PhD defence: How to measure remotely the wind using nacelle lidars for power performance testing

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How to measure remotely the wind using nacelle lidars for power performance testing

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Project: UniTTe

DTU Wind Energy
Department of Wind Energy
Outline

1. Introduction
2. Calibration of wind lidars
3. Wind field reconstruction
4. Power performance testing
Motivations

Source: CDIAC
Motivations
Motivations

• The wind industry is a business
  ➡ strives for making money
  ➡ no such big machines and large scale wind farm without a profitable business
How wind industry ensures it makes money

Wind resource

Power curve of wind turbines

Annual energy production

Is very uncertain

Guaranteed by manufacturer

Basis for bankable wind projects (GWh/year)

Contractual agreements + international standards
Power performance testing

• GOAL 1: relate turbine power to energy available in the wind
This needs measurements of:
  – Turbine power
  – (free stream) Wind speed

  “the wind speed at the turbine position as if the wind turbine was not there”

• GOAL 2: assess power curve uncertainties
  – how far from the true power curve (unmeasurable) is the measured one

  “the wind turbine will produce that much energy at this wind speed, and we’re sure with a probability of XX %”
Power performance testing

The old way

**meteorology mast** far enough away (2-4 diameters) + cup anemometers
Power performance testing
The modern ways (1/2)

Remote sensing instruments –

new IEC standard (2017):
use of **ground-based wind lidars** (profilers) allowed

ZephIR 300 (by ZephirLidar)  WindCube (by Leosphere)
Remote sensing instruments

Future/Now: use of nacelle-based wind lidars

ZephIR Dual Mode (scanning) by ZephirLidar
Wind Iris (4-beam) by AventLidar
Wind Eye (4-beam) by Windar Photonics
Diabrezza (9-beam) by Mitsubishi Electric
Why nacelle lidars for power performance testing

For modern multi-megawatt turbines:

- **Cost-efficiency**
  - met. mast
  - ground-based lidars
  - nacelle-based lidars

- **Representativeness of wind measurements**
  - met. mast
  - ground-based lidars
  - nacelle-based lidars

- especially offshore!
- especially in complex terrain!
Lidar

- **Light Detection And Ranging**: “a radar using light”
- **Remotely measuring**: from some meters to >10 km away

**Principles of coherent Doppler wind lidars**

1. Backscattered light
2. Doppler spectrum
3. LOS velocity
4. Wind Field Characteristics

Credit: N. Vasiljevic
Lidar

- **LIght Detection And Ranging:** “a radar using light”
- **Remotely measuring:** from some meters to >10 km away

**Principles of coherent Doppler wind lidars**

1. Backscattered light → FFT → Doppler spectrum
2. Doppler spectrum → estimator → LOS velocity
3. LOS velocity → WFR model → Wind Field Characteristics

Credit: N. Angelou
Lidar

- **LIght Detection And Ranging**: “a radar using light”
- **Remotely measuring**: from some meters to >10 km away

**Principles of coherent Doppler wind lidars**

1. Backscattered light → FFT → Doppler spectrum
2. Doppler spectrum → estimator → LOS velocity
3. LOS velocity → WFR model → Wind Field Characteristics

![Diagram of Lidar Process]

**5B-demo**
Lidar

- **Light Detection And Ranging:** “a radar using light”
- **Remotely measuring:** from some meters to >10 km away

**Principles of coherent Doppler wind lidars**

1. Backscattered light → FFT
2. Doppler spectrum → LOS velocity → WFR model
3. Wind Field Characteristics

5B-demo
Research questions

1) What are the uncertainties inherent to the measurements performed using a nacelle-mounted lidar?
   ➔ Calibration procedures required
   see article in Remote Sensing journal:
   “Generic Methodology for Field Calibration of Nacelle-Based” (2016)
   A. Borraccino, M. Courtney, R. Wagner

2) How can nacelle-mounted lidars provide free-field wind characteristics for power curve measurement?
   ➔ New wind field reconstruction methodologies
   see article in Wind Energy Science journal:
   “Wind field reconstruction from nacelle-mounted lidar short-range measurements” (2017), A. Borraccino, D. Schlipf, F. Haizmann, R. Wagner

   ➔ Application to power performance testing
Outline

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Calibration of measuring systems

