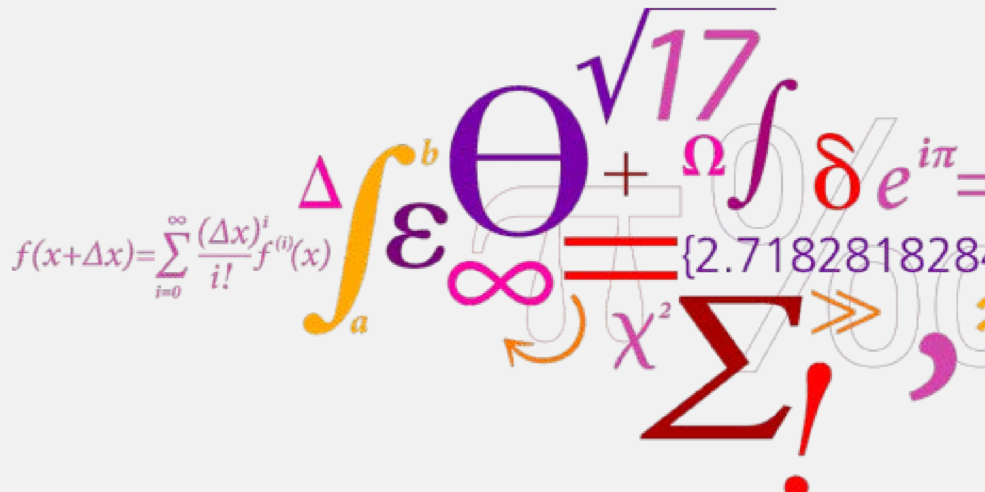
How to measure remotely the wind using nacelle lidars for power performance testing

A. Borraccino

Ph.D. defence, 30th August 2017



Supervisors: Michael Courtney, Rozenn Wagner
Project: UniTTe

DTU Wind Energy
Department of Wind Energy

Innovation Fund Denmark
RESEARCH, TECHNOLOGY & GROWTH

Outline

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

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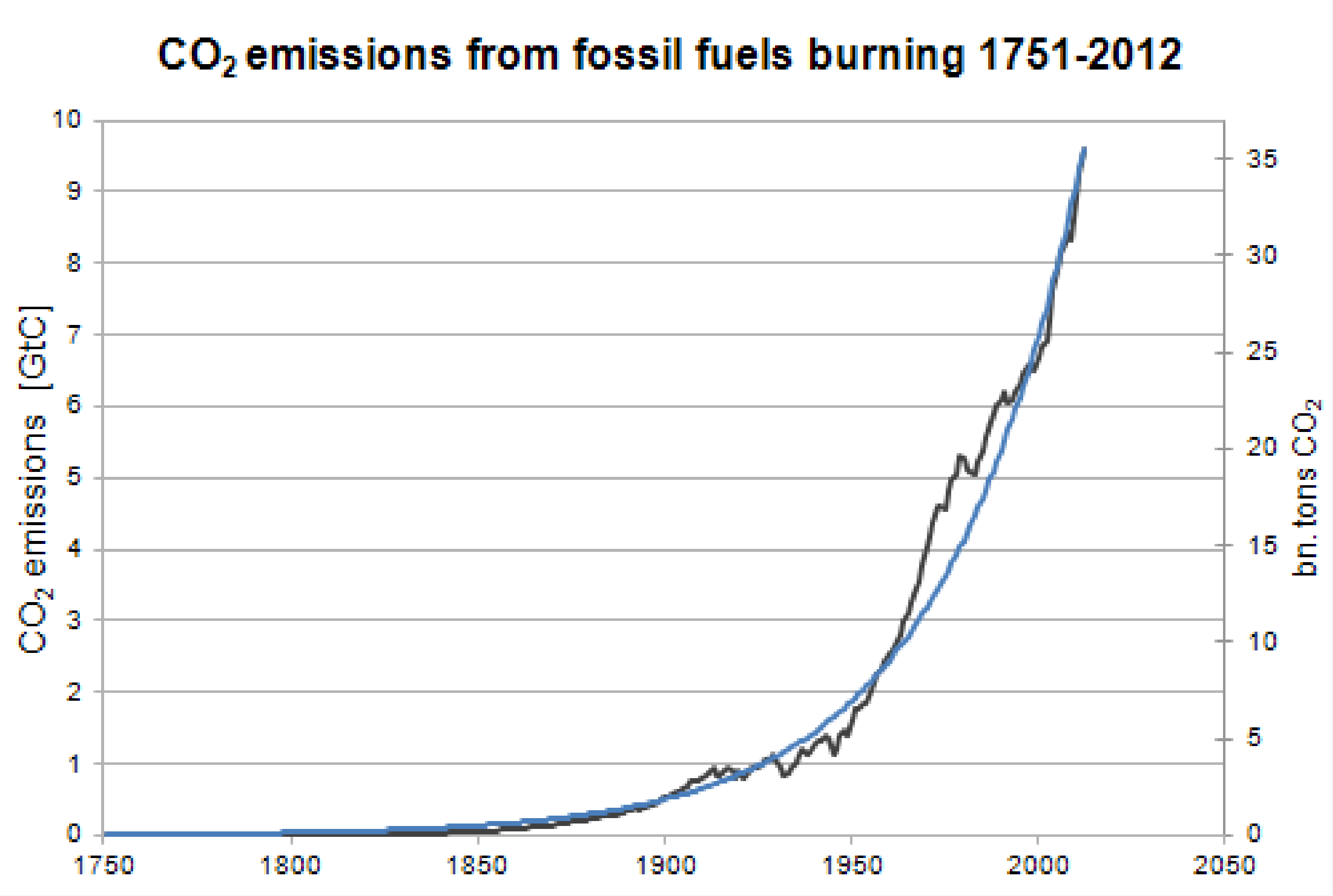
Motivations



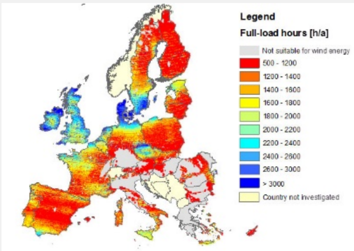
Source: CDIAC

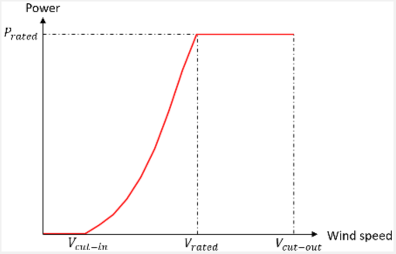
Motivations

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

Contractual agreements + international standards

Basis for bankable wind projects

(GWh/year)

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

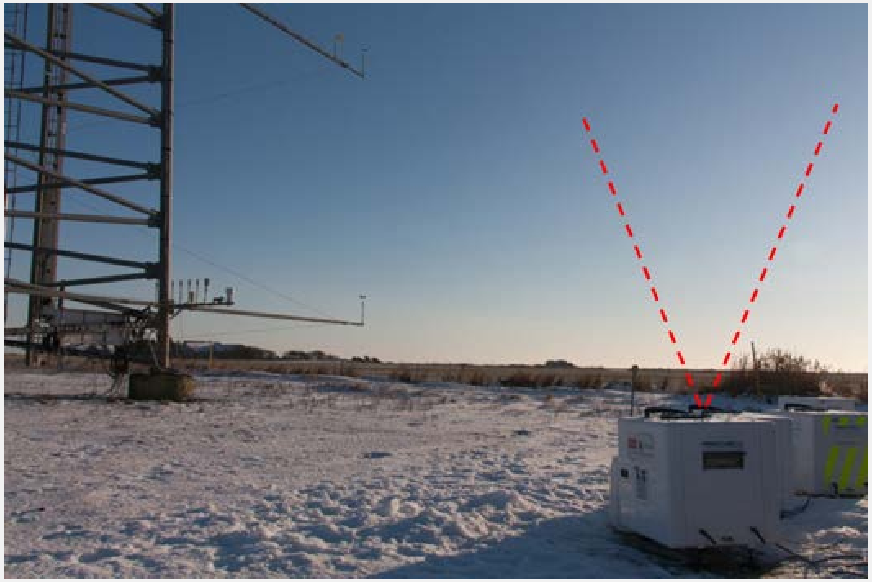
–

new IEC standard (2017):

use of **ground-based wind lidars** (profilers) allowed

ZephIR 300 (by *ZephirLidar*)

WindCube (by *Leosphere*)



Power performance testing
The modern ways (2/2)

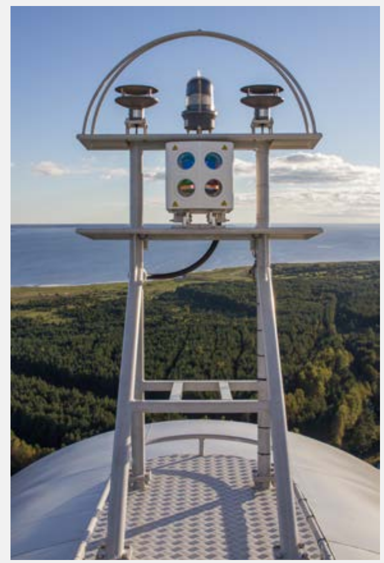
Remote sensing instruments

–

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*

Why nacelle lidars for power performance testing

For modern multi-megawatt turbines:

Cost-efficiency

– → +

met. mast | ground-based lidars | nacelle-based lidars

especially offshore!

Representativity of wind measurements

– → +

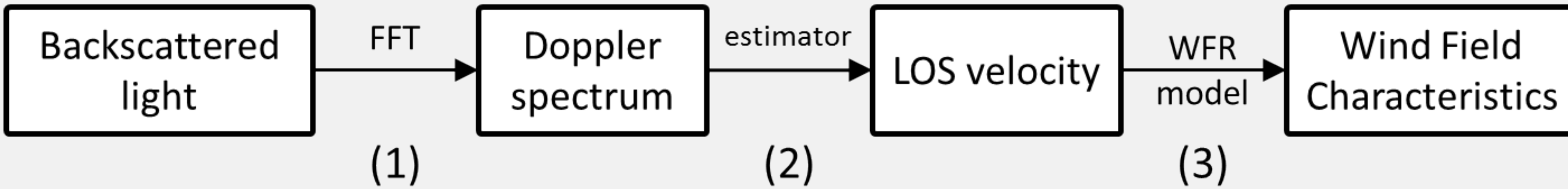
met. mast | ground-based lidars | nacelle-based lidars

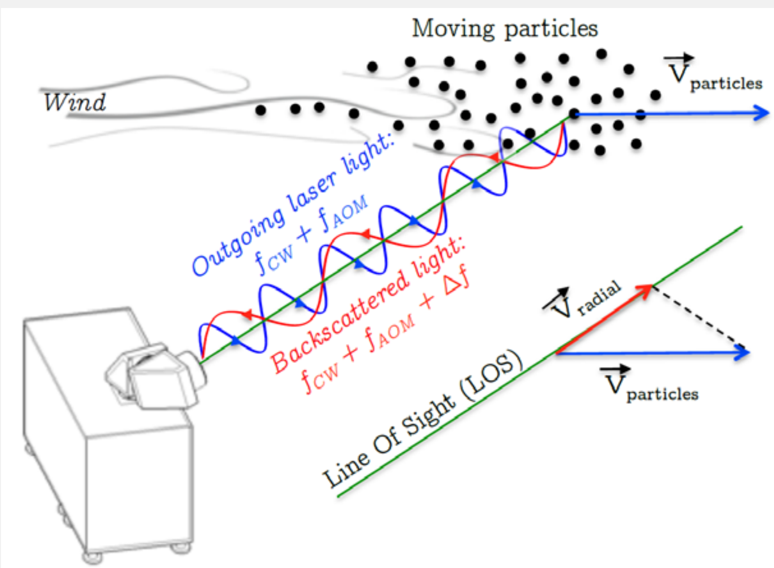
especially in complex terrain!

Lidar

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

- **Principles of coherent Doppler wind lidars**





Credit: N. Vasiljevic

Lidar

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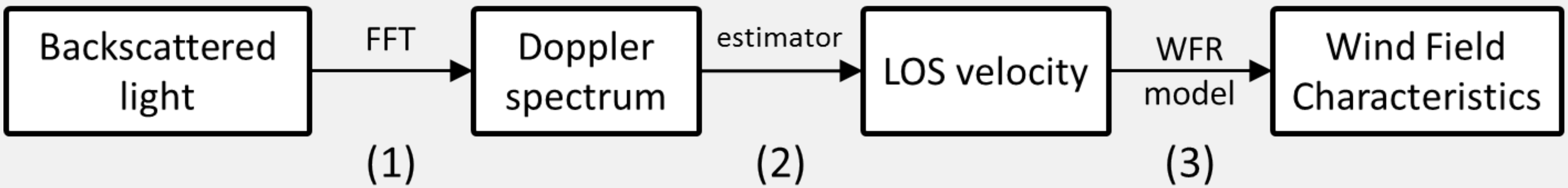

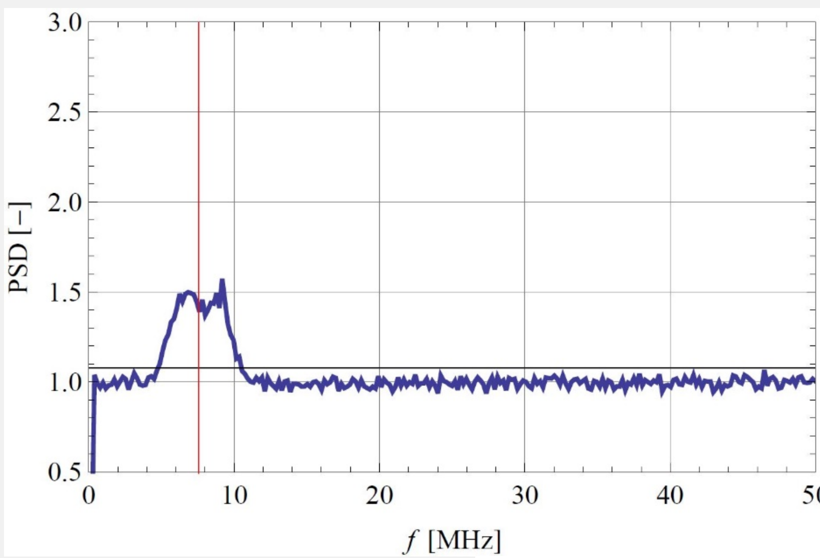

Credit: N. Angelou

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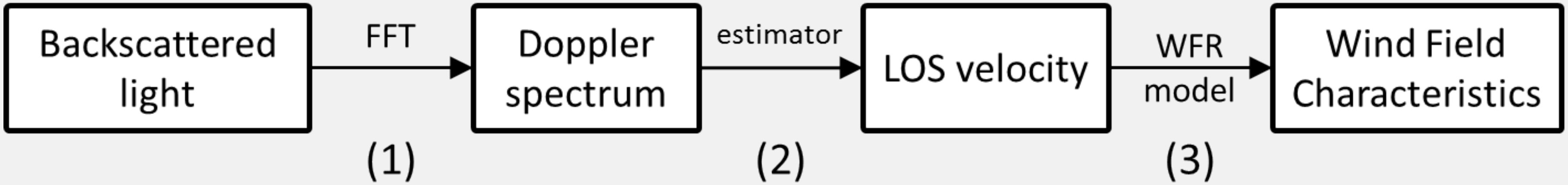
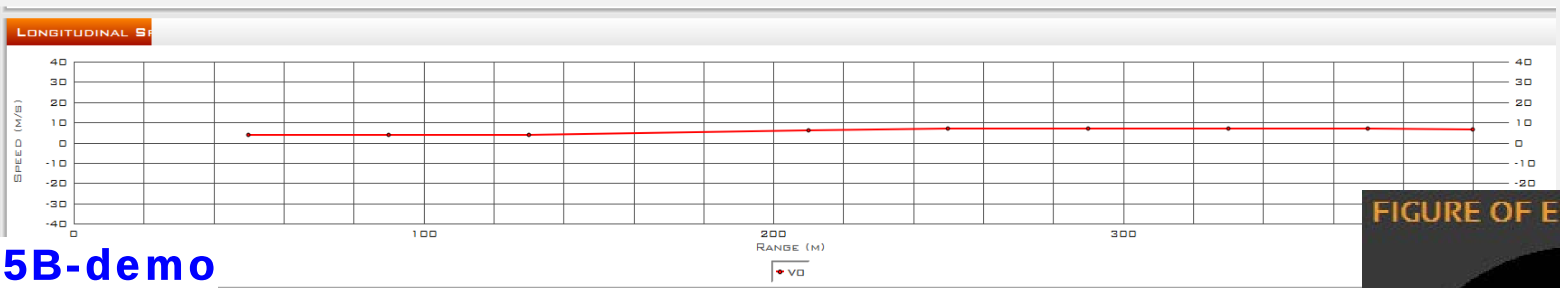
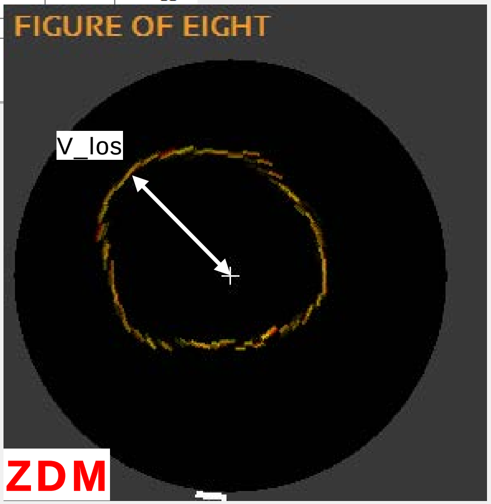




5B-demo

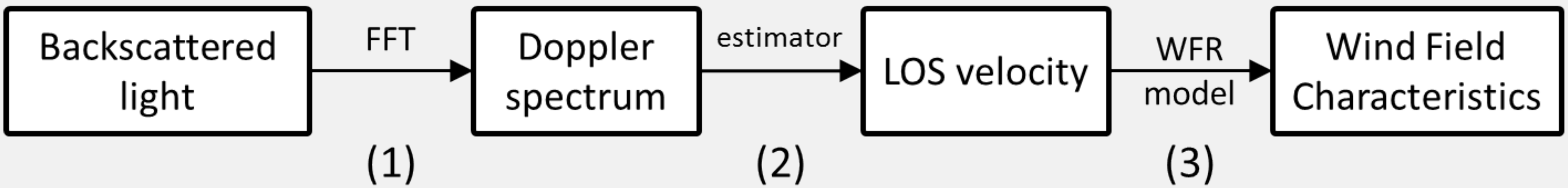


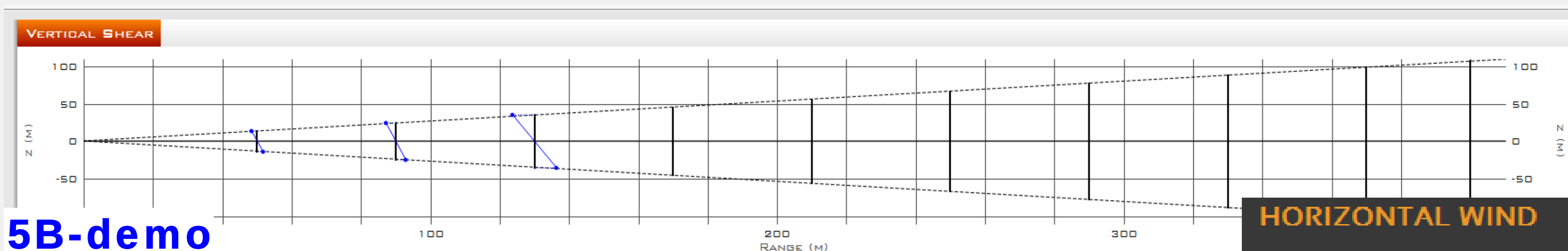
ZDM

Lidar

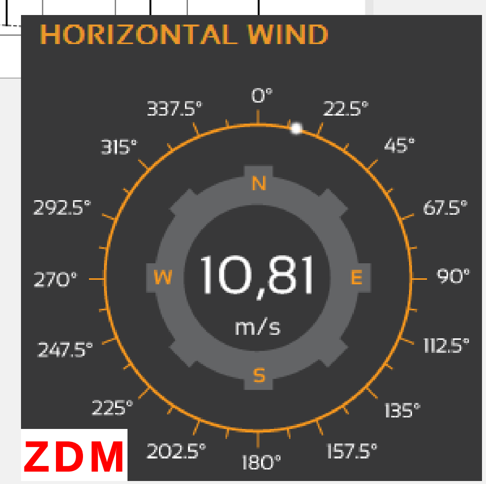
- **LIght Detection And Ranging:** “a radar using light”
- **Remotely measuring**: from some meters to >10 km away

- **Principles of coherent Doppler wind lidars**





5B-demo



ZDM

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

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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?**

Traceability to SI

Uncertainty quantification

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

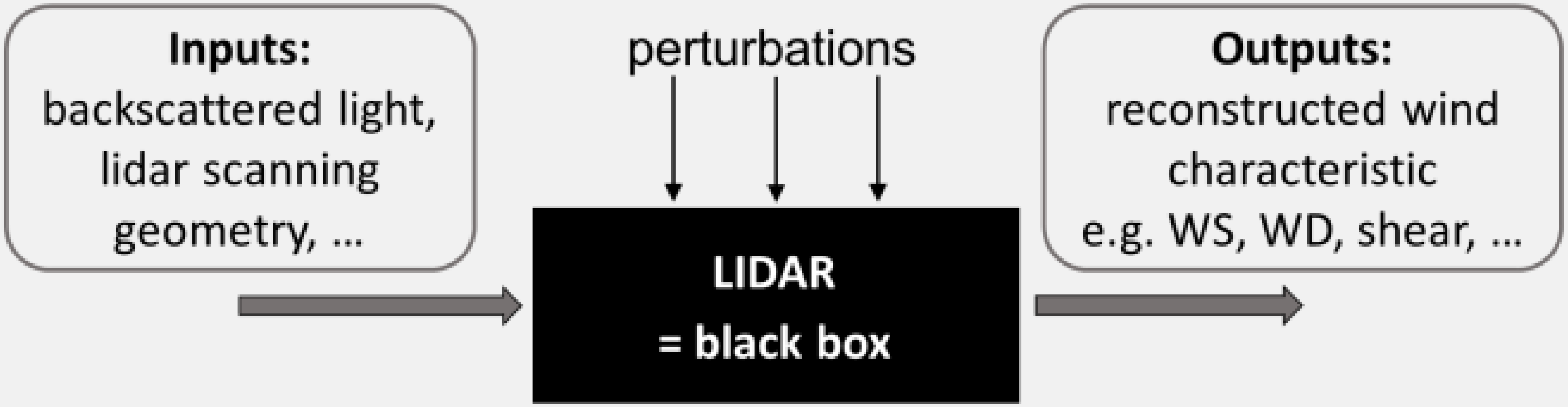
Calibration of wind lidars:
white vs. black-box methodology (1/2)

- **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)

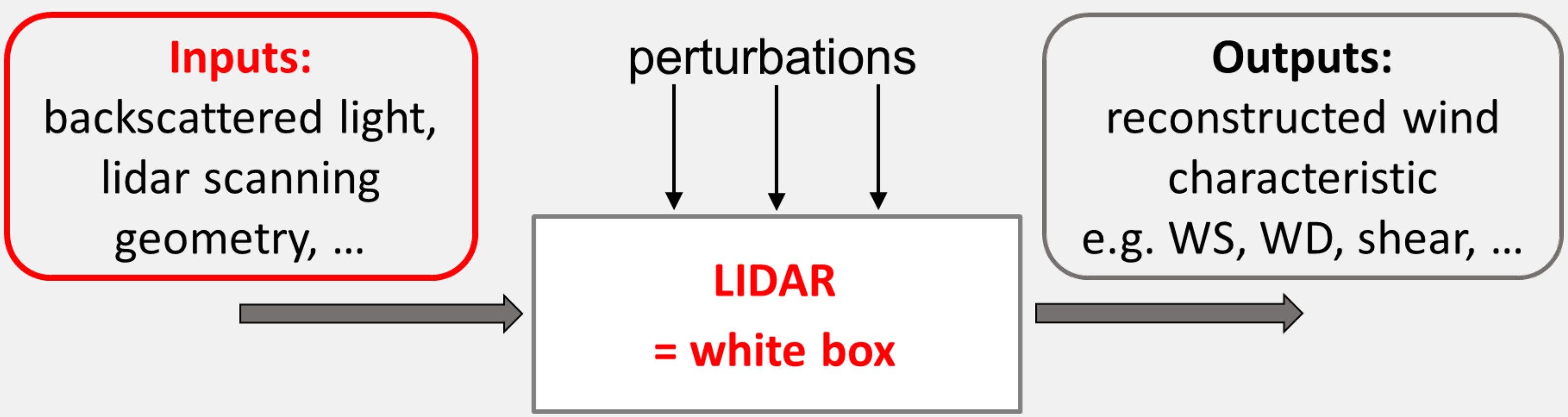
- **White-box**
  - calibration of <u>all the inputs</u> of the Wind Field Reconstruction

PROS

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

CONS

- Longer process
- Need expert knowledge

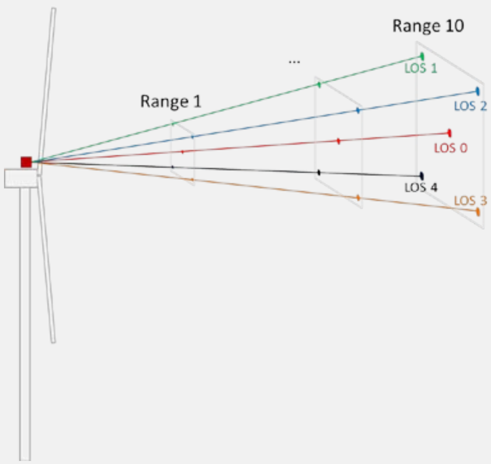


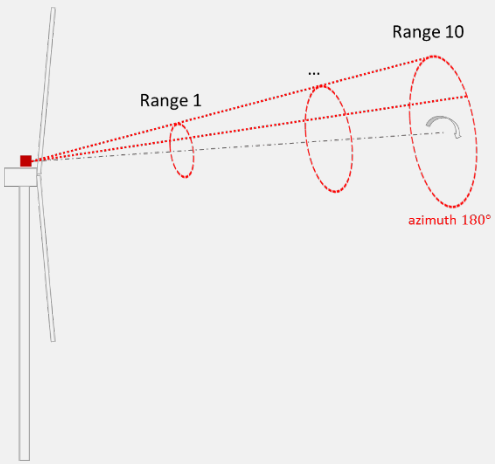
Generic calibration methodology

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

  Courtney M.: “Calibrating nacelle lidars”, [2013], DTU Wind Energy E-0020(EN)

- **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

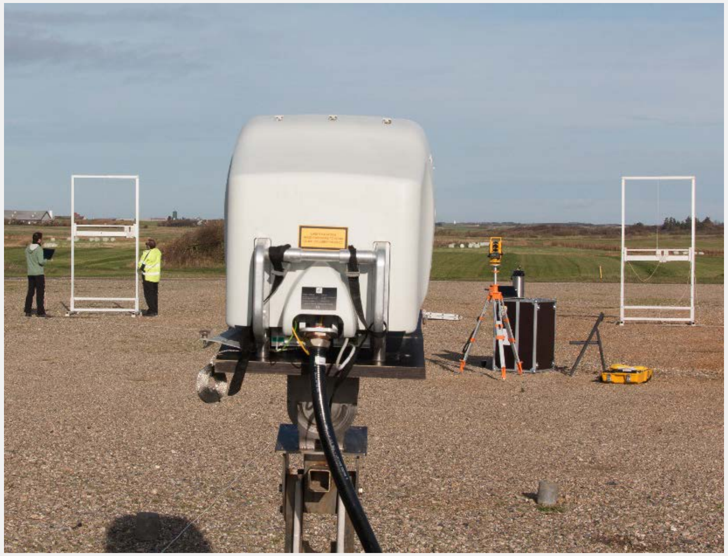
- **Published in journal article + 2 detailed calibration reports**

