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# Nacelle lidar for power perf. – the UniTTe approach to retrieve V

**Borraccino, Antoine; Wagner, Rozenn**

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# Nacelle lidar for power perf. – the UniTTe approach to retrieve V∞

A. Borraccino, R. Wagner

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

**DTU Wind Energy**
Department of Wind Energy

# Power performance testing
## The modern ways

Remote sensing instruments

–

Future/Now: use of **nacelle-based wind lidars**

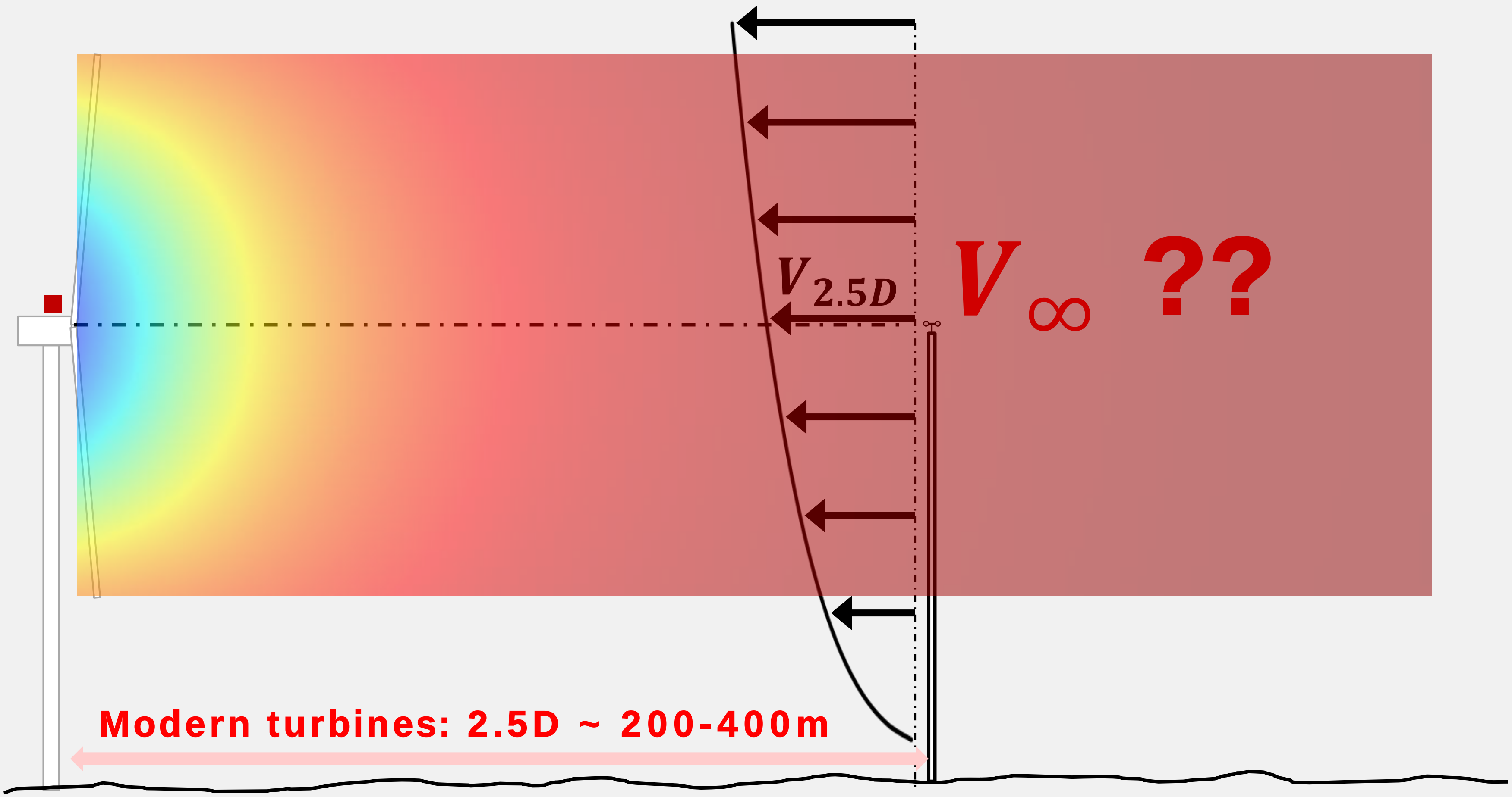
ZephIR Dual Mode
(scanning)
by *ZephirLidar*

Wind Iris
(4-beam)
by *AventLidar*

Wind Eye
(4-beam)
by *Windar Photonics*

Diabrezza
(9-beam)
by *Mitsubishi Electric*

# Searching for free stream wind speed

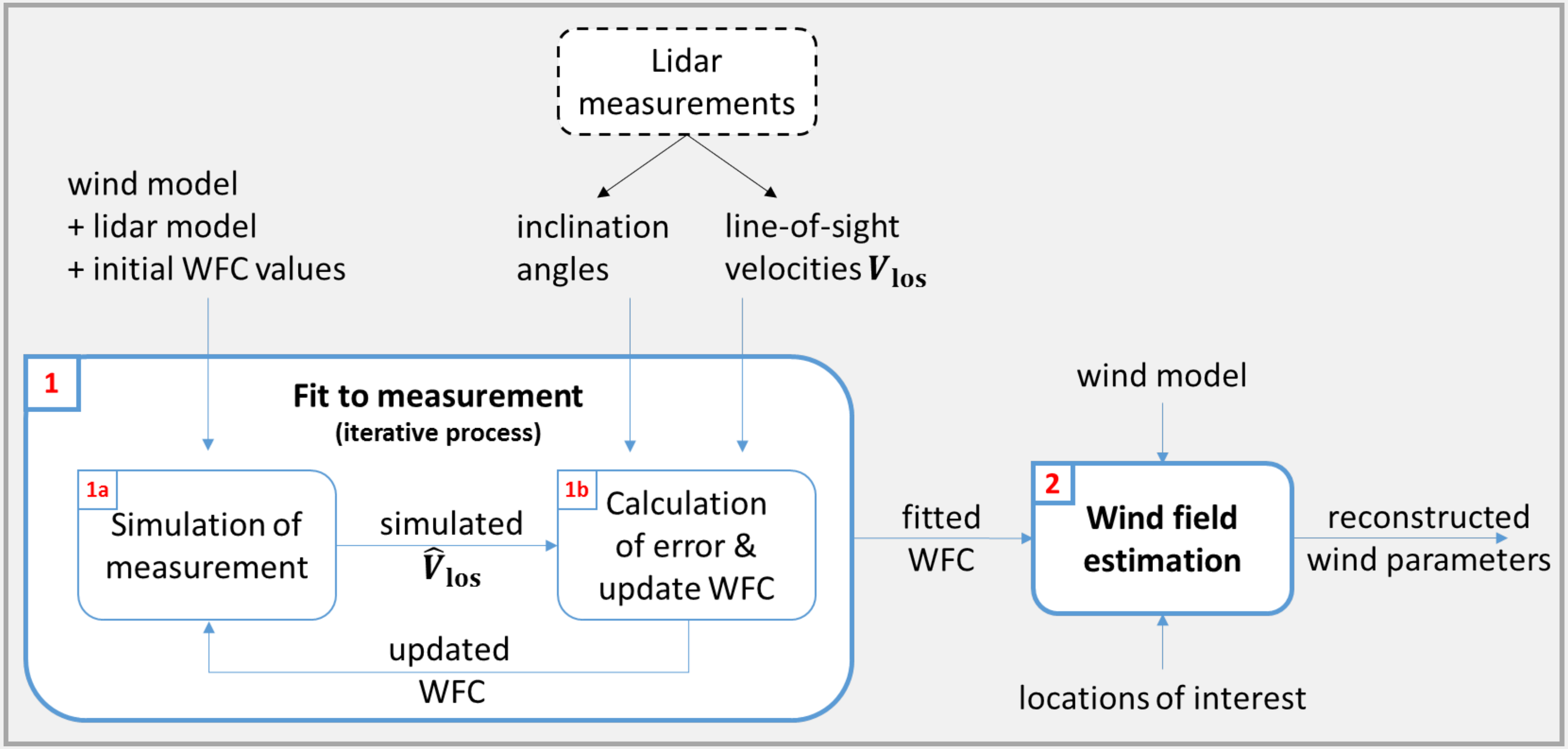



- Decorrelation WSpeed / power
- Hub height speed insufficient?
- 2.5D not really free wind …