• **Metrology** (= science of measurements)
  international standards: JCGM (BIPM, IEC, ISO, etc)
  - VIM: international vocabulary of metrology
  - GUM: guide to uncertainty in measurements

• **Calibration** =
  operation providing as an end-result
  - a relation between measured values and reference ones
    (mathematical model, curve, table, etc)
  - associated measurement uncertainties
  - a correction of the indicated quantity value

• **Why?**

“measurement values are meaningless without their associated uncertainty. The true value is unknowable”
Calibration of wind lidars: white vs. black-box methodology (1/2)

• **Black-box**
  – Direct comparison of reconstructed wind parameters

PROS: simple, limited knowledge required
CONS: lidar-specific, practical setup unrealistic, and ...

→ It simply does not work for nacelle lidars!
Calibration of wind lidars: white vs. black-box methodology (1/2)

• **White-box**
  – calibration of all the inputs of the Wind Field Reconstruction

**PROS**
- Low sensitivity to WFR assumptions
- Genericity
- Uncertainties on any wind characteristics (WFC)

**CONS**
- Longer process
- Need expert knowledge

**Inputs:**
- backscattered light,
- lidar scanning
- geometry, ...

**LIDAR**
= white box

**Outputs:**
- reconstructed wind characteristic
  e.g. WS, WD, shear, ...

[Diagram showing the process of calibration through LIDAR]
Generic calibration methodology

- Based on the original procedures for 2-beam nacelle lidars

- Further developed and tested with two different nacelle lidar systems

Avent 5-beam Demonstrator (5B-Demo): pulsed, step-staring

ZephIR Dual Mode (ZDM): continuous wave, conically scanning

- Published in journal article + 2 detailed calibration reports
Generic calibration methodology
1) beam positioning quantities

• Step 1: calibration of beam positioning quantities
  – inclinometers (tilt, roll)
  – lidar geometry: cone or opening angles

➤ Procedures are lidar-specific
➤ We used hard target methods to detect beam position
Generic calibration methodology

2) calibration of LOS velocity

• Measurement setup, in Høvsøre (DK)
Generic calibration methodology
2) calibration of LOS velocity

- Measurement setup, in Høvsøre (DK) - zoom

- One beam of the Avent Demonstrator

- ZephIR DM beam passage

- 8.9m

- 5m

- 260m

- 5B-demo

- ZDM
2) Calibration of LOS velocity
Method and data analysis

• **Main data**
  - **Cup**: horizontal wind speed $V_{\text{hor}}$
  - **Sonic**: wind direction $\theta$
  - **Lidar**: LOS velocity $V_{\text{los}}$; tilt angle $\phi$

\[
\begin{align*}
\text{Reference quantity} & \\
V_{\text{ref}} &= V_{\text{hor}} \cos \phi \cos (\theta - LOS_{\text{dir}})
\end{align*}
\]

• **LOS direction evaluation**
  - fit of wind direction response (part 1)
  - Residual sum of squares process (part 2)

• **Comparison between**
  - Lidar-measured LOS velocity $V_{\text{los}}$
  - Reference quantity: pseudo-LOS velocity $V_{\text{ref}}$
    - derived from calibrated ref. instruments
2) Calibration of LOS velocity
Results (1/2)

Linear regressions on 10-min data

LOS 0

Bottom LOS
2) Calibration of LOS velocity

Results (2/2)

Linear regressions on binned data

- LOS 0
- Bottom LOS

⇒ the calibration relation is obtained!
Uncertainty of LOS velocity

Method

- **GUM methodology:**
  - based on law of propagation of uncertainties
  - analytical method

- **Measurement model**

```
a \cdot V_{\text{ref}} = y = a \cdot V_{\text{hor}} \cdot \cos \phi \cdot \cos (\theta - \text{LOS}_{\text{dir}})
```

- "Tree of uncertainties": GUM method applied to the $V_{\text{los}}$ calibration

- $u_{\text{cal}}$
- $u_{\text{ope}}$
- $u_{\text{mast}}$
- $u_{\text{pos}}$
- $u_{\text{inc}}$

- $u_{\theta_{\text{los}}}$
- $u_{\theta}$
- $u_{\theta_{\text{r}}}$
- $u_{\phi}$
- $u_{c,y}$
- $u_{c,V_{\text{ref}}}$
- $u_{c,V_{\text{hor}}}$
Uncertainty of LOS velocity

