An investigation on the performance and accuracy of Wind Turbine Power Curve (WTPC) by Nacelle-Mounted Wind Lidar (NMWL) and its uncertainty

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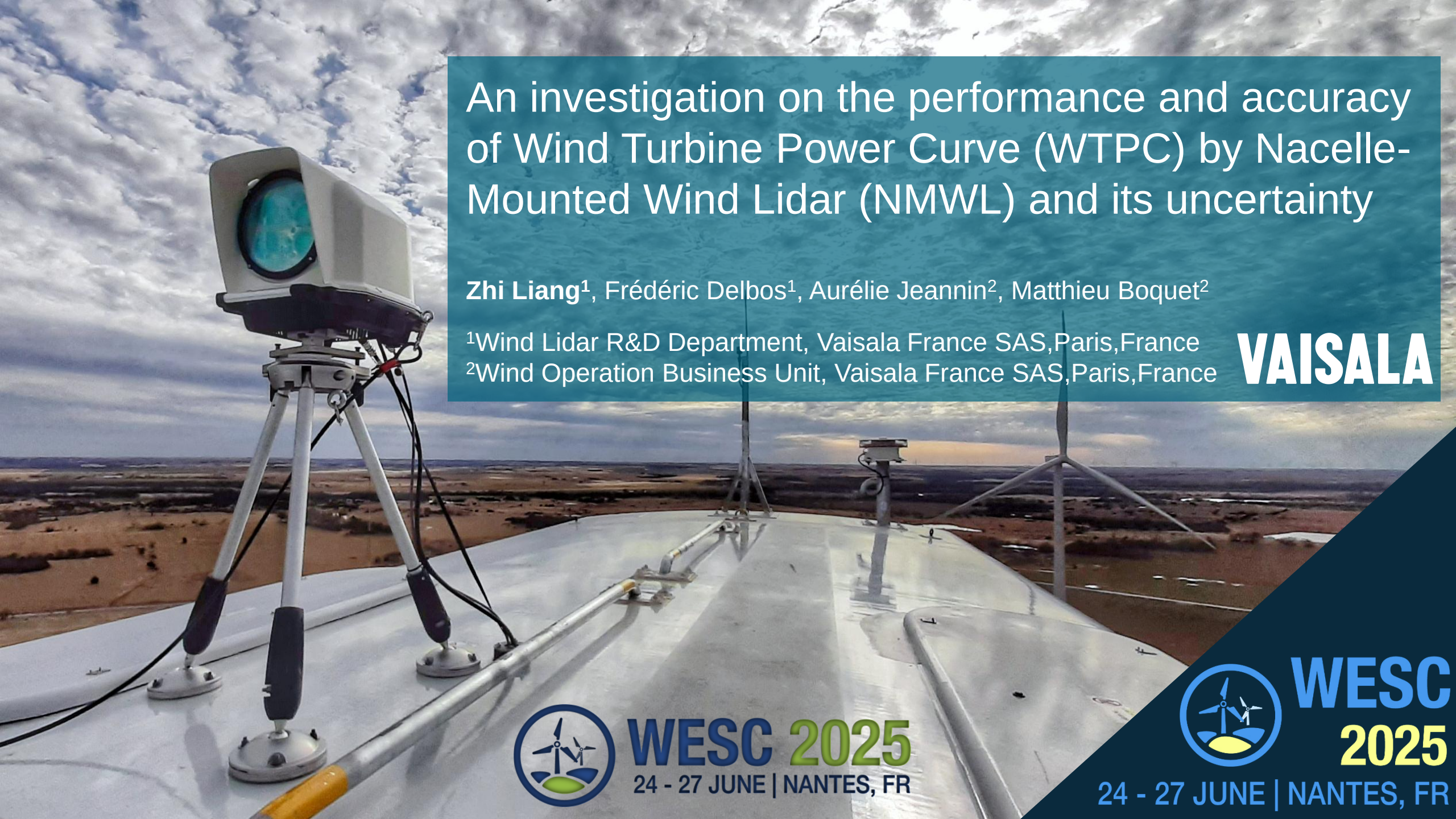

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Outline

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- Introduction
- Measurement
- Result:
  - Wind Speed Comparison
  - Sensitivity analysis
  - Wind Turbine Power Curve
- Conclusions

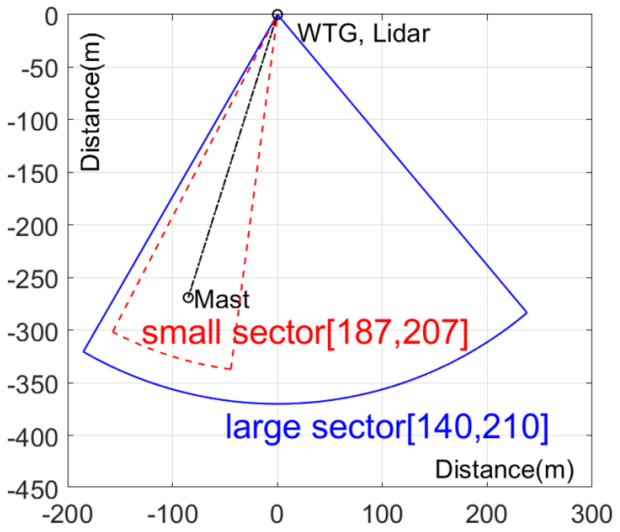
Introduction

Objectives

- Extensive field study to prepare for the use of Nacelle Mounted Lidar(NML) for Power Performance Testing (PPT) on operational basis
- First joint industry project following the context of the IEC 61400-50-3 standard

Methodology

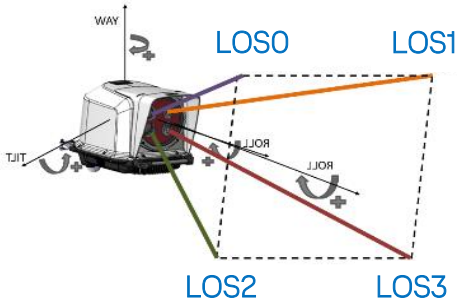
- 3-month campaign in ENGIE's wind farm (US)
- Onshore flat terrain
- Reference instruments: (1) IEC met mast and (2) WindCube Ground-Based lidar (GBL)