# 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**

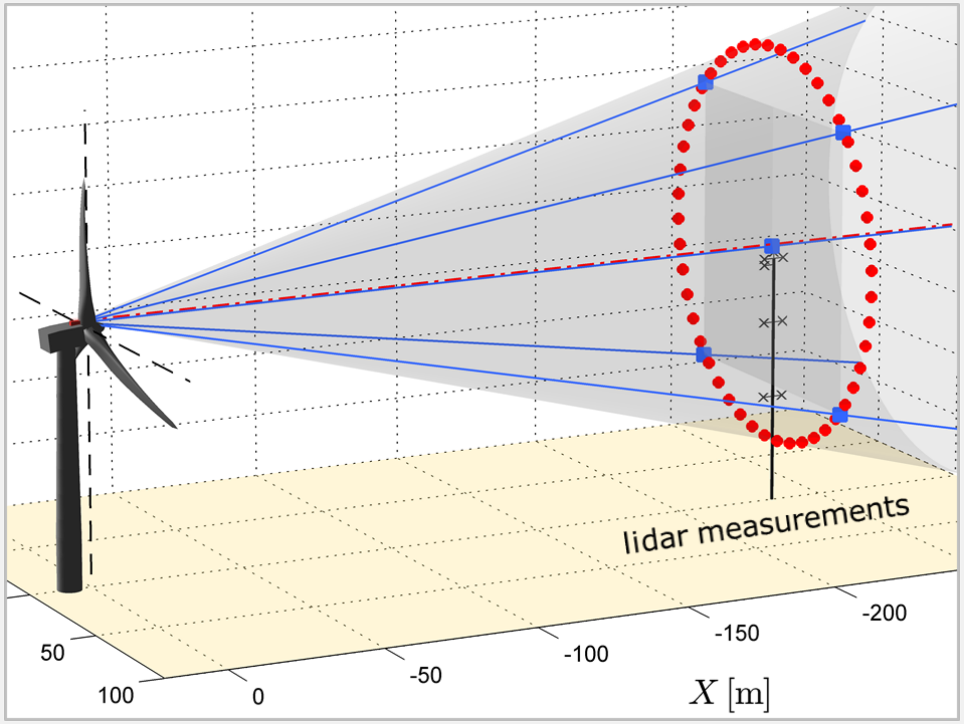
# What’s wrong with 2.5D?

- **Lidar range capabilities**
  - Soon not sufficient for very large turbines
  - Or systems will become more expensive
- **Measurement / beam locations**
  - Are/will be too far away
    - to accept WFR assumptions: inhomogeneity, lack of coherence, etc
    - nac. lidars measure wind less and less representative to what the turbine feels
  - Affected by e.g. terrain or site features
- **”Decorrelation” issues might come back**
- **AND…**
  - **2.5D really is NOT free stream!**
  - Under-estimation of V∞ by about 0.7%
    - According to models, confirmed by measurements
    - Should be accounted into AEP calculations…

# 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. $\theta_r$ (yaw misalignment)
  \+ shear exponent $\alpha_{exp}$



# Combined wind-induction model

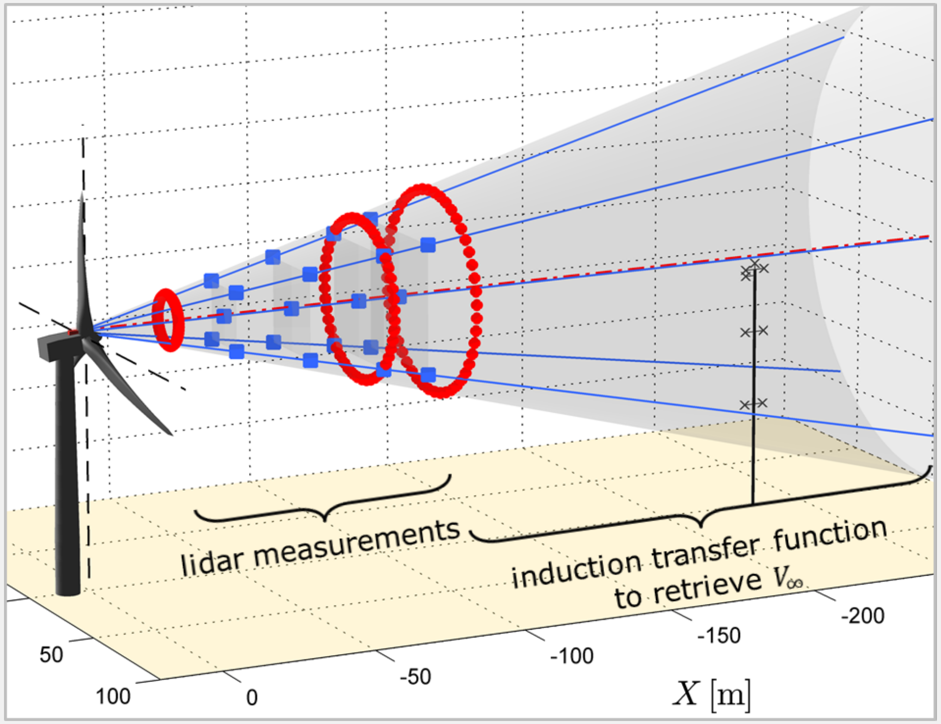
- Use lidar measurements at multiple distances close to rotor
- Additionally assumes simple induction model:

(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 $\mathbf{V}_\infty$ ($@H_{hub}$)
+ relative wind dir. $\boldsymbol{\theta_r}$
+ shear exponent $\boldsymbol{\alpha_{exp}}$
+ induction factor $\boldsymbol{a_{ind}}$