Results

- **Expanded uncertainties (k=2) vs. \( V_{\text{los}} \): in m/s and in %**
  - \( U_{\text{exp}} \) increases linearly (m/s)
    - \( \sim 3\% \) at 4 m/s
    - \( \sim 2\% \) at 10 m/s
  - almost same as cup anemometer
Uncertainty of LOS velocity

Prevailing sources

\[ a \cdot V_{\text{ref}} = y = a \cdot V_{\text{hor}} \cdot \cos \varphi \cdot \cos \left( \theta - \text{LOS}_{\text{dir}} \right) \]

- Conclusions:
  - the lidar \( V_{\text{los}} \) uncertainty is almost entirely inherited from the cup
  - need to improve uncertainty assessment of cup anemometers
  - OR
  - need for new reference sensors
Outline

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4. Power performance testing
Wind Field Reconstruction ...

- Combines LOS velocities measured in multiple locations

\begin{itemize}
  \item Needed to retrieve useful info: wind speed, direction, shear, ...
  \item Assumptions on the flow field must be made
\end{itemize}

- Simplest example
  \begin{itemize}
    \item two-beam nacelle lidar
    \item horizontal homogeneity hyp.
    \item analytical solution for wind speed and relative direction
  \end{itemize}

- Not a good enough method for profiling nacelle lidars
And... searching for free stream wind speed

- Decorrelation WSpeed / power
- Hub height speed insufficient?
- 2.5D not really free wind ...

Modern turbines: 2.5D ~ 200-400m
Does this make it any easier?

Flow disturbed by turbine wakes!

(very) complex terrain

Perdigão.
credit: N. Vasiljevic
Model-fitting Wind Field Reconstruction

- Method is (not new...)
  Schlipf D., Rettenmeier A., Haizmann F., Hofsäß M., Courtney M. and Cheng, P. W.:
  “Model Based Wind Vector Field Reconstruction from Lidar Data”, DEWEK, 2012.

- need new “wind models” for profiling nacelle lidars, suitable for power performance testing
Wind model accounting for shear

- Use lidar measurements at 2.5 rotor diameters
- “static” model: stationarity assumed
- Assumes horizontal homogeneity and power law shear profile

- Fits three wind characteristics
  - wind speed $v_0$ (@$H_{hub}$)
  - relative wind dir. $\theta_r$ (yaw misalignment)
  - shear exponent $\alpha_{exp}$
Combined wind-induction model

• Use lidar measurements at multiple distances close to rotor
• Additionally assumes simple induction model:
(from actuator disk and vortex sheet theory)

$$\frac{U(x)}{U_\infty} = 1 - a_{ind} \left( 1 + \frac{\xi}{\sqrt{1 + \xi^2}} \right)$$

• Fits four wind characteristics
  ➔ Free stream wind speed $V_\infty$ (@$H_{hub}$)
  + relative wind dir. $\theta_r$
  + shear exponent $\alpha_{exp}$
  + induction factor $a_{ind}$
Full-scale campaign: Nørrekær Enge

- in Jutland, Denmark
- owner: Vattenfall
- 13 Siemens turbines of 2.3MW
• **Considered lines-of-sight:**
  – 5B-Demo: all 5 LOS
  – ZDM: 6 LOS / azimuth sectors, ie. 3 pairs (in green)
Wind speed results
Mast comparison, WFR using the wind model

- horizontal speed estimated @ hub height
- IEC “free sector”: [110°, 219°]

5B-demo
use the 5 LOS, @2 D_rot

\[ y = 1.0097x - 0.0345 \quad R^2 = 0.9848 \]

ZDM
use 6 LOS, @2.5 D_rot

\[ y = 1.0192x - 0.1481 \quad R^2 = 0.9844 \]
Wind speed results
Mast comparison, WFR using the wind-induction model

- horizontal speed estimated @ hub height and 2.5D_rot
- IEC “free sector”: [110°, 219°]

5B-demo: use the 5 LOS
4 dist, from 0.5 to @1.2D_rot

\[ y = 0.9952x + 0.0408 \quad R^2 = 0.9877 \]

ZDM: use 6 LOS
3 dist., from 0.3 to 1.2D_rot

\[ y = 0.9987x - 0.0582 \quad R^2 = 0.9885 \]
The simple induction model seems adequate! (enough)
The white-box methodology: where are we?