Generic calibration methodology
1) beam positioning quantities

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

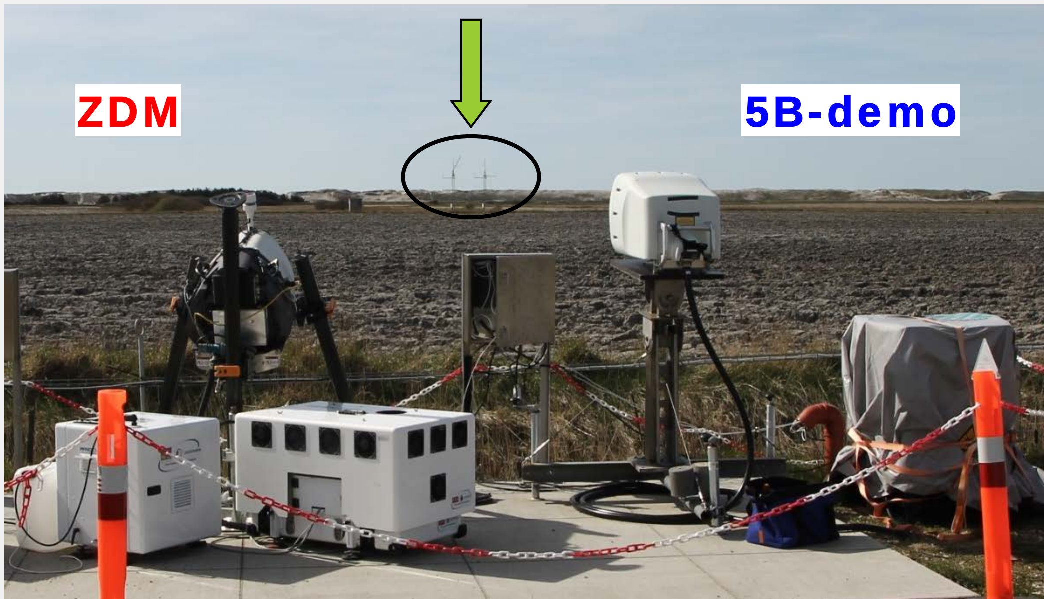
➔ Procedures are lidar-specific

➔ We used hard target methods to detect beam position

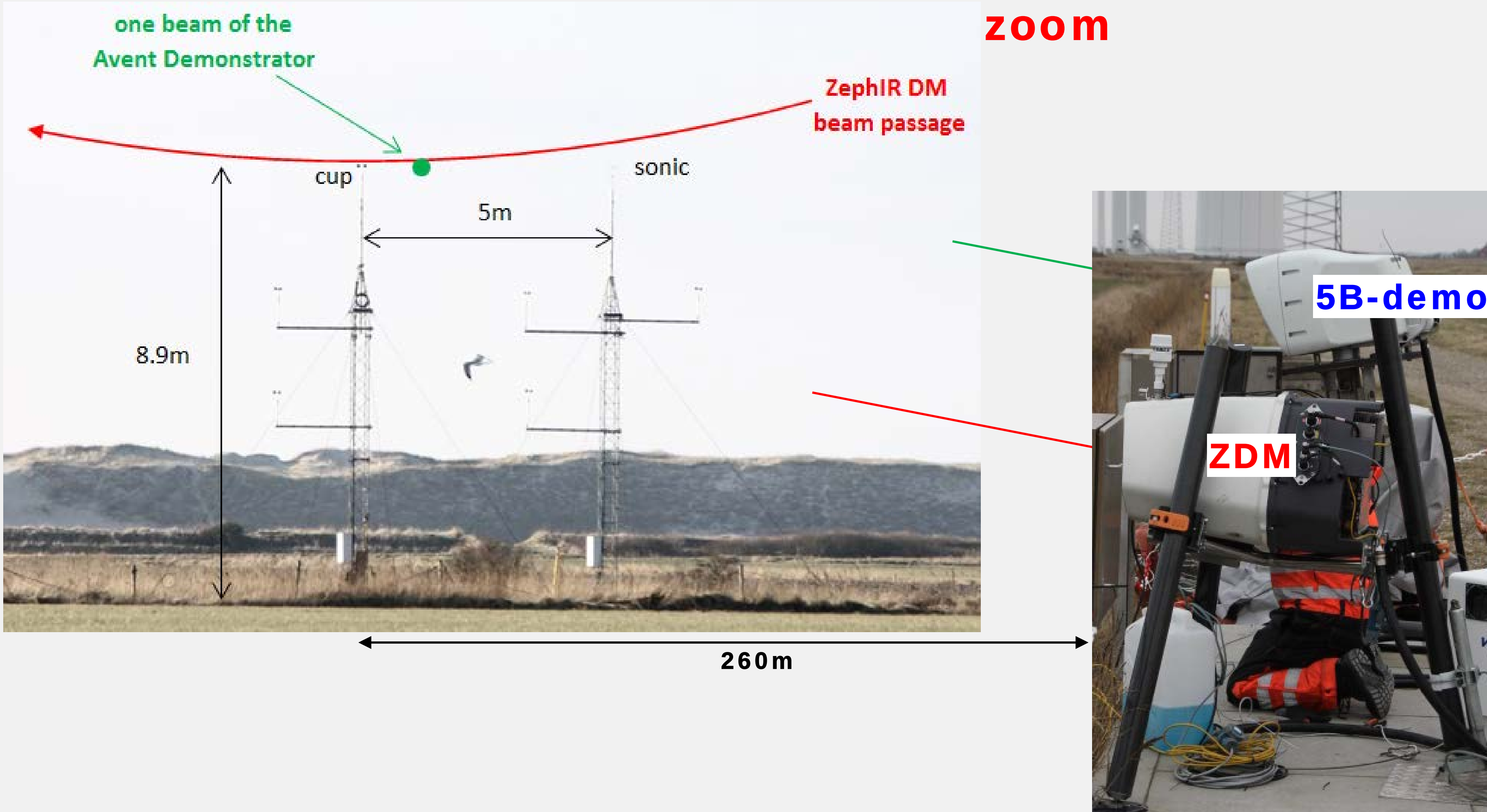


Generic calibration methodology
2) calibration of LOS velocity

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



Generic calibration methodology
2) calibration of LOS velocity



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

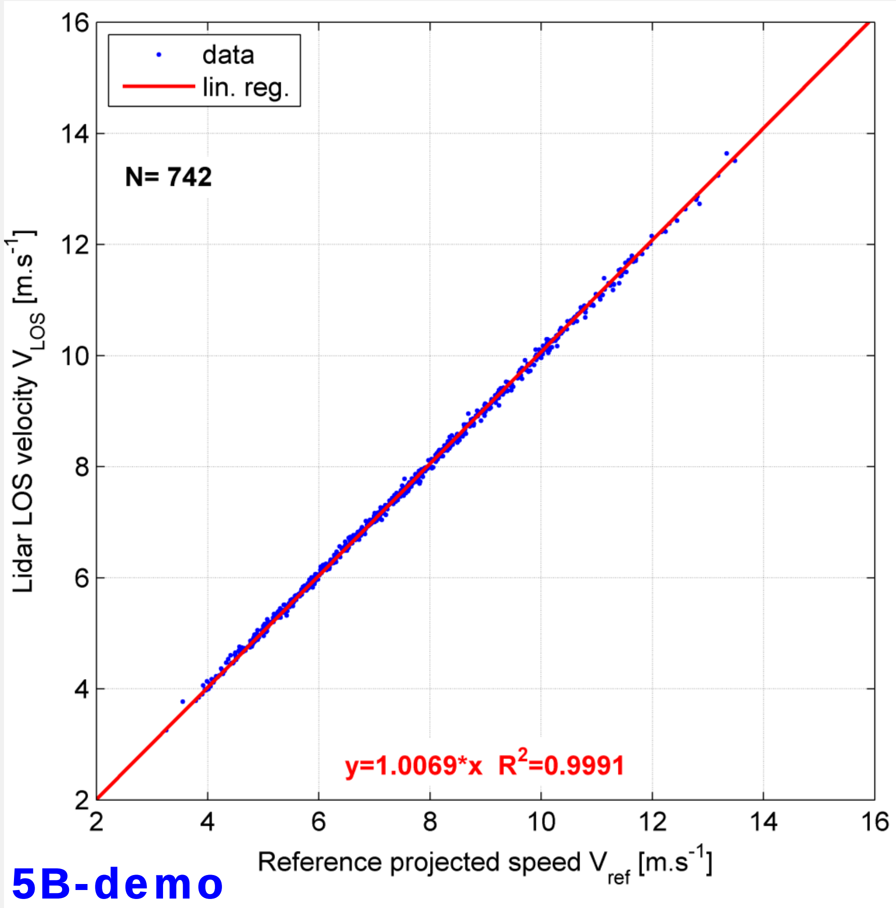
$$V_{ref} = V_{hor} \cos\varphi \cos(\theta - LOS_{dir})$$

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

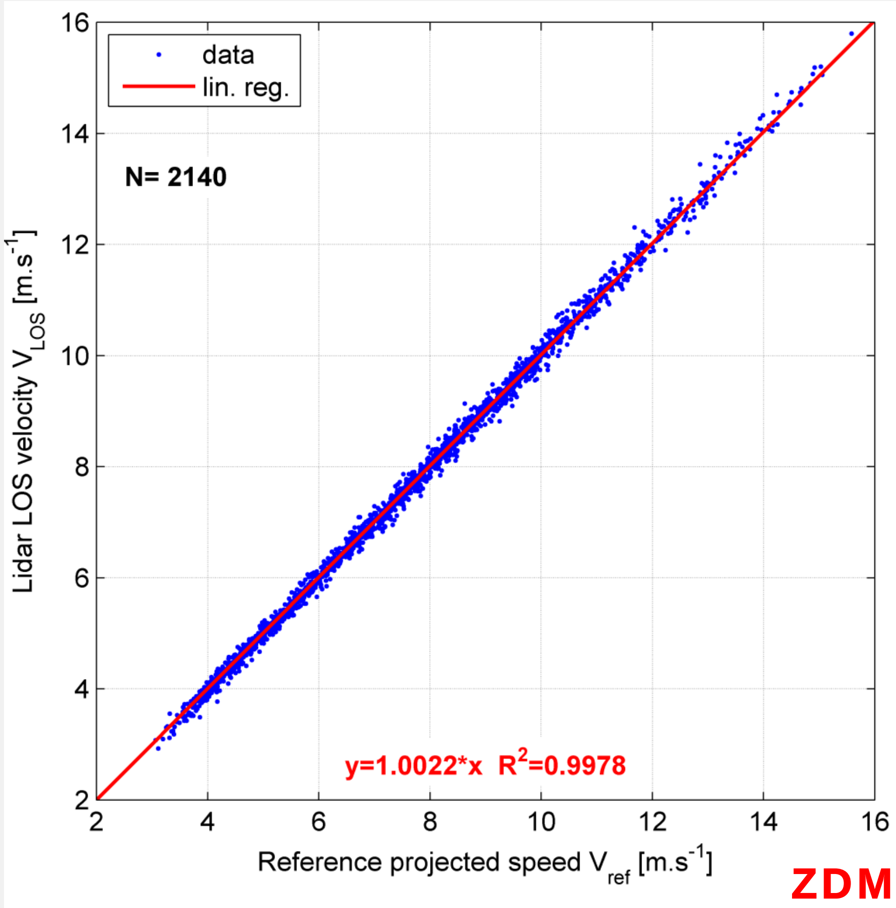
- **Comparison between**
  - Lidar-measured LOS velocity V_{los}
  - Reference quantity: pseudo-LOS velocity V_{ref}
    ➔ derived from calibrated ref. instruments

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

Linear regressions on 10-min data



LOS 0

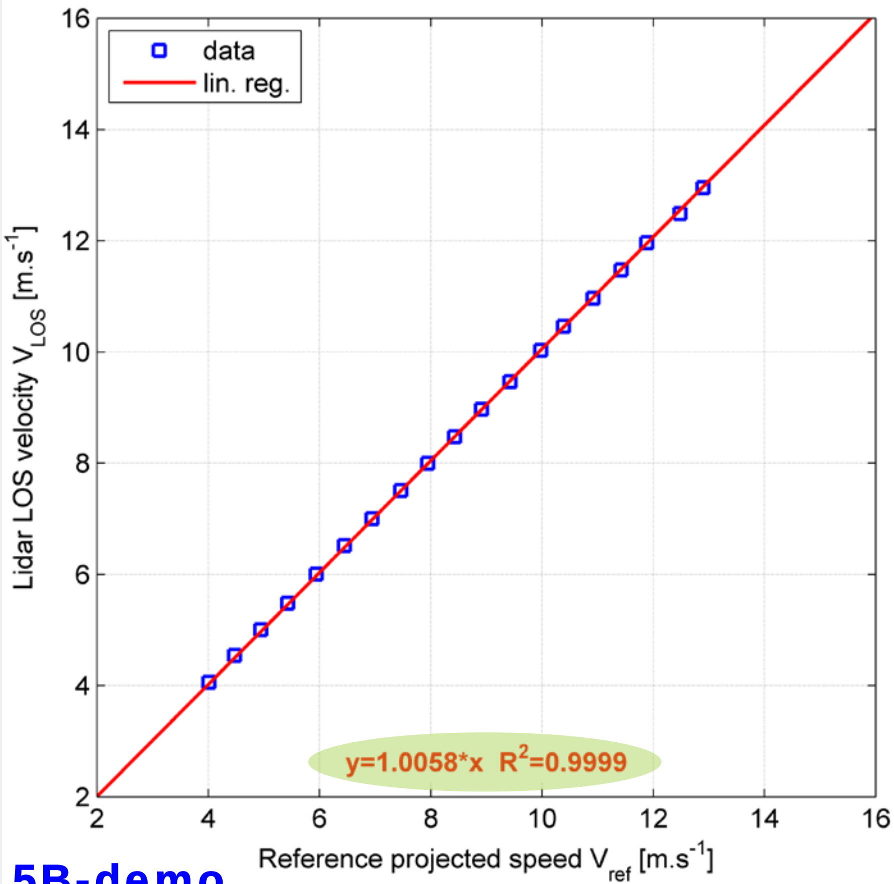


Bottom LOS

2) Calibration of LOS velocity

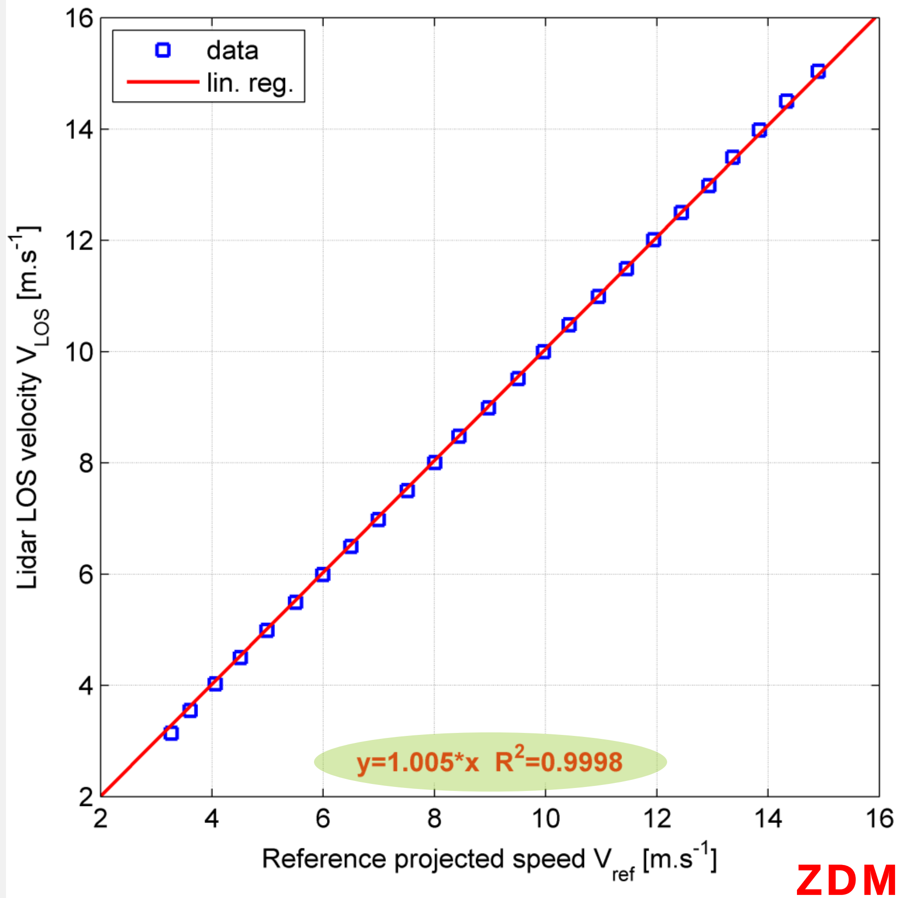
Results (2/2)

Linear regressions on binned data



5B-demo

LOS 0



ZDM

Bottom LOS

➔ the calibration relation is obtained!

Uncertainty of LOS velocity

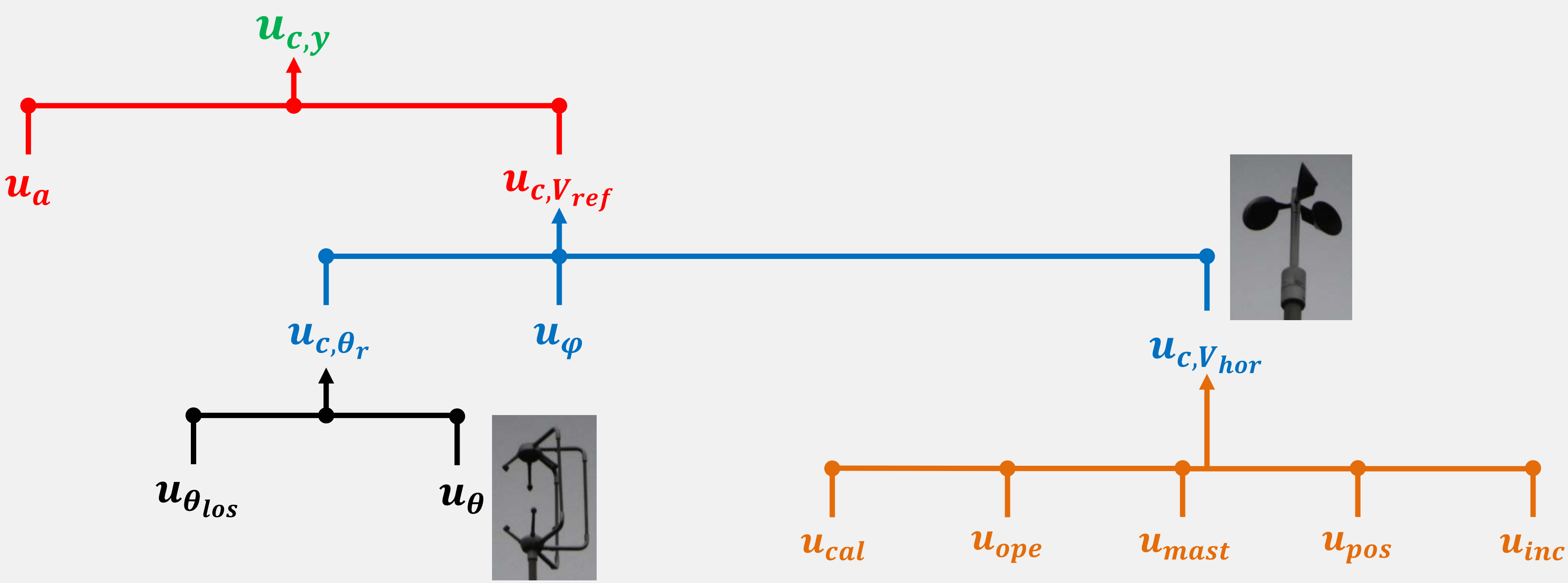
Method

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

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

gain of calibration relation (a); wind speed (V_{hor}); beam tilt angle (φ); wind direction (θ)

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



Uncertainty of LOS velocity

Results

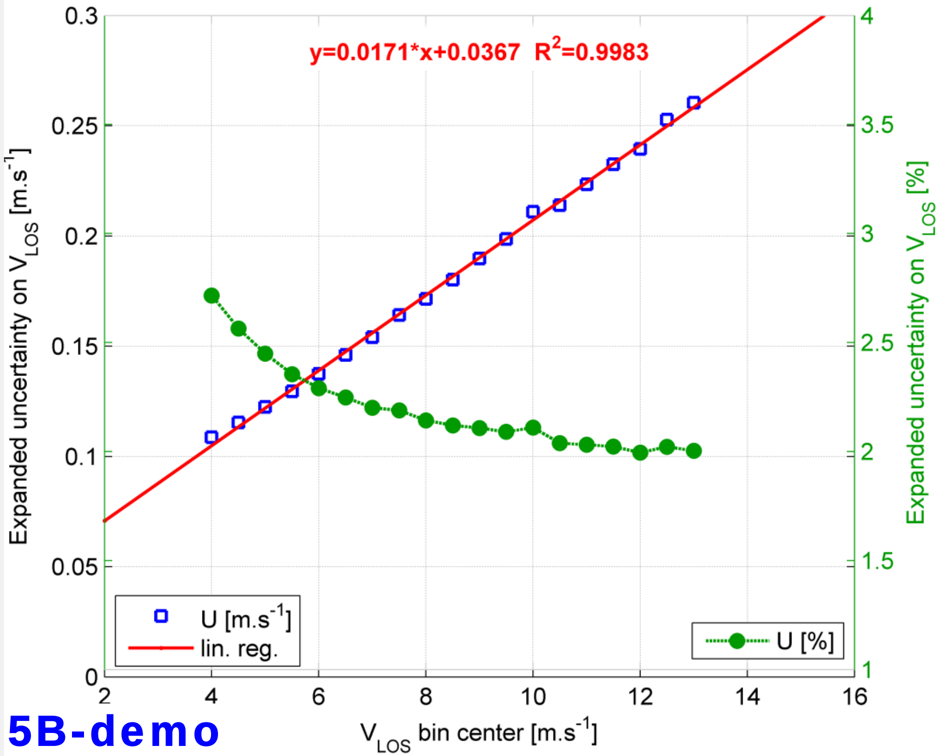
- **Expanded uncertainties (k=2) vs. V_{los}: in m/s and in %**

  U_{exp} increases linearly (m/s)

  ~ 3% at 4m/s

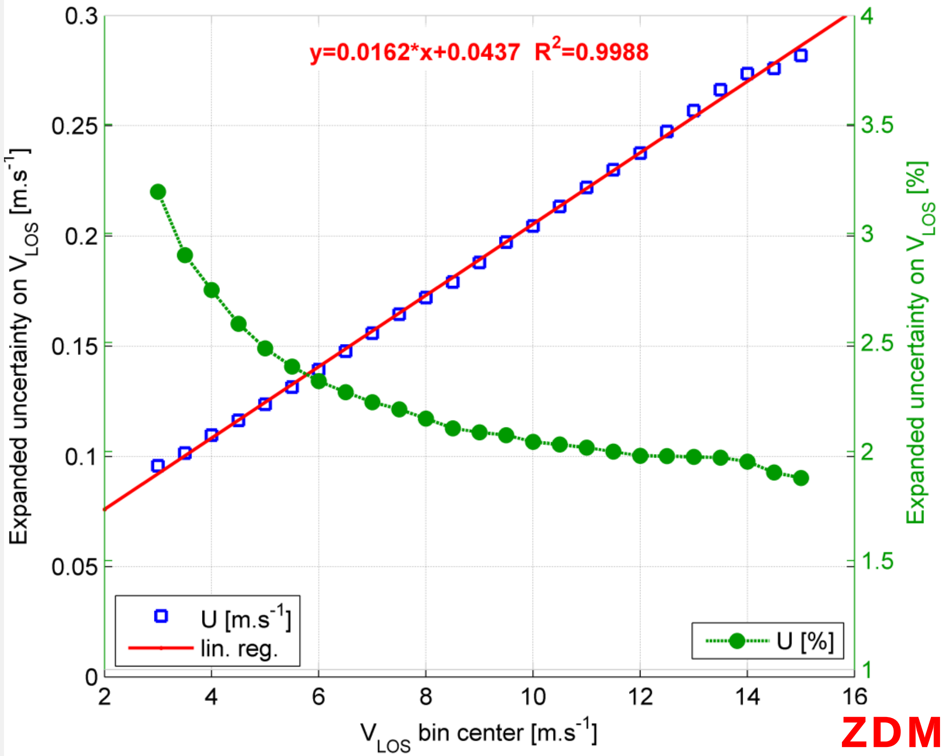
  ~ 2% at 10 m/s

  } **almost same as cup anemometer**



5B-demo

LOS 0



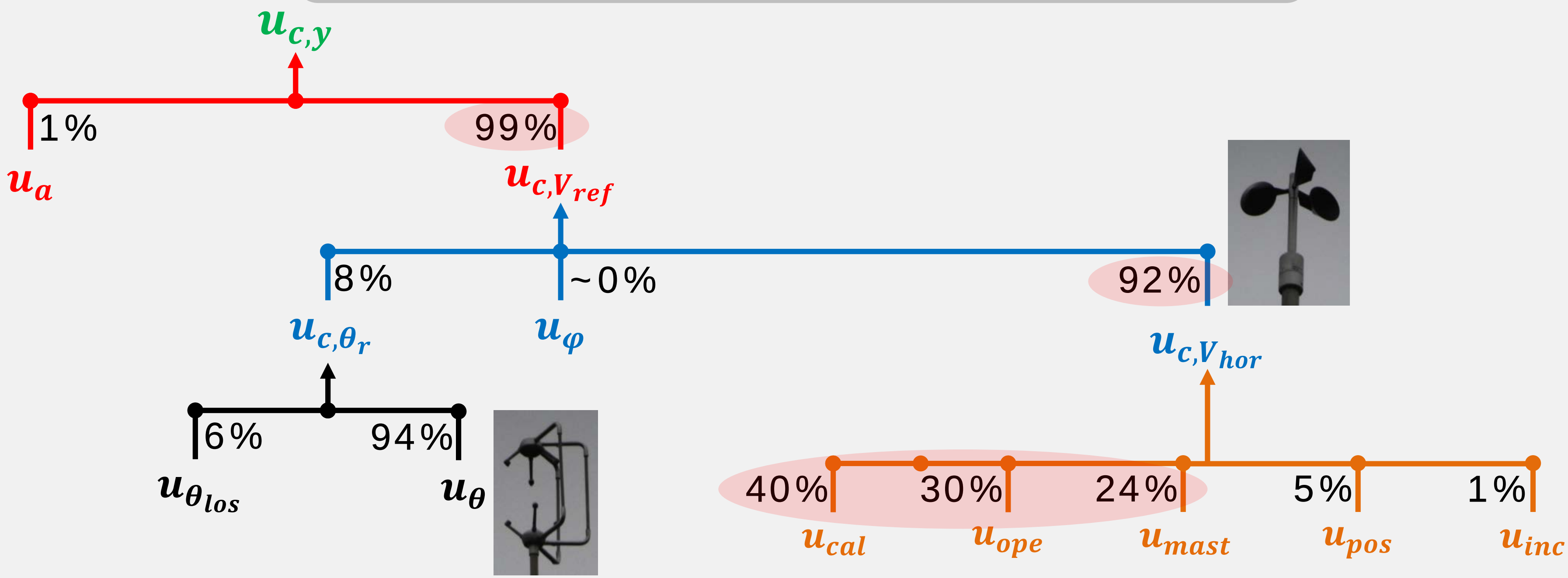
ZDM

Bottom LOS

Uncertainty of LOS velocity

Prevailing sources

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



- **Conclusions:**

  ➔ the lidar $\mathrm{V}_{\mathrm{los}}$ 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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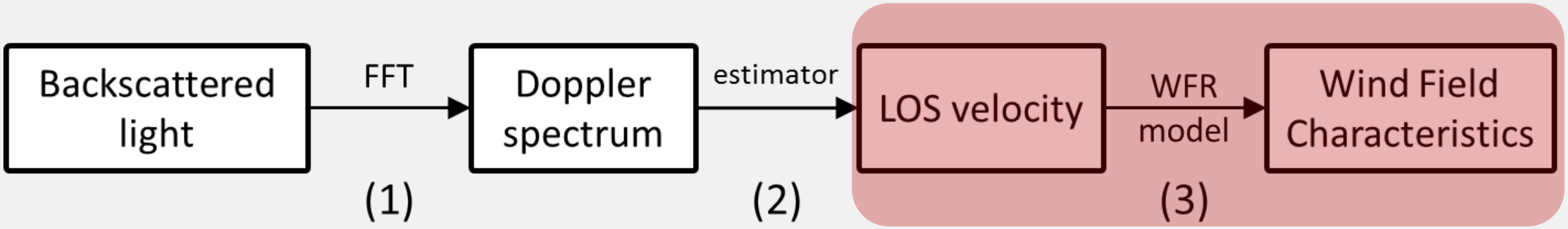
3 • Wind field reconstruction

