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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

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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)

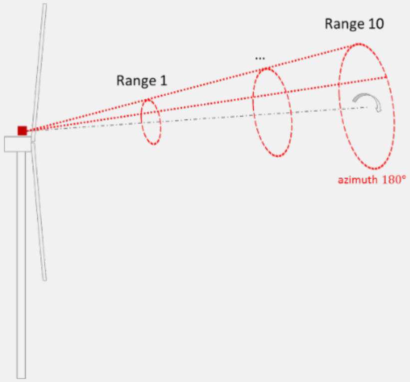
→original procedures for two-beam nacelle lidars

- **Calibrations of: (white-box methodology)**

2-beam

4-beam

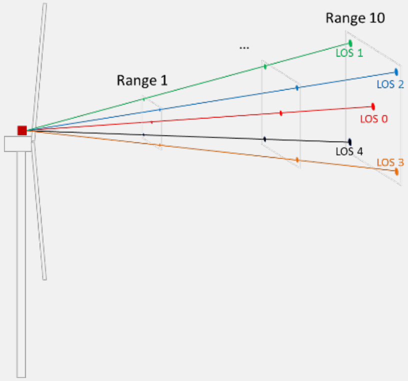
Wind Iris



ZephIR Dual Mode (ZDM)
continuous wave, conically scanning

- **Testing of:**

Wind Eye (2-beam)



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

Calibration of wind lidars:
white-box methodology

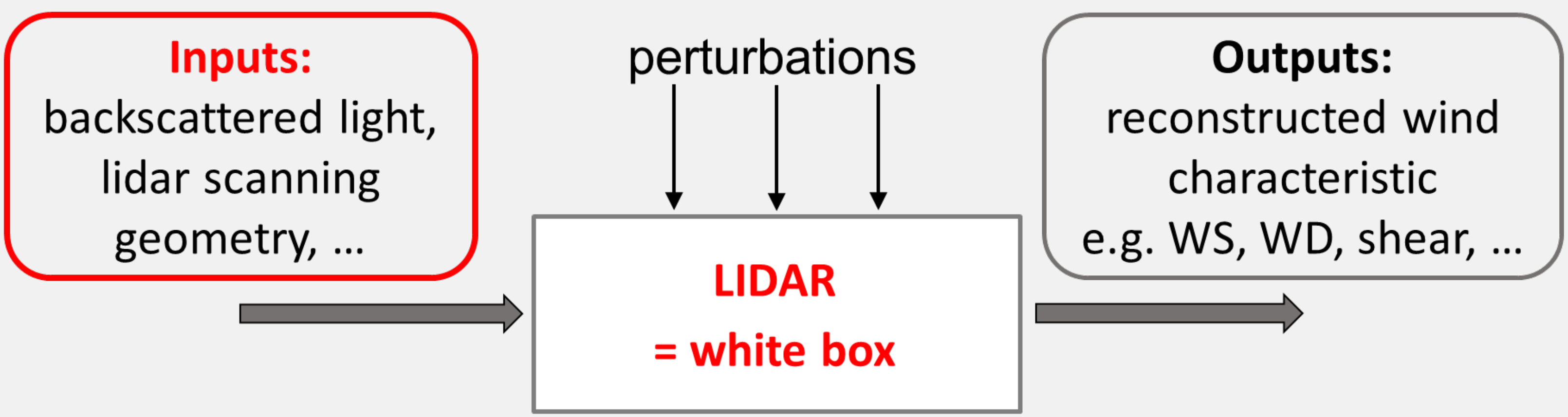
- **White-box**
  - calibration of all the inputs of the Wind Field Reconstruction

PROS

- Low sensititivity to WFR assumptions
- Genericity
- Uncertainties on any wind characteristics (WFC)