- Propagation of input uncertainties (\( V_{\text{los}} \), inclination, etc)
  - Not possible with GUM
  - Use numerical methods instead: **Monte Carlo simulations**
- Get model uncertainties of all (fitted) wind characteristics
Monte Carlo methods for Uncertainty Quantification

- **Monte Carlo methods (MCM):**
  - Statistical techniques used to computationally solve physical or mathematical problems
  - Applications: numerical integration, optimisation, sensitivity or reliability analysis, uncertainty quantification (UQ)
  - References: GUM supplement 1, Cox (2006)

- **Principles:**
  - Propagation of random inputs
  - By evaluation of a model for a large number of samples
  - Outputs characterized through their distribution
Uncertainties of WFC using Monte Carlo on free wind speed $V_\infty$

\[\theta_r = 4^\circ; \alpha_{exp} = 0.2; a_{ind} = \text{nom.}\]

\[V_\infty = 10 \text{ ms}^{-1}; \alpha_{exp} = 0.2; a_{ind} = \text{nom.}\]

\[V_\infty = 10 \text{ ms}^{-1}; \theta_r = 4^\circ; a_{ind} = \text{nom.}\]

- **Conclusions**
  - Linear variation vs speed
  - No variability with input yaw misalignment and shear
  - No significant difference with two-beam lidar results (using GUM)

\[\Rightarrow\] essentially, the wind speed model uncertainty is the one of the cup anemometer used during the calibration in Høvsøre!
Power performance testing
Method – NKE campaign

• Based on international standards IEC 61400-12-1 (2017 ed)
  – for the mast measurements

• Adapted to nacelle-based wind lidars:
  ➔ 5B-Demo and ZDM
  ➔ Wind field reconstruction with:
    1) wind model
    2) combined wind-induction model

• Considering hub height wind speed only
  – No rotor equivalent wind speed

• Derived results
  – Measured power curves
  – Power curve uncertainties
  – Annual Energy Production (AEP)
Measured Power curves (scatter)

WFR using wind-induction model

5B-demo

ZDM

Mast
Measured Power curves (binned)
WFR using wind-induction model
Power curve uncertainties: power, type A
WFR using wind-induction model

- Clear reduction of scatter in power curve
  ➔ nacelle lidars yield smaller type A (statistical) power uncertainty
Power curve uncertainties: combined WFR using wind-induction model

- Results are mostly dependent on type B wind speed uncertainty
  - very sensitive to the “terrain uncertainty”
  - lidar uncertainties are smaller only due to this component...
Annual Energy production

- Derived as percentage of AEP using "mast power curve"

- 3 methods:
  - Wind model
  - Combined wind-induction
    - Wind speed estimated at 2.5D
    - Fitted free stream wind speed ($V_\infty$)

![Graph 5B-demo](image)

![Graph ZDM](image)
Overall conclusions

• **Calibration of wind lidars** ✔
  – the white-box methodology successfully applied
  – is now the preferred technique by wind industry!
  – Lidar LOS velocity uncertainty ≈ ref. anemometer speed

• **V infinity is found !** ✔
  ➔ solution: combined wind-induction WFR model and lidar measurements close to rotor
  ➔ allows to estimate free stream wind speed

• **For power curve measurements:** nacelle-based lidars are
  ➔ at least as accurate as meteorology masts
  ➔ (offshore) likely to replace them systematically ✔
  ➔ to be included in next generation IEC standards?
Future work

• Testing similar methods in complex terrain
  – Hill of Towie
  – Ogorje

  UniTTe campaigns, ongoing analysis

• Standardisation work on nacelle lidars for power perfo.

  IEC 61400-50-3 ED1
  Wind energy generation systems - Part 50-3:
  Use of nacelle mounted lidars for wind
  measurements (proposed project number 61400-
  50-3)

• Optimisation of nacelle lidar trajectory
  – Needs a fully implemented lidar simulator
  – Needs validated CFD tools

• Development of model-fitting wind field reconstruction for:
  – Nacelle lidar measurements in wakes
  – Ground-based, scanning and floating lidars
Thanks for your attention!