4 • Power performance testing

Wind Field Reconstruction …

- **Combines LOS velocities measured in multiple locations**



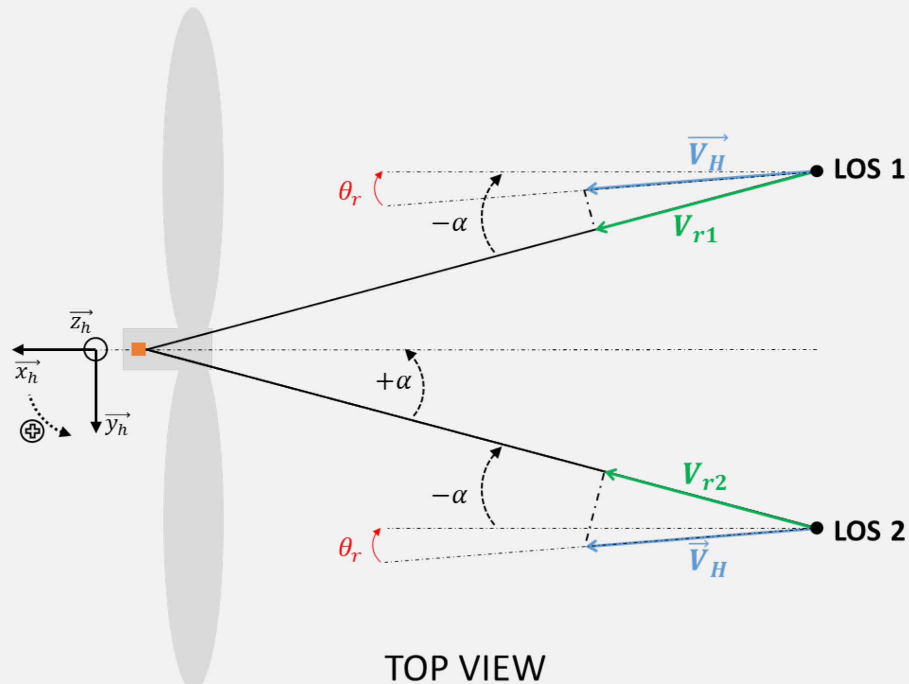
  – Needed to retrieve useful info: wind speed, direction, shear, …
  – **Assumptions on the flow field** must me made

- **Simplest example**

➔ two-beam nacelle lidar

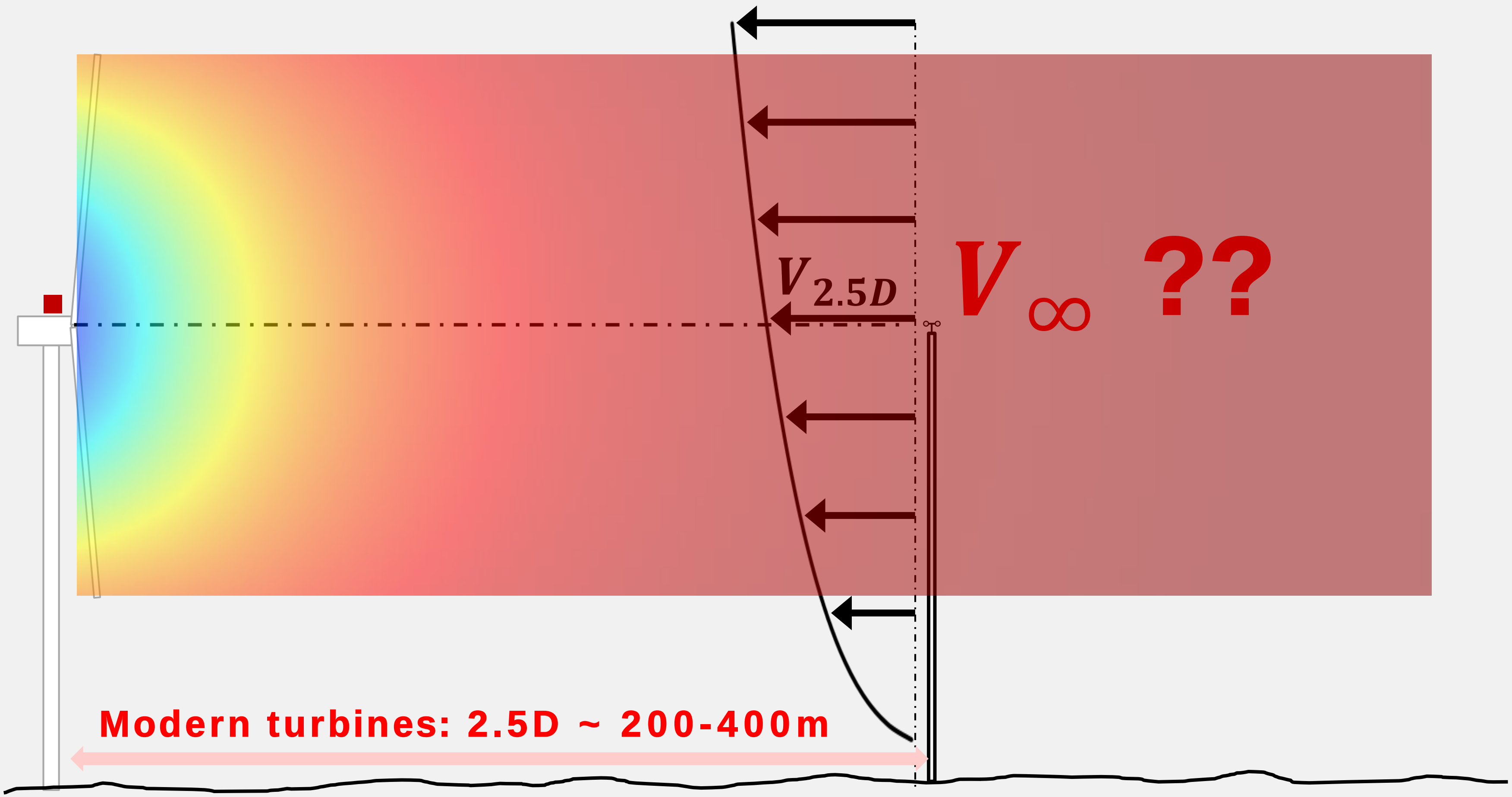
➔ horizontal homogeneity hyp.

➔ analytical solution for wind speed and relative direction



- **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 …

Does this make it any easier?

Flow disturbed by turbine wakes !

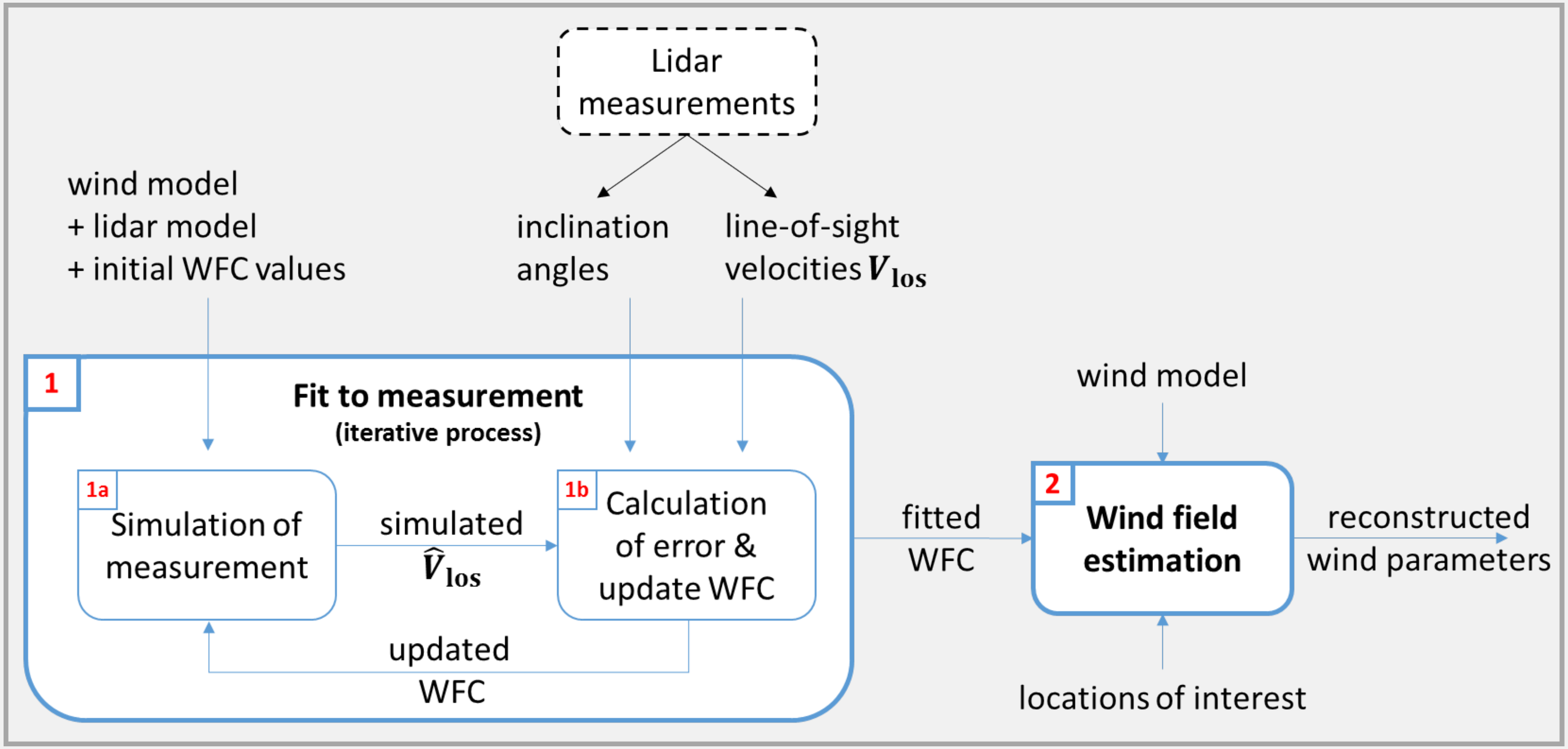
(very) complex terrain

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.

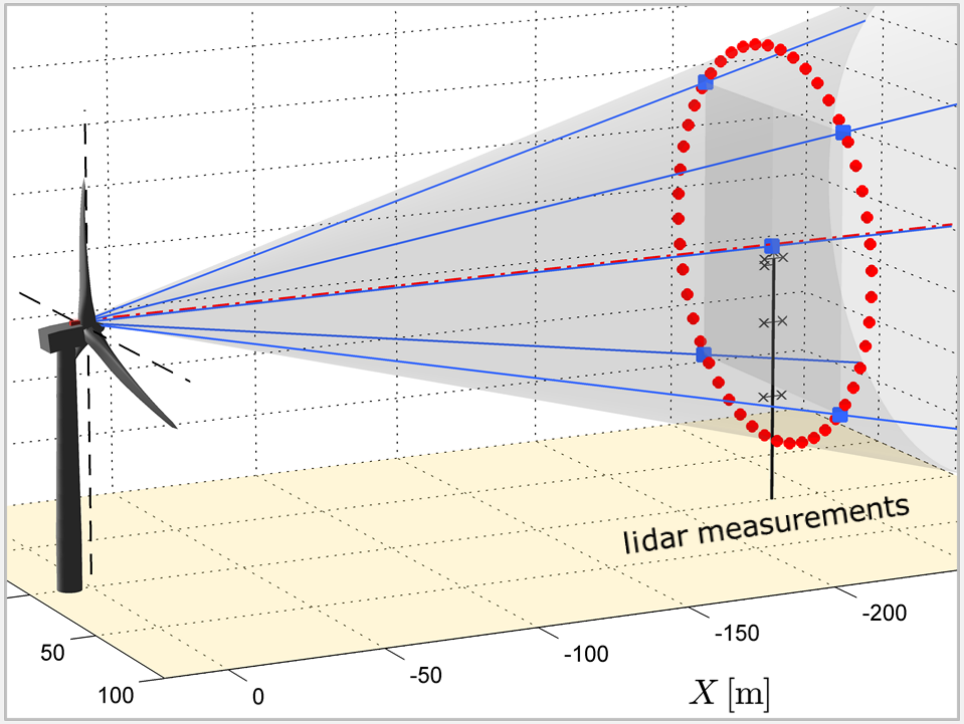


- **need new "wind models" for profiling nacelle lidars, suitable for power performance testing**

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 $\mathbf{V_0}$ ($@H_{hub}$)
  + relative wind dir. θ_r (yaw misalignment)
  + shear exponent α_{exp}



Combined wind-induction model

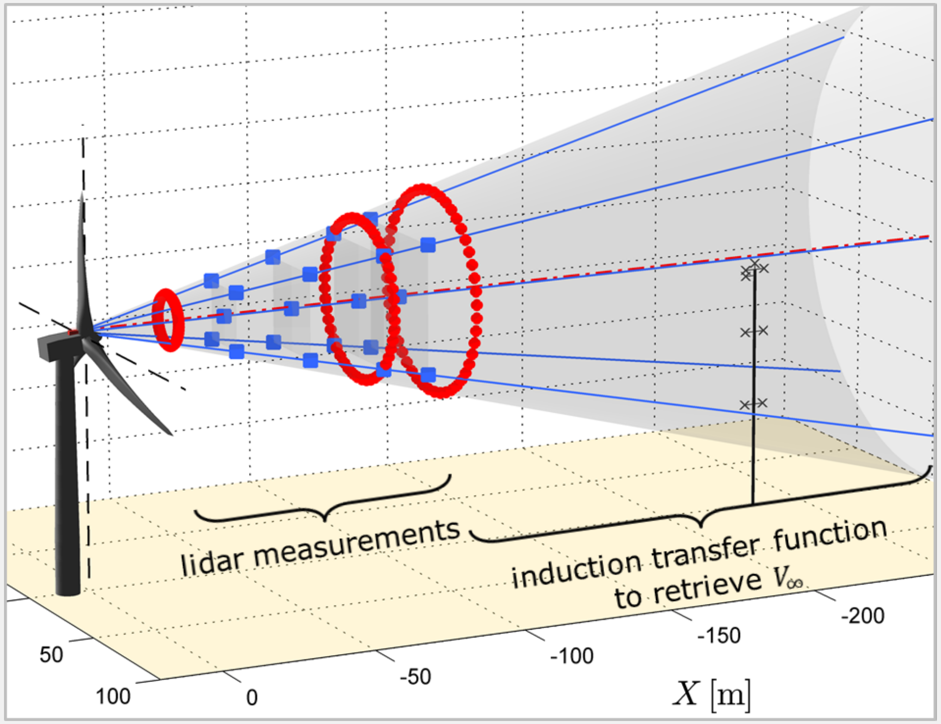
- Use lidar measurements at multiple distances close to rotor
- Additionally assumes simple induction model:

(from actuator disk and vortex sheet theory)

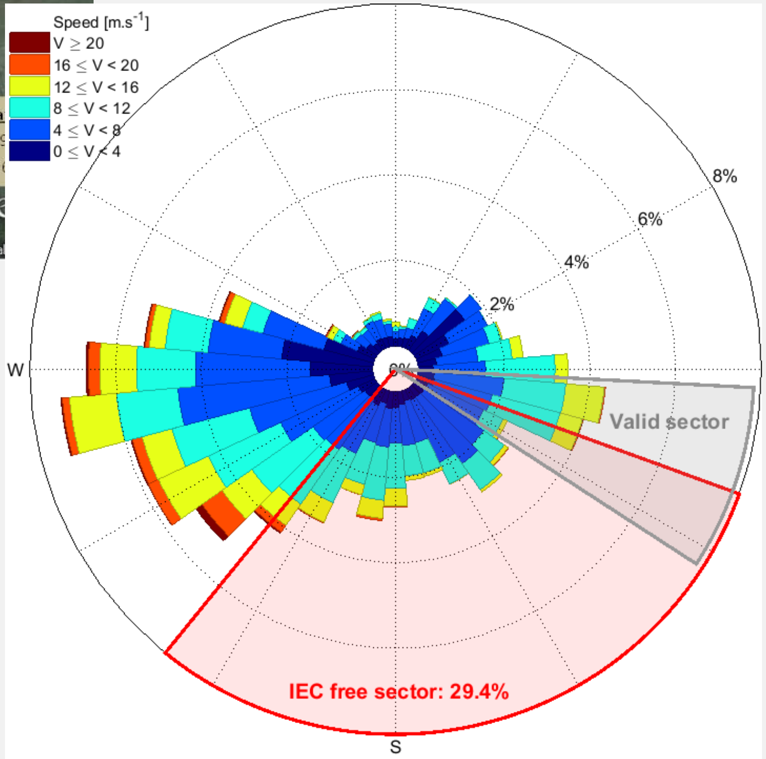
$$\frac{U(x)}{U_\infty} = 1 - a_{ind}\left(1 + \frac{\xi}{\sqrt{1+\xi^2}}\right)$$

- **Fits four wind characteristics**

➔ Free stream wind speed $\mathbf{V}_\infty$ ($@H_{hub}$)
+ relative wind dir. θ_r
+ shear exponent α_{exp}
+ induction factor a_{ind}

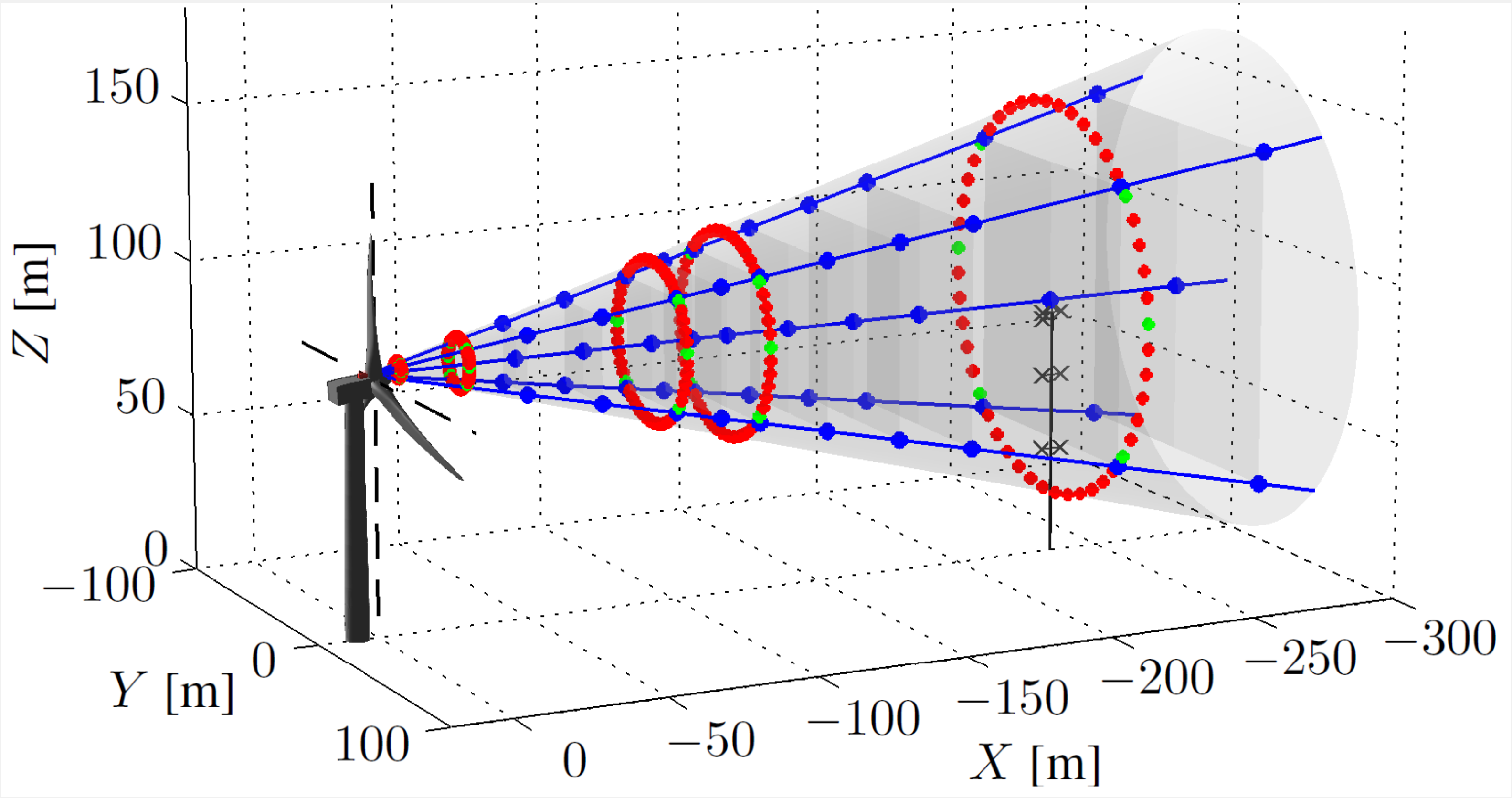


Full-scale campaign: Nørrekær Enge



- in Jutland, Denmark
- owner: Vattenfall
- 13 Siemens turbines of 2.3MW

Nørrekær Enge
nacelle lidars measurement trajectories



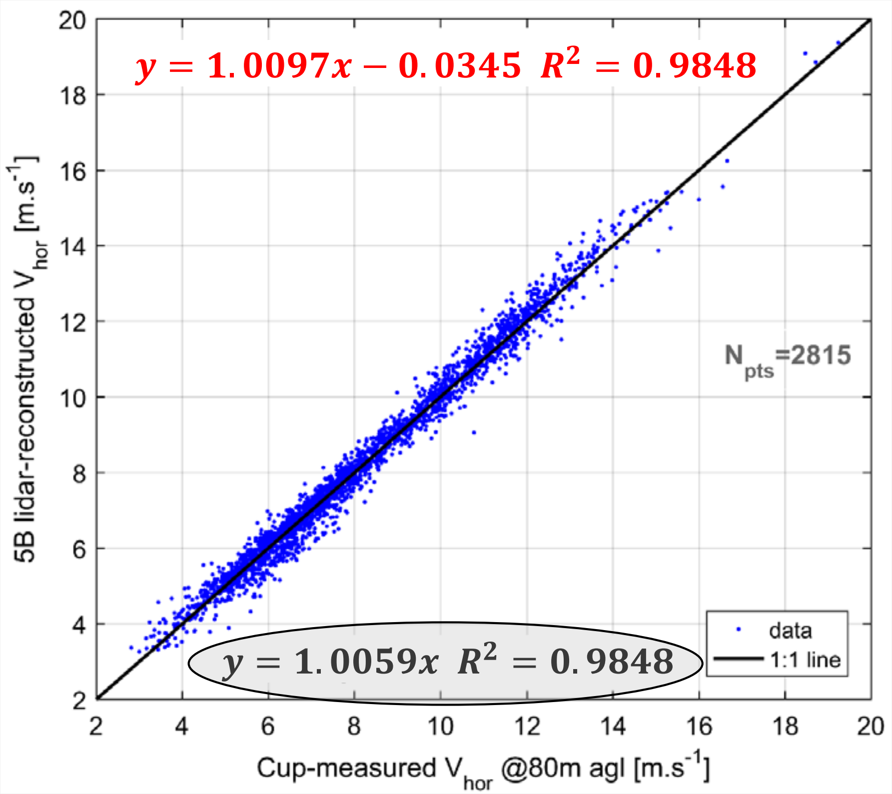
- **Considered lines-of-sight:**
  - 5B-Demo: all 5 LOS
  - ZDM: 6 LOS / azimuth sectors, ie. 3 pairs (in green)

Wind speed results

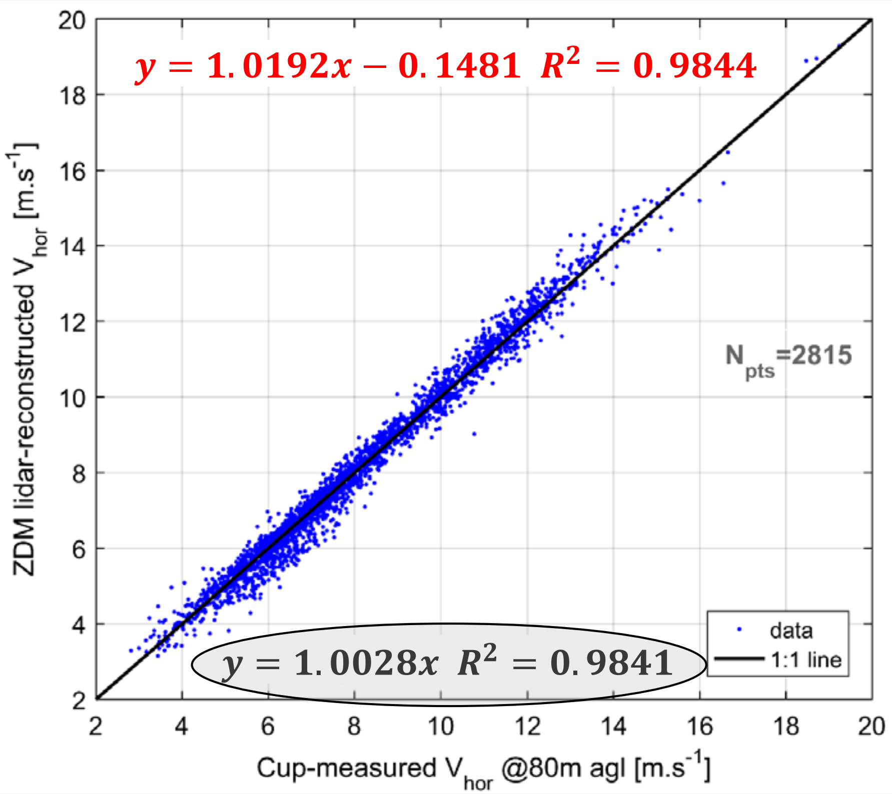
Mast comparison, WFR using the wind model