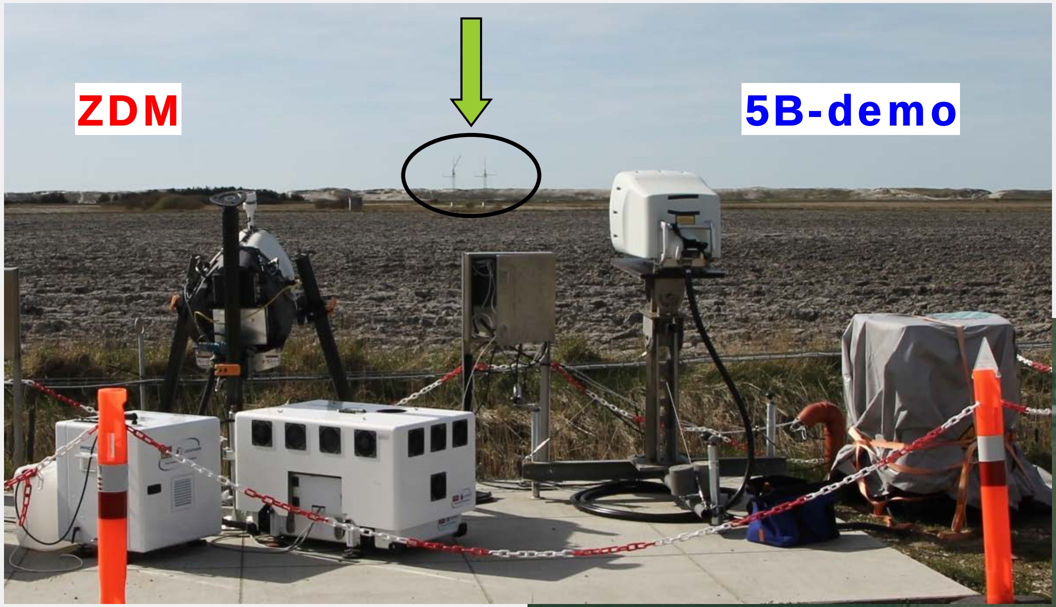
CONS

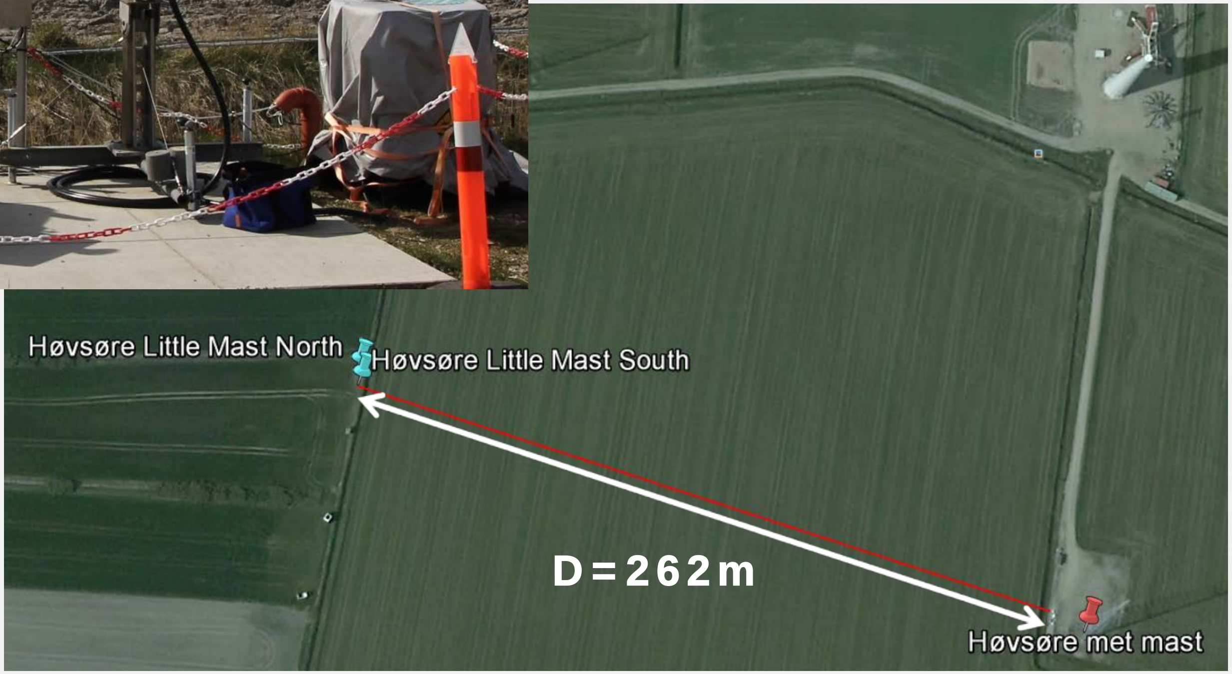
- Longer process
- Need expert knowledge



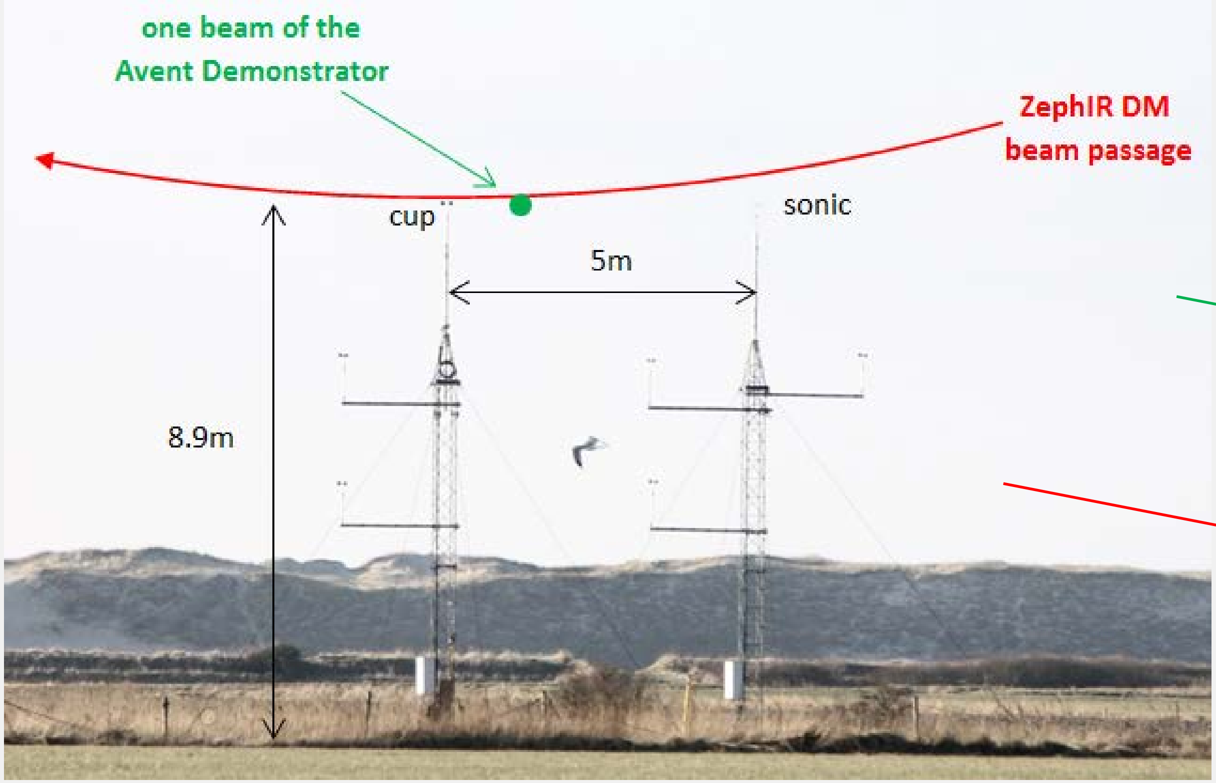
Generic calibration methodology
2) calibration of LOS velocity