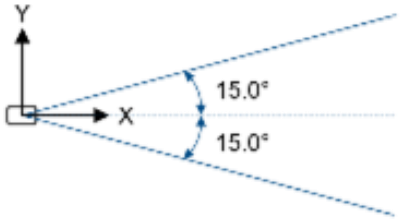
Measurement: Wind Lidar Technology

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

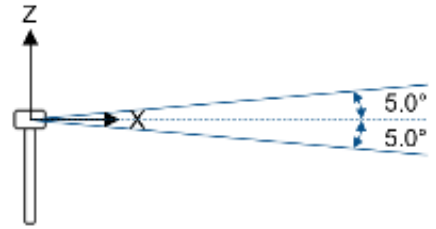
(a) Beam Geometry



(b) Top View



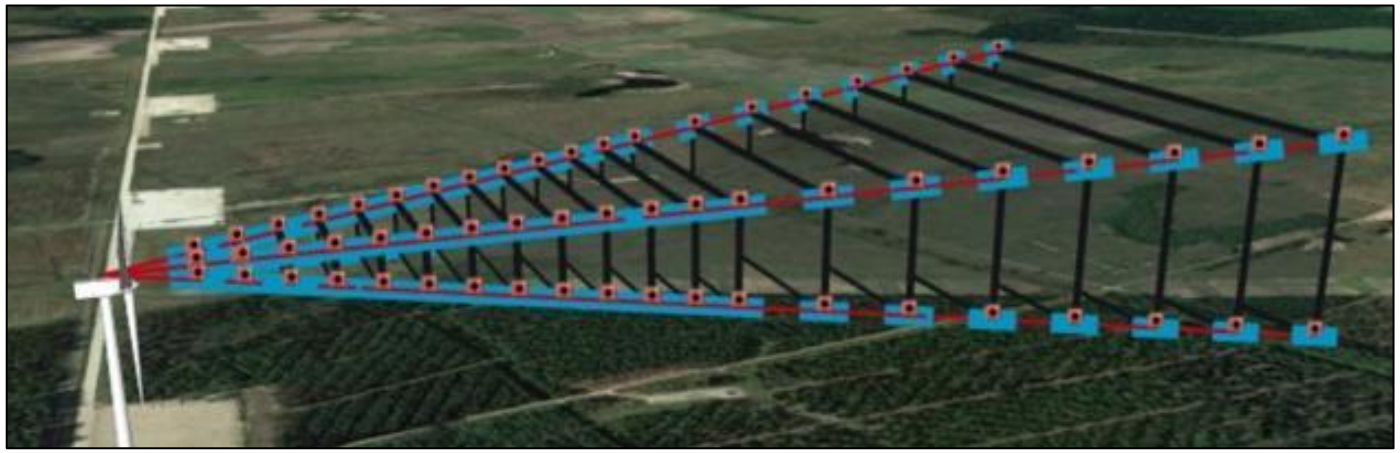
(c) Side View



Processing Unit (inside Turbine Nacelle)

Optical head (on Nacelle Roof)

Tripod for installation



Measurement: Algorithm

(1) From radial to horizontal wind speed

- (1.1) Radial wind speed (RWS) is measured at 1Hz and average over each 10min period
- (1.2) Horizontal Wind Speed (HWS) is calculated by 10min RWS:

$$\begin{cases} U_+ = \dfrac{RWS_0 + RWS_1}{2(\cos\theta_+ \cos\tau - \sin\theta_+ \sin\varphi_+ \sin\tau)} \\ V_+ = \dfrac{RWS_0 - RWS_1}{2\sin\theta_+ \sin\varphi_+} \end{cases}$$

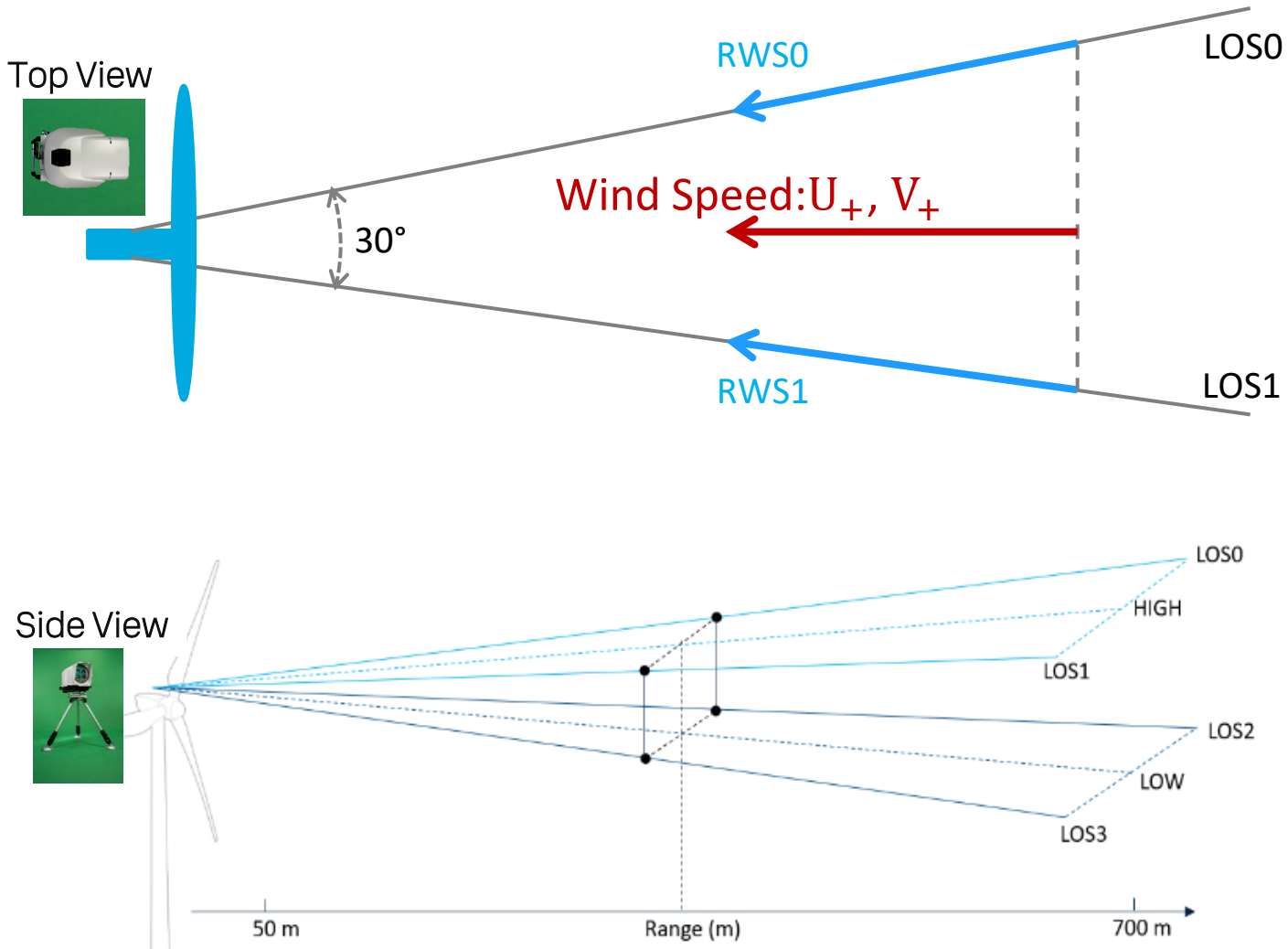
(2) Wind reconstruction at Hub height

- (2.1) Horizontal Wind speed at upper/lower heights: $HWS_+ = \sqrt{U_+^2 + V_+^2}$; $HWS_- = \sqrt{U_-^2 + V_-^2}$
- (2.2) Wind shear by upper & lower heights:

$$Shear = \ln\left(\frac{HWS_+}{HWS_-}\right)/\ln\left(\frac{H_+}{H_-}\right)$$

- (2.3) Horizontal Wind Speed at hub height:

$$HWS_{Huser} = HWS_+ * \left(\frac{H_{user}}{H_+}\right)^{V\ Shear}$$



Measurement: Setup

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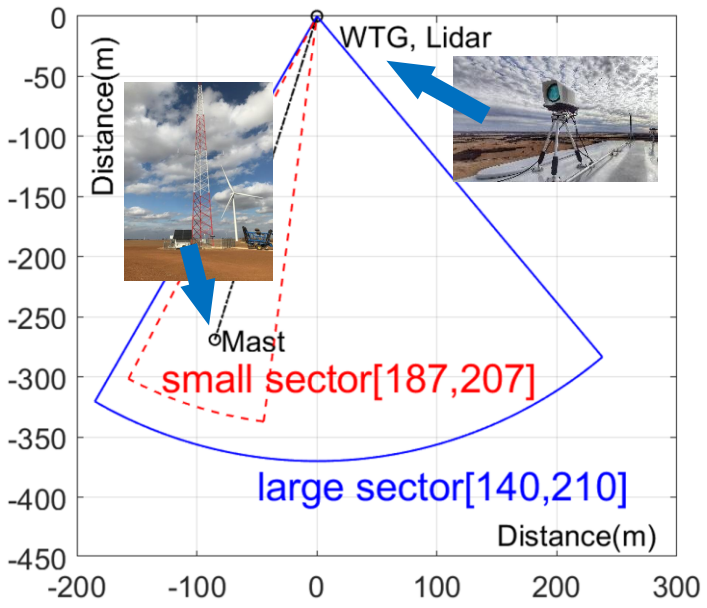
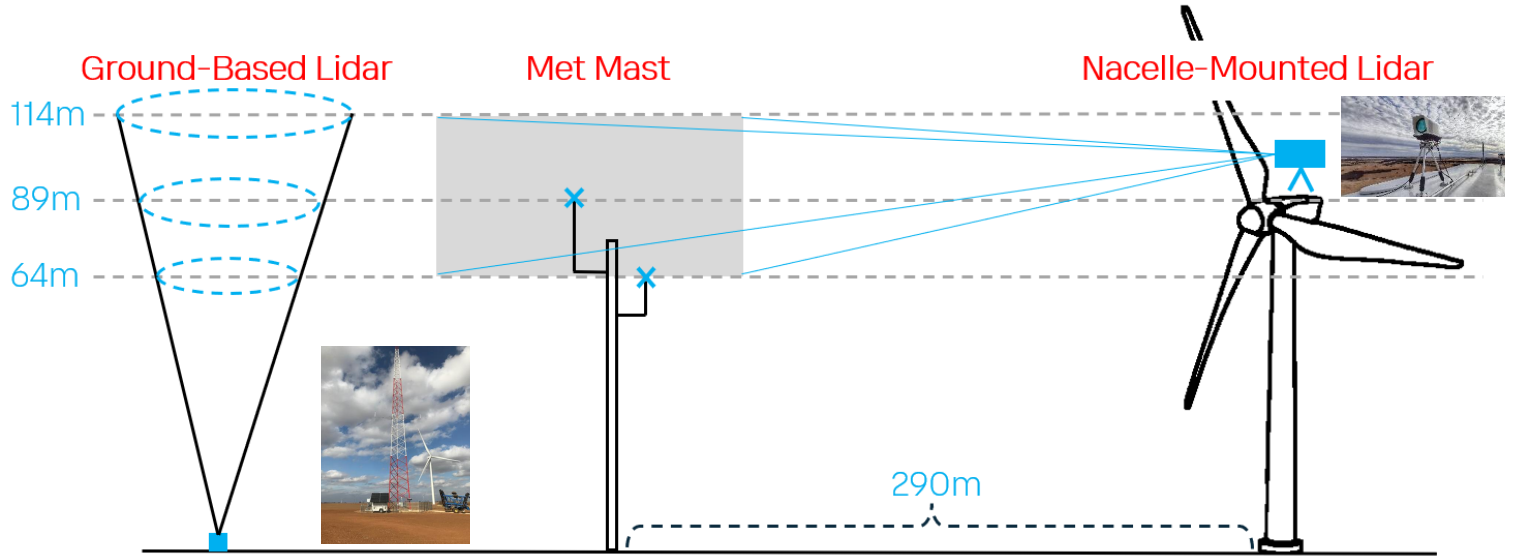
Map



Two wind sectors:

1) 187°-207°: met mast in the center
2) 140°-210°: IEC valid wind sector

Instrumentation	Type	Distance from WTG [m]	Distance from WTG [D=127m]	Measurement Height [m]
Met Mast	IEC compliant	282m	2.2D	32m-89m
Ground-based Lidar	WindCube	290m	2.3D	40m-200m
Nacelle-mounted Lidar	WindCube Nacelle	50m-700m	0.4D-5.5D	89m



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Result: Wind Speed

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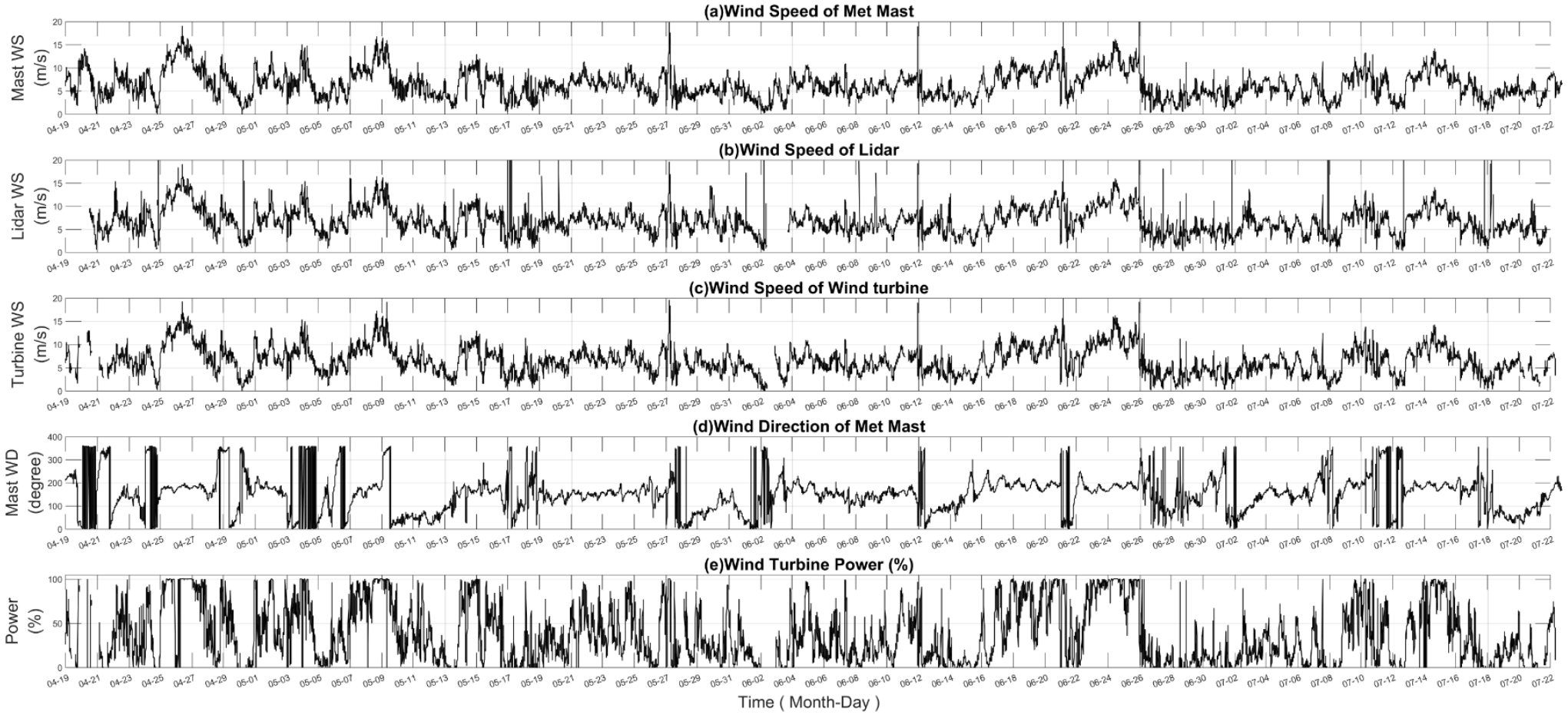
(a) Wind Speed of Met Mast