- ➔ horizontal speed estimated @hub height
- ➔ IEC "free sector": $[110°, 219°]$

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



ZDM
use 6 LOS, @2.5 D_rot

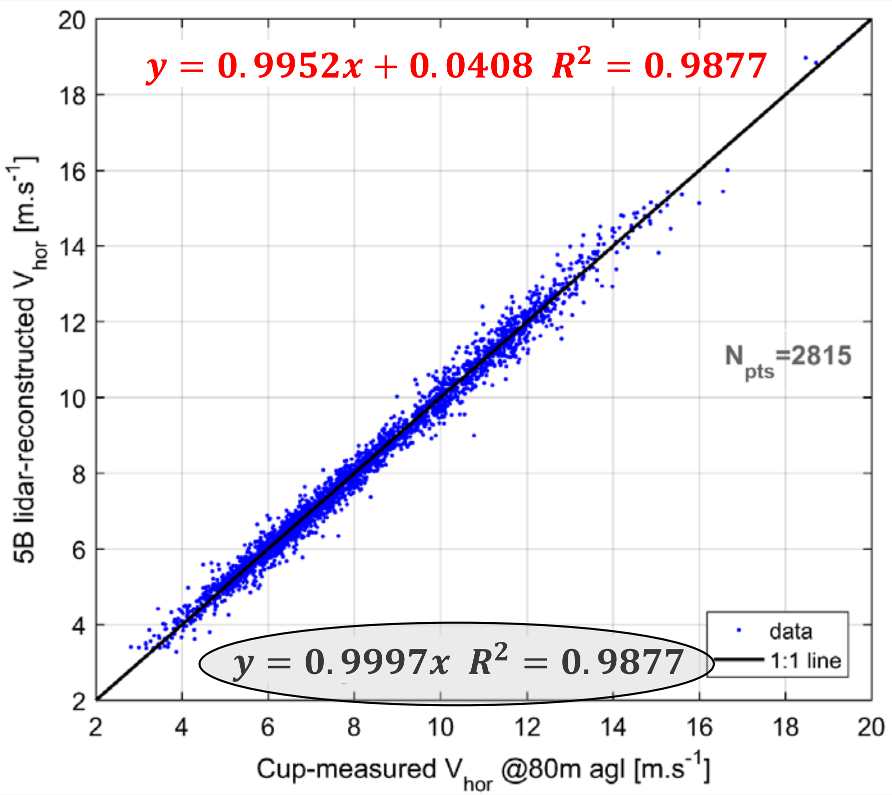


Wind speed results

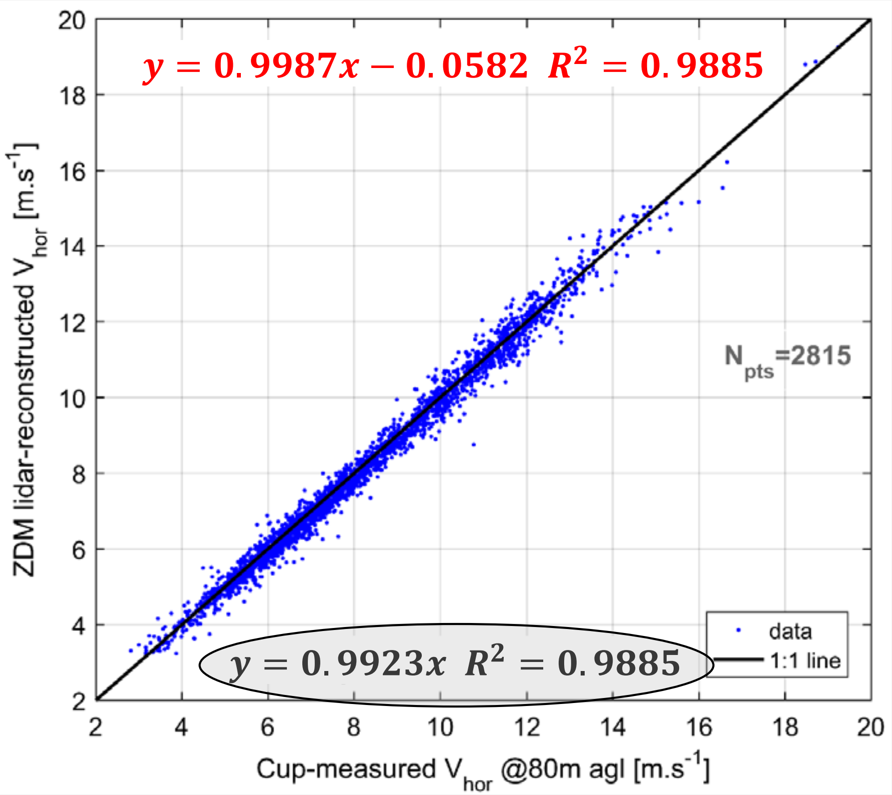
Mast comparison, WFR using the wind-induction model

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

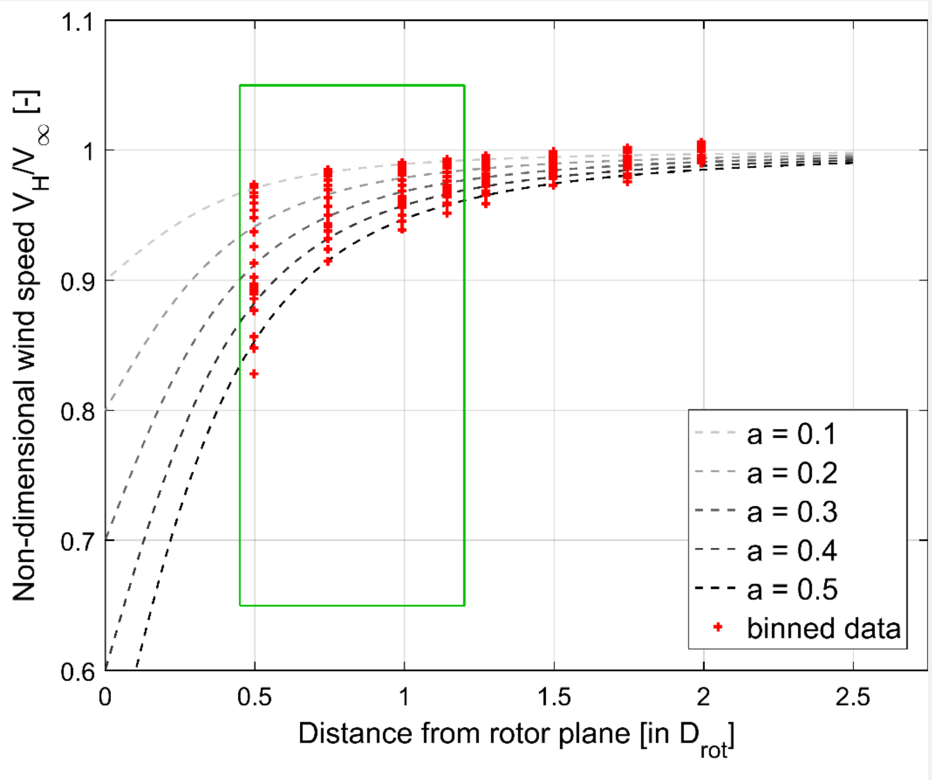
5B-demo: use the 5 LOS
4 dist, from 0.5 to @1.2D_rot

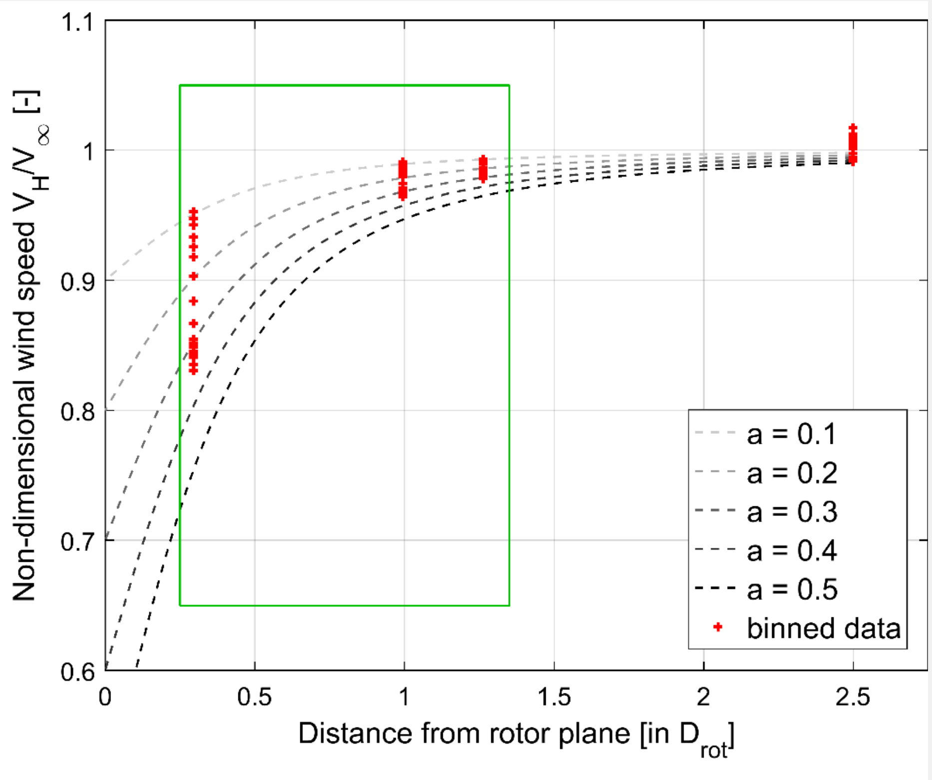


ZDM: use 6 LOS
3 dist., from 0.3 to 1.2D_rot



Wind speed evolution in induction zone

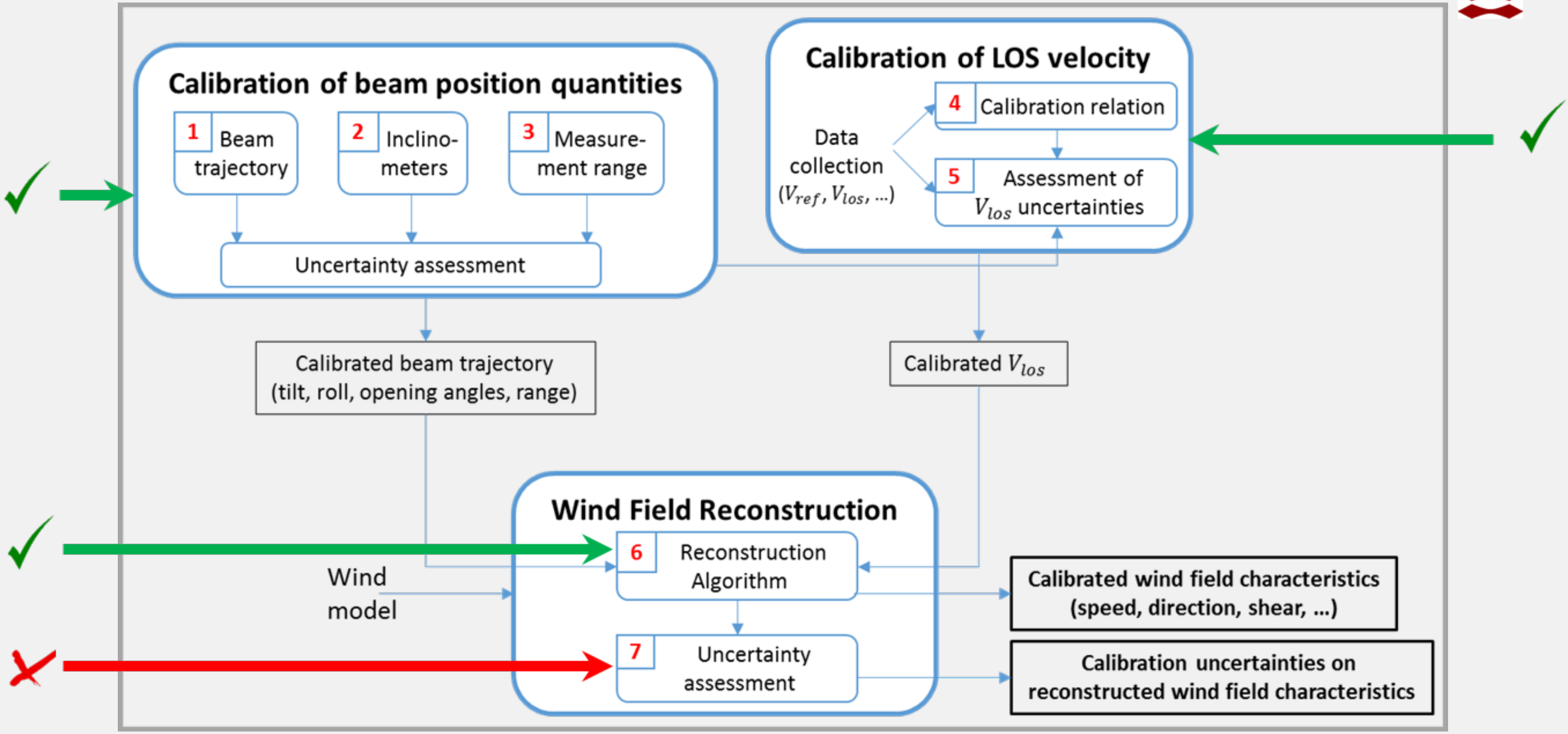




5B-demo **ZDM**

➔ The simple induction model seems adequate! (enough)

The white-box methodology: where are we?

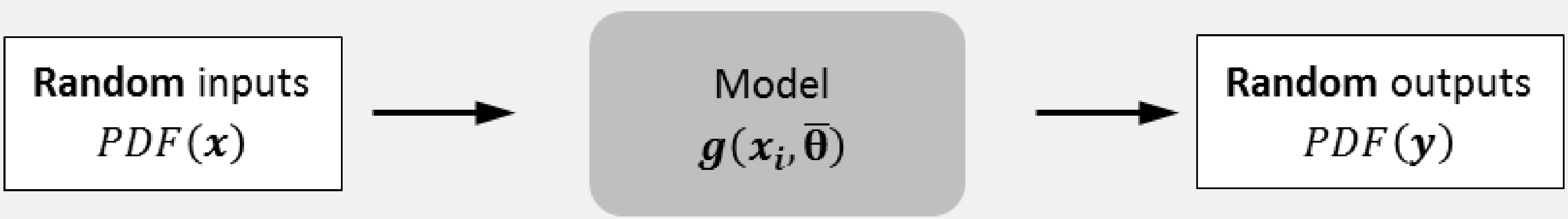


- **Propagation of input uncertainties (V los, inclination, etc)**
  - Not possible with GUM
  - Use numerical methods instead: **Monte Carlo simulations**
- **Get model uncertainties of all (fitted) wind characteristics**

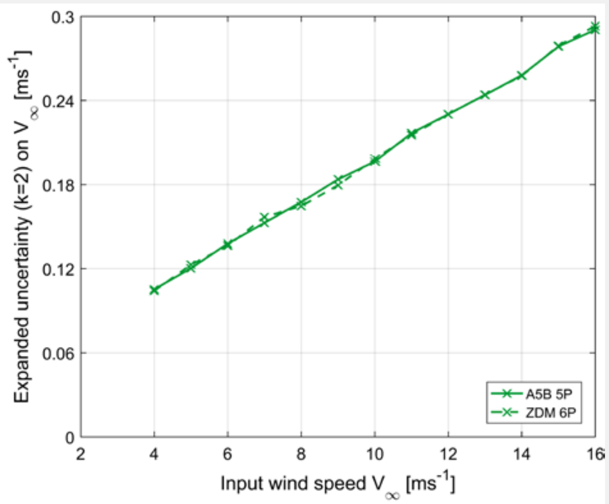
Monte Carlo methods for Uncertainty Quantification

- **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)

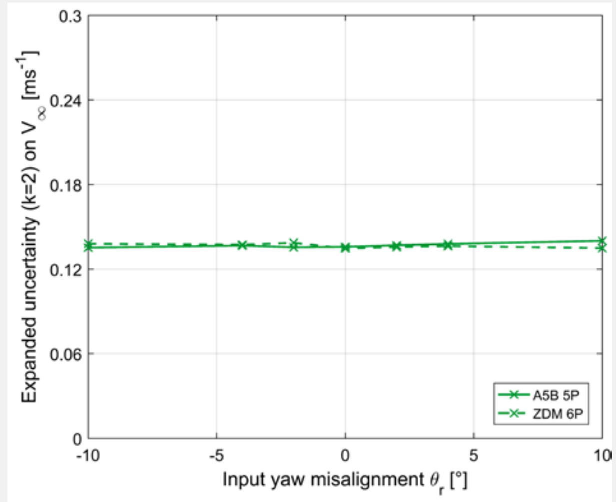
- **Principles:**
  - Propagation of random inputs
  - By evaluation of a model for a large number of samples
  - Outputs characterized through their distribution



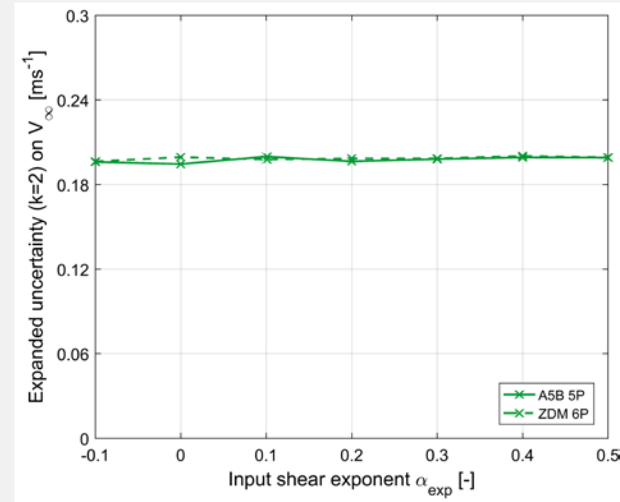
Uncertainties of WFC using Monte Carlo
on free wind speed V_∞



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



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



$V_\infty = 10\ ms^{-1};\ \theta_r = 4°;\ a_{ind} = nor$

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

➔ essentially, the wind speed model uncertainty is the one of the cup anemometer used during the calibration in Høvsøre!

Outline

1 • Introduction

2 • Calibration of wind lidars

3 • Wind field reconstruction

4 • Power performance testing

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:

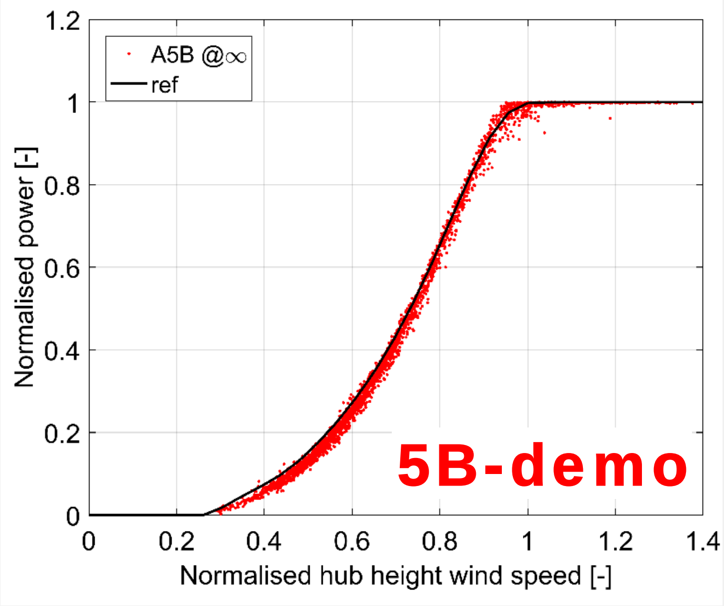
  1) wind model
  2) **combined wind-induction model**

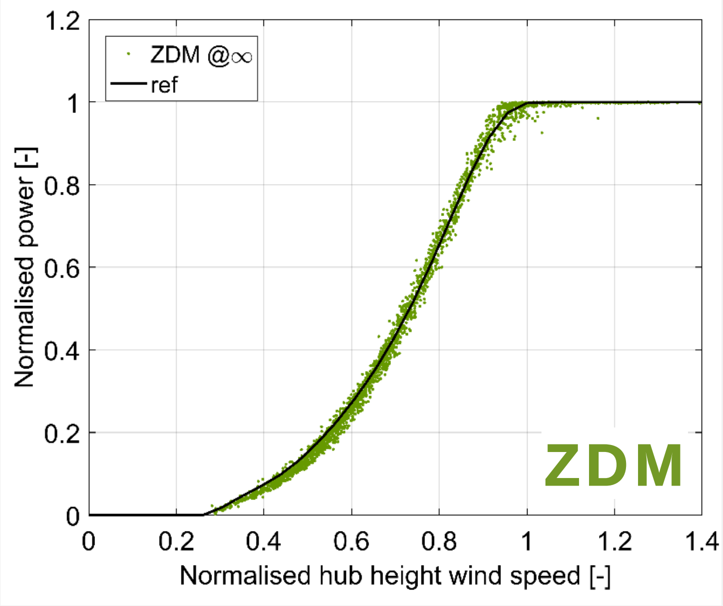
- **Considering hub height wind speed only**
  - No rotor equivalent wind speed

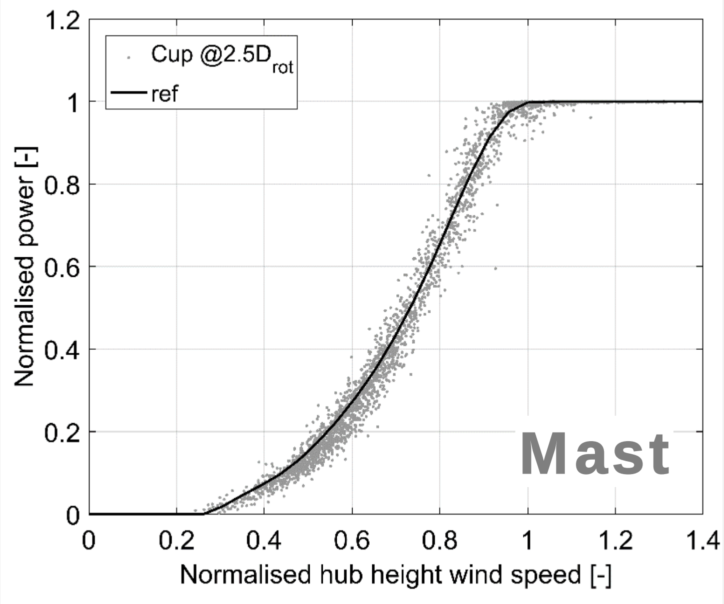
- **Derived results**
  - Measured power curves
  - Power curve uncertainties
  - Annual Energy Production (AEP)

Measured Power curves (scatter)

WFR using wind-induction model

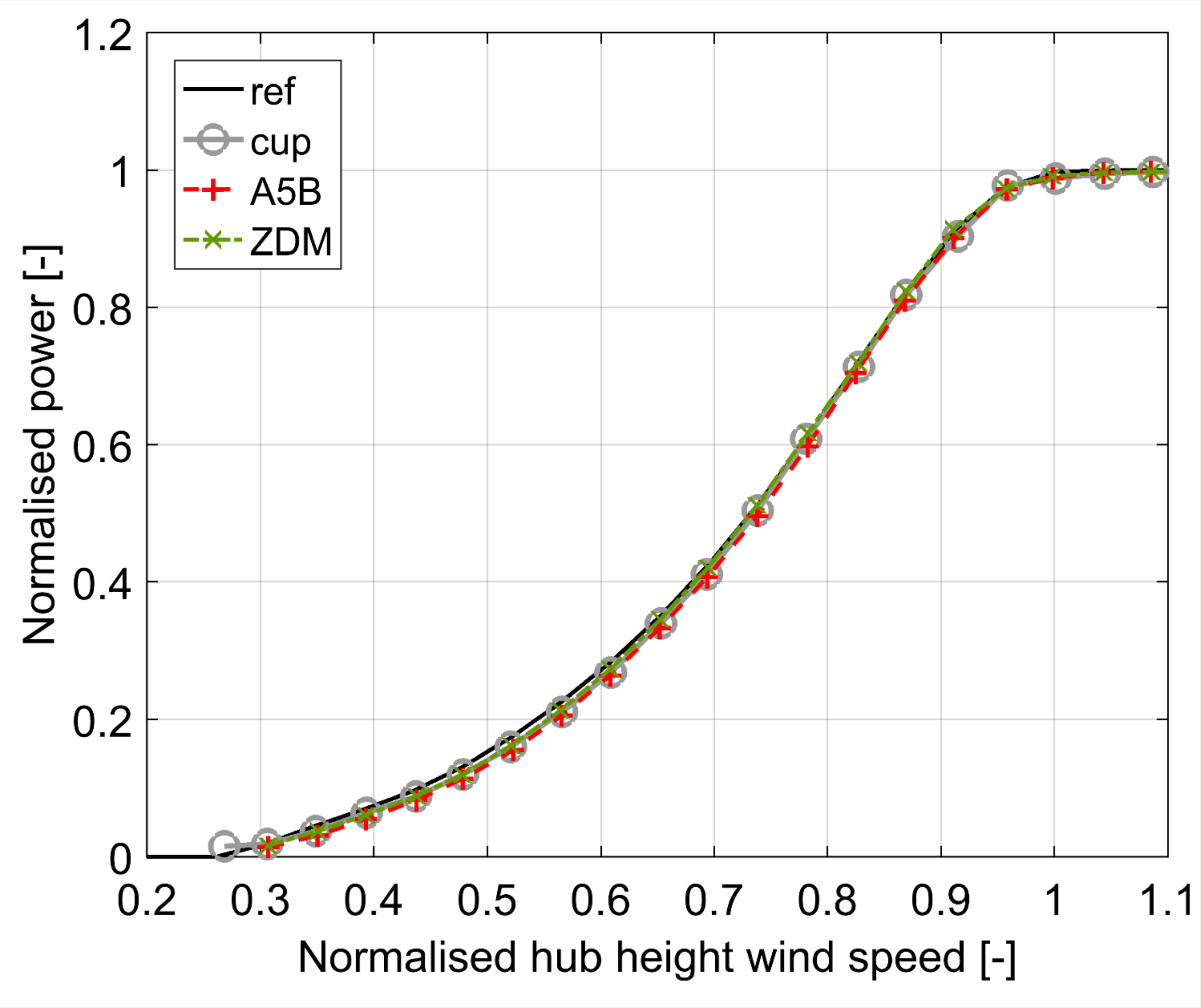






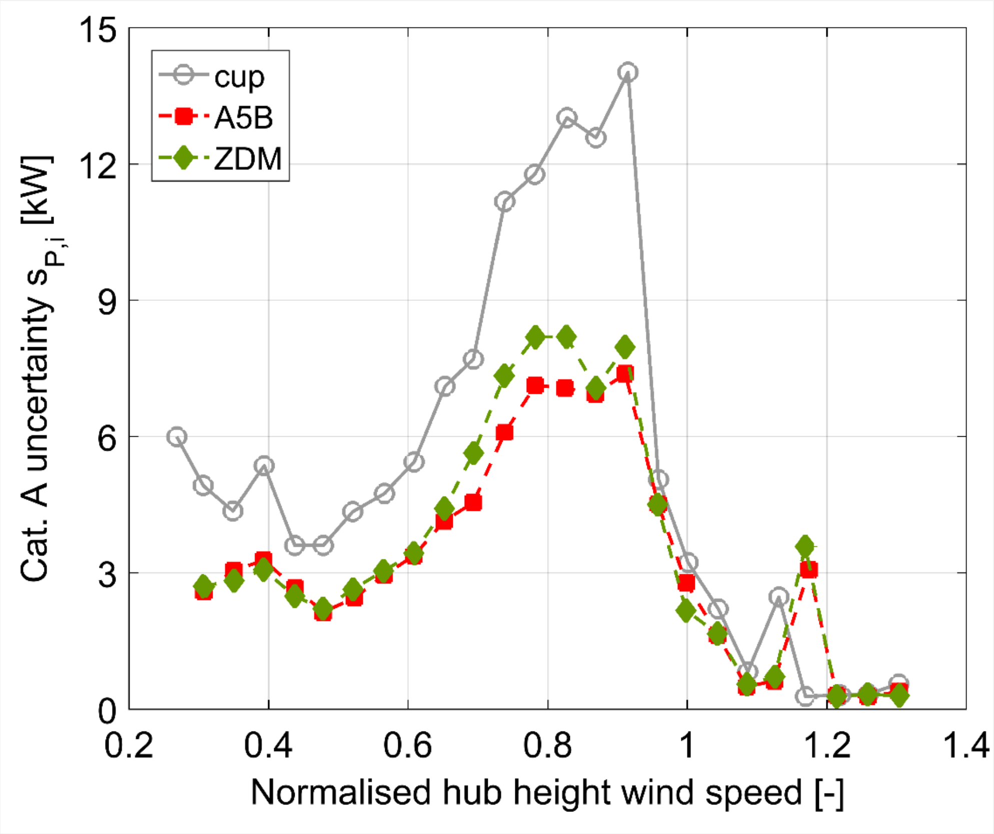
Measured Power curves (binned)