And many many others!!
My Ph.D. project formed part of the UniTTe project (www.unitte.dk) which is financed by Innovation Fund Denmark.
Preparing for questions
-
Calibration of wind lidars
Publications

- Publications:
  - DTU E-0086 report ➔ generic methodology
  - DTU E-0087 report ➔ detailed procedure 5B-demo
  - DTU E-0088 report ➔ detailed procedure ZDM
    ➔ methodology, results, discussions, 2-beam example
    ➔ doi: 10.3390/rs8110907
Lidar

- **LIght Detection And Ranging:** “a radar using light”
- **Remotely measuring:** from some meters to >10 km away

**Principles of coherent Doppler wind lidars**

1. Processing of raw signal \( \rightarrow \) Doppler spectrum
2. Estimate wind velocity along beam path \( \rightarrow \) Line-Of-Sight (LOS) velocity \( V_{los} \)
3. Combine \( V_{los} \) measurement in multiple locations \( \rightarrow \) reconstructed wind field characteristics (WFC): speed, direction, shear, etc
2) Calibration of LOS velocity  
Data analysis (1/2)  

- LOS direction evaluation (part 1)  
  - Cosine / rectified cosine fitting to wind direction response  
  - The lidar LOS is normalised by the horizontal speed  
  ➔ Gives a first good estimation of LOS direction in sonic CS

![Diagram showing LOS direction evaluation](image)
2) Calibration of LOS velocity
Data analysis (1/2) – RSS process

- **LOS direction evaluation (part 2)**
  - Projection angle range: ±1° to cosine fitted LOS_dir
  - Linear reg. each 0.1°
  - **LOS dir = min parabola**

\[ y = +1.3001 \cdot x^2 -743.74 \cdot x +106369.71 \]
\[ \text{min} = 286.0313^\circ \]
\[ R^2 = 0.99982 \]

\[ y = +4.0329 \cdot x^2 -2318.44 \cdot x +333234.84 \]
\[ \text{min} = 287.4383^\circ \]
\[ R^2 = 0.99999 \]
Calibration results

- **Summary:**
  - lidar-measured LOS velocity: error of $\sim 0.5 - 0.9\%$
  - excellent agreement with the reference quantity $V_{ref}$: $R^2 > 0.9998$
  - LOS direction method provides robust results ($\pm 0.05^\circ$)

<table>
<thead>
<tr>
<th>Lidar</th>
<th>LOS</th>
<th>Calibration relation</th>
<th>$\theta_{los}$</th>
<th>$a$</th>
<th>$R^2$</th>
<th>N pts</th>
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</thead>
<tbody>
<tr>
<td>5B</td>
<td>LOS 0</td>
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<td>286.03°</td>
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<td>LOS 2</td>
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<td>285.99°</td>
<td>1.0084</td>
<td>1.0000</td>
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<td>LOS 4</td>
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<tr>
<td>ZDM</td>
<td>179° – 181° azimuth</td>
<td></td>
<td>287.44°</td>
<td>1.0050</td>
<td>0.9998</td>
<td>2140</td>
</tr>
</tbody>
</table>
Uncertainty assessment: how to combine components?

- **GUM methodology**: analytic method
  1. Define measurement model: \( y_m = f(x_1, x_2, \ldots, x_n) \)
  2. Law of propagation of uncertainties:

\[
U_c = \sqrt{\sum_{i=1}^{n} \left( \frac{\partial y_m}{\partial x_i} \cdot u_{x_i} \right)^2}
\] for uncorrelated inputs \( x_i \)

3. Expanded uncertainty with coverage factor \( k \)

\[
U_{exp} = k \cdot U_c
\]

typically, \( k=2 \) corresponds to 95% confidence interval
What are the uncertainty sources?

- **Reference instruments uncertainties**
  - HWS (IEC 61400-12 procedure for cups)
  - Wind tunnel calibration uncertainty
    \[ u_{cal} = u_{cal\, 1} + \frac{0.01}{\sqrt{3}} \cdot \langle HWS \rangle \]
  - Operational uncertainty
    \[ u_{ope} = \frac{1}{\sqrt{3}} \cdot \text{cup class number} \cdot (0.05 + 0.005 \cdot \langle HWS \rangle) \]
  - Mounting uncertainty
    \[ u_{mast} = 0.5\% \cdot \langle HWS \rangle \]

- Wind direction, from calibration certificate of sonic anemometer:
  \[ u_{WD} \approx 0.4^\circ \]
What are the uncertainty sources?

