

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

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



A. Borraccino

IEA Wind task 32 – workshop nacelle lidars 27th September 2017

DTU Wind Energy

Department of Wind Energy

Calibration: why? what?

• Why?

Traceability to SI

Uncertainty quantification

"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



DTU's experience

• Since 2012:

Courtney M.: "Calibrating nacelle lidars", [2013], DTU Wind Energy E-0020(EN) →original procedures for two-beam nacelle lidars

Calibrations of: (white-box methodology)





2-beam 4-beam Wind Iris

Testing of:



Wind Eye (2-beam)



Range 1



ZephIR Dual Mode (ZDM) continuous wave, conically scanning

Range 10





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



Calibration of wind lidars:

white-box methodology

• White-box

-calibration of <u>all the inputs</u> of the Wind Field Reconstruction PROS

- Low sensititivity to WFR assumptions
- Genericity

Uncertainties on any wind characteristics (WFC)
 CONS

- Longer process
- Need expert knowledge





Generic calibration methodology 2) calibration of LOS velocity



Measurement setup, in Høvsøre (DK)



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Generic calibration methodology 2) calibration of LOS velocity





2) Calibration of LOS velocity Results (1/2)



Linear regressions on 10-min data



2) Calibration of LOS velocity Results (2/2)





Linear regressions on binned data

The calibration relation is obtained!

Uncertainty of LOS velocity

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Results

• Expanded uncertainties (k=2) vs. V_{los}: in m/s and in %





Uncertainty of LOS velocity

Prevailing sources



Conclusions:

 \rightarrow the lidar V_{los} uncertainty is almost entirely inherited from the cup

need to improve uncertainty assessment of cup anemometers OR

need for new reference sensors

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Take-aways

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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
- And... maybe dig into what's upstream V_los ! (estimators, ranging, time stability of optics, etc)

Thanks for your attention!



MDPI



Scientific article: <u>Remote Sensing of wind energy</u>



🗧 remote sensing

Article

Generic Methodology for Field Calibration of Nacelle-Based Wind Lidars

Antoine Borraccino *,[†], Michael Courtney [†] and Rozenn Wagner [†]

Example reports DTU E-0087 DTU E-<u>0088</u>

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Preparing for questions -Calibration of wind lidars

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Power performance testing The modern ways (2/2)

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Remote sensing instruments

Future/Now: use of nacelle-based wind lidars









ZephIR Dual Mode (scanning) by ZephirLidar

Wind Iris (4-beam) by *AventLidar*

Wind EyeDiabrezza(4-beam)(9-beam)by Windar Photonicsby Mitsubishi Electric

Publications

- Publications:
 - DTU E-0086 report
 - DTU E-0087 report
 - DTU E-0088 report
 - Journal paper
 - → Remote Sensing of Wind Energy (special issue)
 - → methodology, results, discussions, 2-beam example

→ generic methodology

→ detailed procedure 5B-demo

→ detailed procedure ZDM

→ doi: 10.3390/rs8110907



Article

Generic Methodology for Field Calibration of Nacelle-Based Wind Lidars

Antoine Borraccino *,[†], Michael Courtney [†] and Rozenn Wagner [†]





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Calibration of wind lidars: white-box methodology





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





Method and data analysis

2) Calibration of LOS velocity

Main data

- Cup: horizontal wind speed V_{hor}
- **Sonic**: wind direction θ
- Lidar: LOS velocity V_{los} ; tilt angle φ

LOS direction evaluation

- fit of wind direction response (part 1)
- Residual sum of squares process (part 2)

Comparison between

- Lidar-measured LOS velocity Vlos
- Reference quantity: pseudo-LOS velocity Vref
 - ➔ derived from calibrated ref. instruments

Reference quantity

 $\mathbf{V_{ref}} = \mathbf{V_{hor}} \cos \varphi \cos(\theta - LOS_{dir})$





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



2) Calibration of LOS velocity Data analysis (1/2) – RSS process



LOS direction evaluation (part 2)

- Projection angle range: $\pm 1^{\circ}$ 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 ($\pm 0.05^{\circ}$)

Lidar	LOS	Calibration relation			
		θ_{los}	а	R^2	Npts
5B	LOS 0	286.03°	1.0058	0.9999	742
	LOS 1	285.99°	1.0072	0.9999	502
	LOS 2	285.99°	1.0084	1.0000	1087
	LOS 3	286.06°	1.0090	0.9999	446
	LOS 4	285.99°	1.0059	1.0000	1508
ZDM	$179^\circ - 181^\circ$	287.44°	1.0050	0.9998	2140
	azimuth				

Uncertainty assessment: how to combine components?



- GUM methodology: analytic method
 - 1) Define measurement model: $y_m = f(x_1, x_2, ..., x_n)$
 - 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

$$u_{ope} = \frac{1}{\sqrt{3}} \cdot cup \ class \ number \cdot (0.05 + 0.005 \cdot \langle HWS \rangle)$$
• 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: $u_H = 10 \ cm$, 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)