WFR using wind-induction model



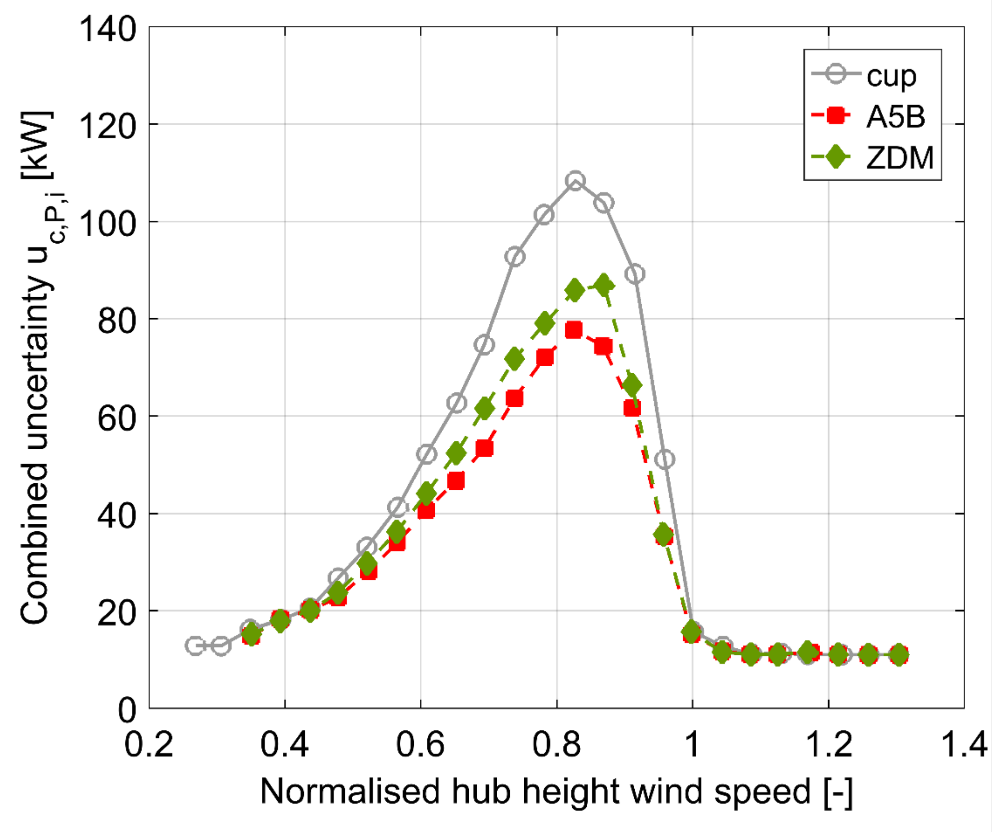
Power curve uncertainties: power, type A
WFR using wind-induction model

- **Clear reduction of scatter in power curve**
  ➔ nacelle lidars yield smaller type A (statistical) power uncertainty



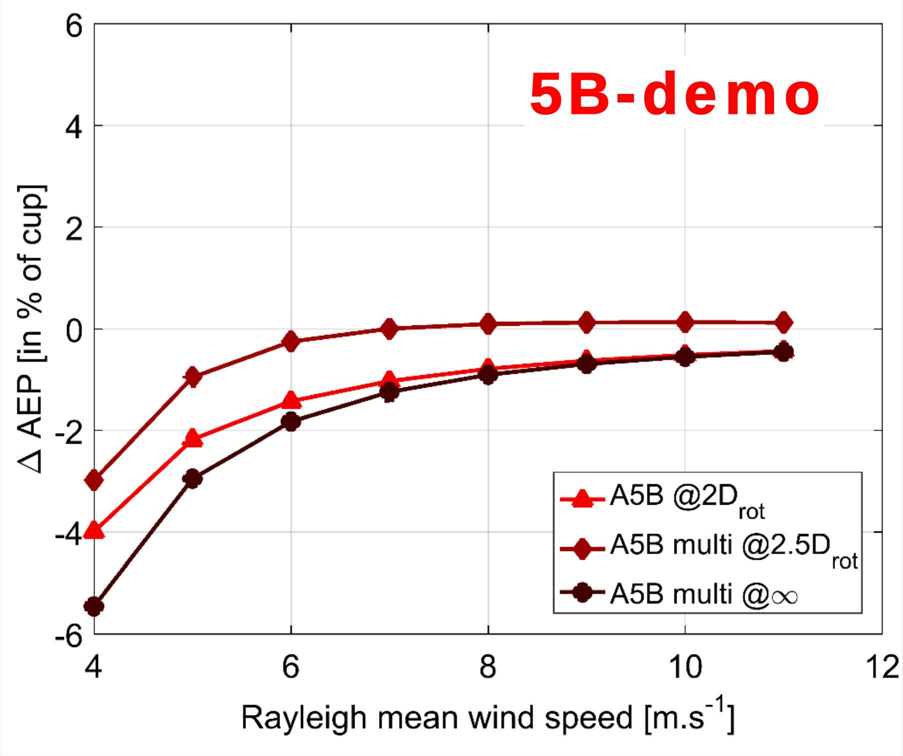
Power curve uncertainties: combined
WFR using wind-induction model

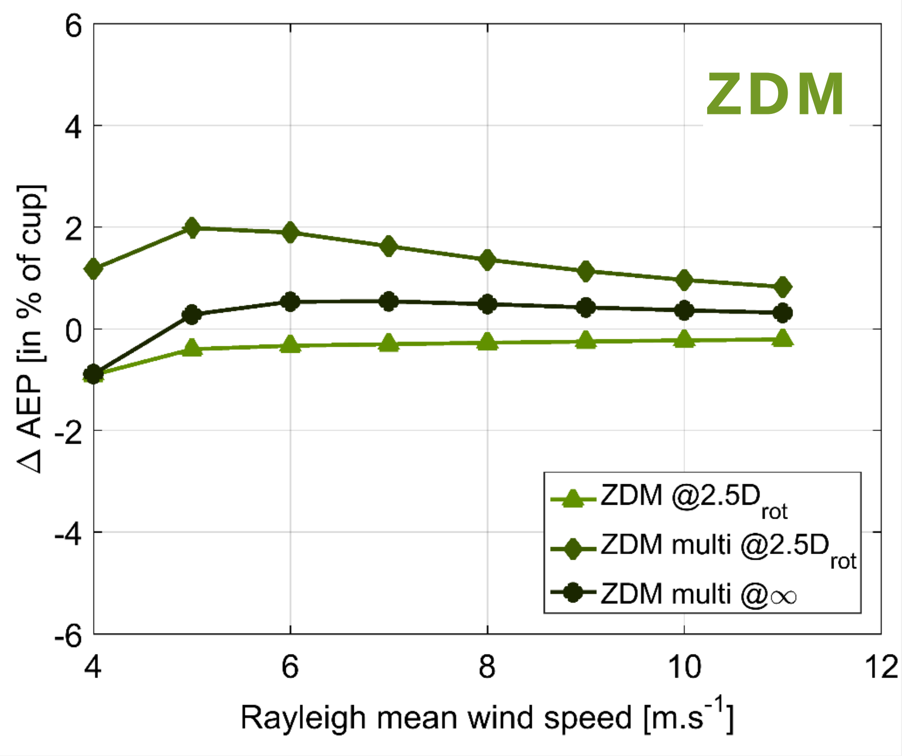
- **Results are mostly dependent on type B wind speed uncertainty**
  ➔ very sensitive to the "terrain uncertainty"
  ➔ lidar uncertainties are smaller only due to this component…



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_∞)





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!


Michael


Antoine


Rozenn


Ameya


Nikolay


David


Niels


Ines


Steen


Guillaume


Alexander


Florian


Nikola


Ioannis


Michael


Matthieu


Anders


Andrea


Per


Kristoffer


Nikolas

And many many others!!

Acknowledgements

My Ph.D. project formed part of the UniTTe project (www.unitte.dk) which is financed by *Innovation Fund Denmark*.

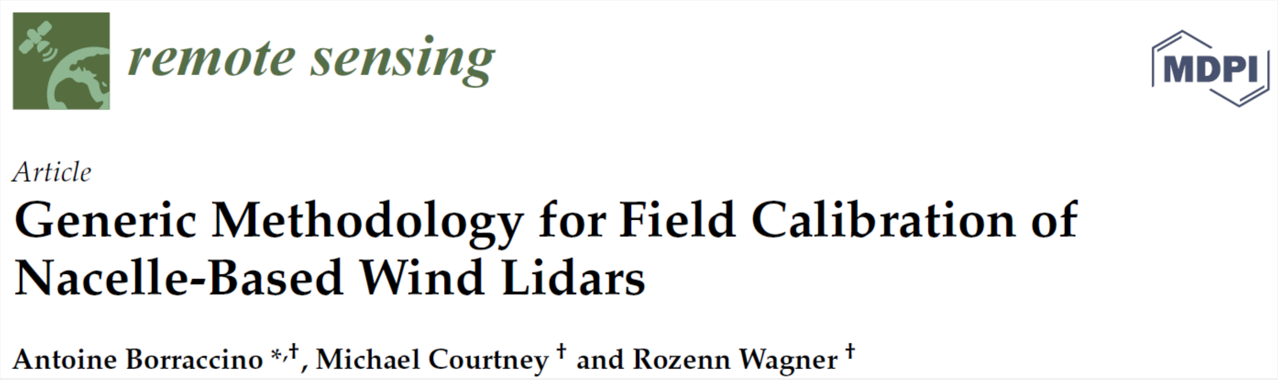
Preparing for questions
-
Calibration of wind lidars

Publications

- **Publications:**

  - <u>DTU E-0086</u> report ➔ generic methodology
  - <u>DTU E-0087</u> report ➔ detailed procedure 5B-demo
  - <u>DTU E-0088</u> report ➔ detailed procedure ZDM

  - <u>Journal paper</u>
    - ➔ *Remote Sensing* of *Wind Energy* (special issue)
    - ➔ methodology, results, discussions, 2-beam example
    - ➔ doi: 10.3390/rs8110907


remote sensing

MDPI

Article

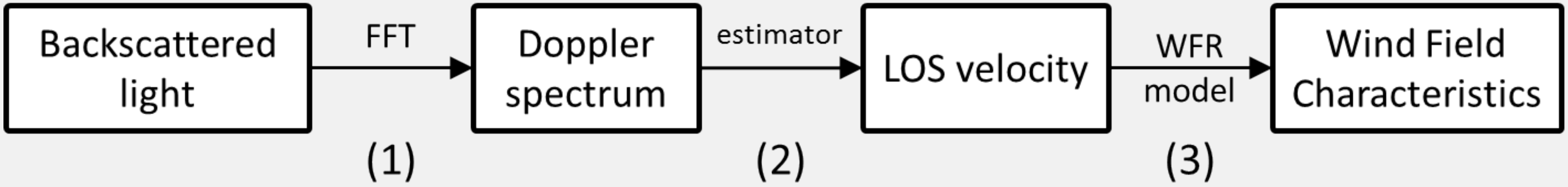
Generic Methodology for Field Calibration of Nacelle-Based Wind Lidars

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

Lidar

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

- **Principles of coherent Doppler wind lidars**



  - sense light backscattered from particles moving with the wind
  - return light is frequency-shifted (Doppler effect)

(1) Processing of raw signal ➔ **Doppler spectrum**

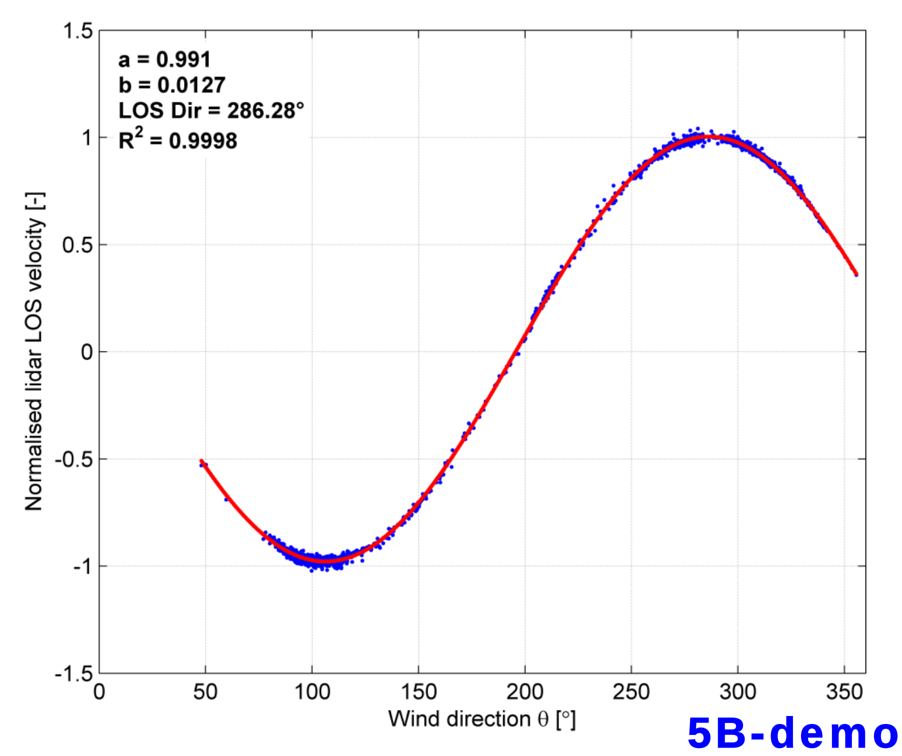
(2) Estimate wind velocity along beam path
➔ **Line-Of-Sight (LOS) velocity** V_{los}

(3) Combine V_{los} measurement in multiple locations
➔ **reconstructed wind field characteristics (WFC): speed, direction, shear, etc**

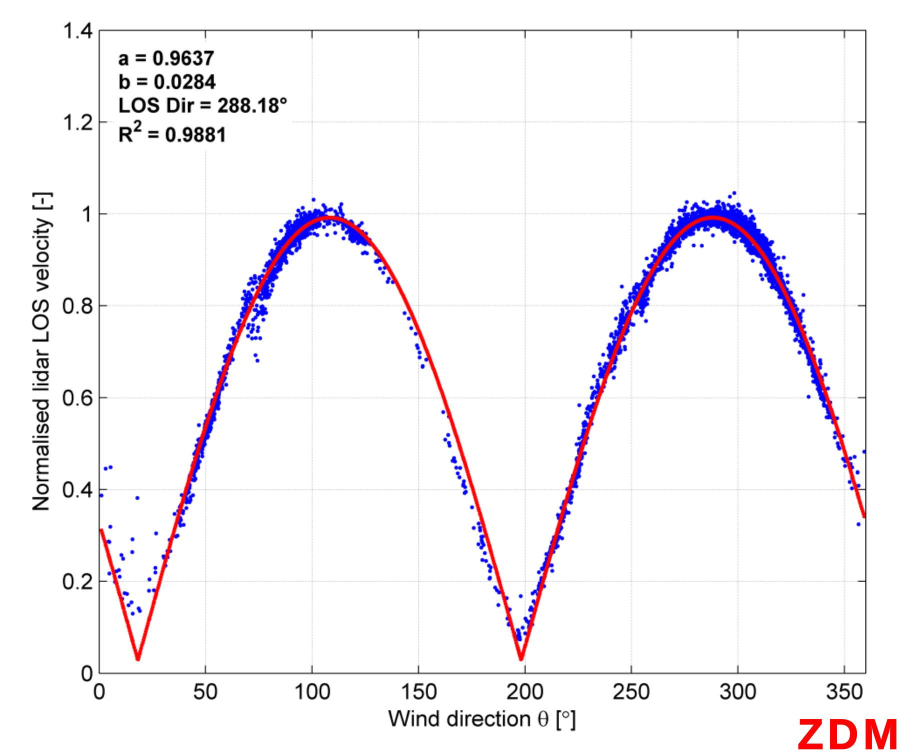
2) Calibration of LOS velocity

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



LOS 0

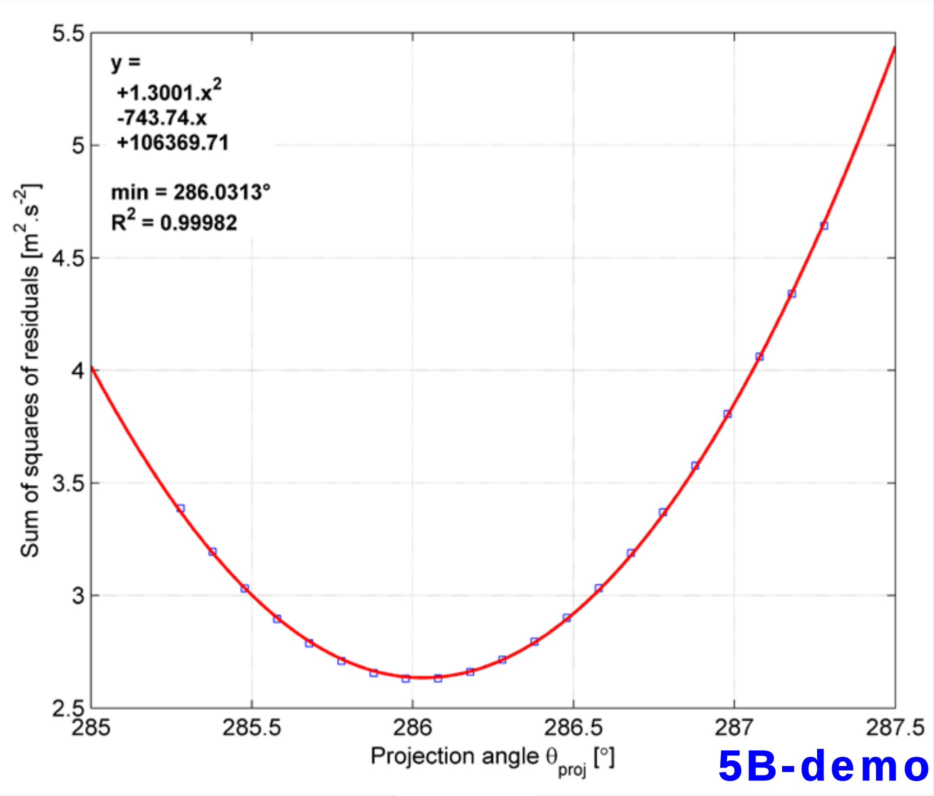


Bottom LOS

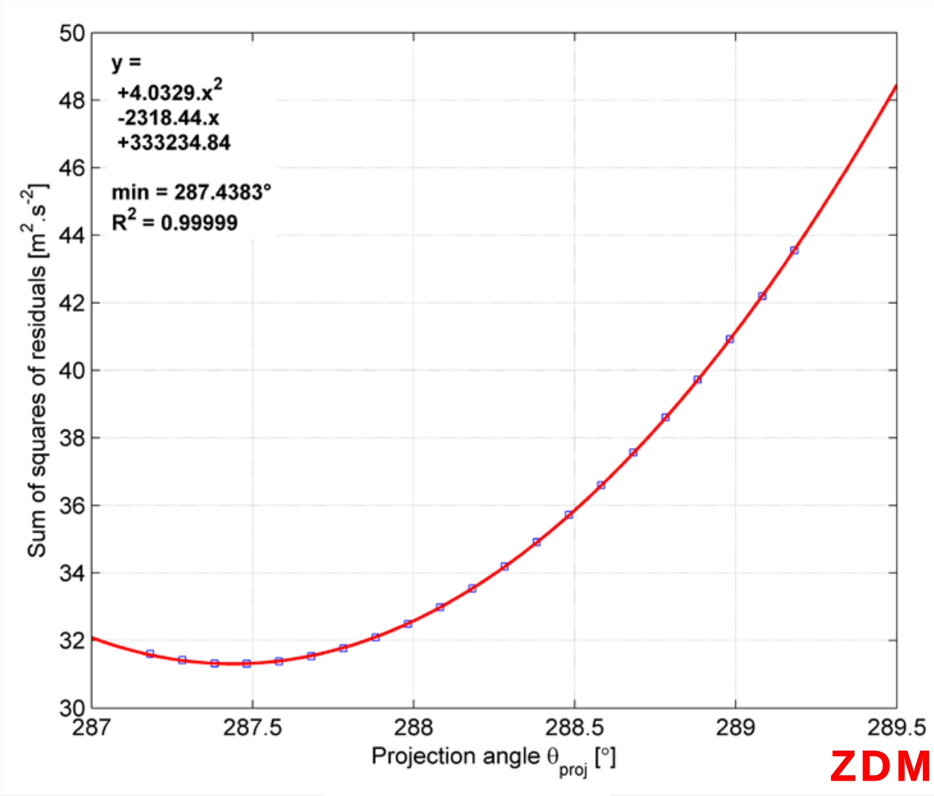
2) Calibration of LOS velocity

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 ~$0.5 - 0.9\%$
  - 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: $y_m = f(x_1, x_2, \dots, x_n)$
  2) Law of propagation of uncertainties:

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

  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)

Preparing for questions

-

Wind Field Reconstruction

Publications

- **Publications:**

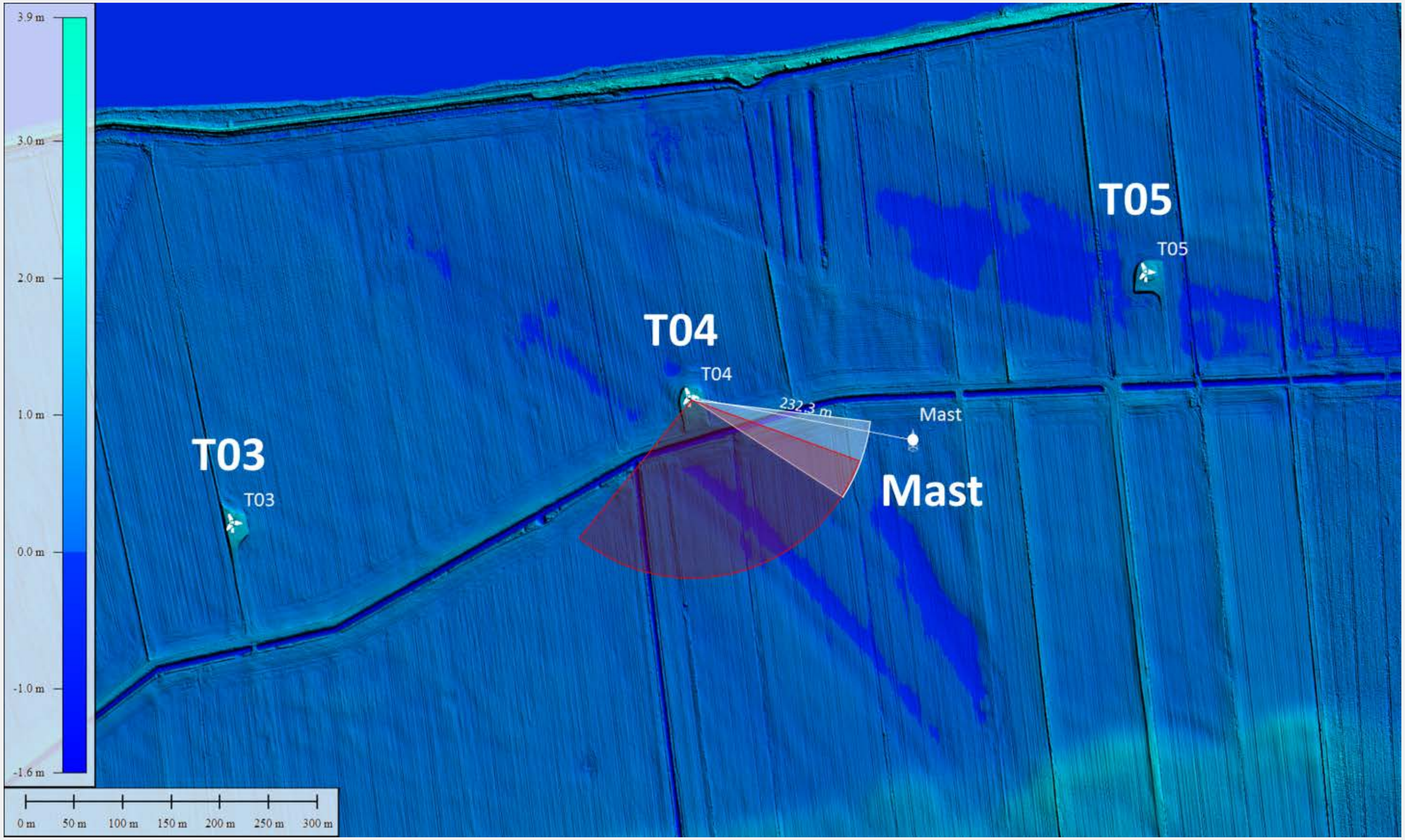
Research articles

Wind Field Reconstruction from Nacelle-Mounted Lidars Short Range Measurements

Antoine Borraccino[1], David Schlipf[2], Florian Haizmann[2], and Rozenn Wagner[1]
[1]DTU Wind Energy, Roskilde, Denmark
[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

Data filtering		Reconstruction case		Forced linear regressions results			
Case	Direction sector	Dataset	Lidar	Input measurement ranges	gain	R^2	Number of periods
1	$[93°, 123°]$	Joint	5B-Demo, 5 LOS	2.0 D_{rot}	1.0146	0.9936	885
			ZDM, 6 LOS	2.5 D_{rot}	1.0090	0.9938	
			5B-Demo, 5 LOS	from 0.5 to 1.15 D_{rot}	1.0063	0.9944	
			ZDM, 6 LOS	from 0.3 to 1.25 D_{rot}	0.9961	0.9947	

- 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

Data filtering		Reconstruction case	Forced linear regressions results				
Case	Direction sector	Dataset	Lidar	Input measurement ranges	gain	R^2	Number of periods
1	[93°, 123°]	Joint	5B-Demo, 5 LOS	2.0 D_{rot}	1.0146	0.9936	885
			ZDM, 6 LOS	2.5 D_{rot}	1.0090	0.9938	
			5B-Demo, 5 LOS	from 0.5 to 1.15 D_{rot}	1.0063	0.9944	
			ZDM, 6 LOS	from 0.3 to 1.25 D_{rot}	0.9961	0.9947	
2	[93°, 123°]	disjoint	5B-Demo, 5 LOS	2.0 D_{rot}	1.0133	0.9953	1476
			ZDM, 6 LOS	2.5 D_{rot}	1.0080	0.9942	2143
			5B-Demo, 5 LOS	from 0.5 to 1.15 D_{rot}	1.0057	0.9961	1123
			ZDM, 6 LOS	from 0.3 to 1.25 D_{rot}	0.9965	0.9962	2659

- Disjoint datasets: similar observations
- Increased number of valid data points (2-3x more)
- R^2 enhanced slightly