- **Calibration process uncertainties**
  - LOS direction uncertainty
    \[ u_{LOS\ dir} = 0.1^\circ \]
  - Uncertainty of tilt inclination angle
    \[ u_\varphi = 0.05^\circ \]
  - Beam positioning uncertainty:
    \[ u_\text{pos} = \alpha_\text{exp} \cdot \frac{u_H}{H} \cdot \langle HWS \rangle \approx 0.23\% \cdot \langle HWS \rangle \]
  - Inclined beam and range uncertainty
    \[ u_{inc} = 0.052\% \cdot \langle HWS \rangle \]

"how the probe volume affects the RWS estimation when the beam is inclined" (see model in DTU report E-0086, Annex A)
Preparing for questions

Wind Field Reconstruction
Publications

- Publications:

  Research articles

  Wind Field Reconstruction from Nacelle-Mounted Lidars Short Range Measurements

  Antoine Borraccino\textsuperscript{1}, David Schlipf\textsuperscript{2}, Florian Haizmann\textsuperscript{2}, and Rozenn Wagner\textsuperscript{1}

  \textsuperscript{1}DTU Wind Energy, Roskilde, Denmark
  \textsuperscript{2}Stuttgart Wind Energy, University of Stuttgart, Germany

  Scientific article: wes-2017-10/
Full-scale campaign: Nørrekær Enge

- in Jutland, Denmark
- owner: Vattenfall
- 13 Siemens turbines of 2.3MW
Wind speed results: summary table

<table>
<thead>
<tr>
<th>Data filtering</th>
<th>Reconstruction case</th>
<th>Forced linear regressions results</th>
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</thead>
<tbody>
<tr>
<td></td>
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<td>Case</td>
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<td></td>
<td>5B-Demo, 5 LOS</td>
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</tr>
</tbody>
</table>

- Overestimation of 1-1.5% with the wind model
- Better performance of wind-induction model using the lidars’ short-range measurements
- Lidar-to-lidar: 5B-Demo about 0.5-1% higher than ZDM
Wind speed results: summary table

<table>
<thead>
<tr>
<th>Case</th>
<th>Direction sector</th>
<th>Dataset</th>
<th>Lidar</th>
<th>Input measurement ranges</th>
<th>gain</th>
<th>$R^2$</th>
<th>Number of periods</th>
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<tbody>
<tr>
<td>1</td>
<td>[93°, 123°]</td>
<td>Joint</td>
<td>5B-Demo, 5 LOS</td>
<td>2.0 $D_{rot}$</td>
<td>1.0146</td>
<td>0.9936</td>
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<td></td>
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<td>ZDM, 6 LOS</td>
<td>2.5 $D_{rot}$</td>
<td>1.0090</td>
<td>0.9938</td>
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<td></td>
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<td>5B-Demo, 5 LOS</td>
<td>from 0.5 to 1.15 $D_{rot}$</td>
<td>1.0063</td>
<td>0.9944</td>
<td>885</td>
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<tr>
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<td>ZDM, 6 LOS</td>
<td>from 0.3 to 1.25 $D_{rot}$</td>
<td>0.9961</td>
<td>0.9947</td>
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<tr>
<td>2</td>
<td>[93°, 123°]</td>
<td>disjoint</td>
<td>5B-Demo, 5 LOS</td>
<td>2.0 $D_{rot}$</td>
<td>1.0133</td>
<td>0.9953</td>
<td>1476</td>
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<tr>
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<td>ZDM, 6 LOS</td>
<td>2.5 $D_{rot}$</td>
<td>1.0080</td>
<td>0.9942</td>
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<td>5B-Demo, 5 LOS</td>
<td>from 0.5 to 1.15 $D_{rot}$</td>
<td>1.0057</td>
<td>0.9961</td>
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<td>ZDM, 6 LOS</td>
<td>from 0.3 to 1.25 $D_{rot}$</td>
<td>0.9965</td>
<td>0.9962</td>
<td>2659</td>
</tr>
</tbody>
</table>

- Disjoint datasets: similar observations
- Increased number of valid data points (2-3x more)
- $R^2$ enhanced slightly
Wind speed results: summary table