- **Measurement setup, in Høvsøre (DK)**





Generic calibration methodology
2) calibration of LOS velocity



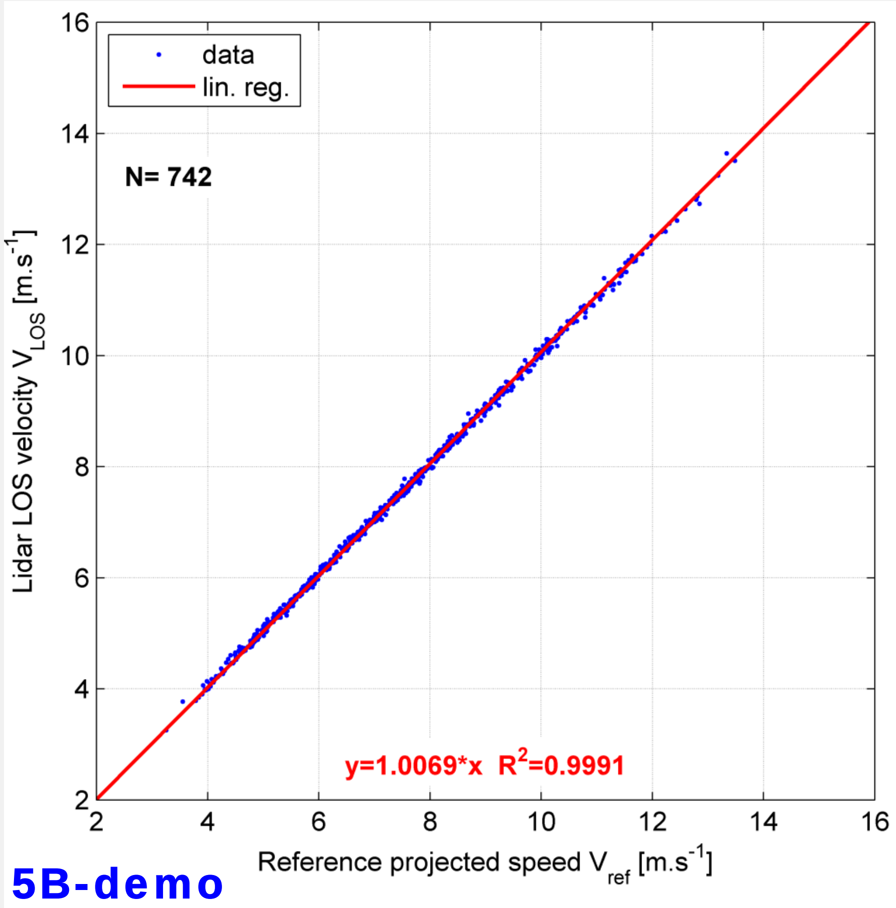
zoom

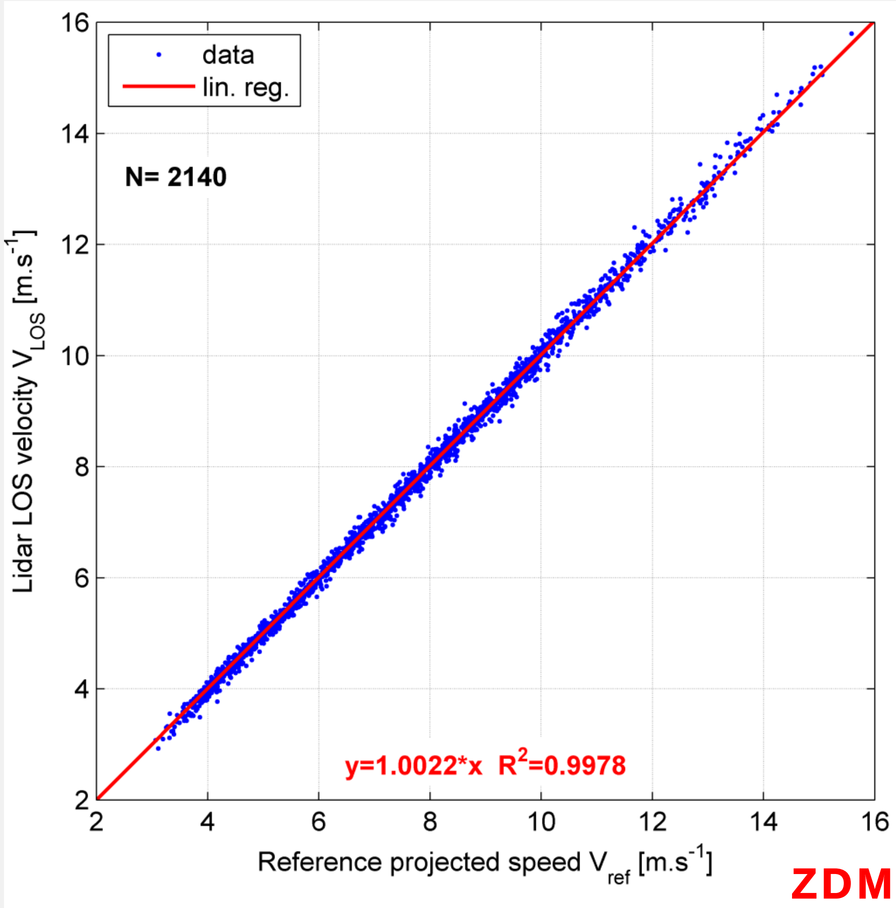
260m

2) Calibration of LOS velocity

Results (1/2)