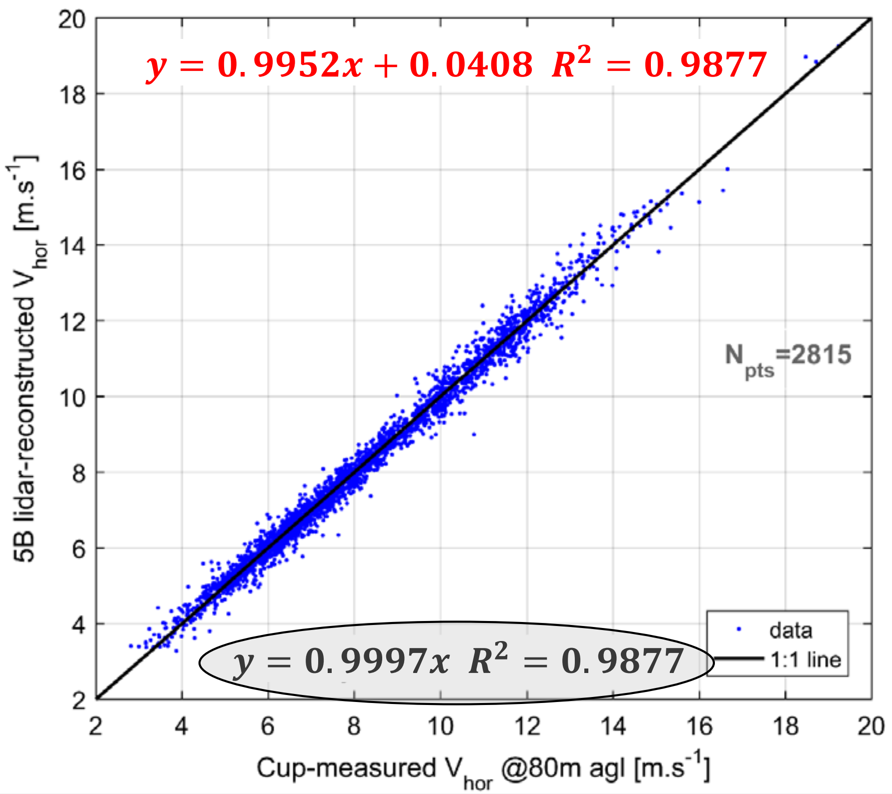


# Wind speed results

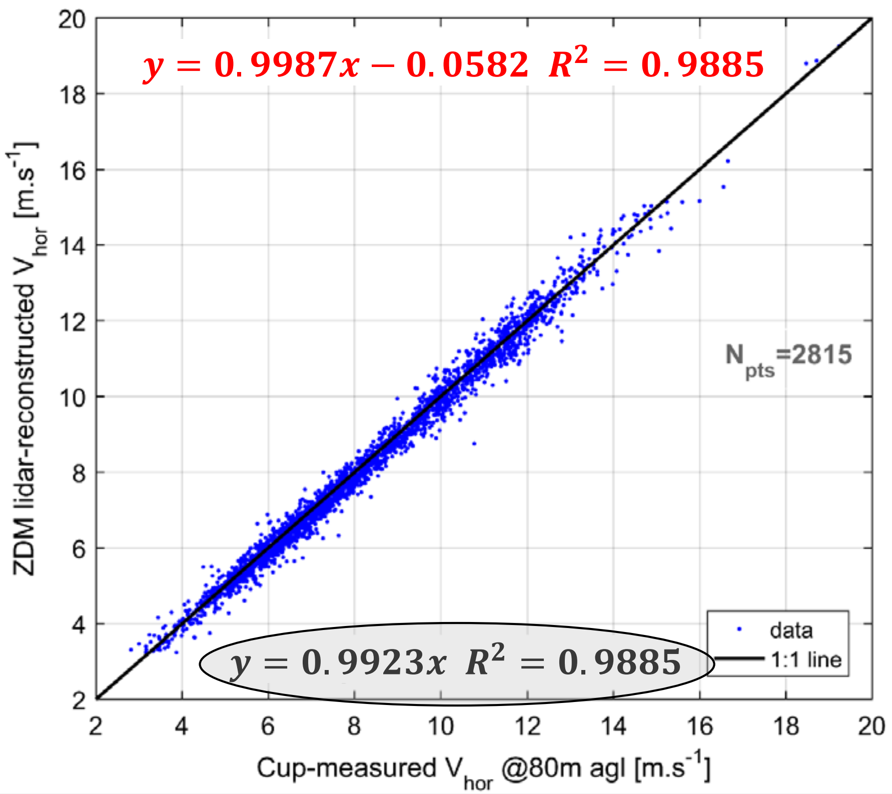
## Mast comparison, WFR using the wind-induction model

- ➔ 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**

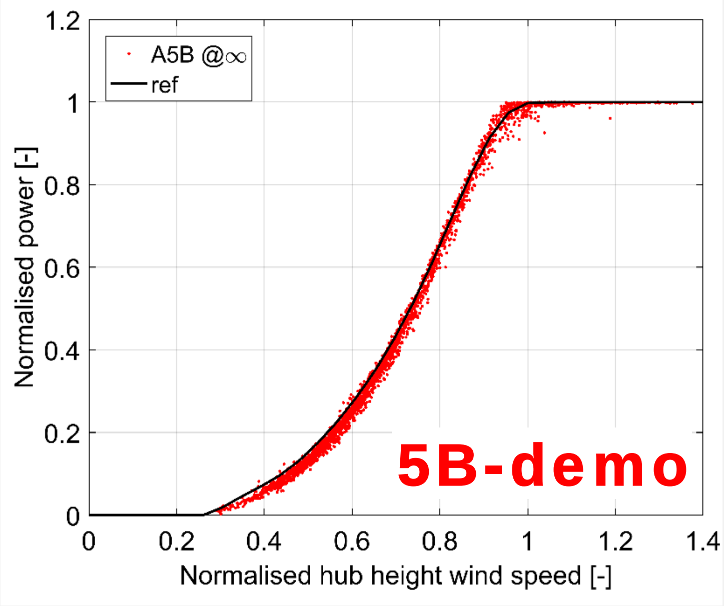


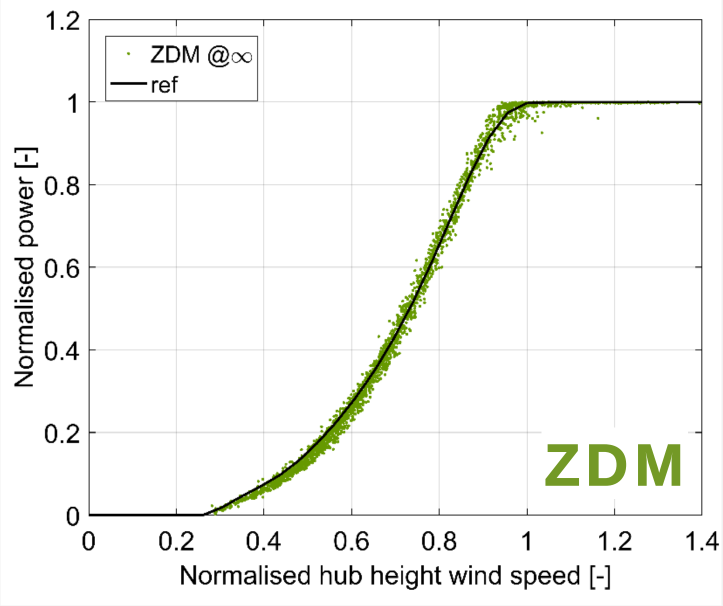

**ZDM: use 6 LOS**
**3 dist., from 0.3 to 1.2D_rot**

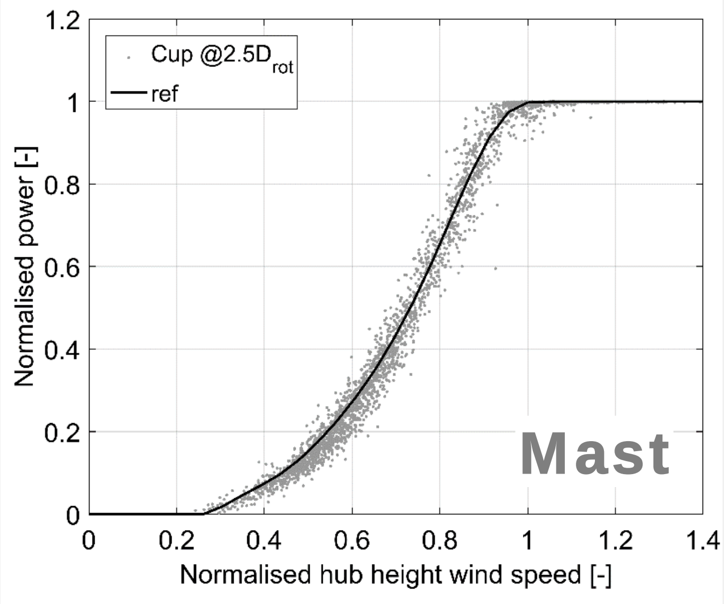


# Measured Power curves (scatter)

## WFR using wind-induction model



# Challenges in PCV with nacelle lidars

- **Need to give directions to methods for wind field reconstruction**
  - WFR model is of critical importance for accurate wind estimates
  - What kind of shear/veer model?
  - How to quantify model inadequacy? (e.g. fitting residuals)
- **Rotor equivalent wind speed**
  - By integration of shear profile?
  - Some geometrical issues...
- **Accounting for terrain**
  - Elevation data integrated as inputs to the WFR codes?
  - Classification of terrain: different WFR models to recommend?
- **Practical questions**
  - integration of brackets into turbine design
  - alignment of nacelle lidar to rotor axis

# Thanks for your attention!

Scientific article: *Wind Energy Science*

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

My PhD thesis:

*Remotely measuring the wind using turbine-mounted lidars*

More info:

- website www.unitte.dk
- contact: borr@dtu.dk, rozn@dtu.dk

# Does this make it any easier?

Flow disturbed by turbine wakes !

