Nacelle lidar calibration – how we do it at DTU Wind Energy

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Calibration: why? what?

• Why?

  • "measurement values are meaningless without their associated uncertainty. The true value is unknowable"

  • **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

  • **Traceability to SI**

  • **Uncertainty quantification**
DTU’s experience

• Since 2012:
  ➔ original procedures for two-beam nacelle lidars

• Calibrations of:
  (white-box methodology)

  2-beam
  4-beam
  Wind Iris

• Testing of:

  Wind Eye (2-beam)

  ZephIR Dual Mode (ZDM)
  continuous wave, conically scanning

  Avent 5-beam Demonstrator (5B-Demo): pulsed, step-staring
Calibration of wind lidars: white-box methodology

- **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,

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

LIDAR = white box
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
8.9m
5m
260m

one beam of the Avent Demonstrator
ZephIR DM beam passage

cup
sonic

5B-demo
ZDM
2) Calibration of LOS velocity

Results (1/2)

Linear regressions on 10-min data

- **LOS 0**
  - N = 742
  - \( y = 1.0069x \), \( R^2 = 0.9991 \)

- **Bottom LOS**
  - N = 2140
  - \( y = 1.0022x \), \( R^2 = 0.9978 \)
2) Calibration of LOS velocity
Results (2/2)

Linear regressions on binned data

5B-demo

LOS 0

Bottom LOS

⇒ the calibration relation is obtained!
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

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

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
Take-aways

- Calibration of nacelle lidars at DTU
  - the white-box methodology is now
    - a well-proven method
    - the preferred technique by industry
  - Procedures available for different types of commercial systems

- The barriers, what we need:
  1. better reference anemometers: move away from cups? (their uncertainty prevail massively)
  2. shorter calibration procedures: especially true for pulsed syst.
  3. unify methods and improve measurement setups
  4. work on the propagation of lidar $V_{los}$ uncertainty to reconstructed wind field characteristics
  5. And... maybe dig into what’s upstream $V_{los}$! (estimators, ranging, time stability of optics, etc)
Thanks for your attention!

Scientific article:
*Remote Sensing of wind energy*

Example reports
DTU E-0087
DTU E-0088

More info:
- website [www.unitte.dk](http://www.unitte.dk)
- contact: borr@dtu.dk, mike@dtu.dk
Preparing for questions
- Calibration of wind lidars
Power performance testing
The modern ways (2/2)

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
**Publications**

- **Publications:**
  - **DTU E-0086 report** ➔ generic methodology
  - **DTU E-0087 report** ➔ detailed procedure 5B-demo
  - **DTU E-0088 report** ➔ detailed procedure ZDM
  - **Journal paper**
    ➔ *Remote Sensing of Wind Energy* (special issue)
    ➔ methodology, results, discussions, 2-beam example
    ➔ doi: 10.3390/rs8110907
Calibration of wind lidars: white-box methodology

Calibration of beam position quantities

1. Beam trajectory
2. Inclinometers
3. Measurement range

Uncertainty assessment

Calibrated beam trajectory (tilt, roll, opening angles, range)

Calibration of LOS velocity

4. Calibration relation
5. Assessment of $V_{los}$ uncertainties

Data collection ($V_{ref}, V_{los}, ...$)

Calibrated $V_{los}$

Wind Field Reconstruction

6. Reconstruction Algorithm
7. Uncertainty assessment

Calibrated wind field characteristics (speed, direction, shear, ...)

Calibration uncertainties on reconstructed wind field characteristics

Wind model
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!
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
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 \( \varphi \)

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

• 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 \( V_{\text{ref}} \)
    \( \Rightarrow \) derived from calibrated ref. instruments
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

![Graph 1: LOS 0](image1.png)
![Graph 2: Bottom LOS](image2.png)
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
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>$\theta_{los}$</th>
<th>$a$</th>
<th>$R^2$</th>
<th>Npts</th>
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<tbody>
<tr>
<td>5B</td>
<td>LOS 0</td>
<td>286.03°</td>
<td>1.0058</td>
<td>0.9999</td>
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<td>1.0000</td>
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<td>0.9999</td>
<td>446</td>
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<tr>
<td></td>
<td>LOS 4</td>
<td>285.99°</td>
<td>1.0059</td>
<td>1.0000</td>
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<tr>
<td>ZDM</td>
<td>$179^\circ$</td>
<td>287.44°</td>
<td>1.0050</td>
<td>0.9998</td>
<td>2140</td>
</tr>
<tr>
<td></td>
<td>$- 181^\circ$</td>
<td>azimuth</td>
<td></td>
<td></td>
<td></td>
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</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
    \[ u_{\text{cal}} = u_{\text{cal} 1} + \frac{0.01}{\sqrt{3}} \cdot \langle HWS \rangle \]
  - Operational uncertainty
    \[ u_{\text{ope}} = \frac{1}{\sqrt{3}} \cdot \text{cup class number} \cdot (0.05 + 0.005 \cdot \langle HWS \rangle) \]
  - Mounting uncertainty
    \[ u_{\text{mast}} = 0.5\% \cdot \langle HWS \rangle \]

- 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
    \[ u_\phi = 0.05^\circ \]
  - Beam positioning uncertainty: \[ u_H = 10\ cm,\ shear\ \alpha_{exp} = 0.2 \]
    \[ u_{pos} = \alpha_{exp} \cdot \frac{u_H}{H} \cdot \langle HWS \rangle \approx 0.23\% \cdot \langle HWS \rangle \]
  - 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)