Linear regressions on 10-min data



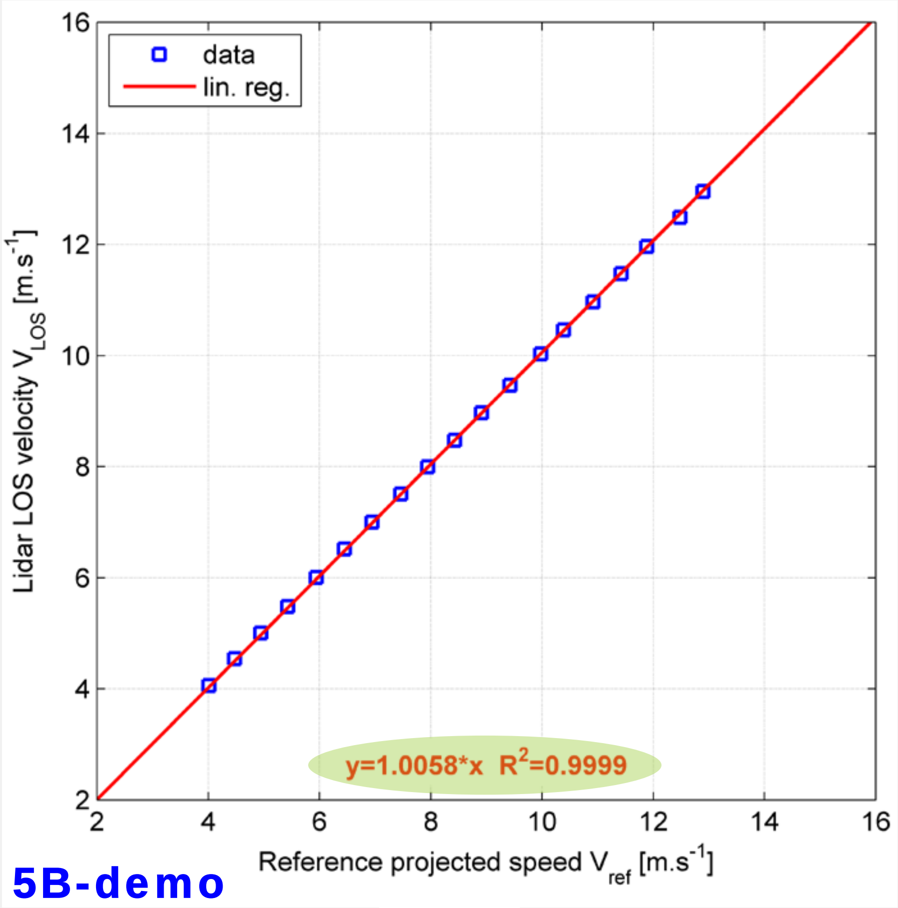


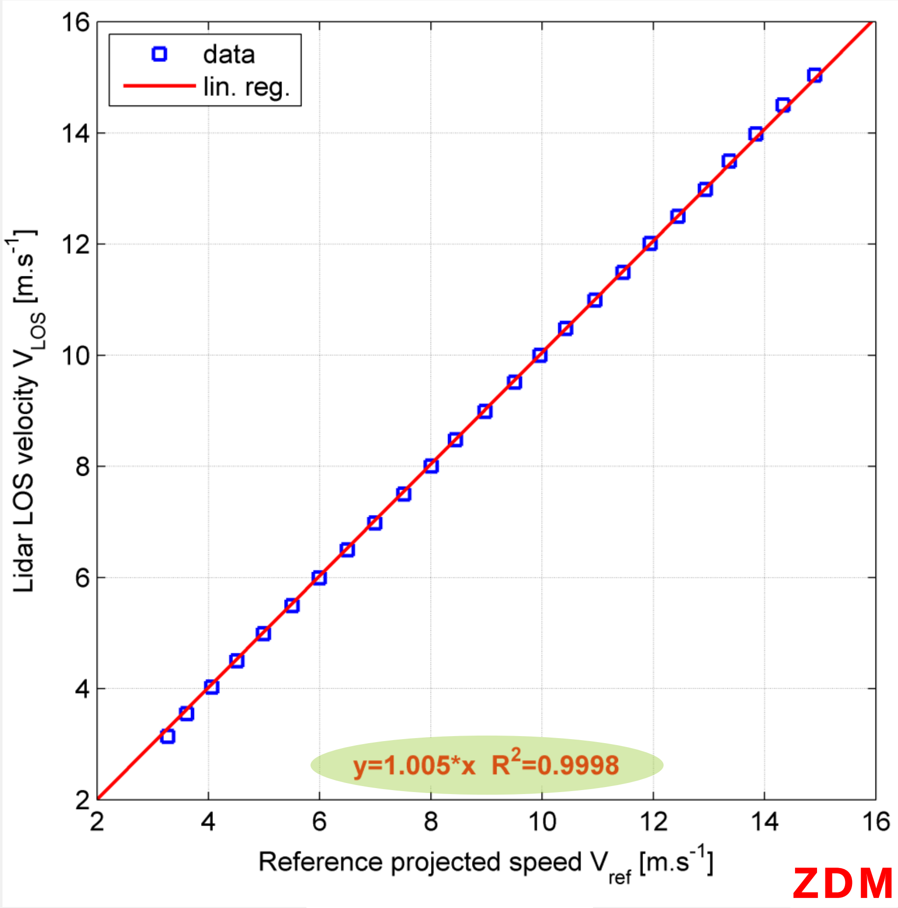
LOS 0 **Bottom LOS**

2) Calibration of LOS velocity

Results (2/2)

Linear regressions on binned data





LOS 0

Bottom LOS

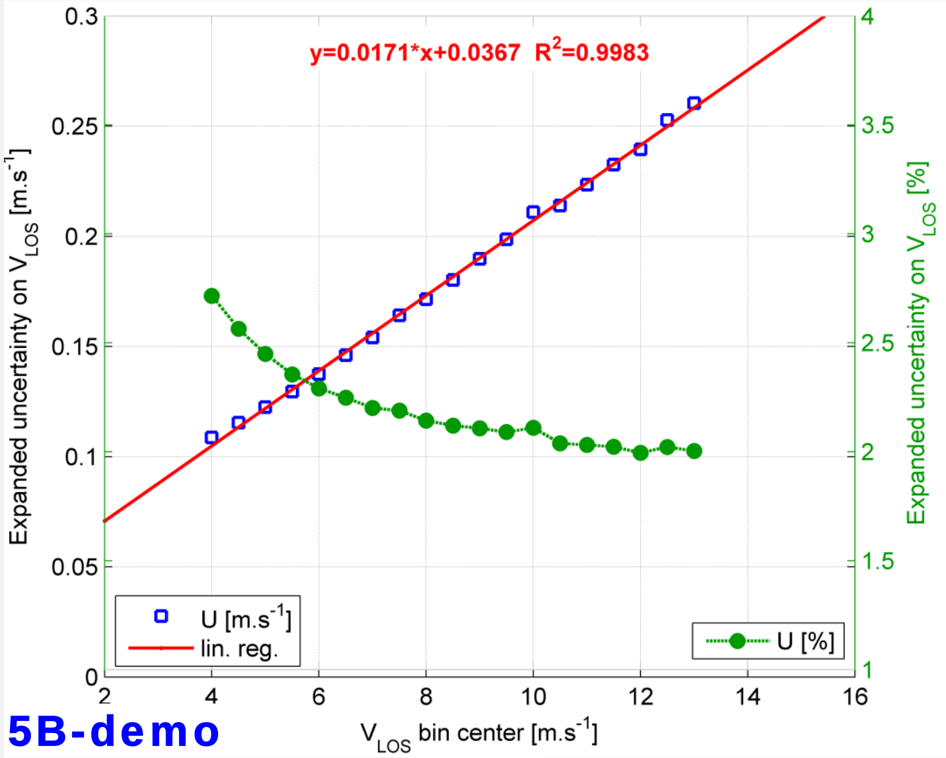
➔ the calibration relation is obtained!