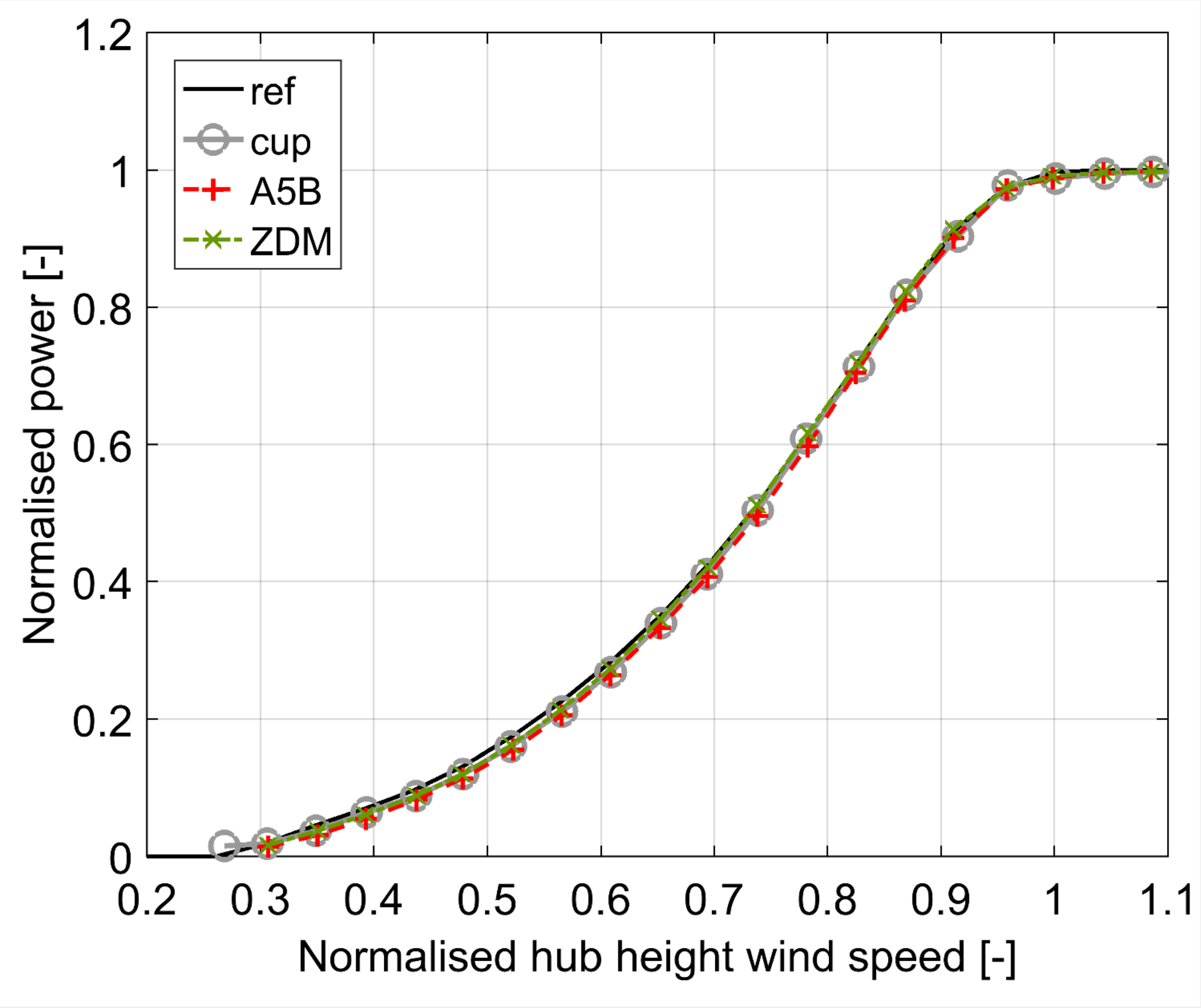
(very) complex terrain

Perdigão.
credit: N. Vasiljevic

# Preparing for questions
# -
# Wind Field Reconstruction

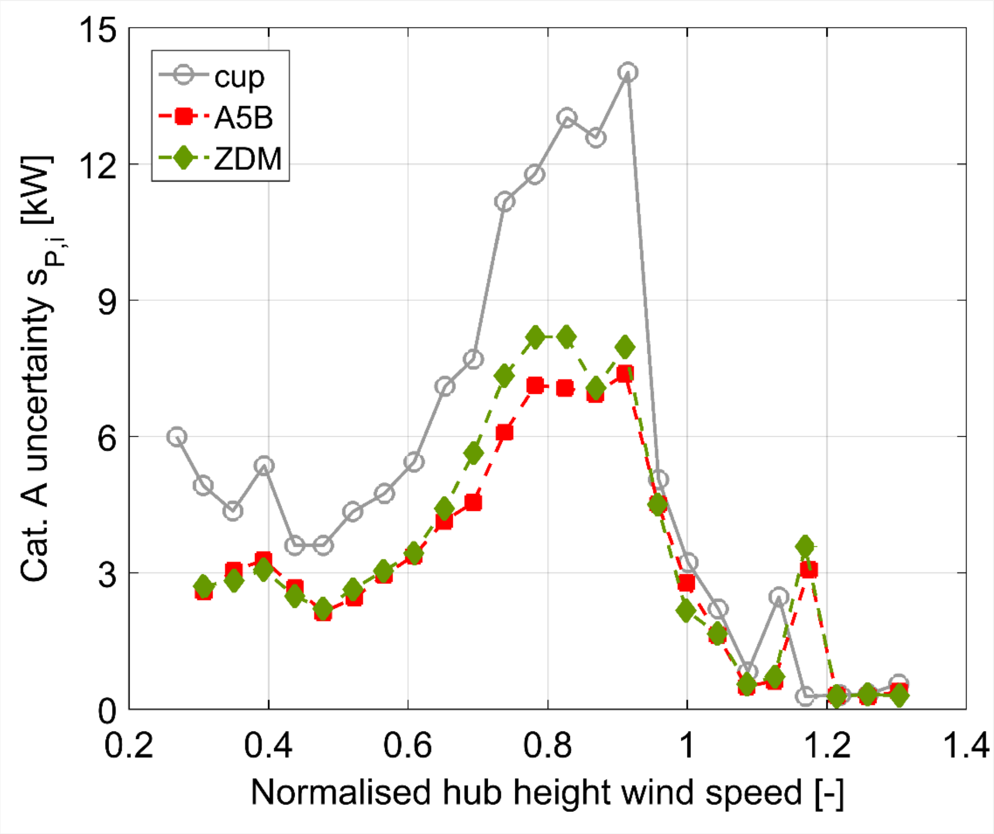
# Measured Power curves (binned)

## WFR using wind-induction model



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

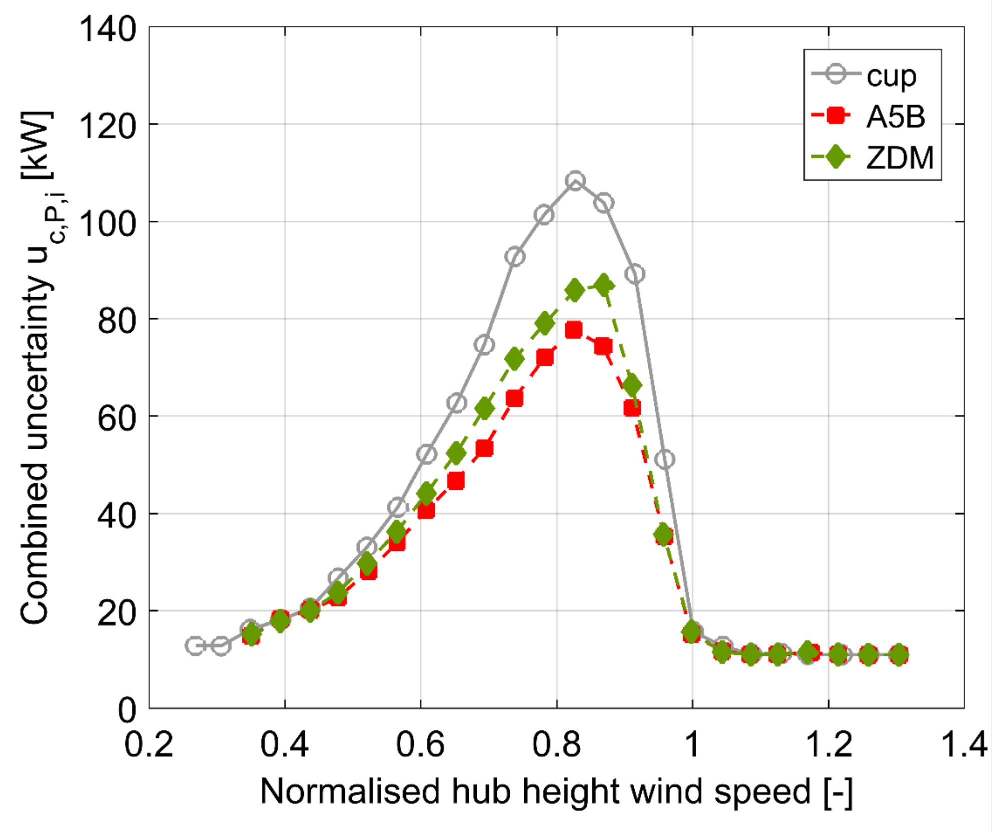
- **Clear reduction of scatter in power curve**
  ➔ nacelle lidars yield smaller type A (statistical) power uncertainty



