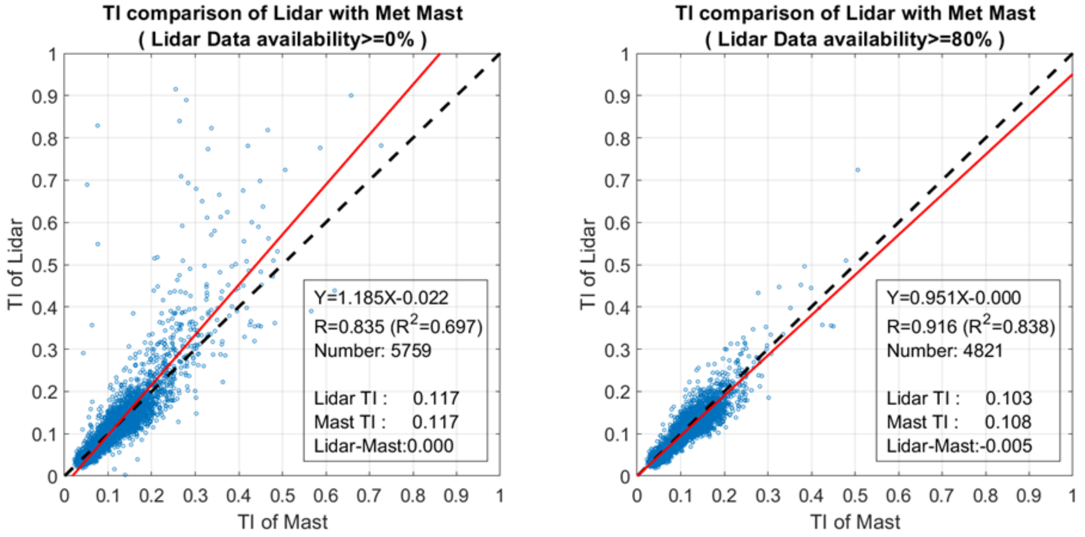
- TI comparison: two field measurements
  - Two right figures compare the TI with filtering out the data of NML by the data availability of 80%.
  - Correlation coefficient is above 0.916; the slope is 0.951~1.029.
  - TI by NML is accurate.

- The remaining data percentages in the two campaigns are 83.7% and 71.9% respectively
  - The data coverage of valid TI reaches the same level as the one for wind speed.

First campaign:



Second campaign:



Results: wind turbine classes

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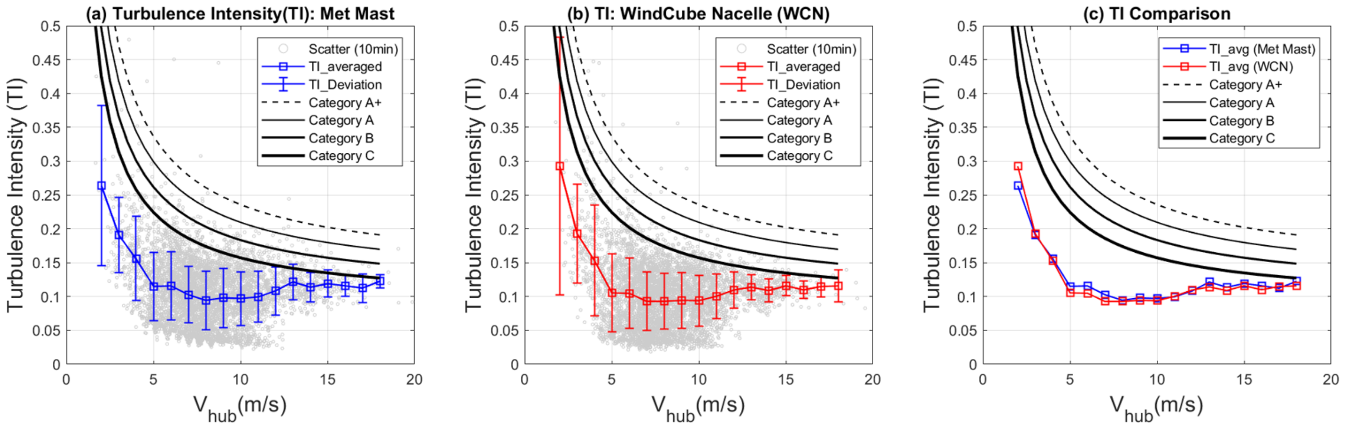
- TI Comparison of Met Mast and NML:
  - Blue line in figs is TI by Met Mast.
  - Red line in figs is TI by NML.
  - TI by NML is close to Met Mast (Fig. c).