<table>
<thead>
<tr>
<th>Data filtering</th>
<th>Reconstruction case</th>
<th>Forced linear regressions results</th>
<th>Number of periods</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Input measurement ranges</td>
<td>gain</td>
</tr>
<tr>
<td>Case</td>
<td>Direction sector</td>
<td>Dataset</td>
<td>Lidar</td>
</tr>
<tr>
<td>1</td>
<td>[93°, 123°] Joint</td>
<td>5B-Demo, 5 LOS</td>
<td>2.0 $D_{rot}$</td>
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<td></td>
<td></td>
<td>ZDM, 6 LOS</td>
<td>2.5 $D_{rot}$</td>
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<td></td>
<td>5B-Demo, 5 LOS</td>
<td>from 0.5 to 1.15 $D_{rot}$</td>
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<td>ZDM, 6 LOS</td>
<td>from 0.3 to 1.25 $D_{rot}$</td>
</tr>
<tr>
<td>2</td>
<td>[93°, 123°] disjoint</td>
<td>5B-Demo, 5 LOS</td>
<td>2.0 $D_{rot}$</td>
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<td>from 0.3 to 1.25 $D_{rot}$</td>
</tr>
<tr>
<td>3</td>
<td>[110°, 219°] Joint (IEC free sector)</td>
<td>5B-Demo, 5 LOS</td>
<td>2.0 $D_{rot}$</td>
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<tr>
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<td></td>
<td>ZDM, 6 LOS</td>
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<td></td>
<td>ZDM, 6 LOS</td>
<td>from 0.3 to 1.25 $D_{rot}$</td>
</tr>
</tbody>
</table>

- Better agreement between lidar and mast
- Much larger scatter ("signal decorrelation")
- Still 5B-Demo above ZDM (about 0.5%)
## Wind speed results: summary table

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<tr>
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<td>案头 maintenance ranges</td>
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<tr>
<td>2</td>
<td>[93°, 123°]</td>
<td>disjoint</td>
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</table>
Yaw misalignment results:
WFR using the wind-induction model

- Wind sector: $[110^\circ, 219^\circ]$ (joint datasets)
- “Ref.” yaw misalignment from spinner anemometer

Higher scatter with lidars than spinner
“mean” yaw misalignment: $\approx -3^\circ$
The two nacelle lidars seem to provide similar results
Shear exponent results: WFR using the wind-induction model

• Wind sector: \([110^\circ, 219^\circ]\) (joint datasets)

• “Ref.” shear exponent: from mast, using cups at 80 and 57m aegl

5B-demo: 4 dist, from 0.5 to @1.2D_rot

\[ y = 0.9793x + 0.0183 \quad R^2 = 0.6664 \]
\[ y = 1.0301x \quad R^2 = 0.6641 \]

ZDM: 3 dist.
From 0.3 to 1.2D_rot

\[ y = 0.9701x + 0.0372 \quad R^2 = 0.6660 \]
\[ y = 1.0732x \quad R^2 = 0.6559 \]

→ Slight overestimation vs. mast → Similar results between the two lidars
Induction factor results:
WFR using the wind-induction model

- Wind sector: $[110^\circ, 219^\circ]$ (joint datasets)
- “Ref.” induction factor: $C_T$ from “HAWC2” simu, $a = 0.5 \cdot (1 - \sqrt{1 - C_T})$

5B-demo: 4 dist, from 0.5 to @1.2D_rot
ZDM: 3 dist. From 0.3 to 1.2D_rot
LOS velocity fitting residuals

• Definitions:
  - $V_{\text{los}}$ and $\hat{V}_{\text{los}}$ are column vectors of length = $N$ meas. points
    (e.g. 5B-Demo = 4 dist*5 los =20; ZDM = 3 dist*6 los =18)
  - “bias” = $V_{\text{los}} - \hat{V}_{\text{los}}$ ; “error”: = $\text{abs}(V_{\text{los}} - \hat{V}_{\text{los}})$
LOS velocity fitting residuals

- **Computed stats:**
  - M: mean, N: normalised; F: fractional;
  - S: squared; R: root; SS: sum of squares
  - \( \text{MB}, \text{ME}, \text{NMB}, \text{NME}, \text{MFB}, \text{MFE}, \text{SSE}, \text{MSE}, \text{RMSE}, \text{NMSE} \)
V_los fitting residuals: mean bias
WFR using the wind-induction model

- Wind sector: $[110^\circ, 219^\circ]$ (joint datasets)