# Power curve uncertainties: combined

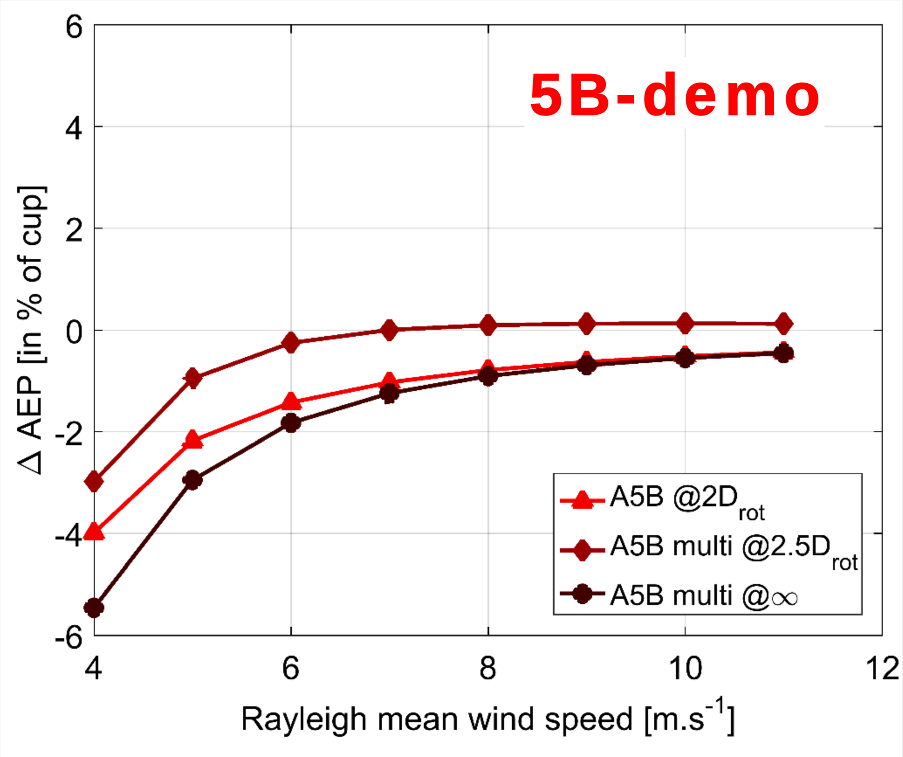
## WFR using wind-induction model

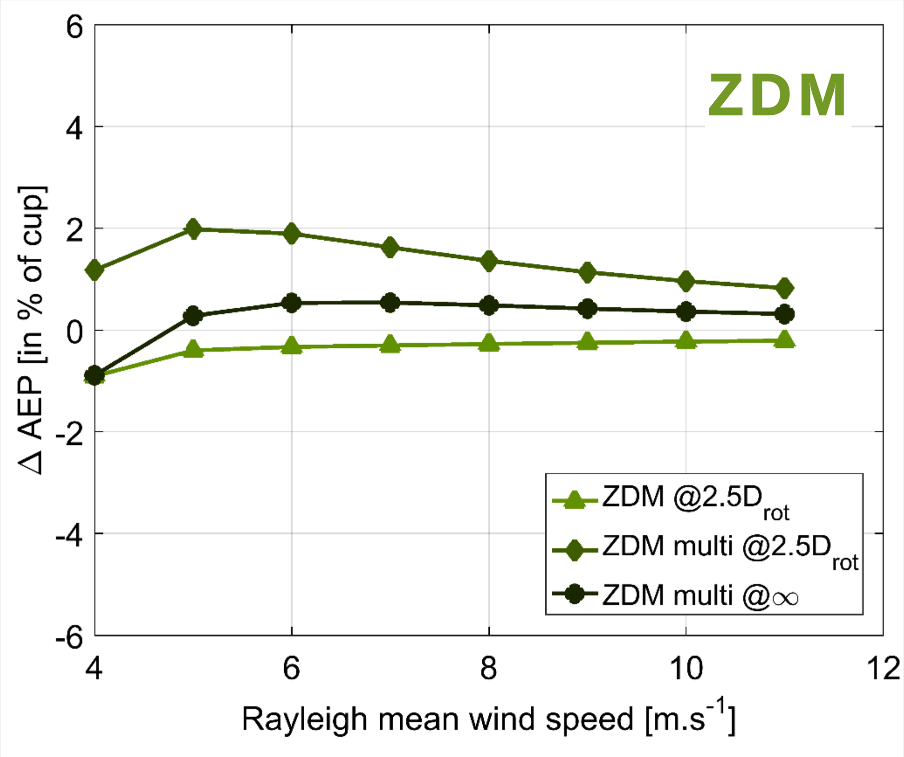
- **Results are mostly dependent on type B wind speed uncertainty**
  ➔ very sensitive to the ”terrain uncertainty”
  ➔ lidar uncertainties are smaller only due to this component…