Uncertainty of LOS velocity

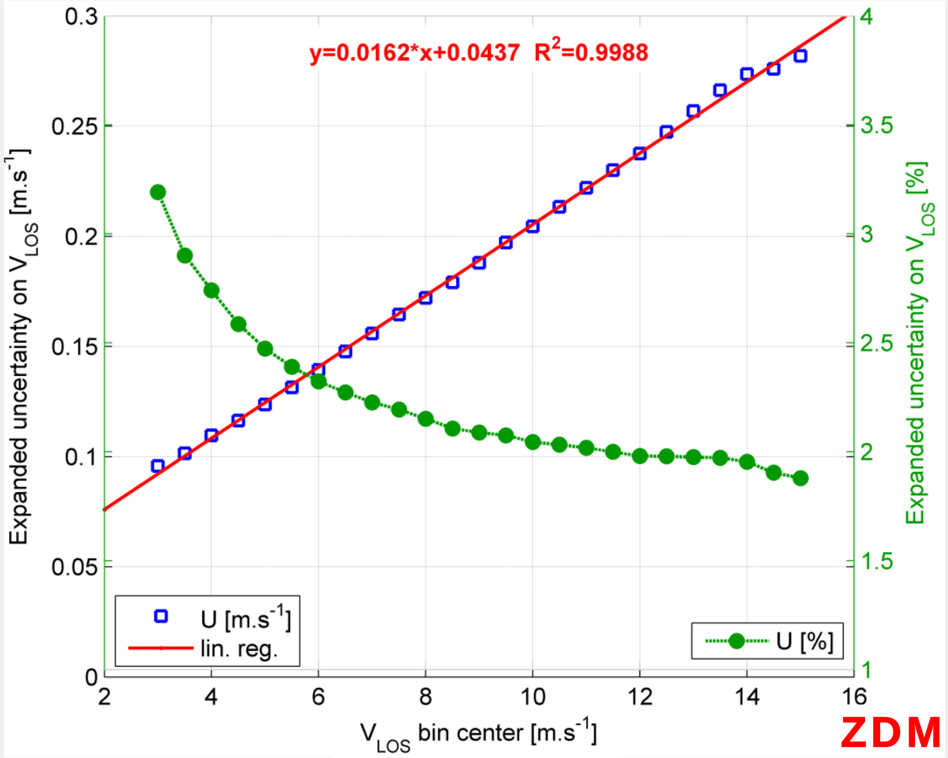
Results

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

  U_{exp} increases linearly (m/s)
  ~ 3% at 4m/s
  ~ 2% at 10 m/s
  } **almost same as cup anemometer**



LOS 0

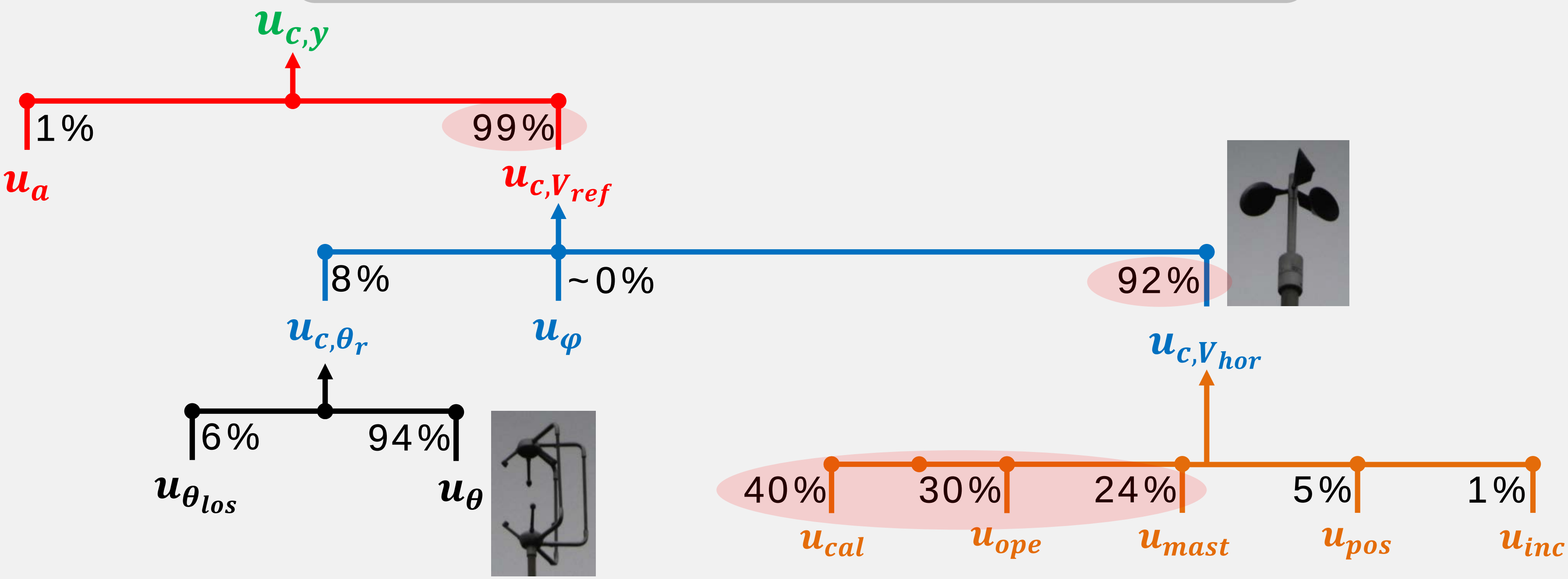


Bottom LOS

Uncertainty of LOS velocity

Prevailing sources

$$a \cdot V_{ref} = \boldsymbol{y} = \boldsymbol{a} \cdot V_{hor} \cdot \boldsymbol{\cos\varphi} \cdot \boldsymbol{\cos}\underbrace{(\boldsymbol{\theta} - \boldsymbol{LOS_{dir}})}_{\boldsymbol{\theta_r}}$$



- **Conclusions:**
  - ➔ 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

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

remote sensing

MDPI

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-0088

More info:

- website 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)