- Conclusions:
  - NML has a good measurement capability to verify turbulence category at the range of wind speed.
  - Results from the two sites further prove that NML can characterize the TI at different sites.
  - Further investigation on the different wind direction might be interesting.

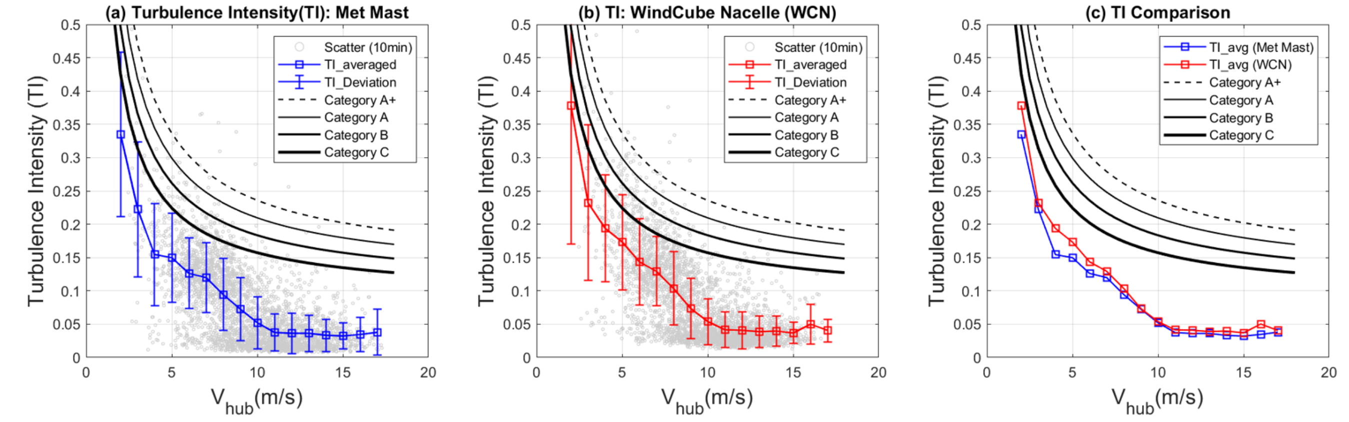
Wind turbine class		I	II	III
V_{ave}	(m/s)	10	8,5	7,5
V_{ref}	(m/s)	50	42,5	37,5
	Tropical (m/s) $V_{ref,T}$	57	57	57
A+	I_{ref} (-)	0,18		
A	I_{ref} (-)	0,16		
B	I_{ref} (-)	0,14		
C	I_{ref} (-)	0,12		

IEC 61400-1: 6.2 Wind turbine classes
Wind turbine classes are defined in terms of wind speed, wind turbine class I, II and III, and turbulence parameters, turbulence category A+, A, B, and C.

First campaign:



Second campaign:



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Conclusions

- Results from White Box Comparison (WBC) :
  - (a) correlation coefficient of TI LOS varies from 0.923 to 0.955; slope varies from 0.978 to 1.030;
  - (b) 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.
- Results from Black box Comparison (BBC):
  - (a) correlation coefficient is 0.916 and 0.932 with slopes of 0.951 and 1.029;
  - (b) data coverage percent of valid TI is high: 83.7% and 71.9%;
  - (c) global accuracy of TI measurements is high: bias is within 4.9%.
- The high accuracy and data coverage implies TI by NML is ready for industrial applications.

- Wind lidars can benefit further researches on the turbulence in ABL (Atmosphere Boundary Layer).

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Thank you!

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