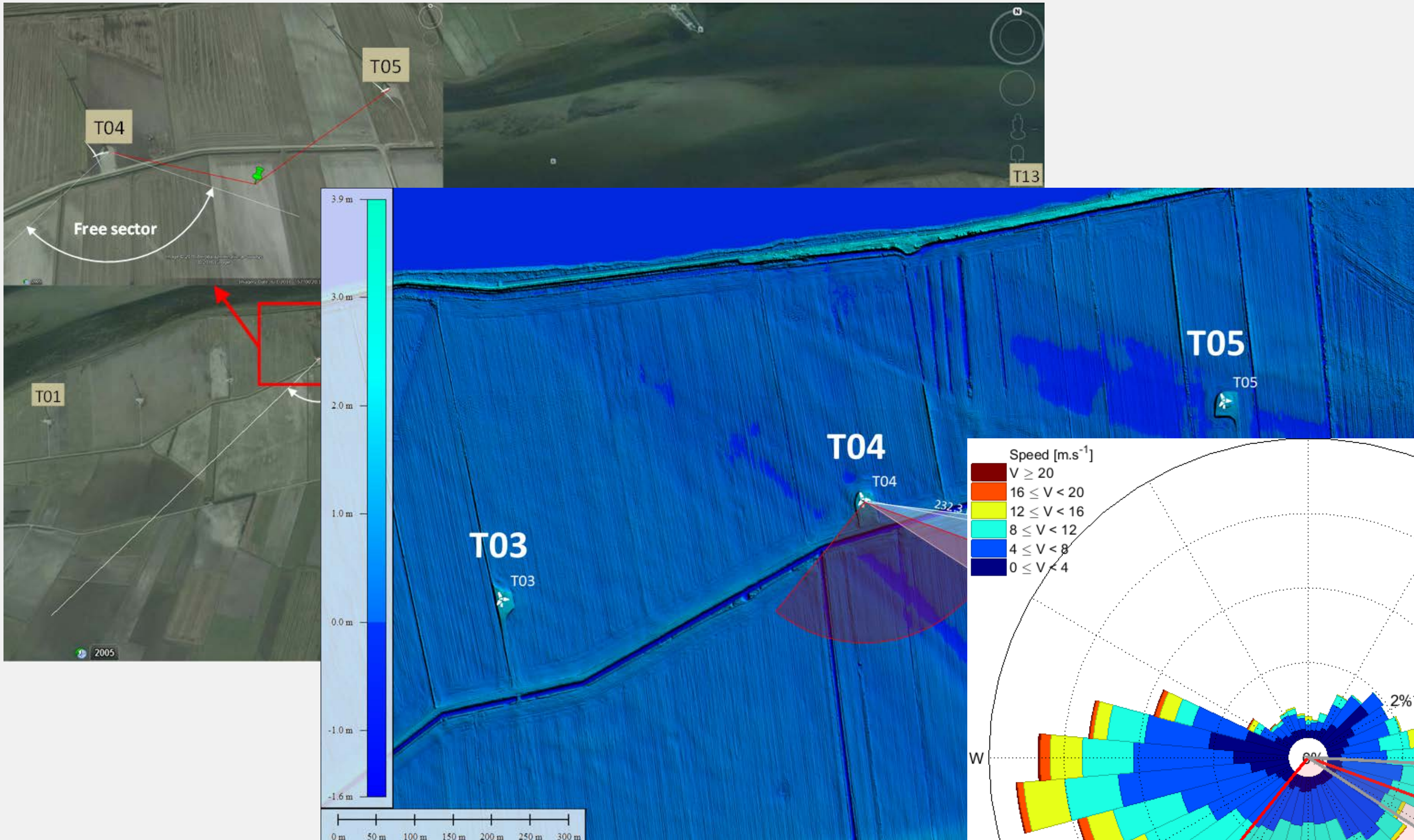
# Annual Energy production

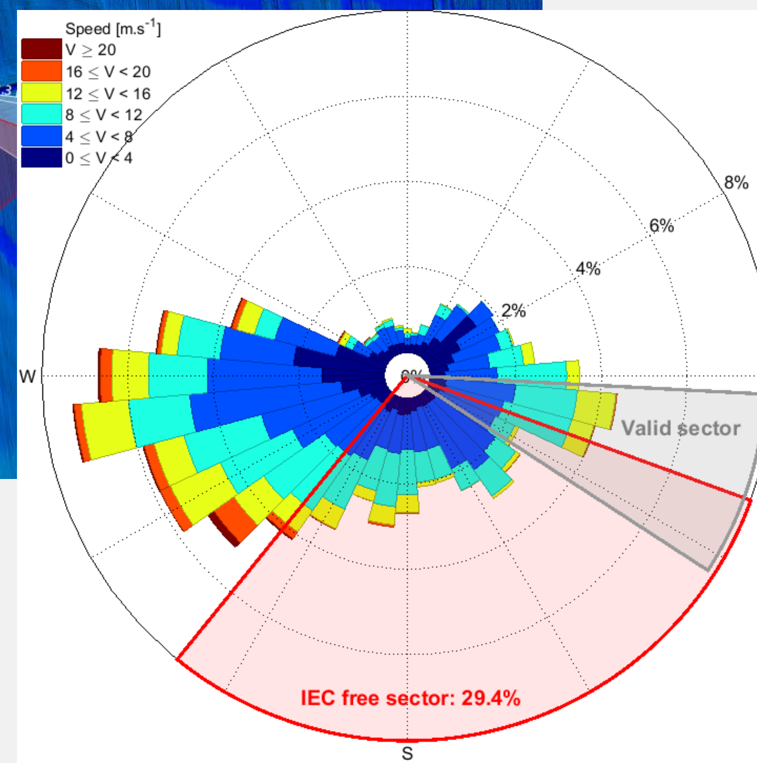
- **Derived as percentage of AEP using "mast power curve"**
- **3 methods:**
  - Wind model
  - Combined wind-induction
    - Wind speed estimated at 2.5D
    - fitted free stream wind speed ($V_\infty$)



# 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 | | | |
| --- | --- | --- | --- | --- | --- | --- | --- |
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| 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 | | | | |
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| 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 | | | |
|---|---|---|---|---|---|---|---|
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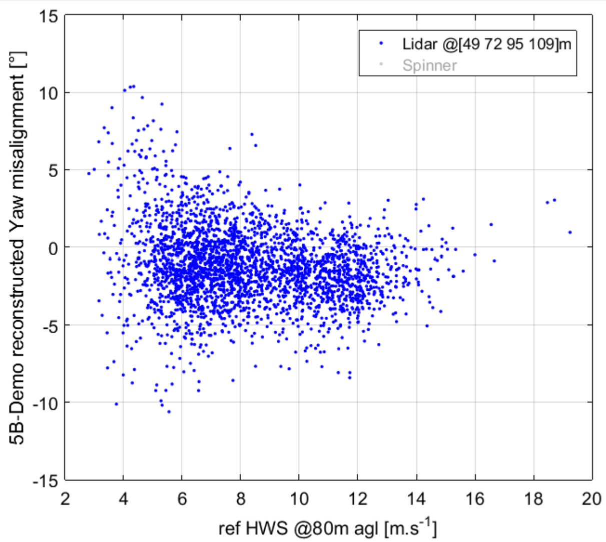
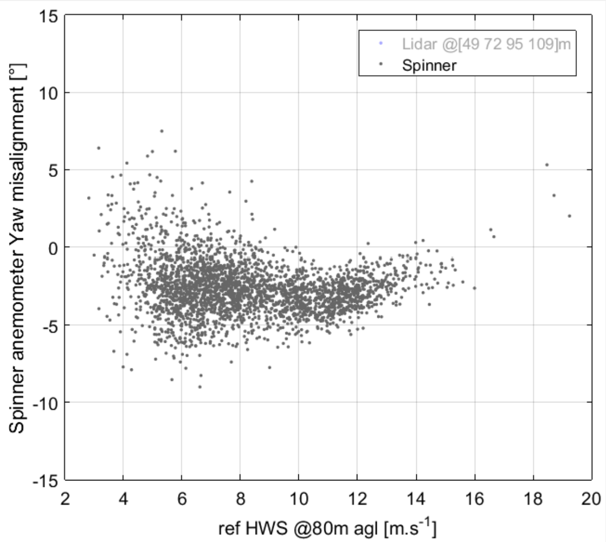
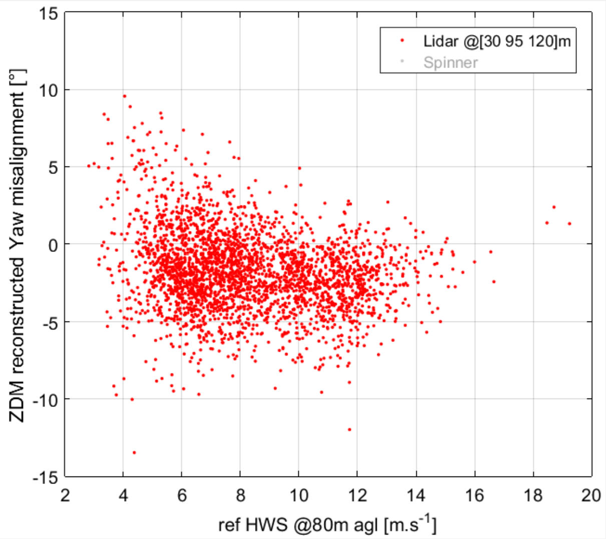
| | | | ZDM, 6 LOS | from 0.3 to 1.25 $D_{rot}$ | 0.9923 | 0.9885 | |
| 4 | $[110°, 219°]$ (IEC free sector) | disjoint | 5B-Demo, 5 LOS | 2.0 $D_{rot}$ | 1.0041 | 0.9840 | 4588 |
| | | | ZDM, 6 LOS | 2.5 $D_{rot}$ | 1.0038 | 0.9860 | 5615 |
| | | | 5B-Demo, 5 LOS | from 0.5 to 1.15 $D_{rot}$ | 0.9988 | 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**

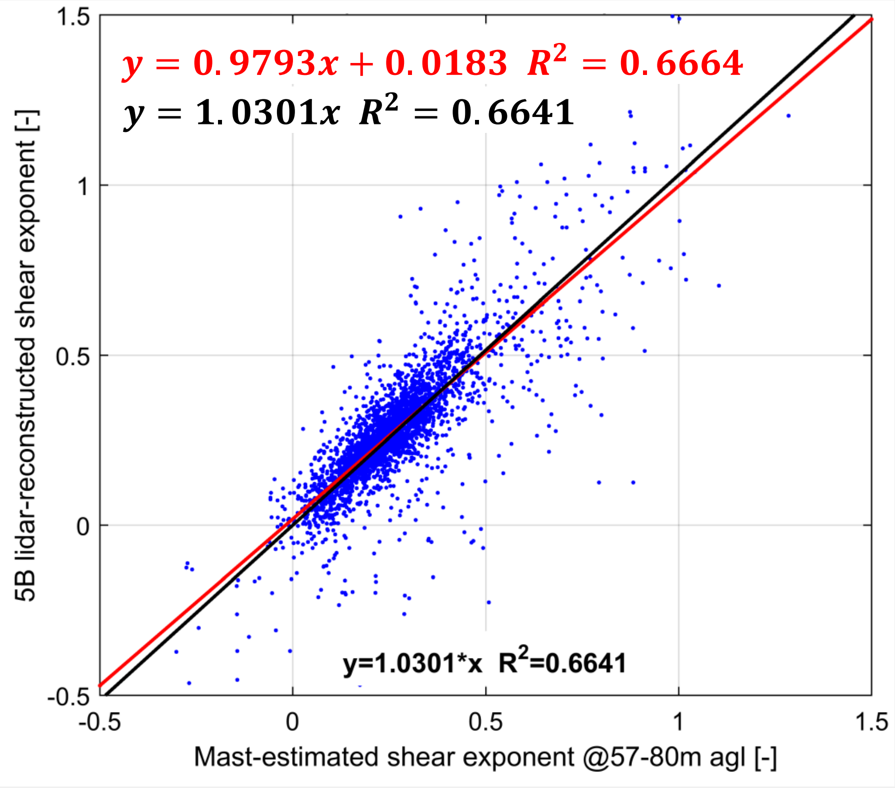
➔ Higher scatter with lidars than spinner