(b) Wind Speed of NML Lidar

(c) Wind Speed of Wind Turbine

(d) Wind Direction of Met Mast

(e) Wind Turbine Power



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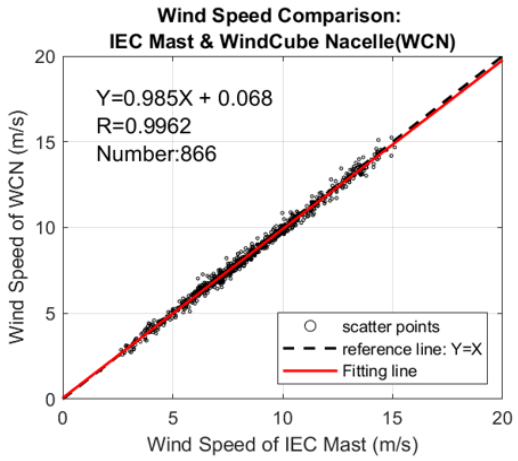
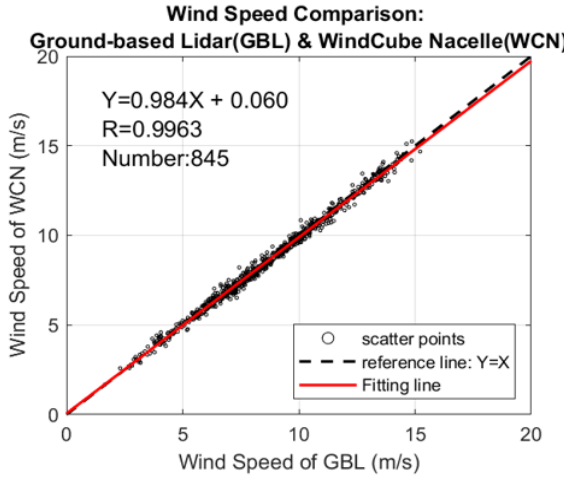
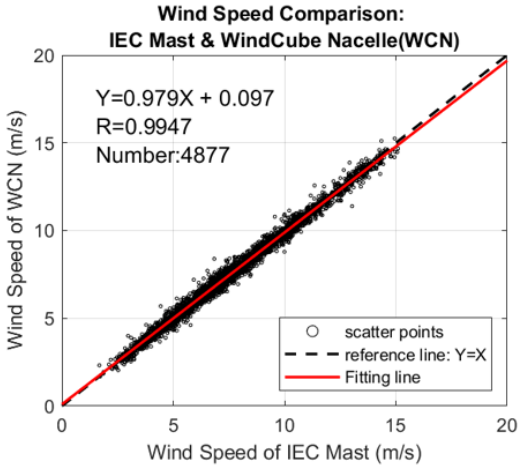
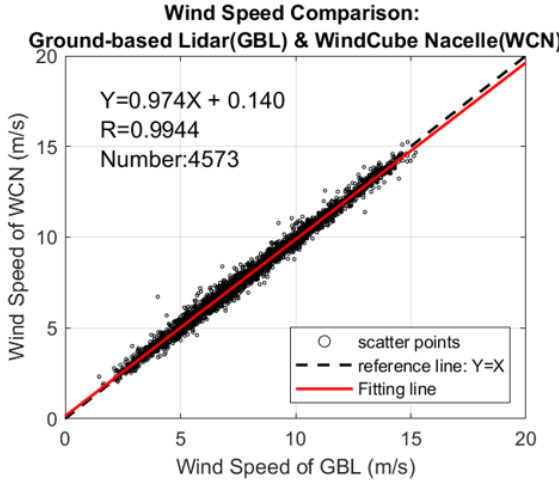
Result: Wind Speed





Centered wind sector: 187°-207°



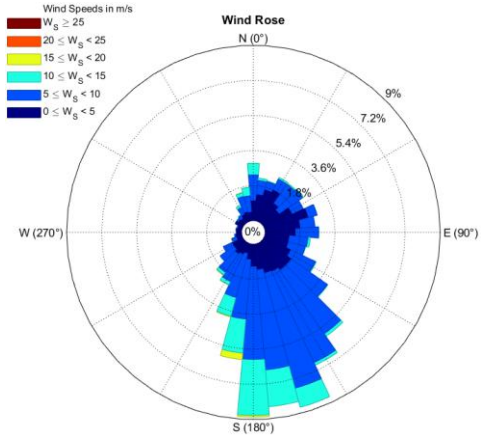


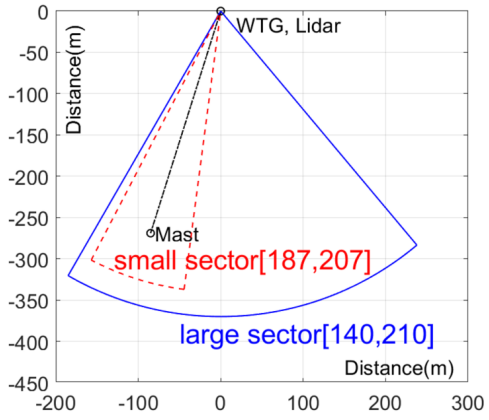
Valid IEC wind sector: 140°- 210°

Key take away

- Better wind speed correlation between the IEC met mast and nacelle lidar when using a smaller wind sector.
- Sampling points in small sector is not enough for an accurate PPT.

Sector	ALL	187°-207°	140°-210°
Data points	13743	1232	6507





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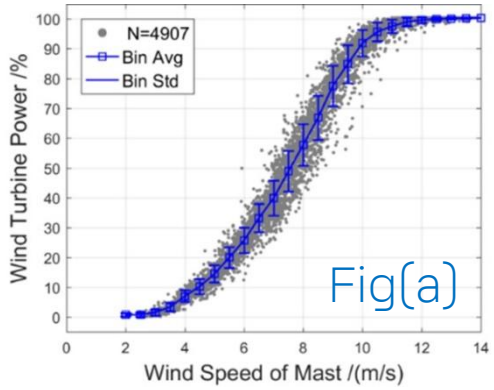
Wind Turbine Power Curve and Method for sensitivity analysis

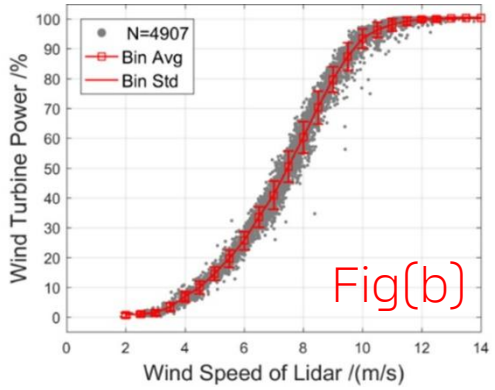
Result of WTPC by Mast and NML

- Fig(a): WTPC by Mast
- Fig(b): WTPC by NML
- Scatters: 10min data
- Data filtering: same, to have the data sample

Conclusion:

- Scattering points for WTPC of NML in fig(b) are more concentrated than WTPC of Mast in fig(a).