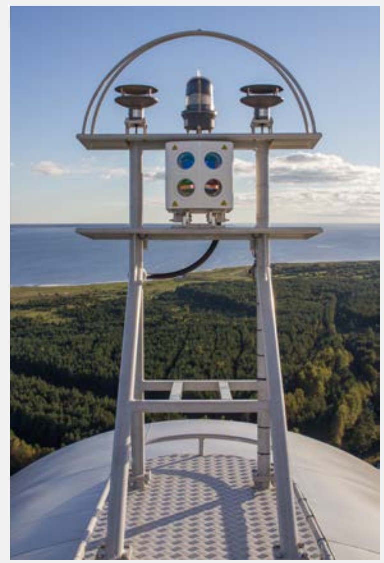
Remote sensing instruments

–

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*

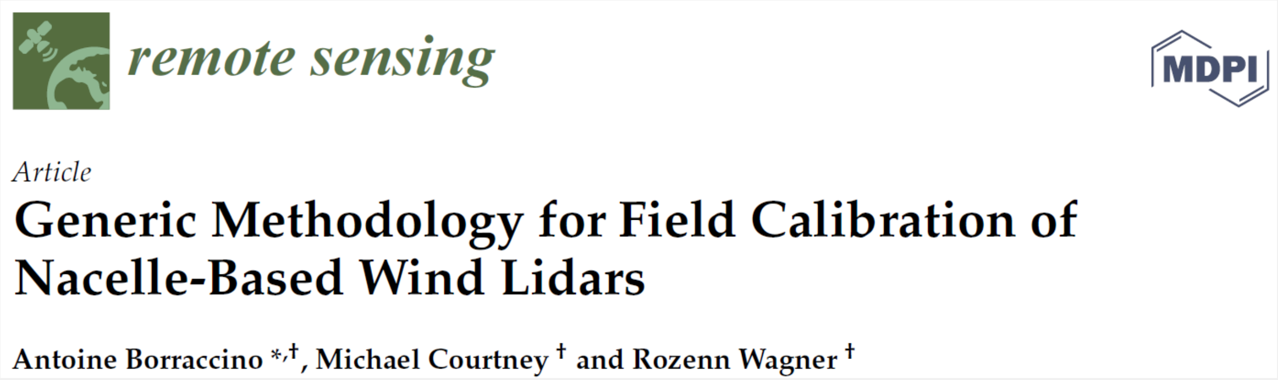
Publications

- **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



remote sensing

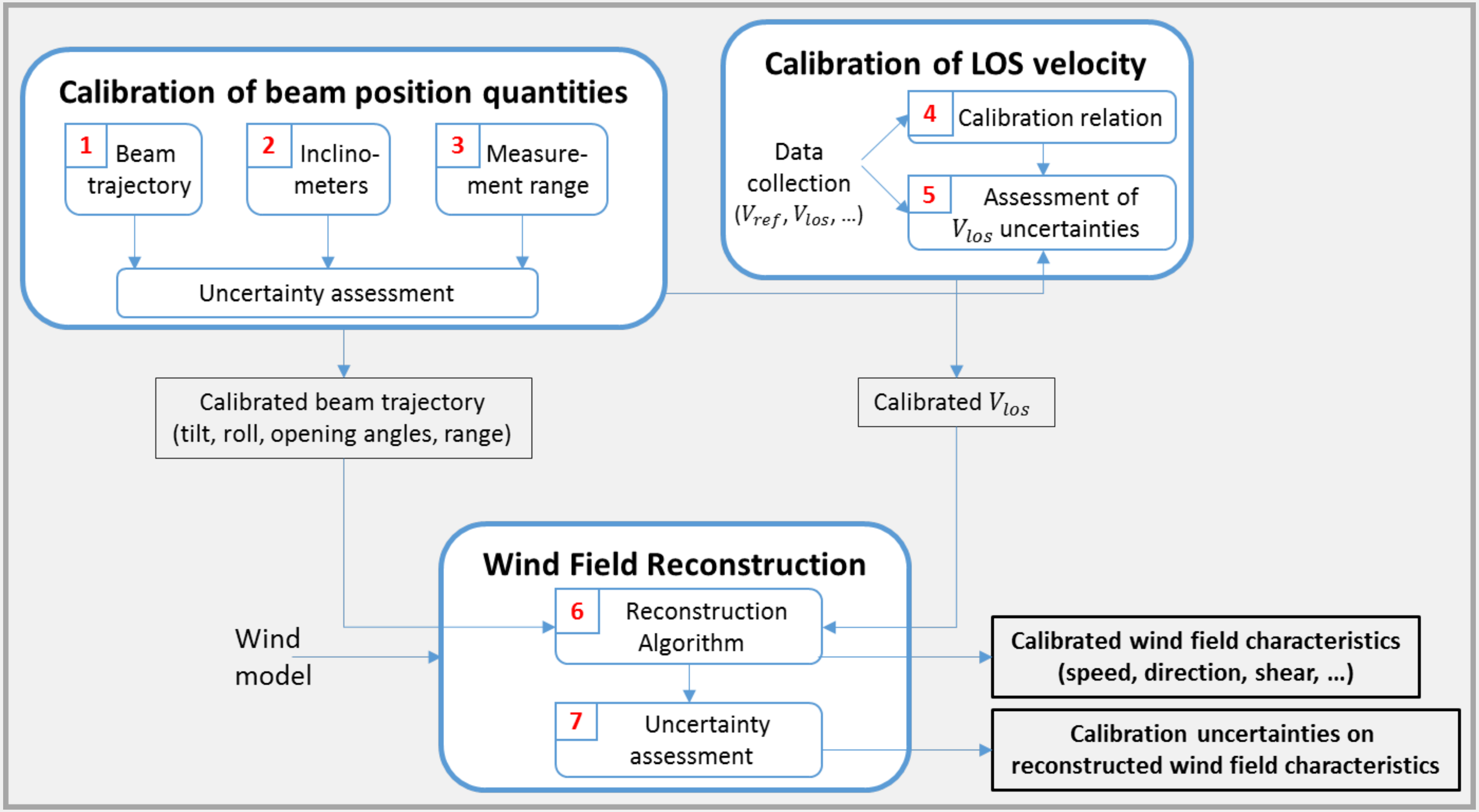
MDPI

Article

Generic Methodology for Field Calibration of Nacelle-Based Wind Lidars

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

Calibration of wind lidars:
white-box methodology



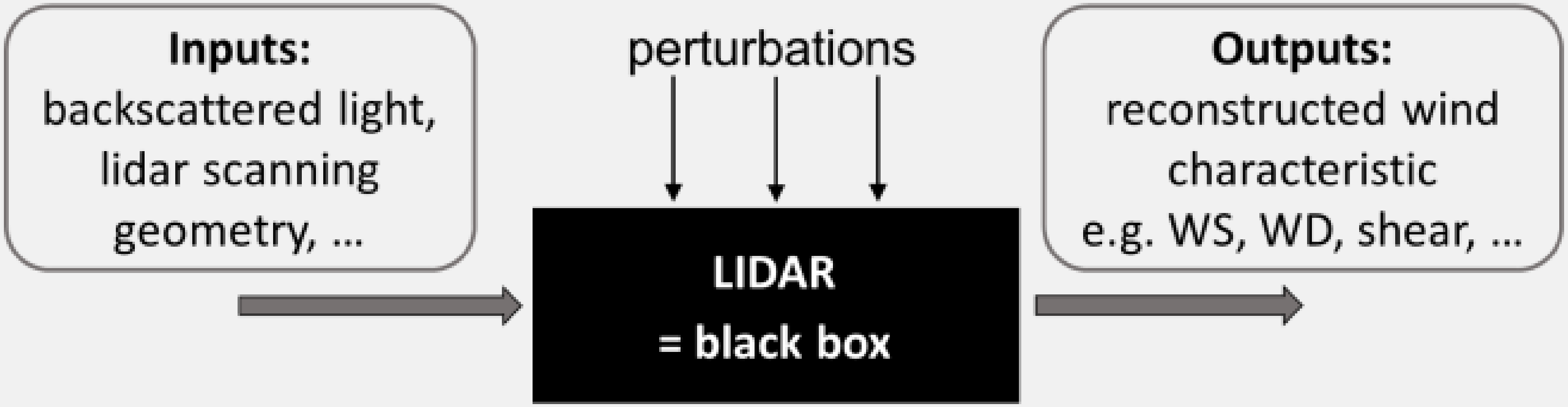
Calibration of wind lidars:
white vs. black-box methodology (1/2)

- **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!