$\rightarrow$ MB show very low values;
$\rightarrow$ Histogram centered on zero: the used model is “unbiased”
\textbf{V\textsubscript{los} fitting residuals: mean bias}

\textit{WFR using the wind-induction model}

- Wind sector: $[110^\circ, 219^\circ]$ (joint datasets)

$\rightarrow$ RMSE values between 0 and 0.25 m/s

$\rightarrow$ Similar distributions for both lidars, with a slightly larger mean for ZDM

\begin{itemize}
  \item \textbf{5B-demo}
    \begin{itemize}
      \item 4 dist. from 0.5 to $@1.2D\_rot$
    \end{itemize}
  \item \textbf{ZDM}
    \begin{itemize}
      \item 3 dist. from 0.3 to 1.2D\_rot
    \end{itemize}
\end{itemize}
A simple induction model

- Derived from the Biot-Savart law
  - see *The upstream flow of a wind turbine: blockage effect*
  - two parameters: induction factor $a$, free wind speed $U_\infty$

\[
\frac{U}{U_\infty} = 1 - a \left( 1 + \frac{\xi}{\sqrt{1 + \xi^2}} \right), \quad \text{with} \quad \xi = \frac{x_W}{R_{rot}}
\]
Simple induction models

- One- or two-dimensional?
Preparing for questions - propagation of uncertainties with Monte Carlo methods
Model uncertainty framework

\[
\tilde{y}_i = y_t + \epsilon_e = g(x_i + \epsilon_x, \theta) + \epsilon_g + \epsilon_a
\]

\(\tilde{y}_i\) is a measured value of \(g\);
\(\epsilon_x\) represents the error related to the inputs;
\(\epsilon_g\) is the random error due to the model uncertainty;
\(\epsilon_a\) characterises the error due to the model inadequacy
\(\epsilon_e\) is the error between observations \(\tilde{y}_i\) (measured) and the true value \(y_t\);

Reproduced from:

Huard, D., and A. Mailhot (2006),

A Bayesian perspective on input uncertainty in model calibration: Application to hydrological model “abc”,

Uncertainties of WFC yaw misalignment $\theta_r$

- Decreasing vs speed: consistent with NKE campaign results!
- Values are very (too ??) low: due to assumed high correlation between $V_{los}$
- No variability with input yaw misalignment and shear

\[ \theta_r = 4^\circ; \alpha_{exp} = 0.2; a_{ind} = \text{nom.} \]
\[ V_\infty = 10 \text{ m s}^{-1}; \alpha_{exp} = 0.2; a_{ind} = \text{nom.} \]

\[ V_\infty = 10 \text{ m s}^{-1}; \theta_r = 4^\circ; a_{ind} = \text{nom.} \]
Uncertainties of WFC shear exponent $\alpha_{exp}$

- Decreasing vs speed
- No variability with input yaw misalignment
- Increasing with shear
- Order of magnitude: 5-10%

$\theta_r = 4^\circ$; $\alpha_{exp} = 0.2$; $a_{ind} = nom.$

$V_\infty = 10 \text{ ms}^{-1}$; $\alpha_{exp} = 0.2$; $a_{ind} = nom.$
Uncertainties of WFC induction factor $a_{ind}$

- Decreasing vs speed
- No variability with input yaw misalignment and shear

- Much higher for 5B-Demo than ZDM: why??
- Order of magnitude:
  
  5% at high CT (low spd), up to 20% at low CT (high spd)

\[ \theta_r = 4^\circ; \alpha_{exp} = 0.2; a_{ind} = \text{nom.} \]
\[ V_\infty = 10 \text{ ms}^{-1}; \alpha_{exp} = 0.2; a_{ind} = \text{nom.} \]
\[ V_\infty = 10 \text{ ms}^{-1}; \theta_r = 4^\circ; a_{ind} = \text{nom.} \]
MCM convergence

Wind speed uncertainties (k=2)
MCM convergence
Yaw misalignment uncertainties (k=2)
Shear exponent uncertainties (k=2)
Induction factor uncertainties \((k=2)\)
Preparing for questions - power performance testing
Measured Power curves (scatter)
WFR using wind model

5B-demo

ZDM

Mast
Measured Power curves (scatter)

WFR using wind model
Power curve uncertainties: power, type A
WFR using wind model
Power curve uncertainties: combined WFR using wind model