➔ "mean" yaw misalignment: $\approx -3°$

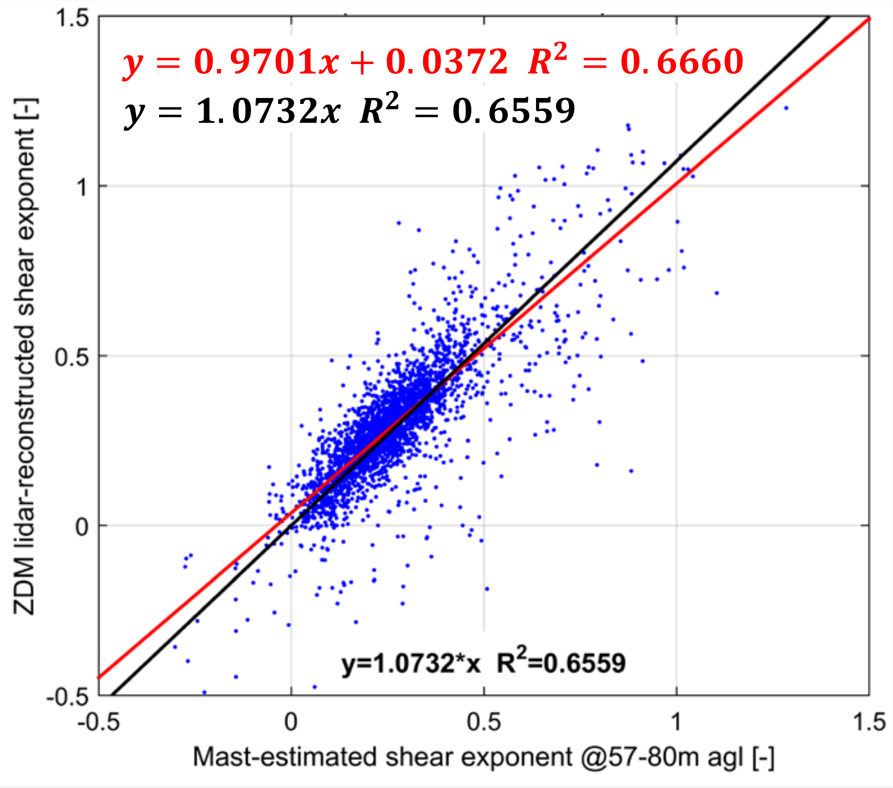
➔ The two nacelle lidars seem to provide similar results

# 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**



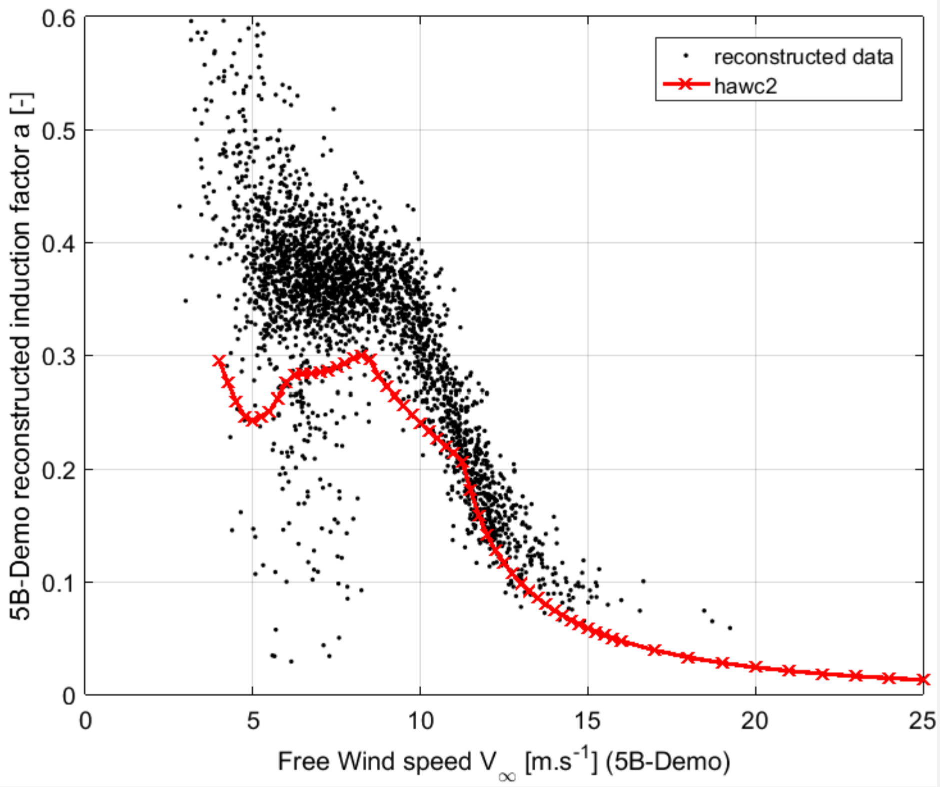

**ZDM: 3 dist. From 0.3 to 1.2D_rot**

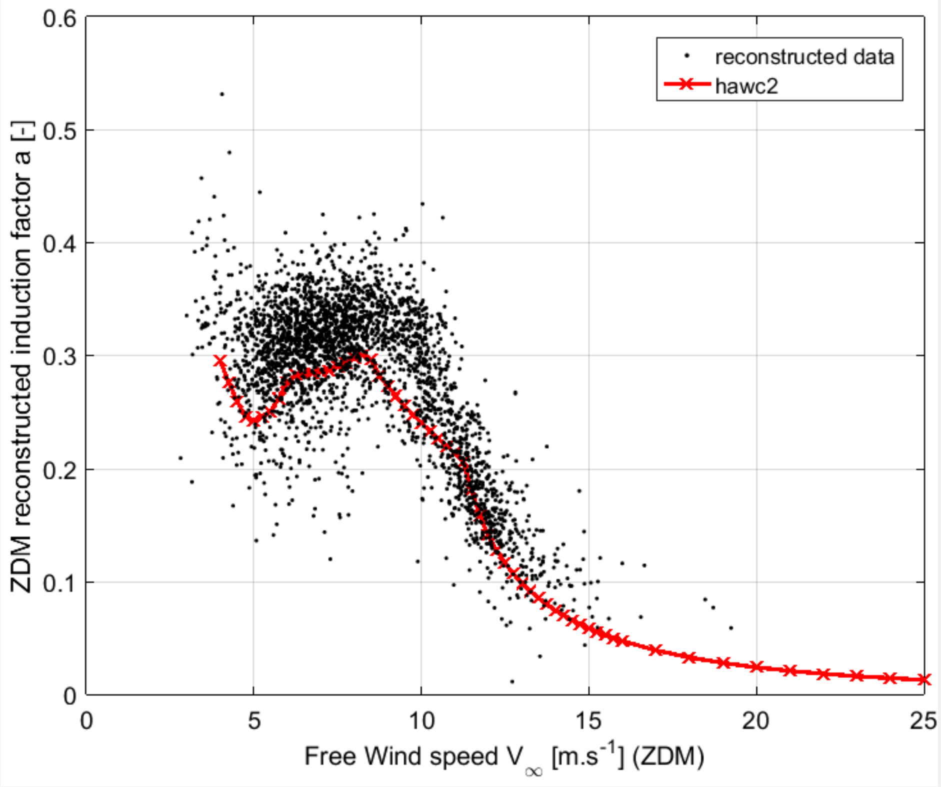
➔ Slight overestimation vs. mast ➔ Similar results between the two lidars