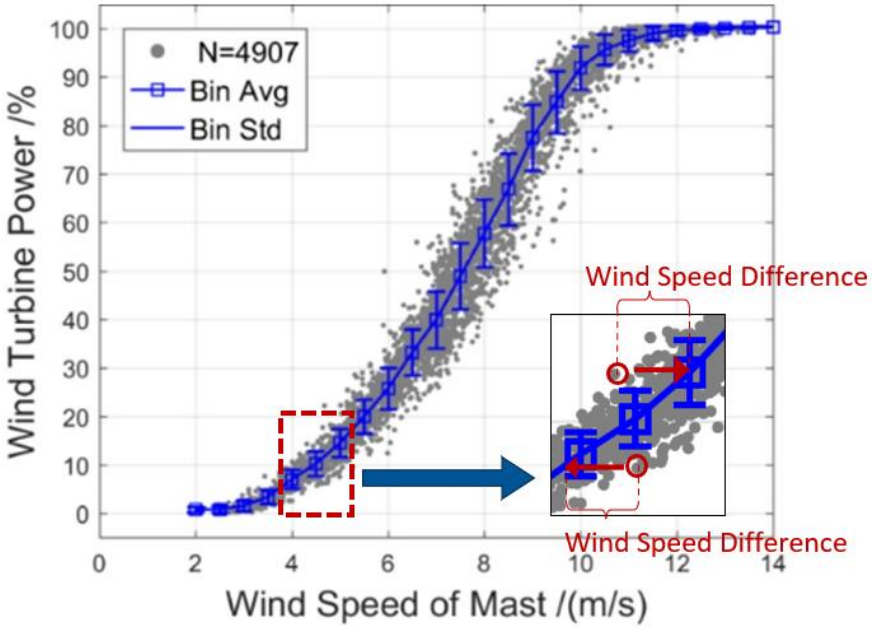


Method for sensitivity analysis

- Step(1): to average **scatters (gray)** to WTPC(blue line).
- Step(2): to calculate Wind Speed Difference from real time wind spead, WS_{real} (gray points) to wind speed at WTPC, WS_{ref} (blue line):

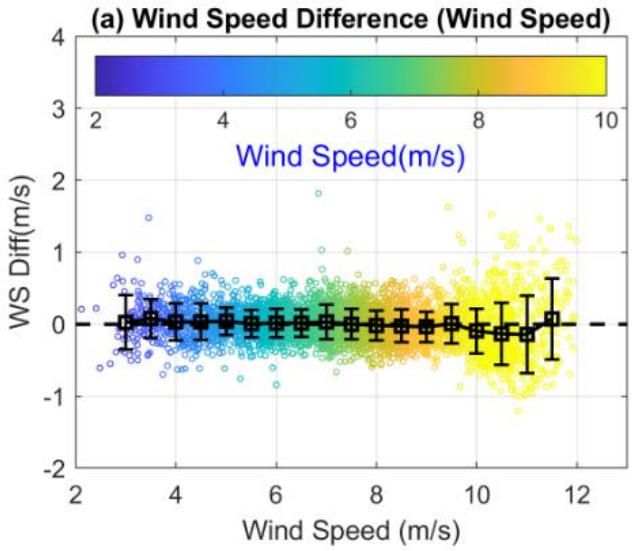
$$WS\ Diff = WS_{real} - WS_{ref}$$

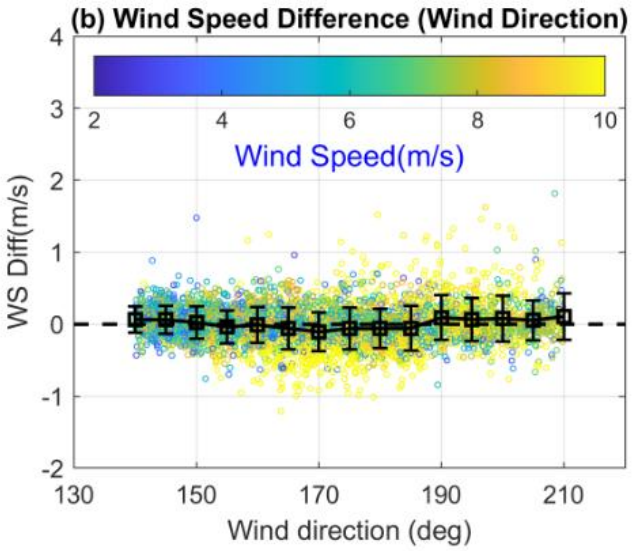
Step(3): to analyze sensitivity of WTPC on wind speed, direction, shear and TI.

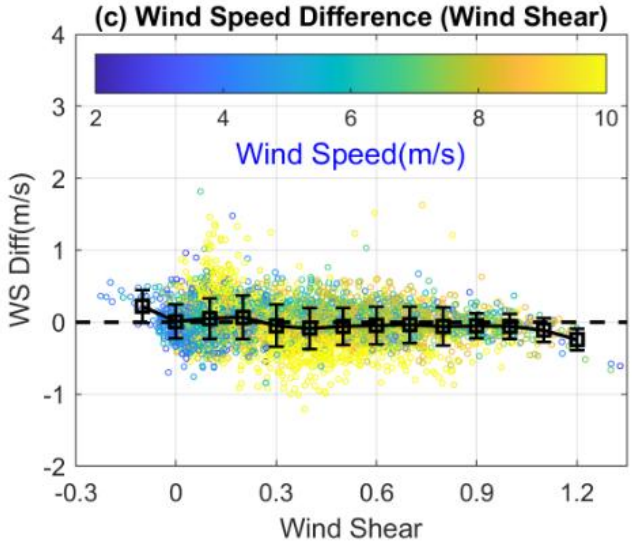


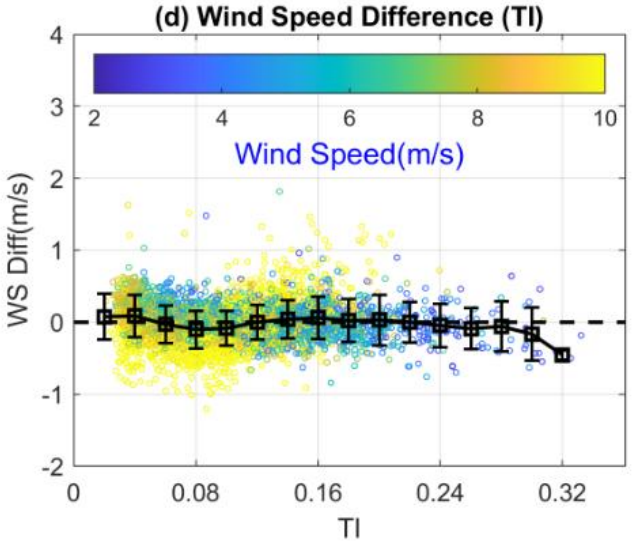
Sensitivity of NML

- Sensitivity
  - Y-axis: Wind Speed Difference (WS Diff)
  - X-axis: Parameters
  - Scatter color: wind speed
- Parameters:
  - (a) Wind speed
  - (b) Wind direction
  - (c) Wind Shear
  - (d) TI
- Conclusion:
  - No clear sensitivity for NML