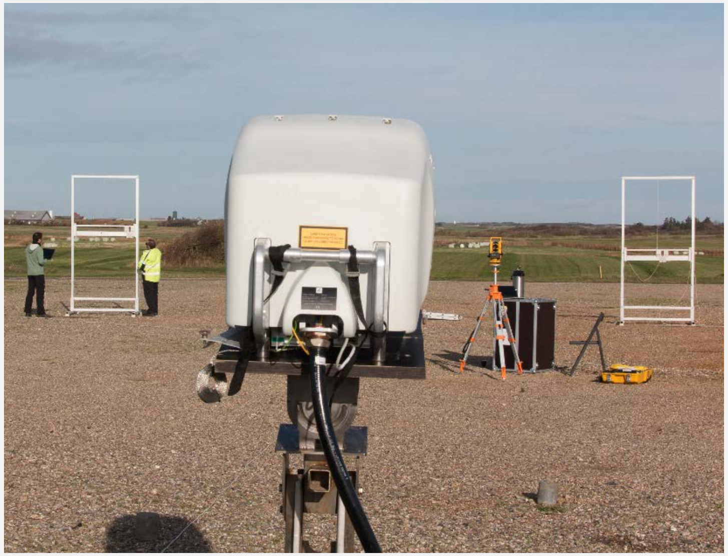


Generic calibration methodology
1) beam positioning quantities

- **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



2) Calibration of LOS velocity

Method and data analysis

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

Reference quantity

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

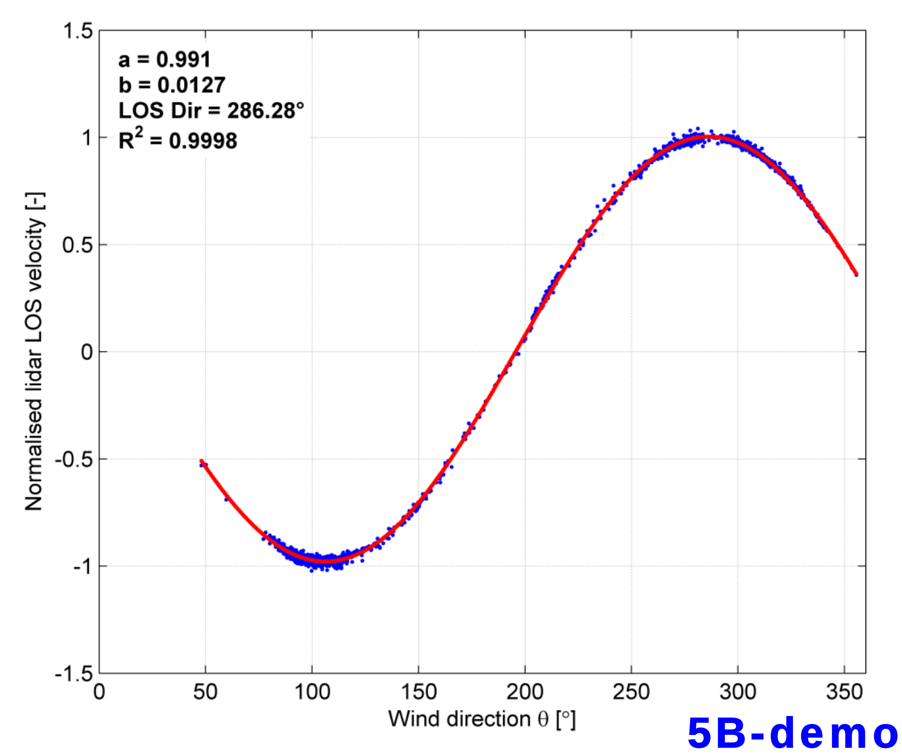
- **LOS direction evaluation**
  - fit of wind direction response (part 1)
  - Residual sum of squares process (part 2)

- **Comparison between**
  - Lidar-measured LOS velocity V_{los}
  - Reference quantity: pseudo-LOS velocity V_{ref}
    ➔ derived from calibrated ref. instruments