Wind speed results: summary table

Data filtering			Reconstruction case		Forced linear regressions results		
Case	Direction sector	Dataset	Lidar	Input measurement ranges	gain	R^2	Number of periods
1	[93°, 123°]	Joint	5B-Demo, 5 LOS	2.0 D_{rot}	1.0146	0.9936	885
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			ZDM, 6 LOS	from 0.3 to 1.25 D_{rot}	0.9965	0.9962	2659
3	[110°, 219°] (IEC free sector)	Joint	5B-Demo, 5 LOS	2.0 D_{rot}	1.0059	0.9848	2815
			ZDM, 6 LOS	2.5 D_{rot}	1.0028	0.9841	
			5B-Demo, 5 LOS	from 0.5 to 1.15 D_{rot}	0.9997	0.9877	
			ZDM, 6 LOS	from 0.3 to 1.25 D_{rot}	0.9923	0.9885	

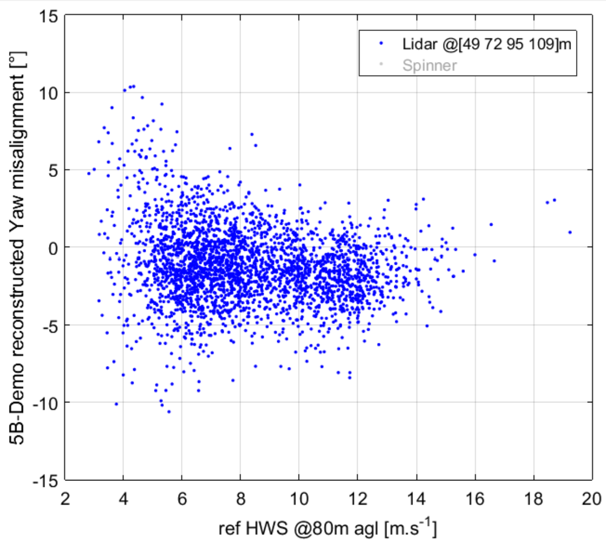
- Better agreement between lidar and mast
- Much larger scatter (“signal decorrelation”)
- Still 5B-Demo above ZDM (about 0.5%)

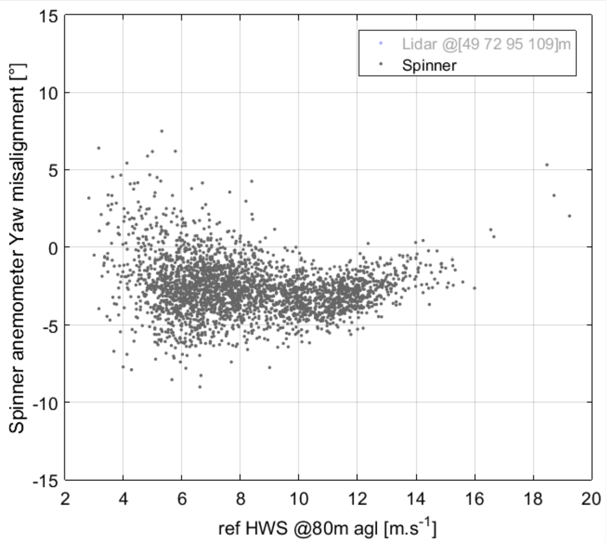
Wind speed results: summary table

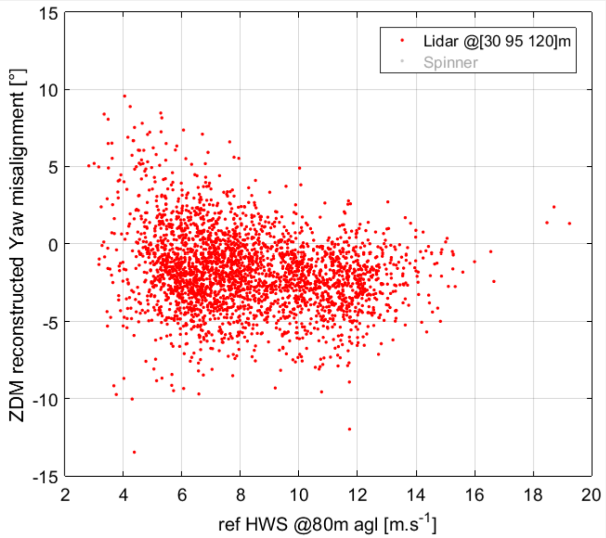
Data filtering			Reconstruction case	Forced linear regressions results			
Case	Direction sector	Dataset	Lidar	Input measurement ranges	gain	R^2	Number of periods
1	$[93°, 123°]$	Joint	5B-Demo, 5 LOS	2.0 D_{rot}	1.0146	0.9936	885
			ZDM, 6 LOS	2.5 D_{rot}	1.0090	0.9938	
			5B-Demo, 5 LOS	from 0.5 to 1.15 D_{rot}	1.0063	0.9944	
			ZDM, 6 LOS	from 0.3 to 1.25 D_{rot}	0.9961	0.9947	
2	$[93°, 123°]$	disjoint	5B-Demo, 5 LOS	2.0 D_{rot}	1.0133	0.9953	1476
			ZDM, 6 LOS	2.5 D_{rot}	1.0080	0.9942	2143
			5B-Demo, 5 LOS	from 0.5 to 1.15 D_{rot}	1.0057	0.9961	1123
			ZDM, 6 LOS	from 0.3 to 1.25 D_{rot}	0.9965	0.9962	2659
3	$[110°, 219°]$ (IEC free sector)	Joint	5B-Demo, 5 LOS	2.0 D_{rot}	1.0059	0.9848	2815
			ZDM, 6 LOS	2.5 D_{rot}	1.0028	0.9841	
			5B-Demo, 5 LOS	from 0.5 to 1.15 D_{rot}	0.9997	0.9877	
			ZDM, 6 LOS	from 0.3 to 1.25 D_{rot}	0.9923	0.9885	
4	$[110°, 219°]$ (IEC free sector)	disjoint	5B-Demo, 5 LOS	2.0 D_{rot}	1.0041	0.9840	4588
			ZDM, 6 LOS	2.5 D_{rot}	1.0038	0.9860	5615
			5B-Demo, 5 LOS	from 0.5 to 1.15 D_{rot}	0.9988	0.9888	4099
			ZDM, 6 LOS	from 0.3 to 1.25 D_{rot}	0.9935	0.9897	6199

Yaw misalignment results:
WFR using the wind-induction model

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







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

Spinner anemometer

ZDM: 3 dist. From 0.3 to 1.2D_rot

➔ Higher scatter with lidars than spinner

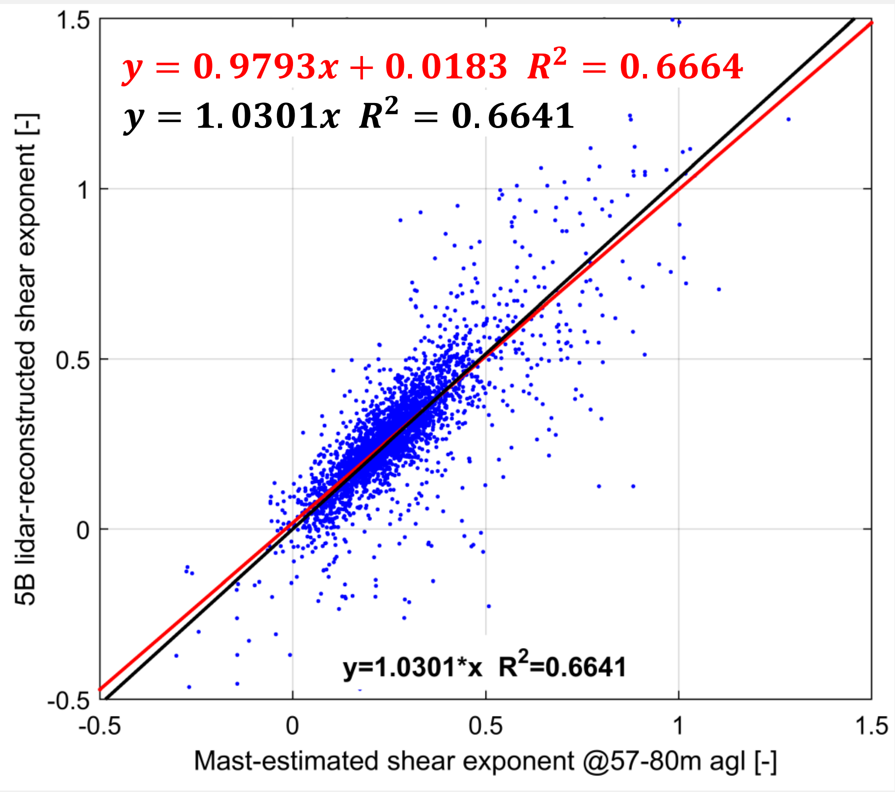
➔ “mean” yaw misalignment: $\approx -3°$

➔ The two nacelle lidars seem to provide similar results

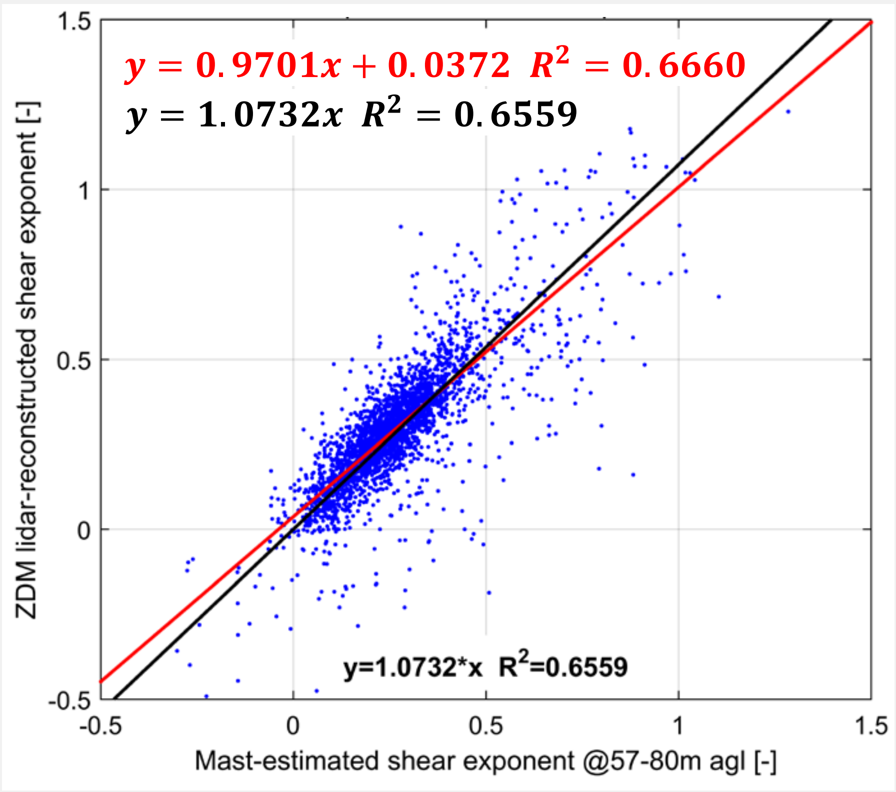
Shear exponent results:

WFR using the wind-induction model

- Wind sector : [110°, 219°] (joint datasets)
- "Ref." shear exponent: from mast, using cups at 80 and 57m agl



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

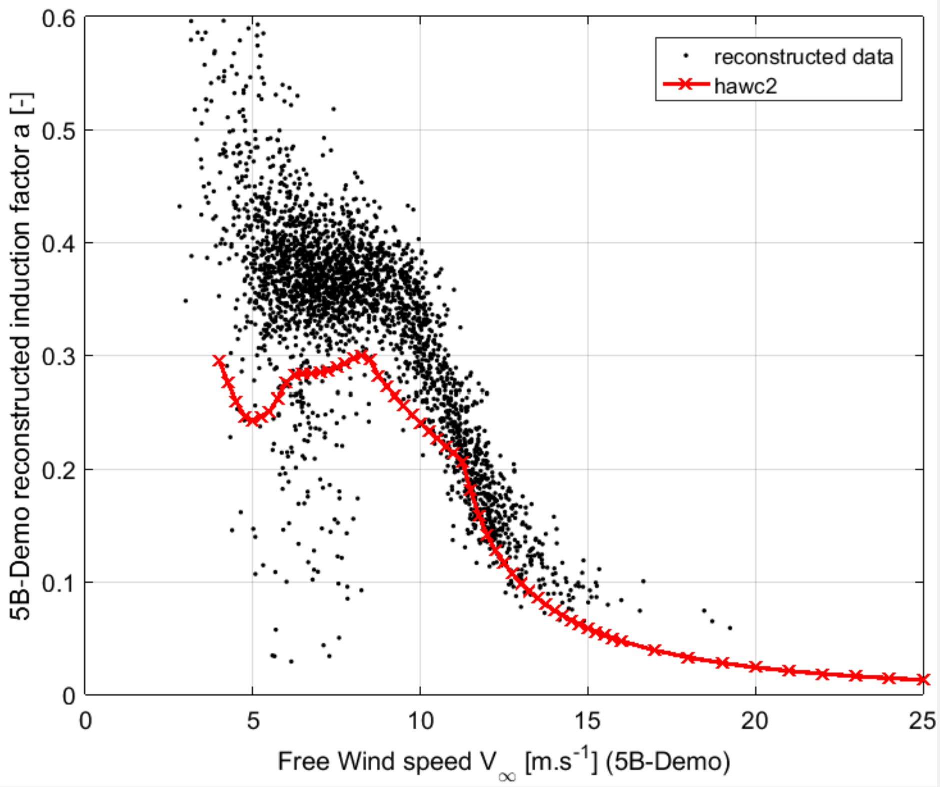


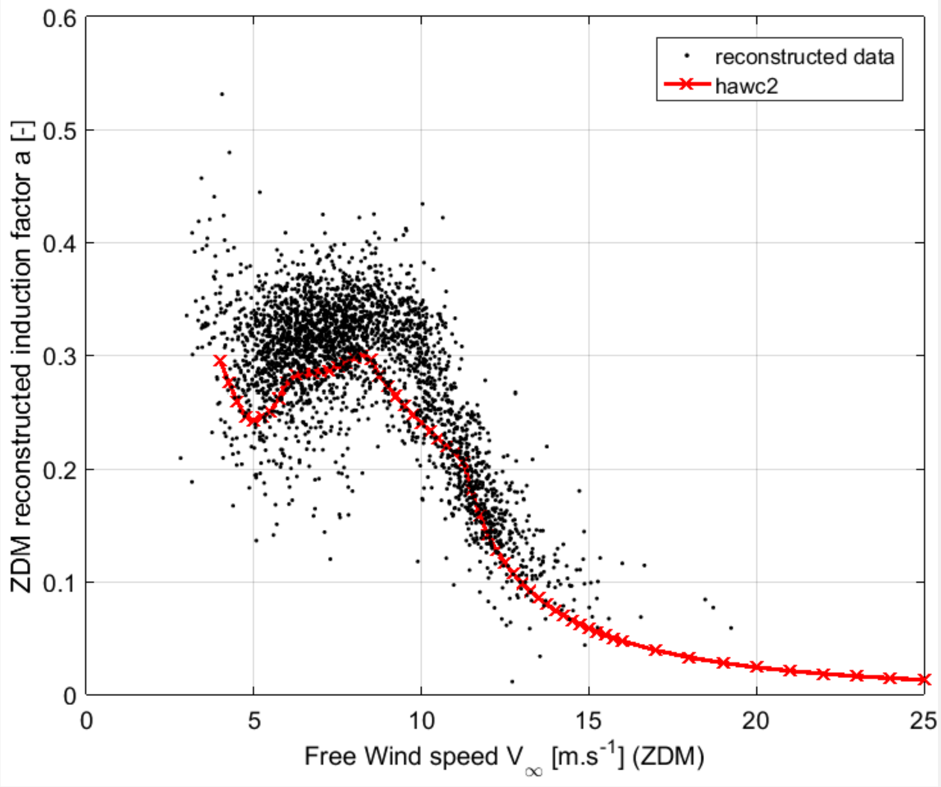
ZDM: 3 dist.
From 0.3 to 1.2D_rot

➔ Slight overestimation vs. mast ➔ Similar results between the two lidars

Induction factor results:
WFR using the wind-induction model

- Wind sector : $[110°, 219°]$ (joint datasets)
- "Ref." induction factor: C_T from "HAWC2" simu, $a = 0.5 \cdot \left(1 - \sqrt{1 - C_T}\right)$

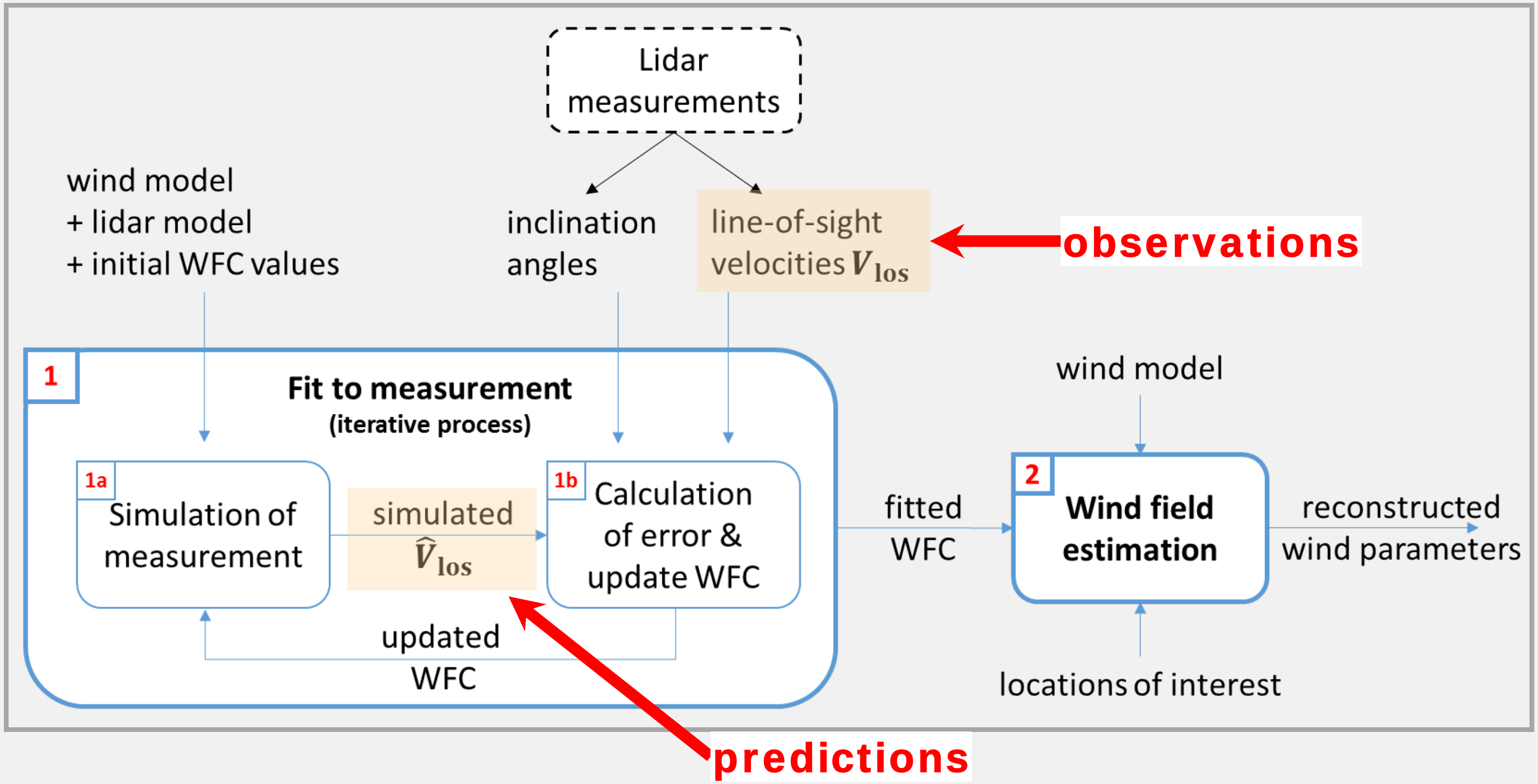




5B-demo: 4 dist, from 0.5 to @1.2D_rot

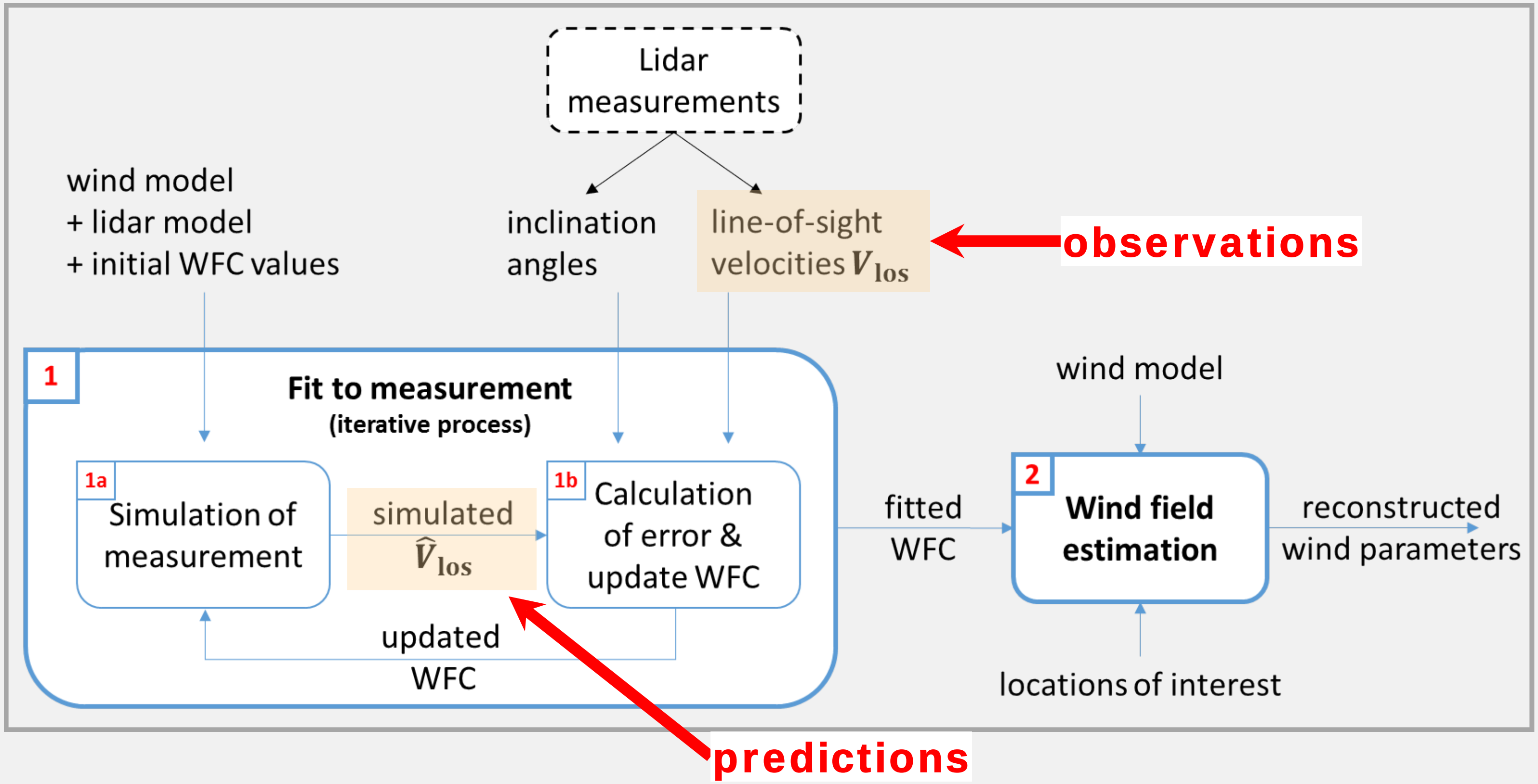
ZDM: 3 dist. From 0.3 to 1.2D_rot

LOS velocity fitting residuals



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

LOS velocity fitting residuals

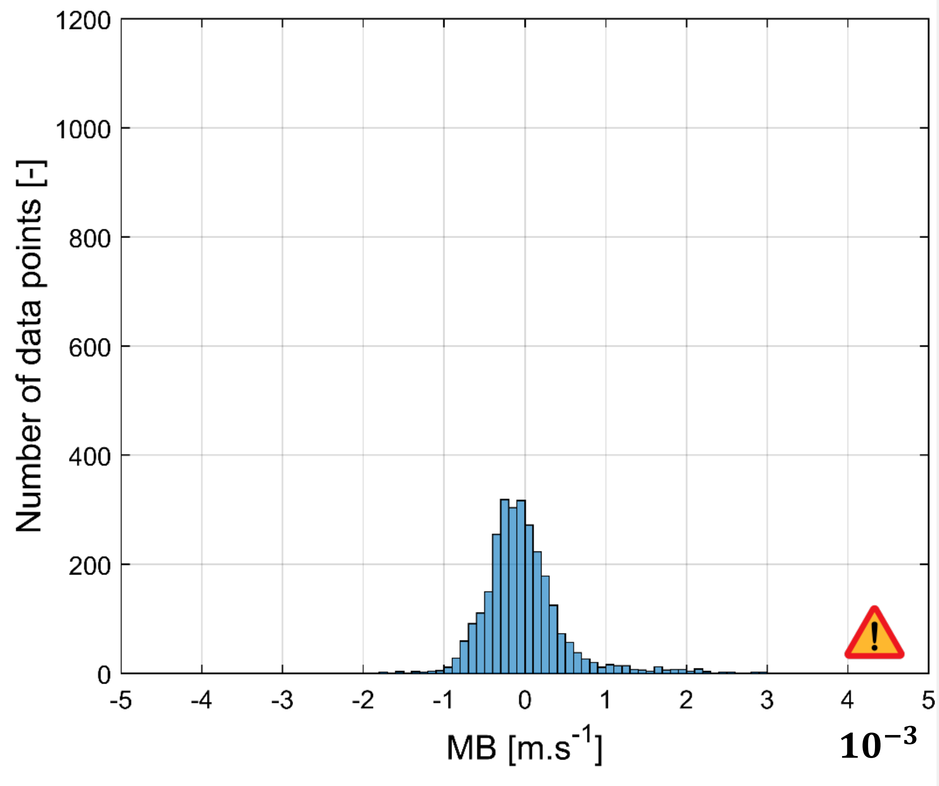


- **Computed stats:**
  - M: mean, N: normalised; F: fractional;
  - S: squared; R: root; SS: sum of squares
  - **MB**, ME, NMB, NME, MFB, MFE, SSE, MSE, **RMSE**, NMSE

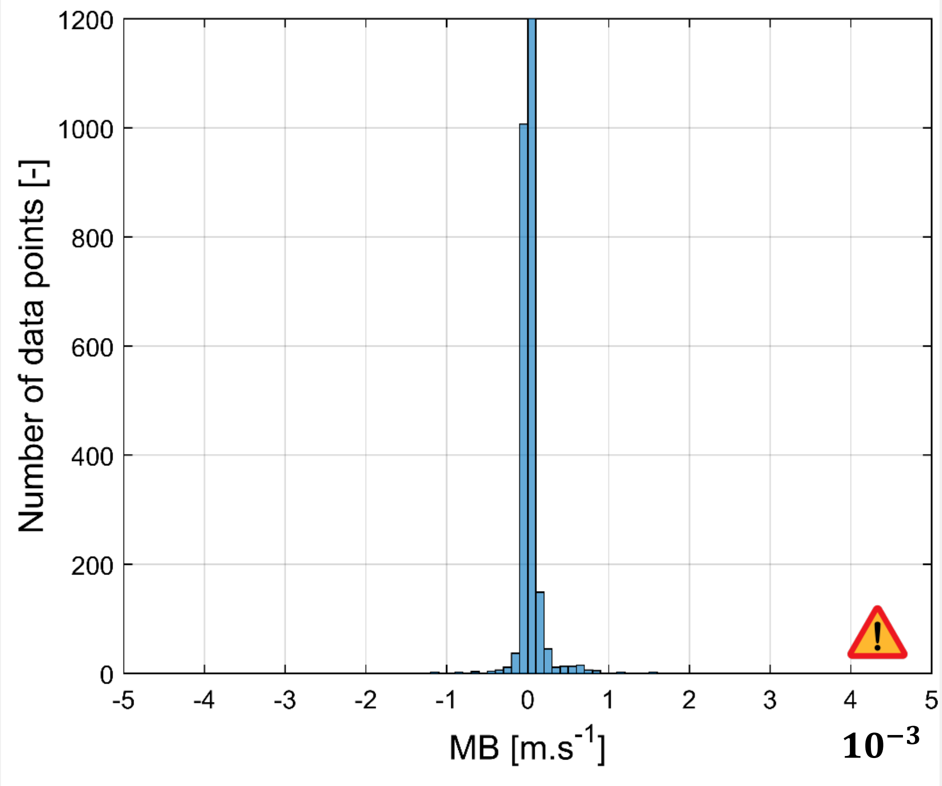
V_los fitting residuals: mean bias

WFR using the wind-induction model

- Wind sector : $[110°, 219°]$ (joint datasets)