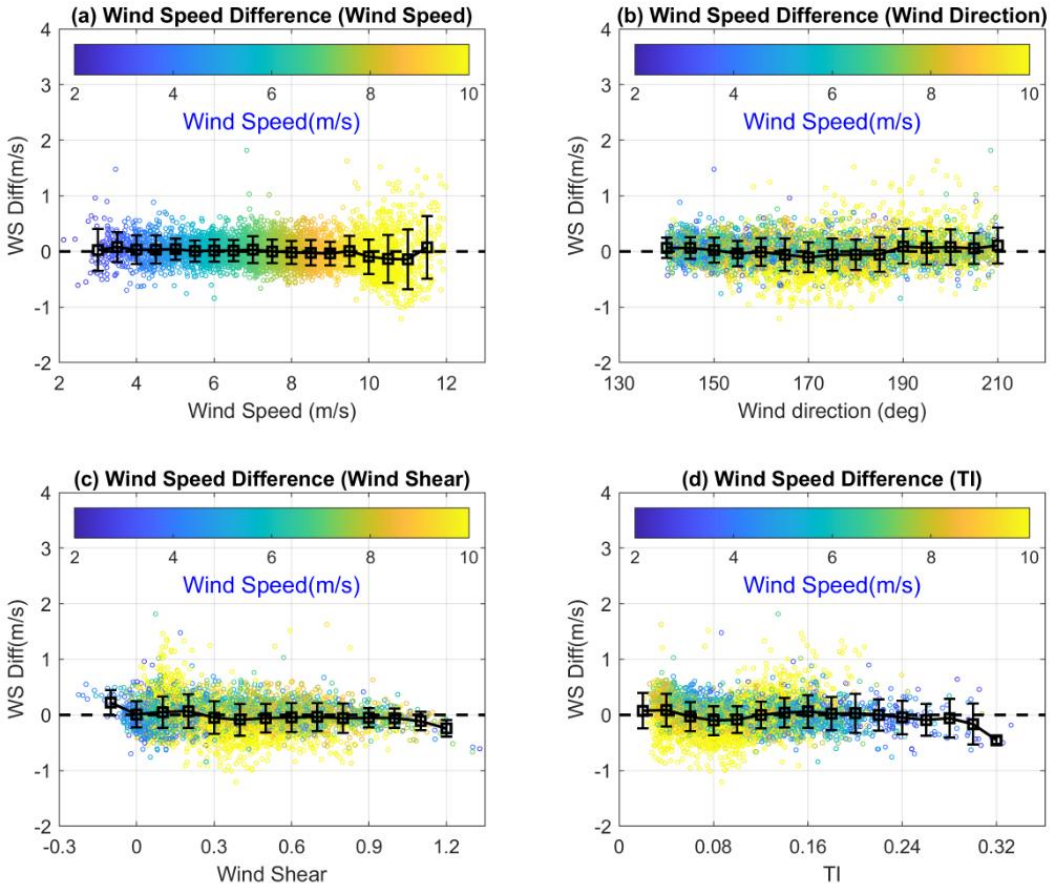




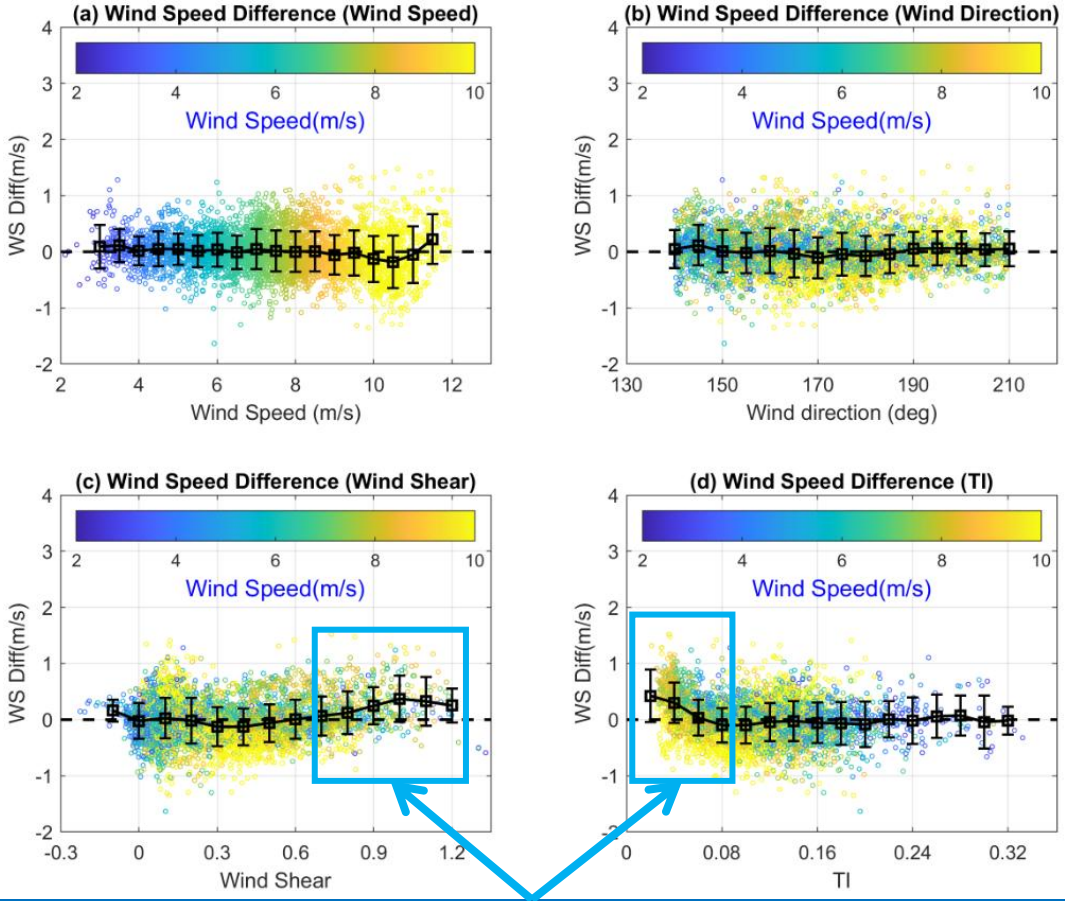


Sensitivity Comparison

(a)~(d): Result of NML



(a)~(d): Result of Met Mast:



Sensitivity: (1) big wind shear: Shear>0.7; (2) small TI: TI<0.08. The wind transfer function from **met mast** to **turbine location** has some sensitivity under this air flow condition, while NML doesn't have this phenomenon of sensitivity.

Comparison for Wind Turbine Power Curve

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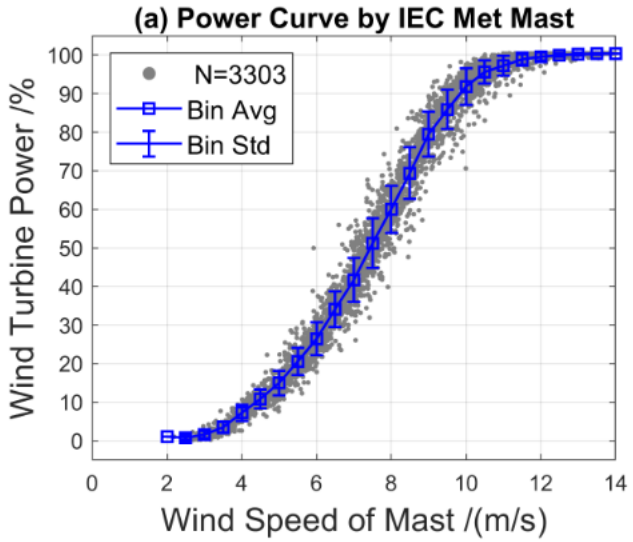
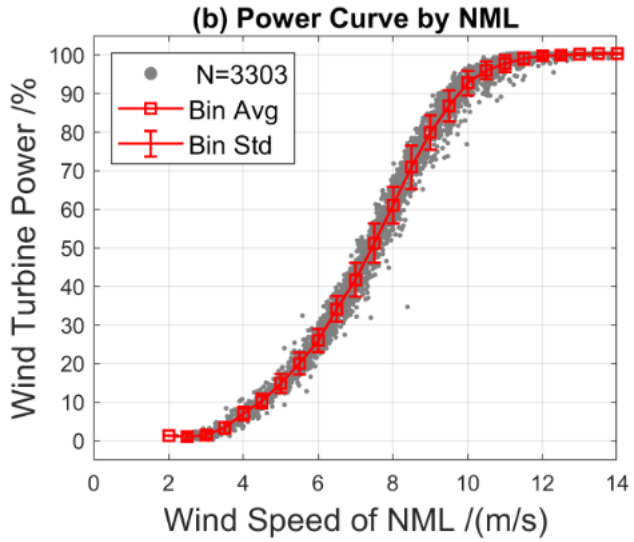
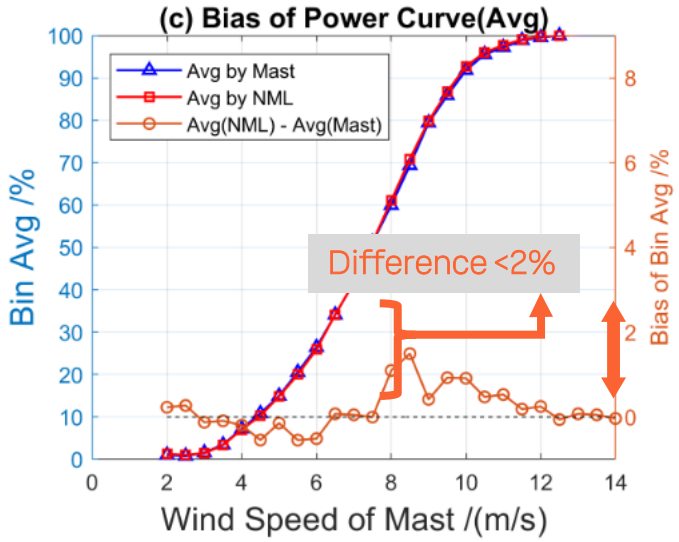
WTPC by Mast and NML