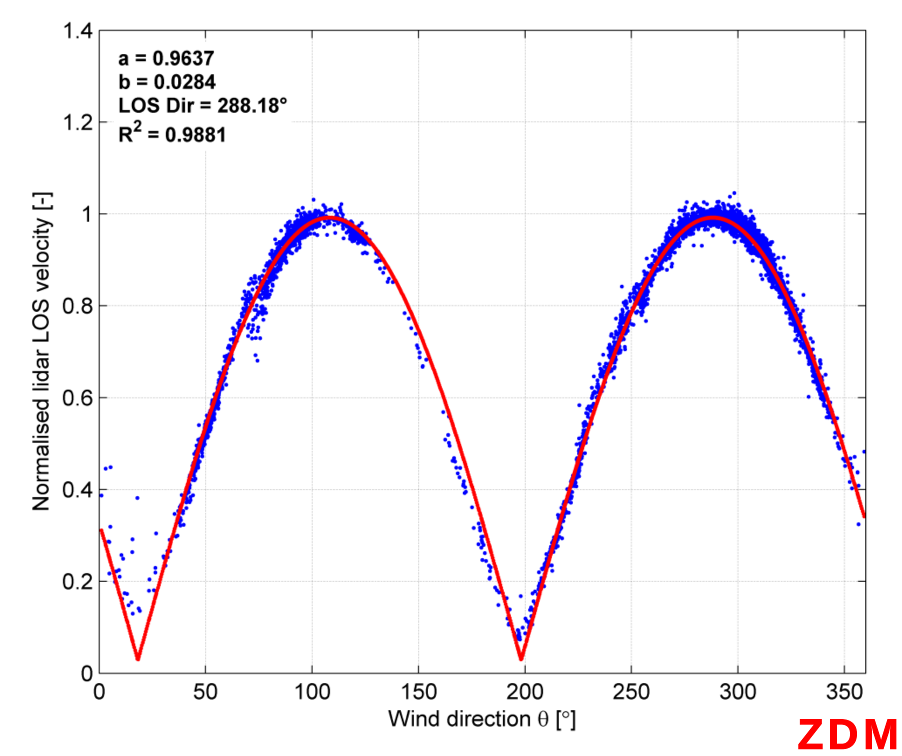
2) Calibration of LOS velocity

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



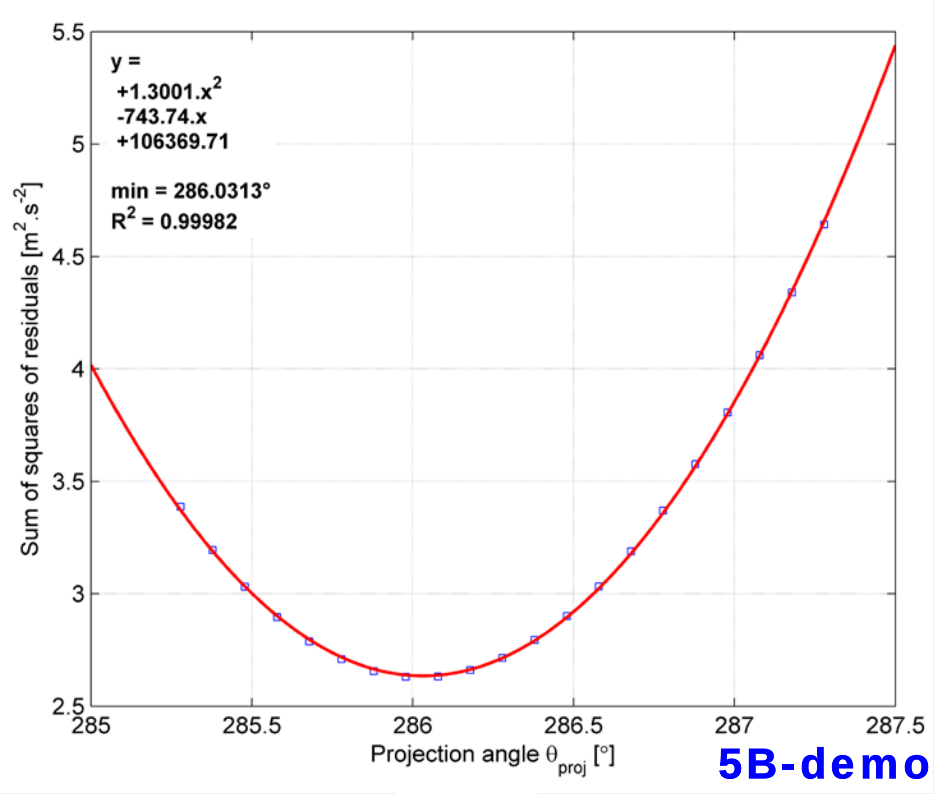
LOS 0



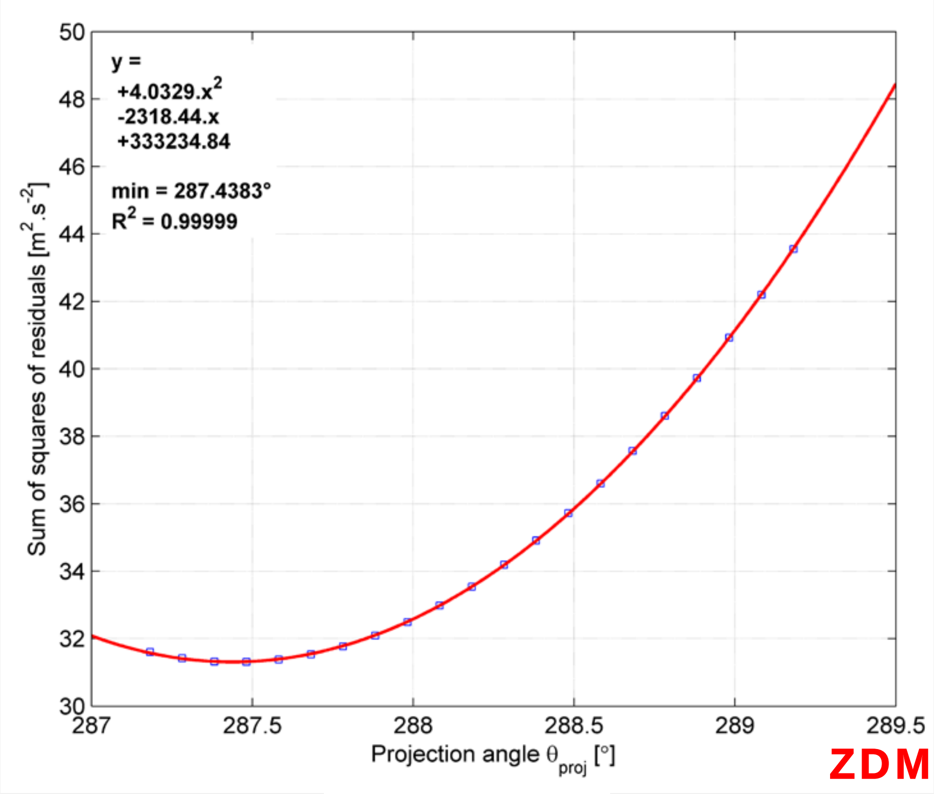
Bottom LOS

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**



LOS 0



Bottom LOS

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 ($\pm 0.05°$)

Lidar	LOS	Calibration relation			
		θ_{los}	a	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° – 181° azimuth	287.44°	1.0050	0.9998	2140

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

$$u_{ope} = \frac{1}{\sqrt{3}} \cdot cup\ class\ number \cdot (0.05 + 0.005 \cdot \langle HWS \rangle\ )$$

    - Mounting uncertainty

$$u_{mast} = 0.5\% \cdot \langle HWS \rangle$$

  - Wind direction, from calibration certificate of sonic anemometer:

$$u_{WD} \approx 0.4°$$

What are the uncertainty sources?

- **Calibration process uncertainties**
  - LOS direction uncertainty

$$u_{LOS\ dir} = 0.1°$$

  - Uncertainty of tilt inclination angle

$$u_{\varphi} = 0.05°$$

  - 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)