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



ZDM
3 dist. from 0.3 to 1.2D_rot

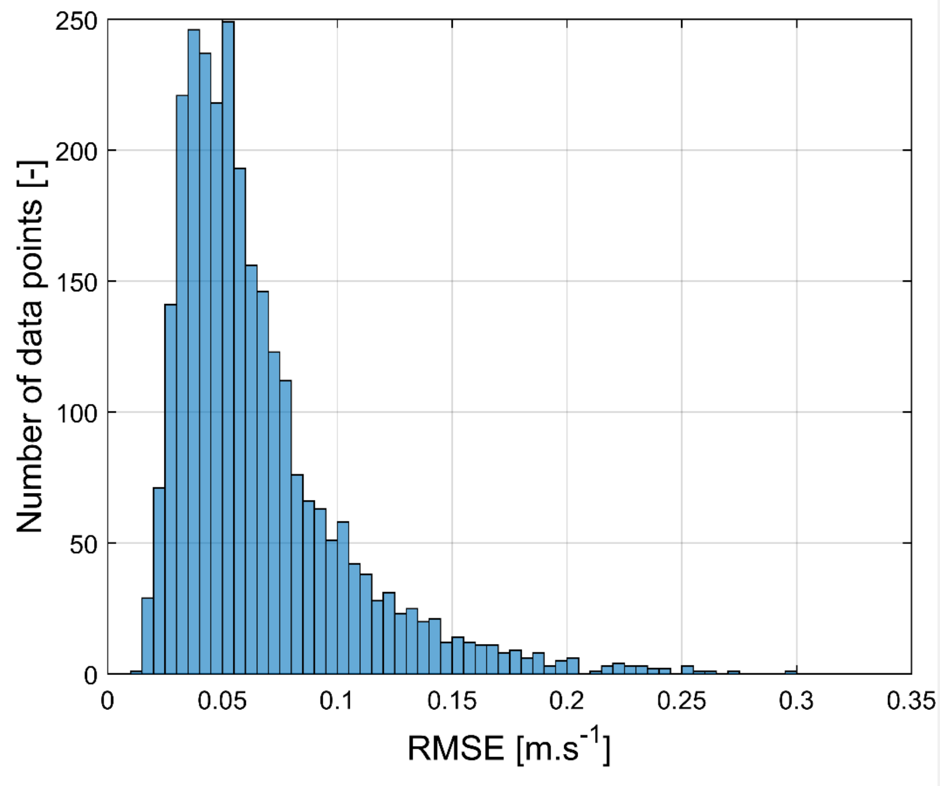
➔ MB show very low values;

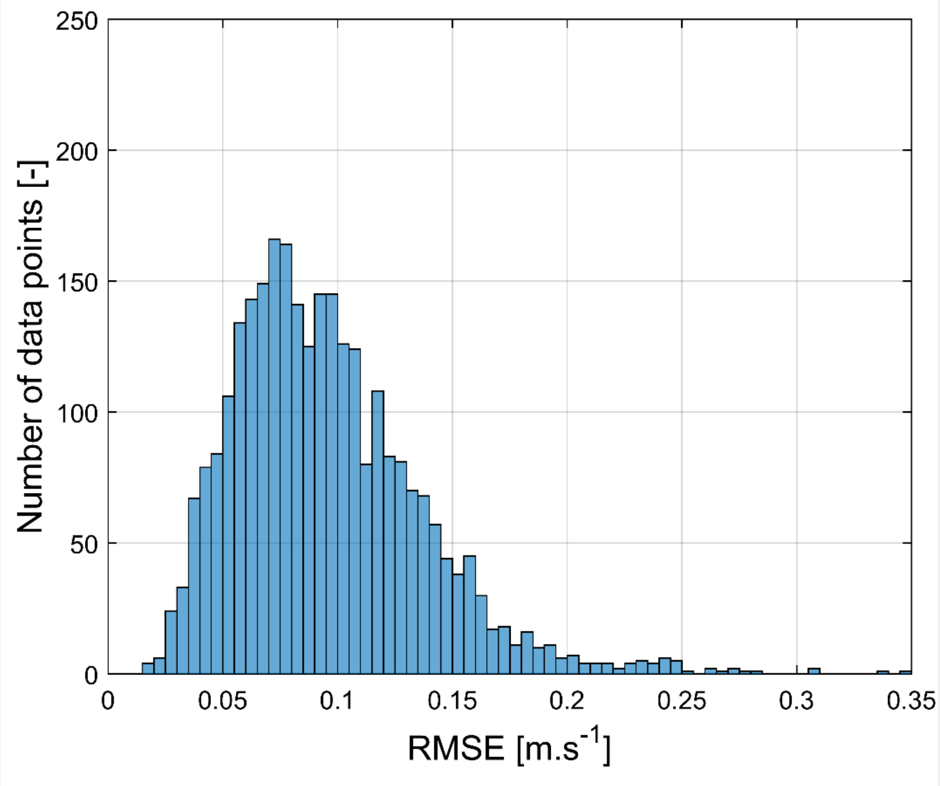
➔ Histogram centered on zero: the used model is “unbiased”

V_los fitting residuals: mean bias

WFR using the wind-induction model

- Wind sector : $[110°, 219°]$ (joint datasets)





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

ZDM
3 dist. from 0.3 to 1.2D_rot

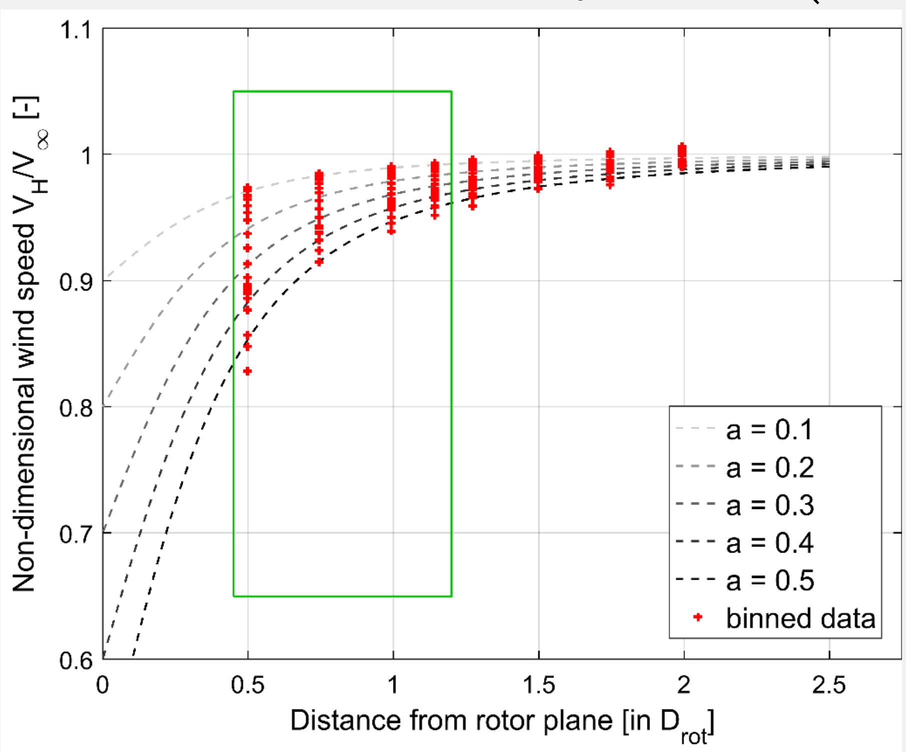
➔ RMSE values between 0 and 0.25 m/s

➔ Similar distributions for both lidars, with a slightly larger mean for ZDM

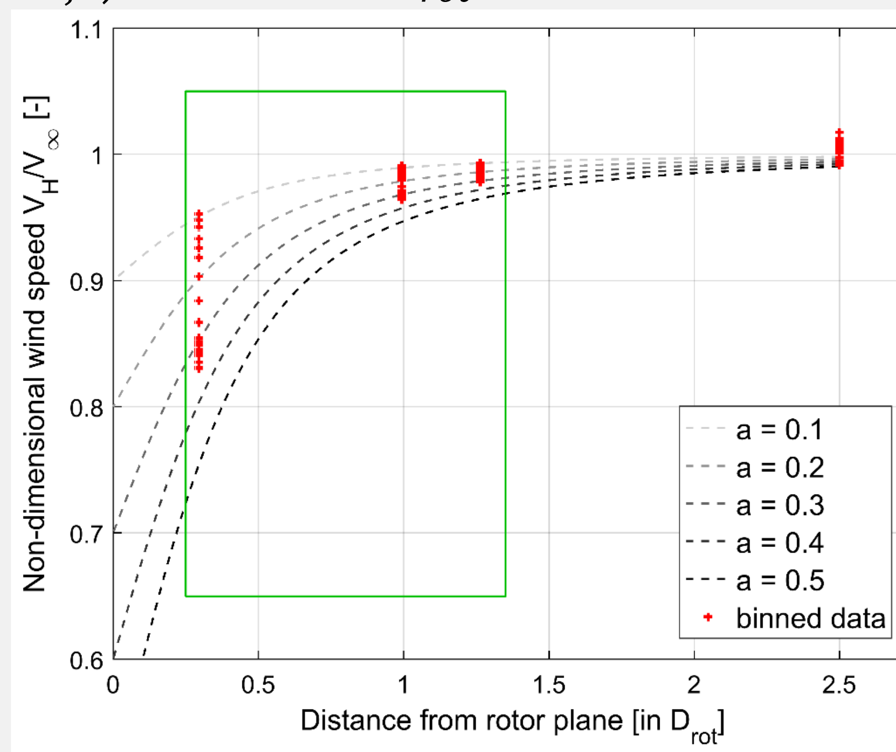
A simple induction model

- **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_∞

$$\frac{U}{U_\infty} = 1 - a\left(1 + \frac{\xi}{\sqrt{1+\xi^2}}\right), \text{ with } \xi = \frac{x_W}{R_{rot}}$$



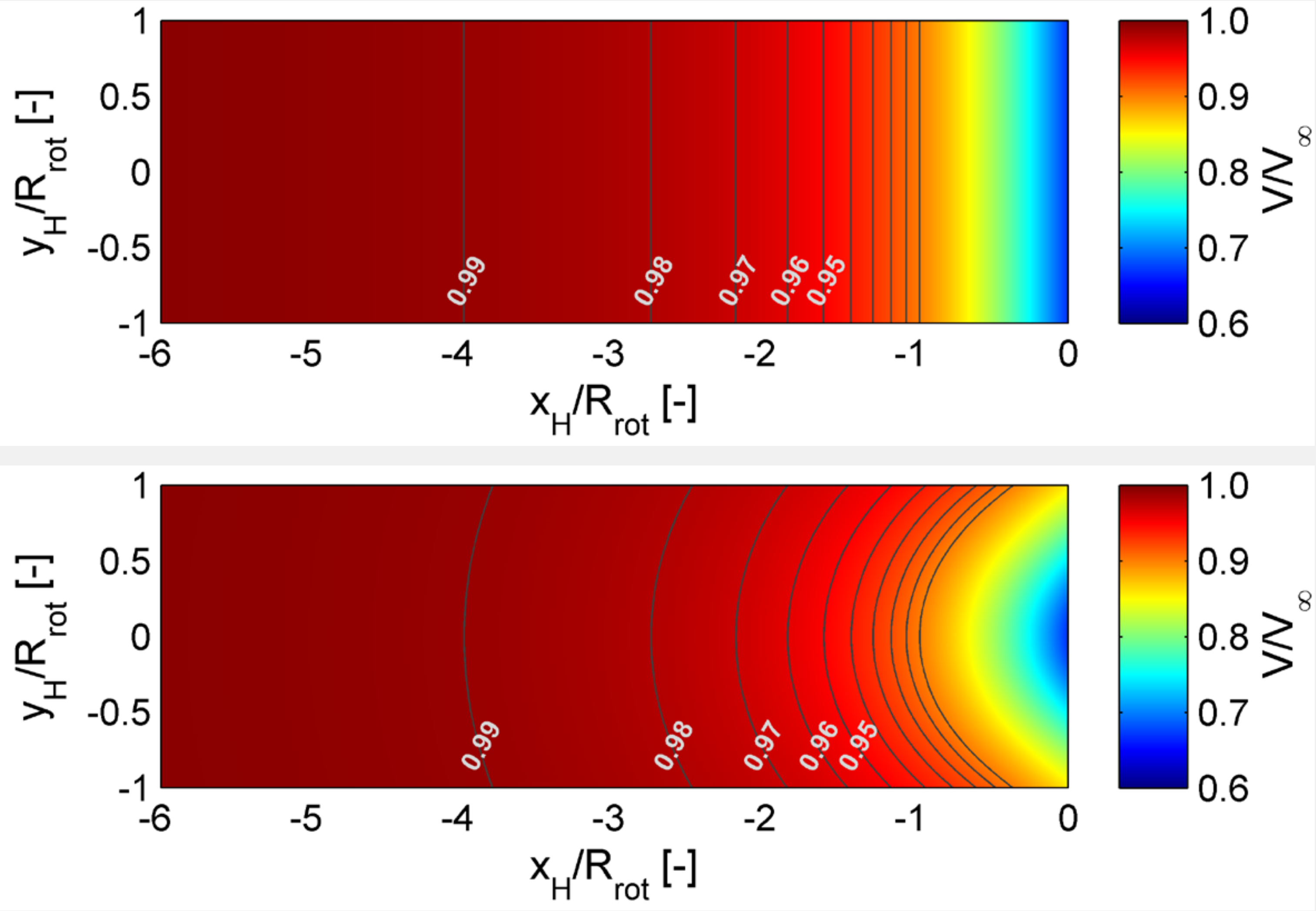
5B-demo



ZDM

Simple induction models

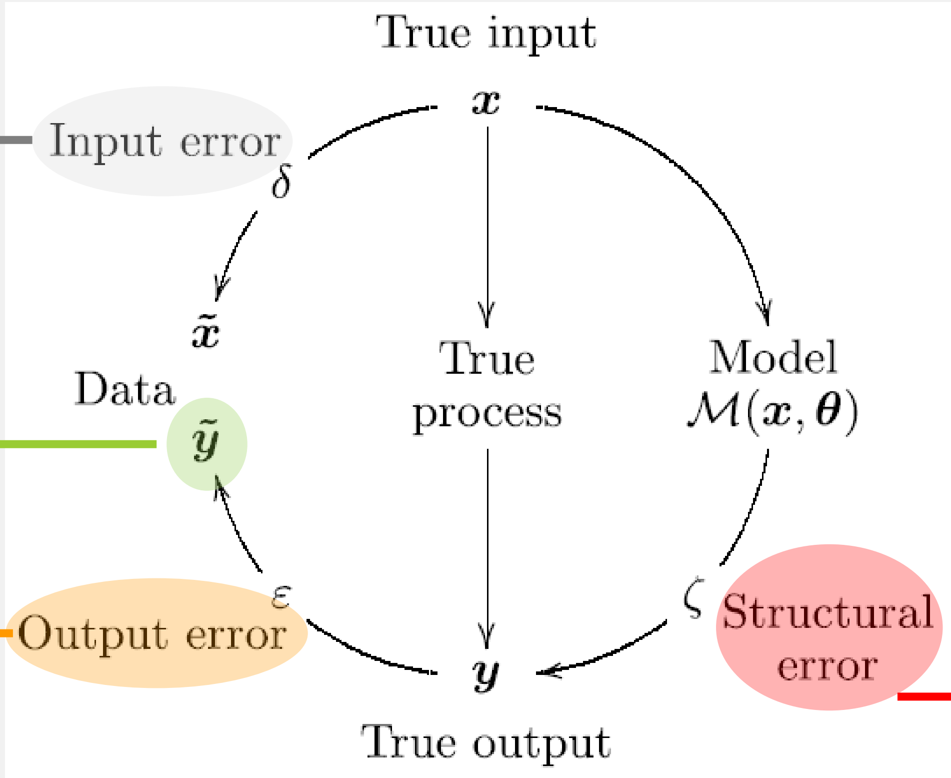
- One- or two- dimensional?



Preparing for questions
-
propagation of uncertainties with Monte Carlo methods

Model uncertainty framework

$$\bar{\mathbf{y}}_{\mathbf{i}} = \mathbf{y}_{\mathbf{t}} + \boldsymbol{\epsilon}_{\mathbf{e}} = g(\mathbf{x}_{\mathbf{i}} + \boldsymbol{\epsilon}_{\mathbf{x}}, \bar{\boldsymbol{\theta}}) + \boldsymbol{\epsilon}_{\mathbf{g}} + \boldsymbol{\epsilon}_{a}$$



Reproduced from:

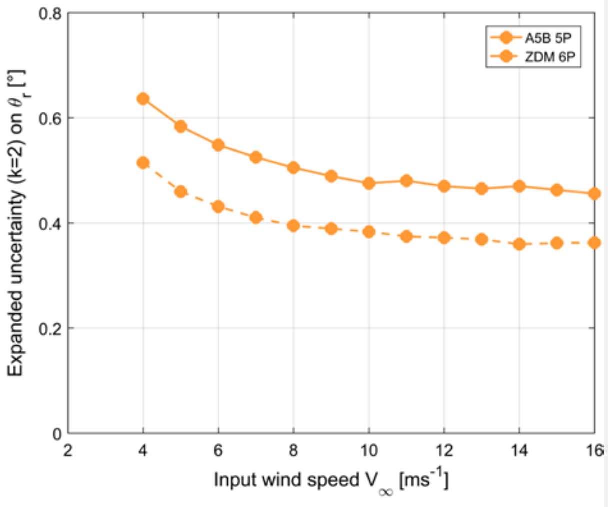
Huard, D., and A. Mailhot (2006),

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

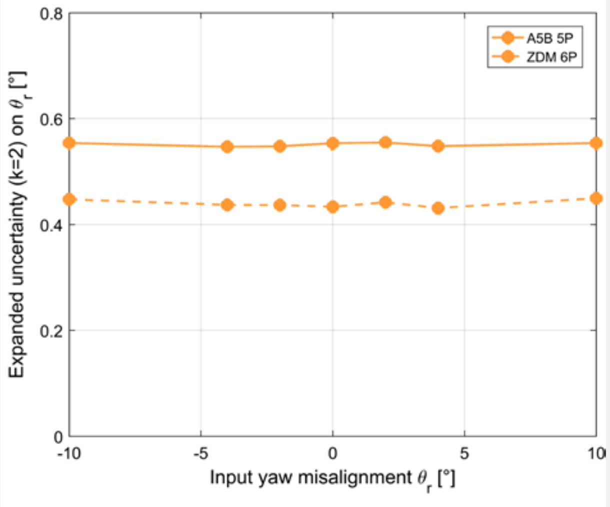
Water Resour. Res., 42, W07416, *doi:10.1029/2005WR004661*

- $\bar{\mathbf{y}}_{\mathbf{i}}$ is a measured value of g;
- $\boldsymbol{\epsilon}_{\mathbf{x}}$ represents the error related to the inputs;
- $\boldsymbol{\epsilon}_{\mathbf{g}}$ is the random error due to the model uncertainty;
- $\boldsymbol{\epsilon}_{\mathbf{a}}$ characterises the error due to the model inadequacy
- $\boldsymbol{\epsilon}_{\mathbf{e}}$ is the error between observations $\bar{\mathbf{y}}_{\mathbf{i}}$ (measured) and the true value $\mathbf{y}_{\mathbf{t}}$;

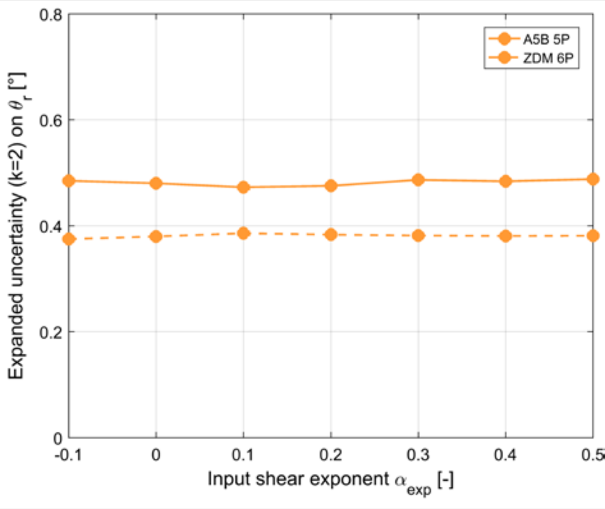
Uncertainties of WFC
yaw misalignment θ_r



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



$V_\infty = 10\, ms^{-1};\ \alpha_{exp} = 0.2;\ a_{ind} = nom.$

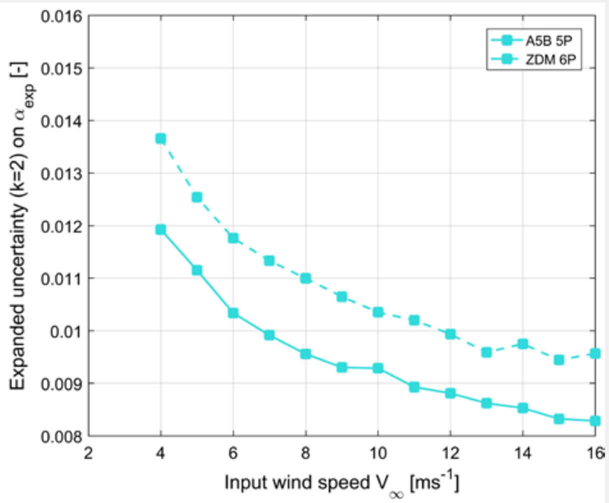


$V_\infty = 10\, ms^{-1};\ \theta_r = 4°;\ a_{ind} = nom$

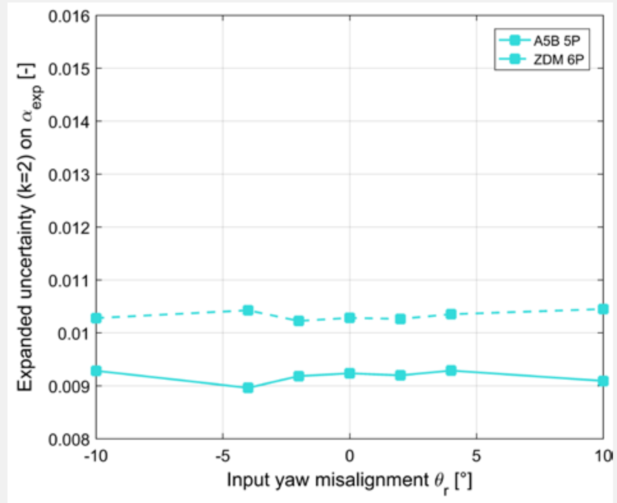
- Decreasing vs speed: consistent with NKE campaign results!
- Values are very (too ??) low: due to assumed high correlation between V_los
- No variability with input yaw misalignment and shear

Uncertainties of WFC

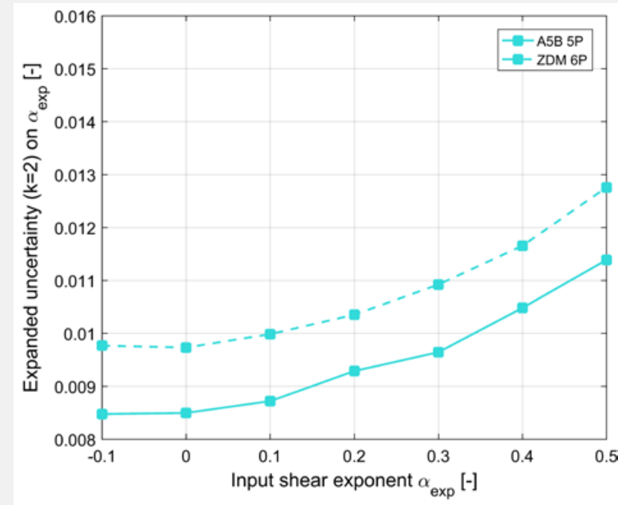
shear exponent α_{exp}



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



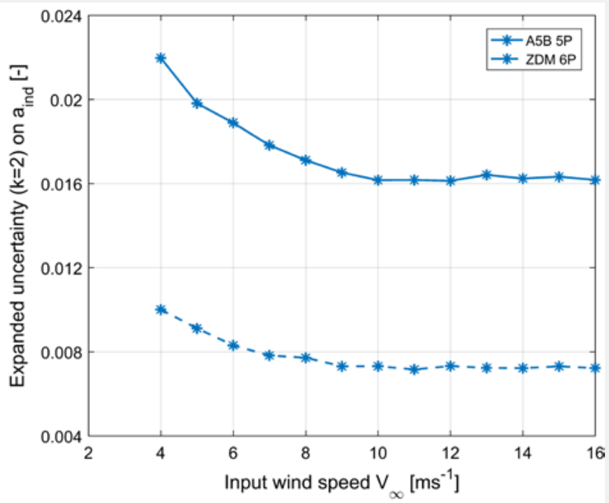
$V_\infty = 10\ ms^{-1};\ \alpha_{exp} = 0.2;\ a_{ind} = nom.$



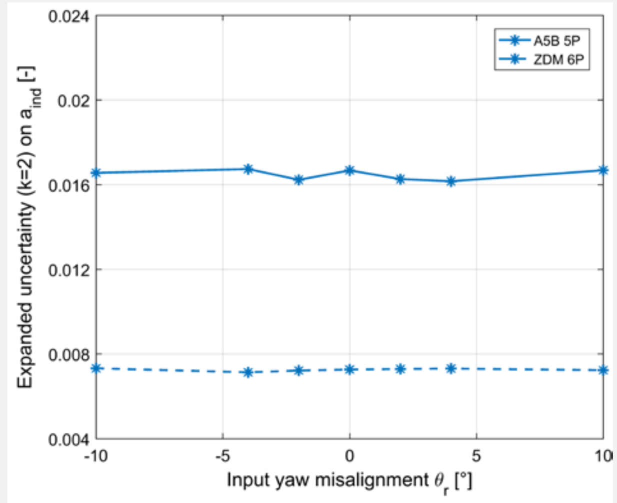
$V_\infty = 10\ ms^{-1};\ \theta_r = 4°;\ a_{ind} = nor$

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

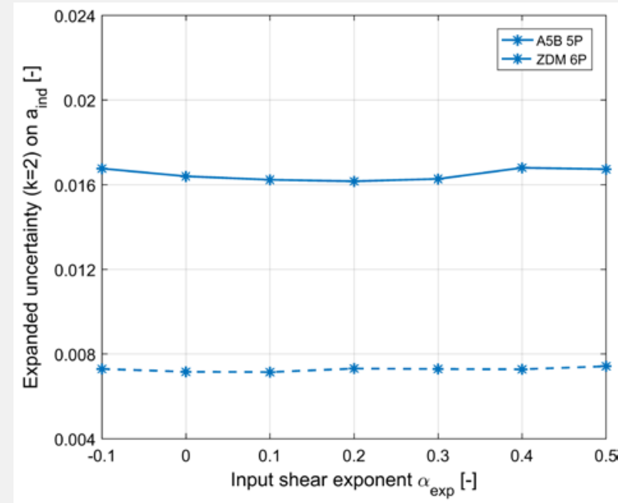
Uncertainties of WFC
induction factor a_{ind}