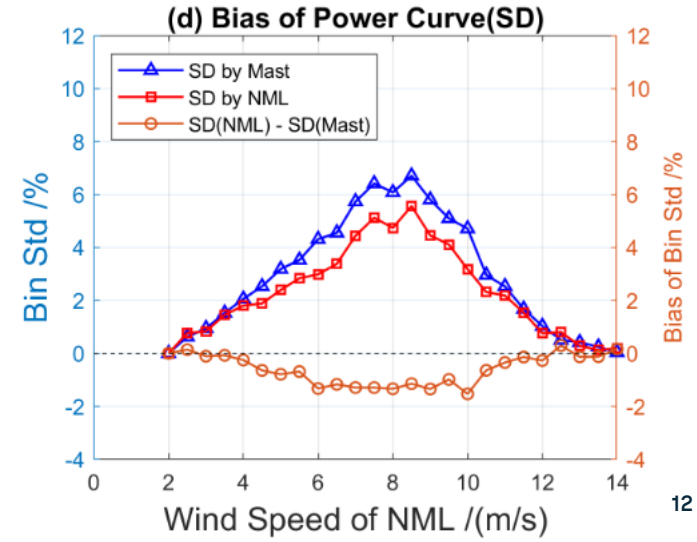
- Fig(a): WTPC by Mast
- Fig(b): WTPC by NML
- Added more filtering: (1) wind shear<0.7; (2) TI>0.08

- Comparison
  - Fig(c): Averaged value of WTPC
  - Fig(c): SD value of WTPC
- Conclusion
  - Difference of Averaged WTPC by mast and NML is <2%.
  - SD of WTPC by NML is lower.
  - NML always yaws with turbine nacelle and measure the wind speed in front of the turbine.









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Result: Wind Speed

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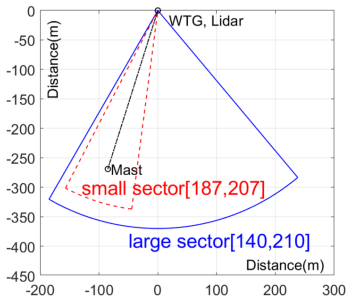
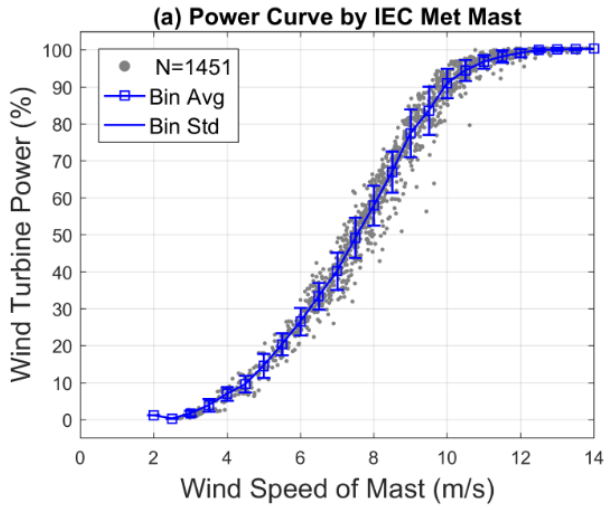
Small wind sector:

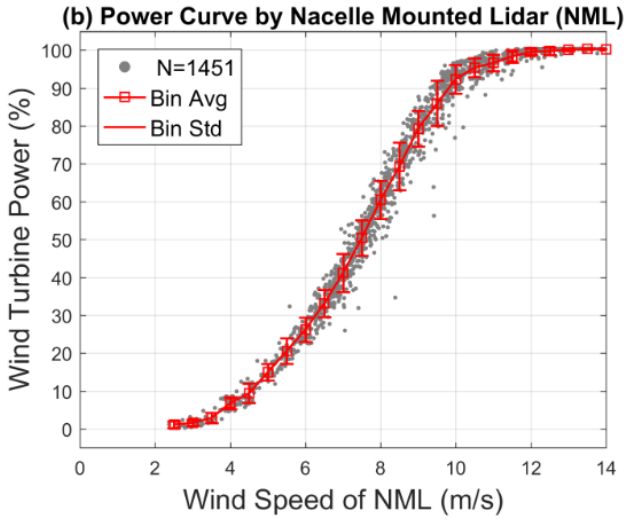
187-207°

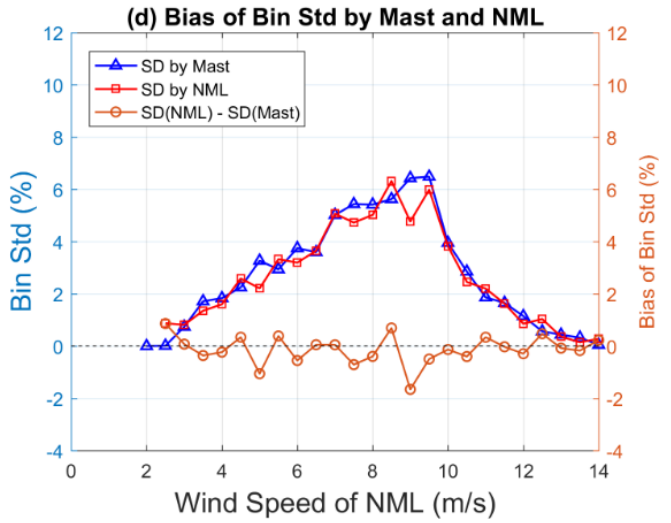


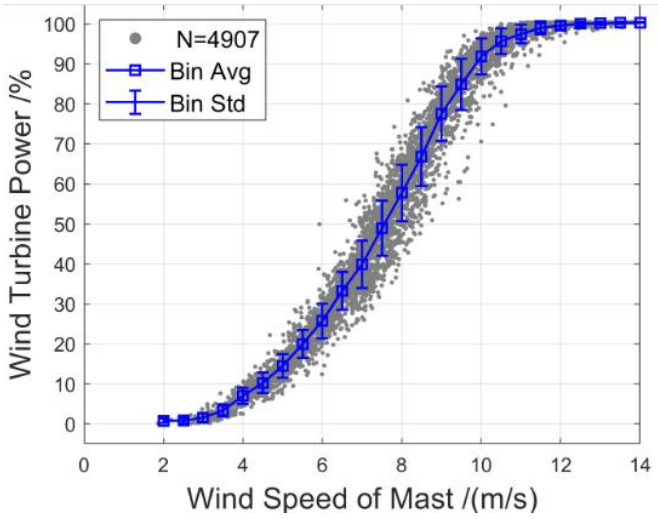
Big wind sector:

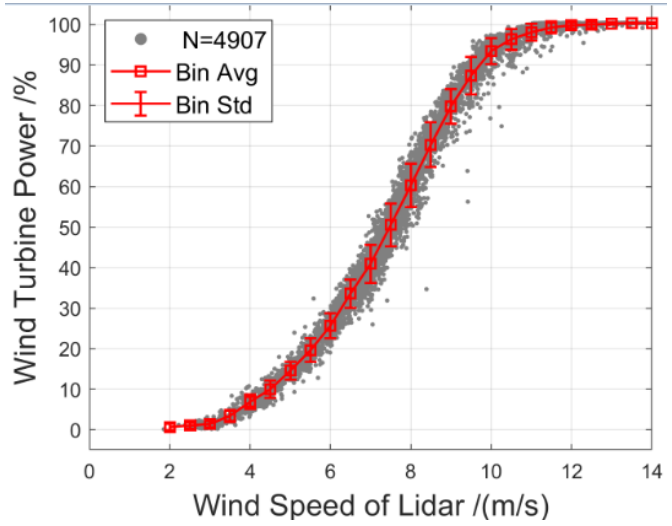
140-210°

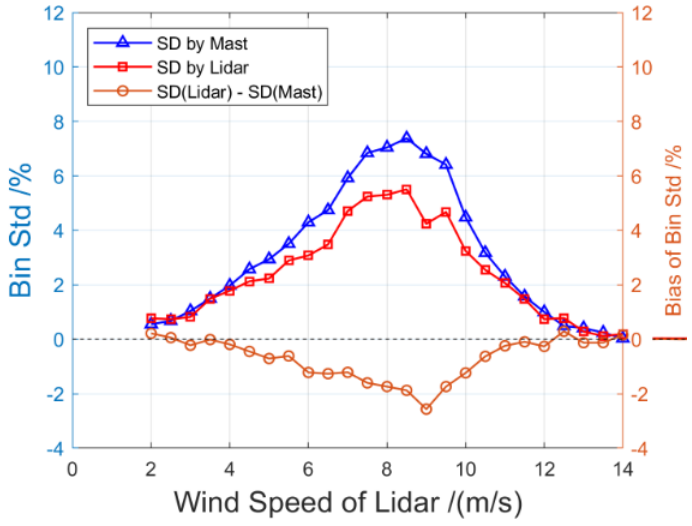












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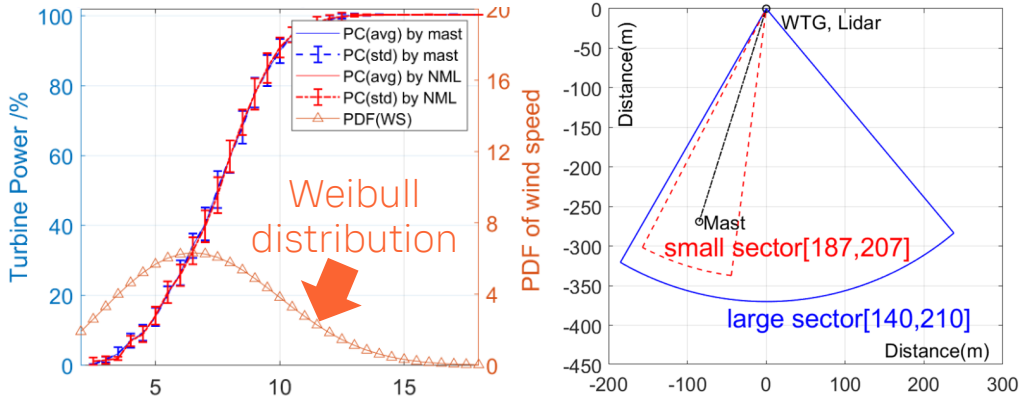
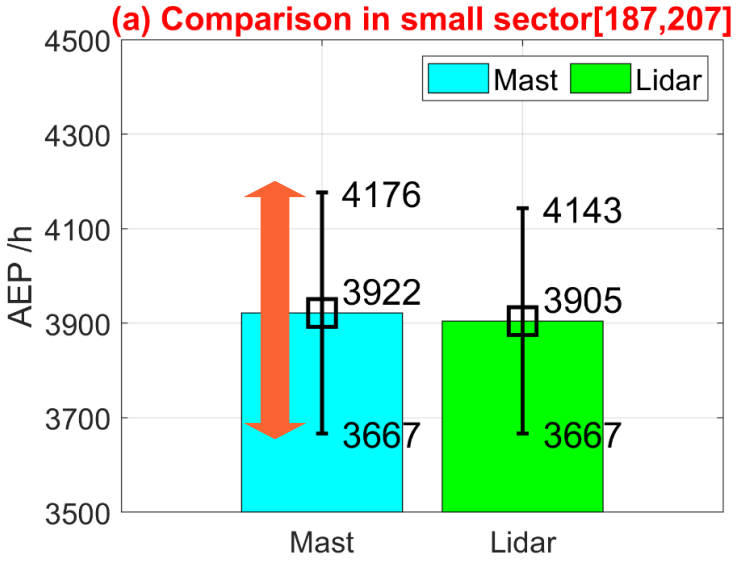
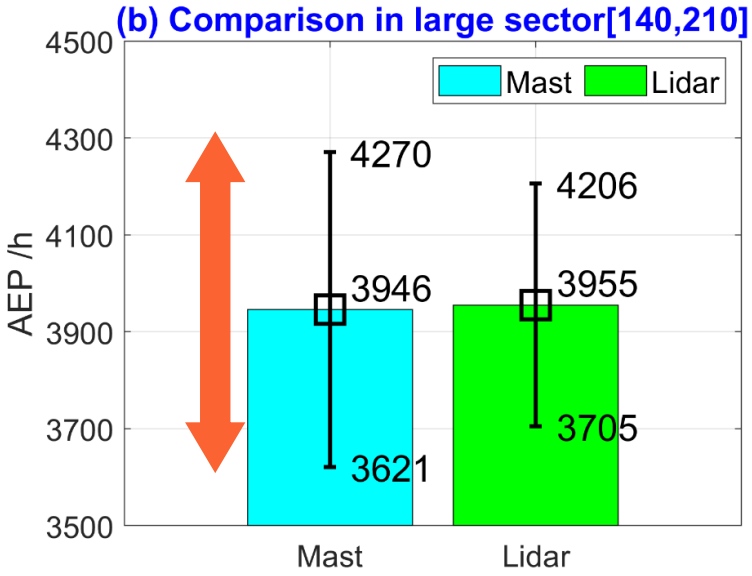
Uncertainty on AEP

- The evaluation of PPT by two devices on the uncertainty of Annual Energy Production(AEP), assuming wind Weibull distribution
- Equivalent Operating Hours (EOHs) is used to analyze AEP
- AEP Range using large wind sector:
  - Mast: [3621h, 4270h], in fig(b)
  - NML: [3705h, 4206h], in fig(a)
- The overall uncertainty of NML is within the uncertainty range of Met Mast.







Conclusions:

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- Conclusions:
  - Better spatial coherence of the nacelle lidar measurements than met mast.
  - Difference between Wind Turbine Power Curve (WTPC) with IEC met mast and nacelle lidar is <2%.
  - Standard Deviation (Uncertainty) of both WTPC and AEP is lower for Nacelle Mounted Lidar (NML), especially in the wider sector.
  - Industry is ready for WTPC using NML on the operational basis following IEC 61400-50-3.

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