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



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



$V_\infty = 10\ ms^{-1};\ \theta_r = 4°;\ a_{ind} = nor$

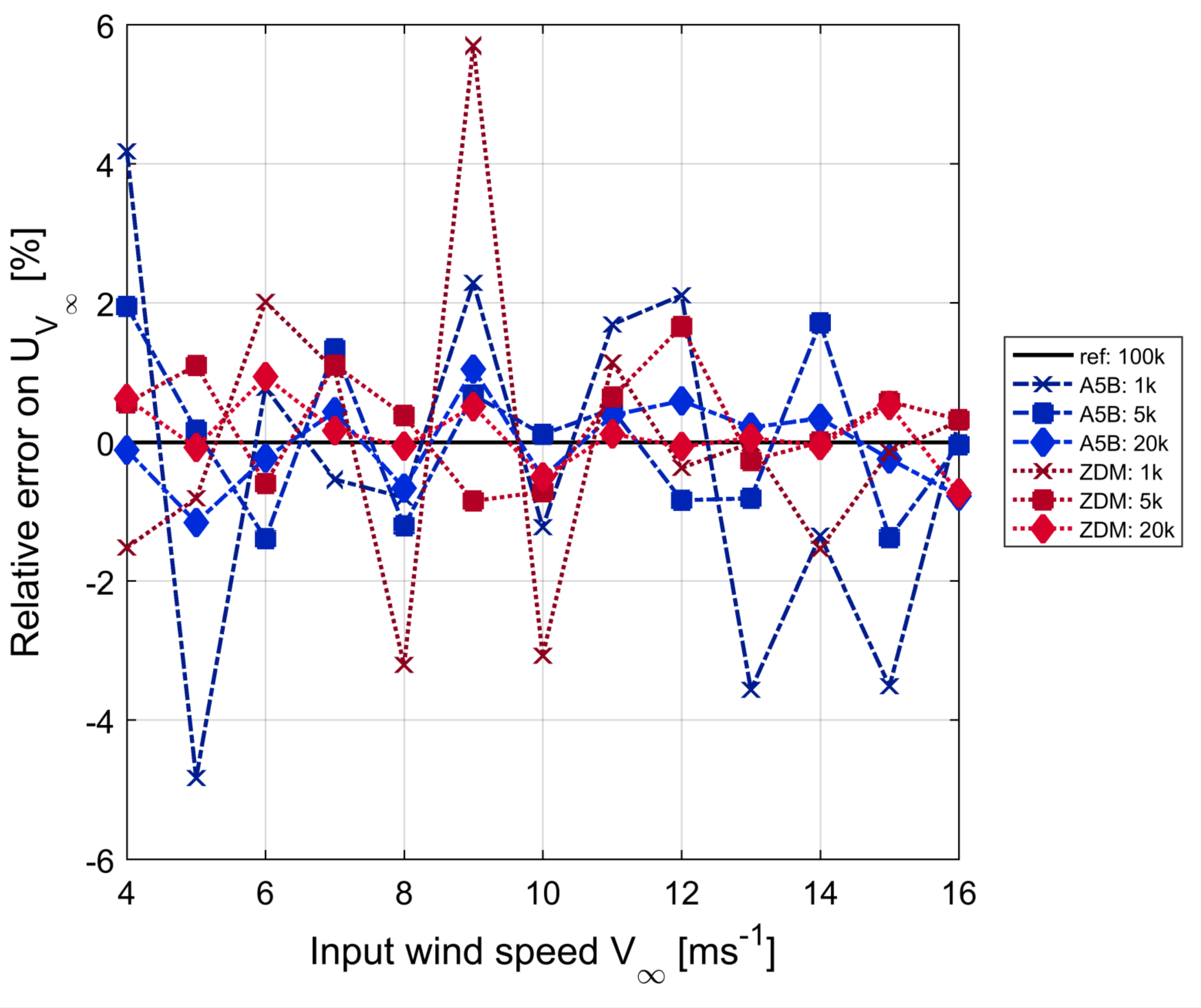
- Decreasing vs speed
- No variability with input yaw misalignment and shear

- 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)

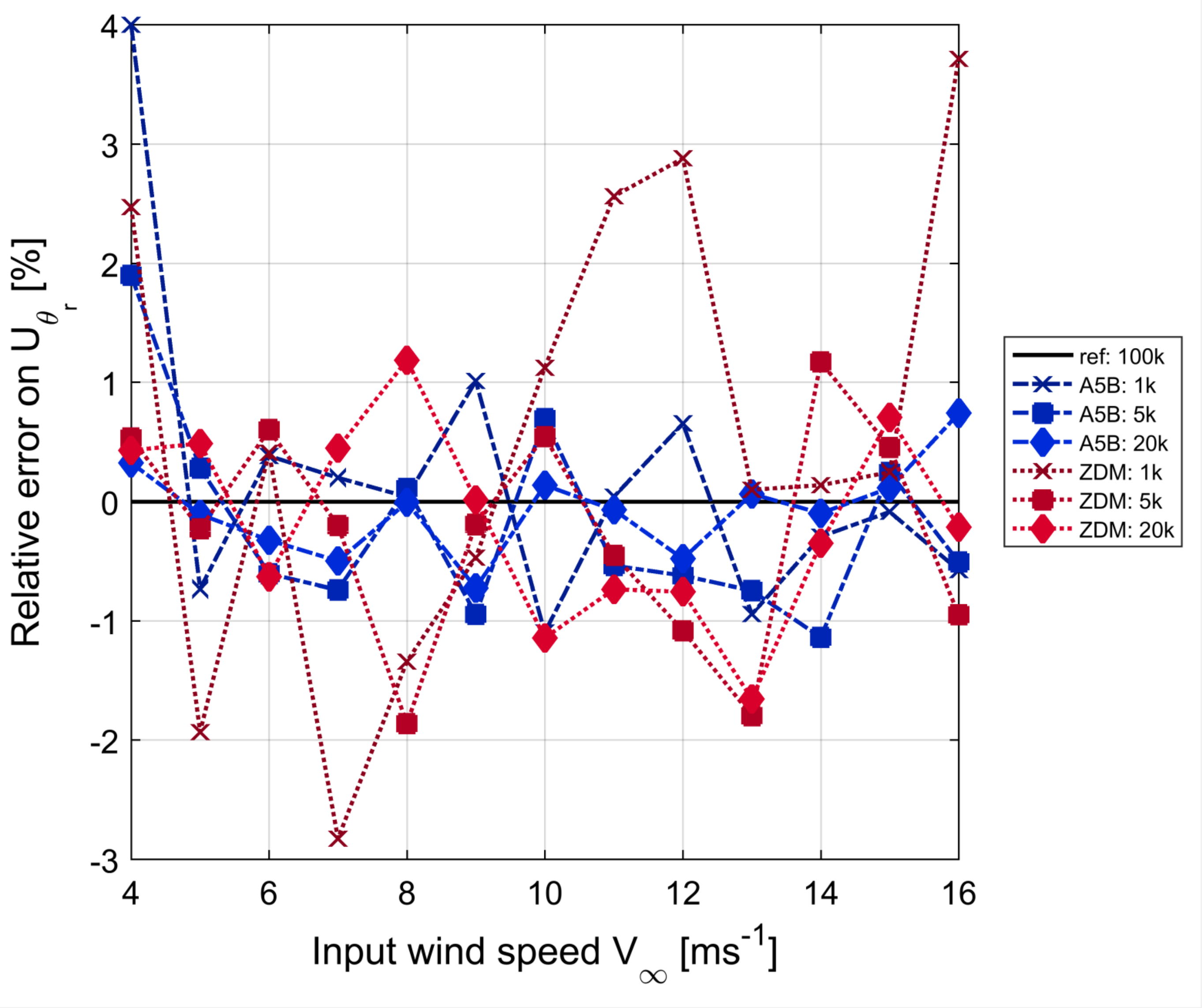
MCM convergence

Wind speed uncertainties (k=2)

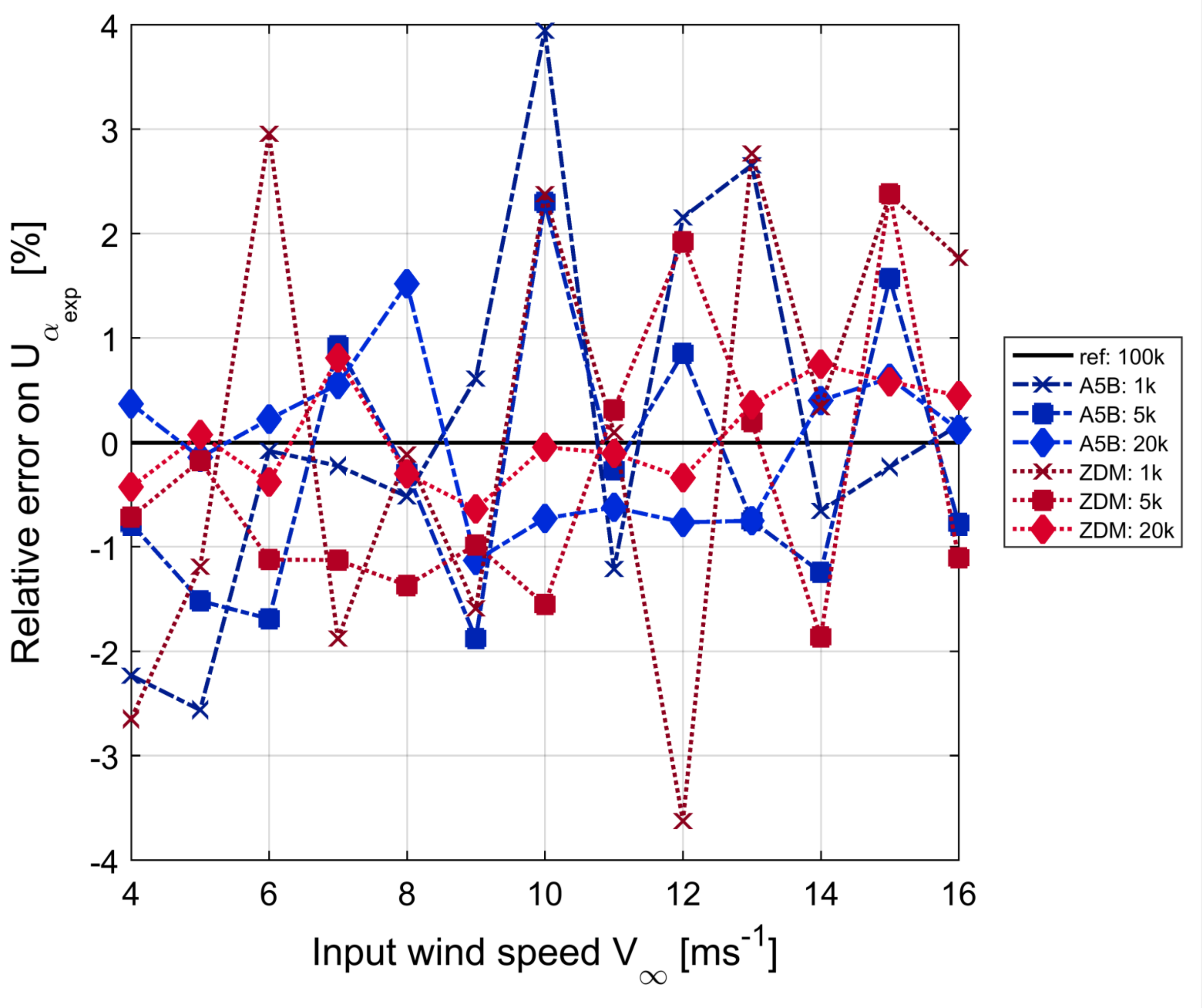


MCM convergence

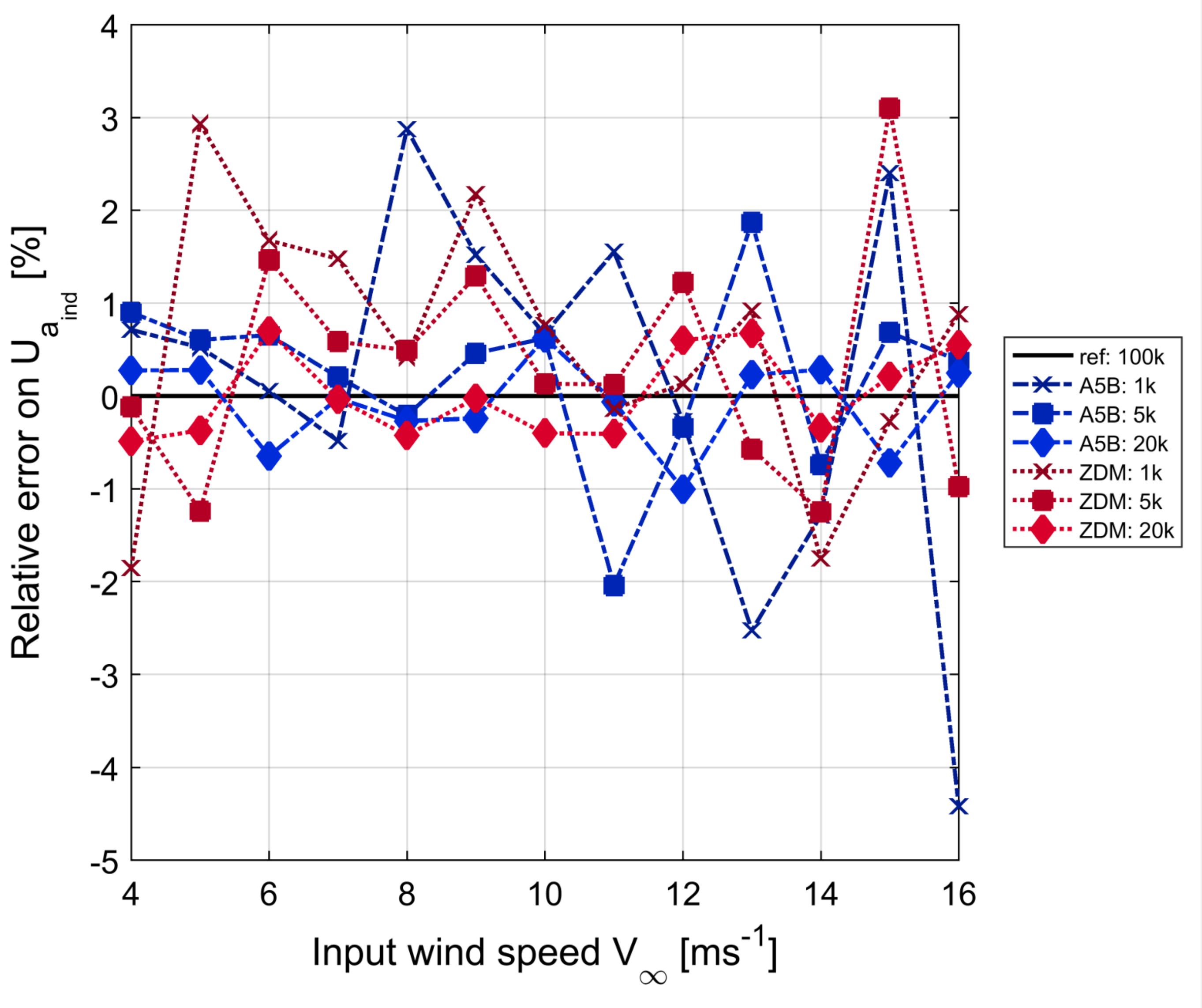
Yaw misalignment uncertainties (k=2)



Shear exponent uncertainties (k=2)



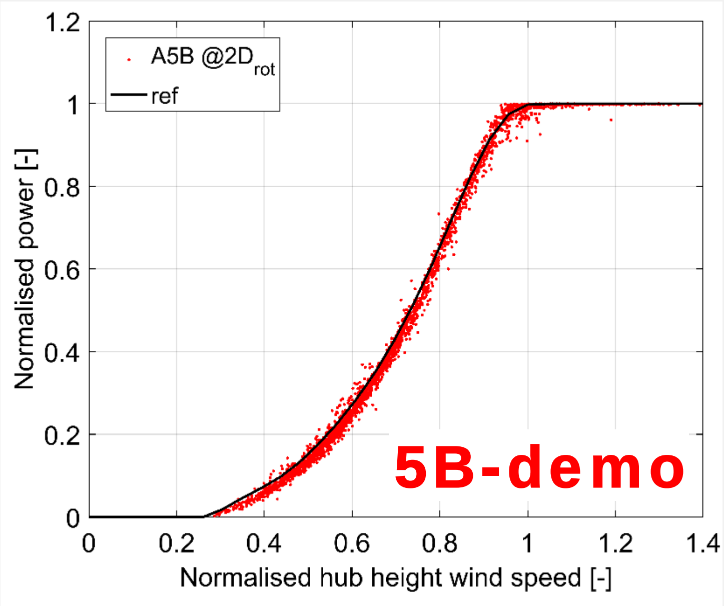
Induction factor uncertainties (k=2)

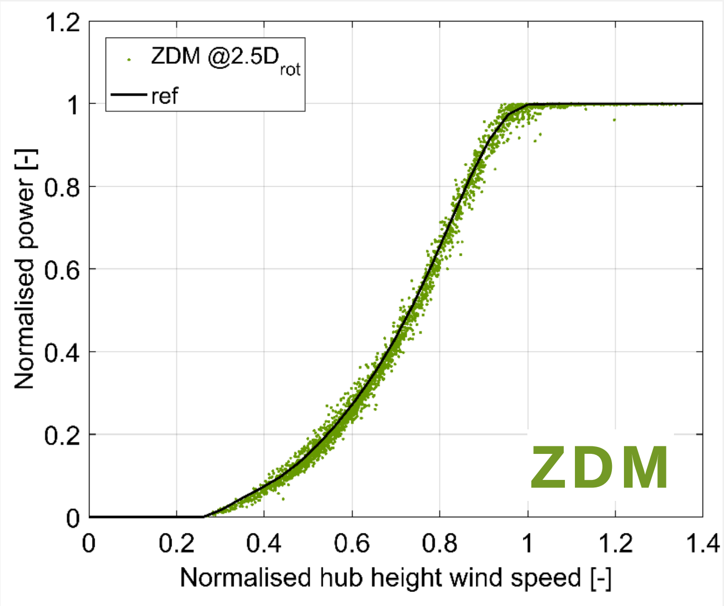


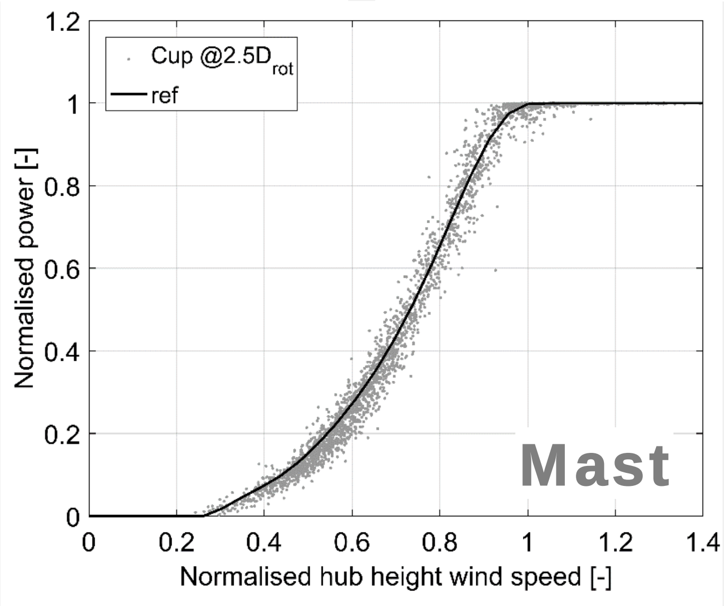
Preparing for questions
-
power performance testing

Measured Power curves (scatter)

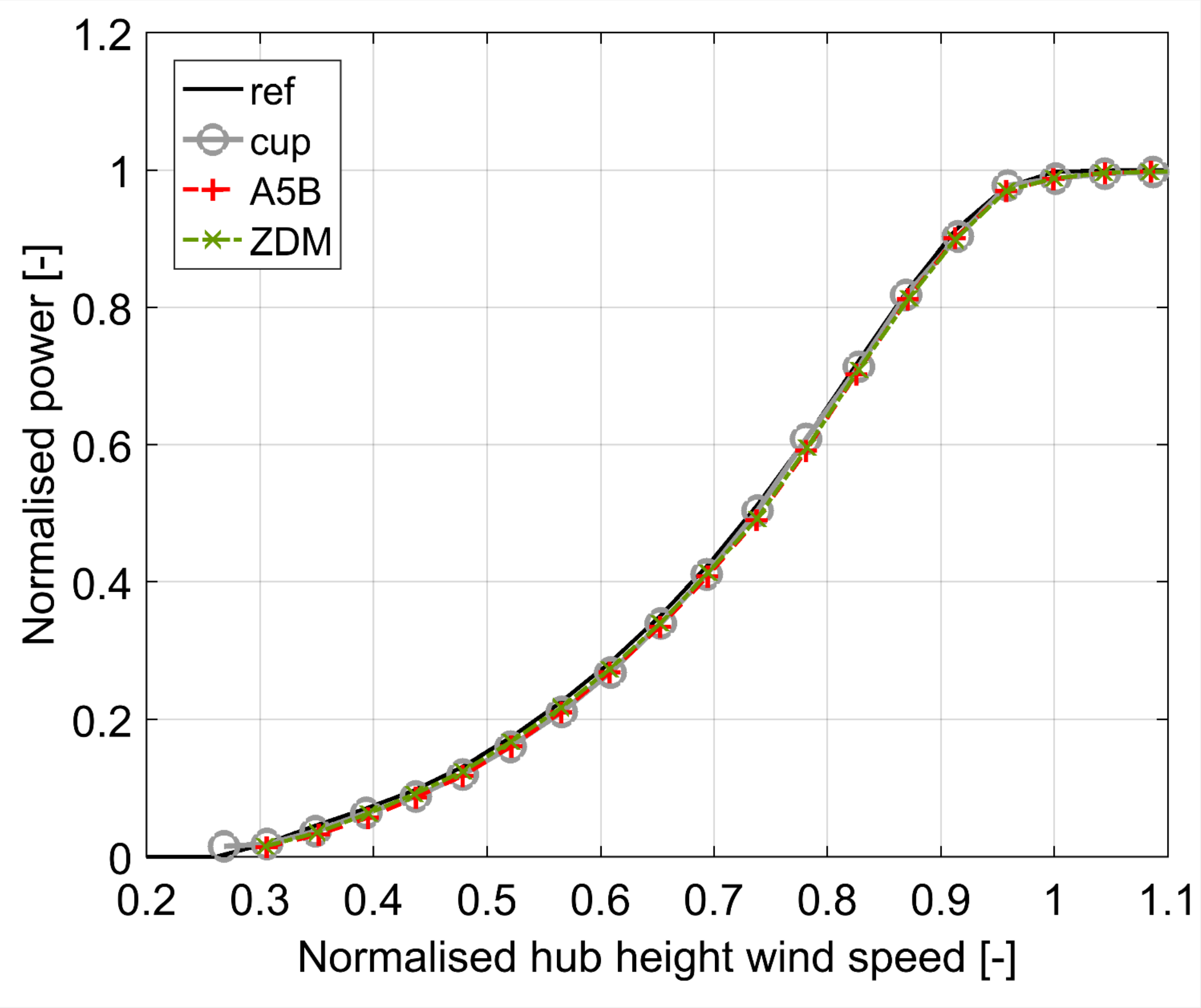
WFR using wind model





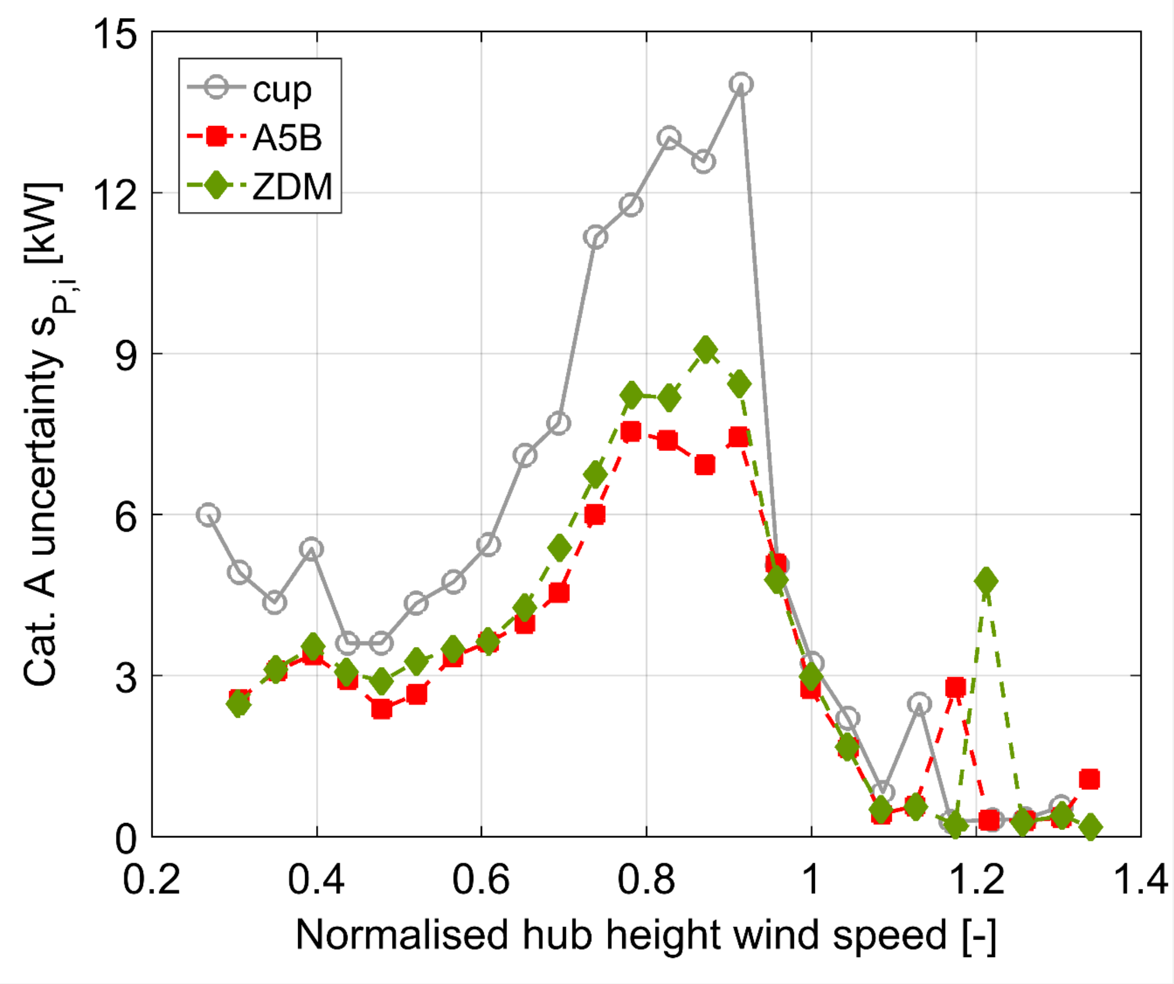


Measured Power curves (scatter)
WFR using wind model



Power curve uncertainties: power, type A

WFR using wind model



Power curve uncertainties: combined

WFR using wind model