# Induction factor results:

## WFR using the wind-induction model

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

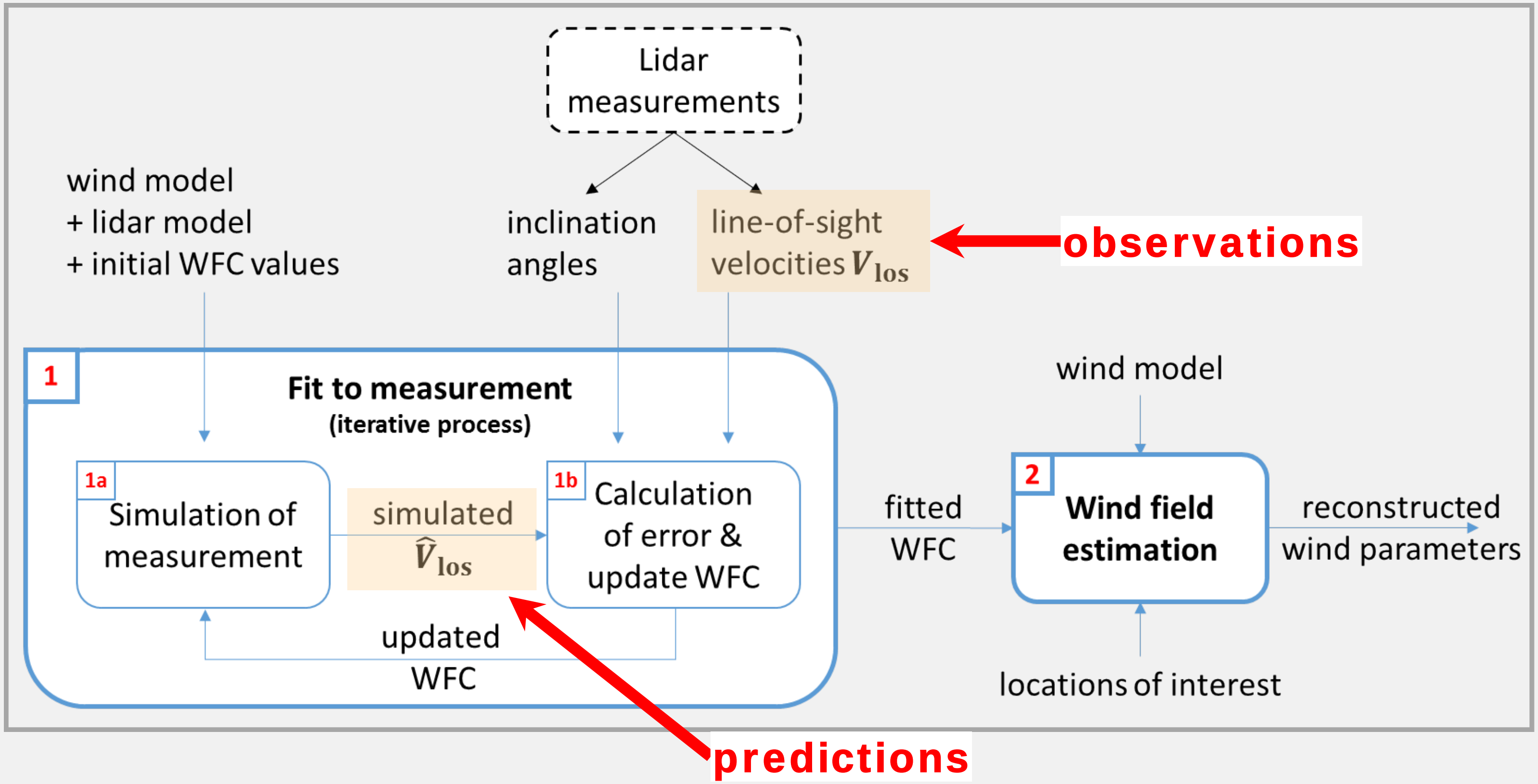



**5B-demo: 4 dist,**
**from 0.5 to @1.2D_rot**

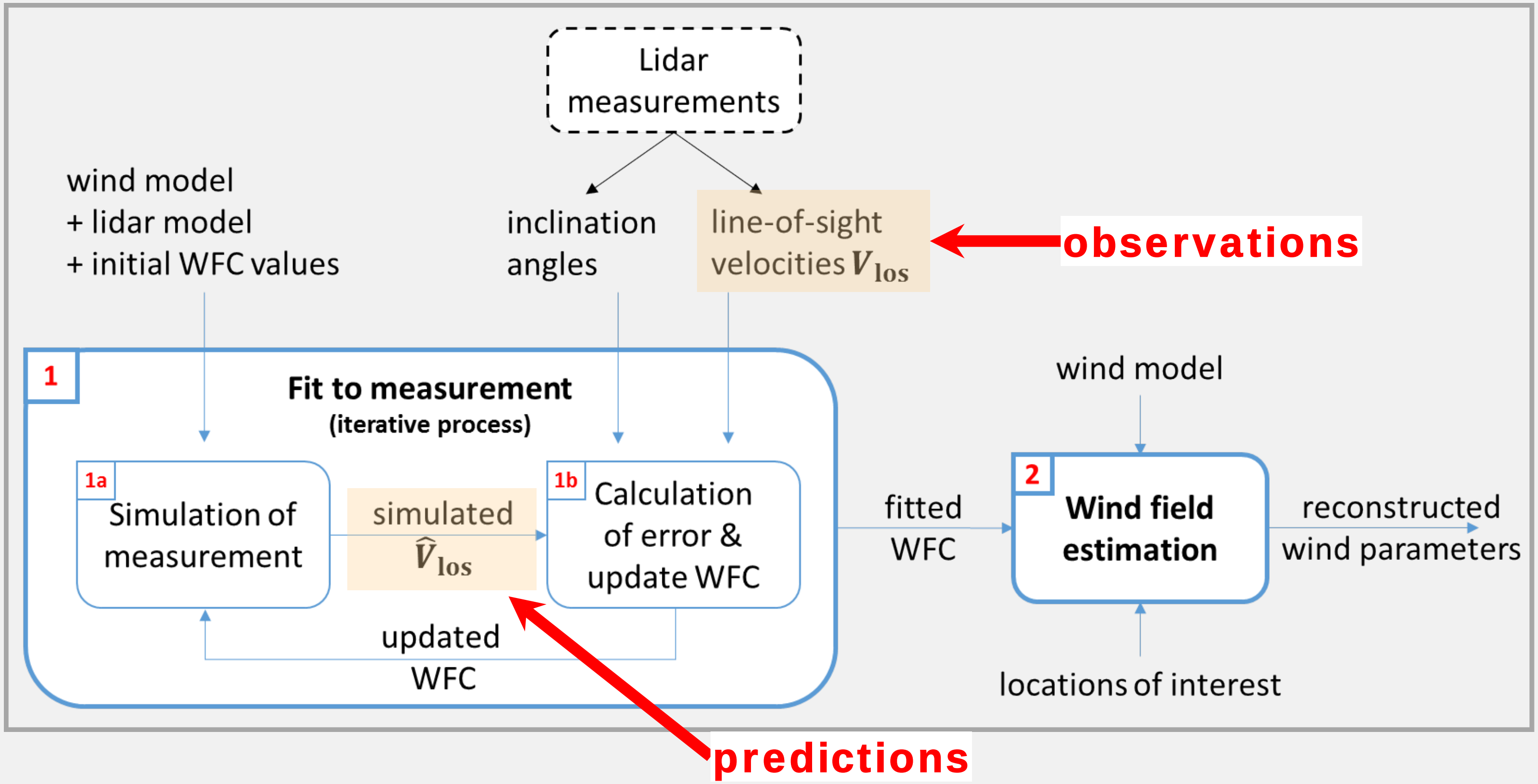
**ZDM: 3 dist.**
**From 0.3 to 1.2D_rot**

# 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": $= abs(V_{los} - \hat{V}_{los})$

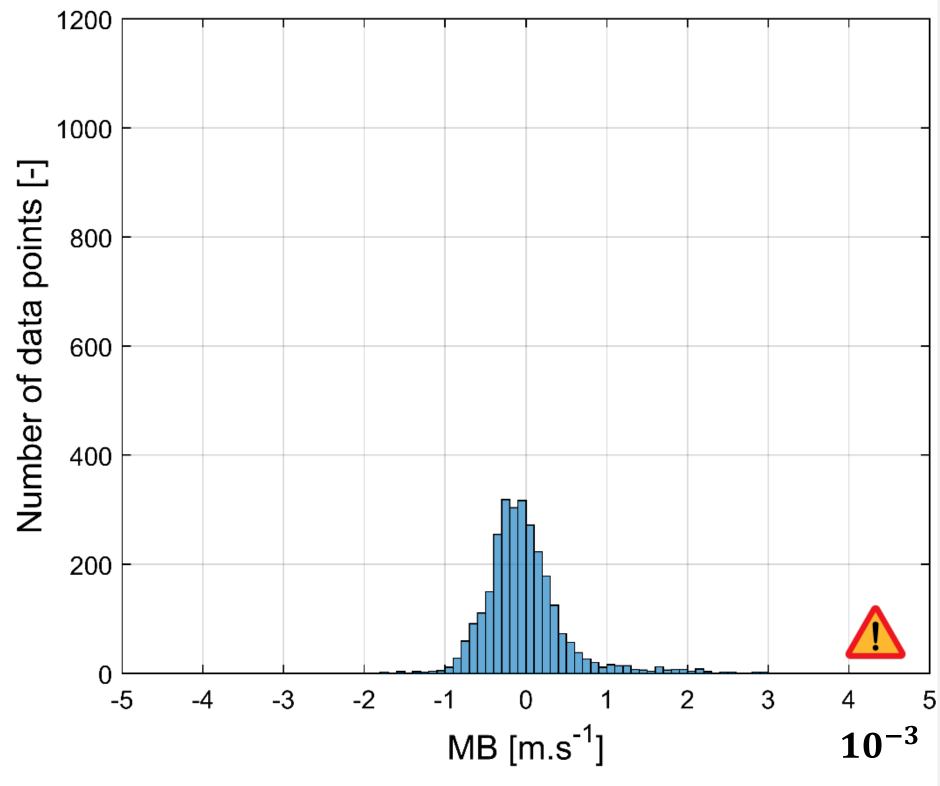
# LOS velocity fitting residuals

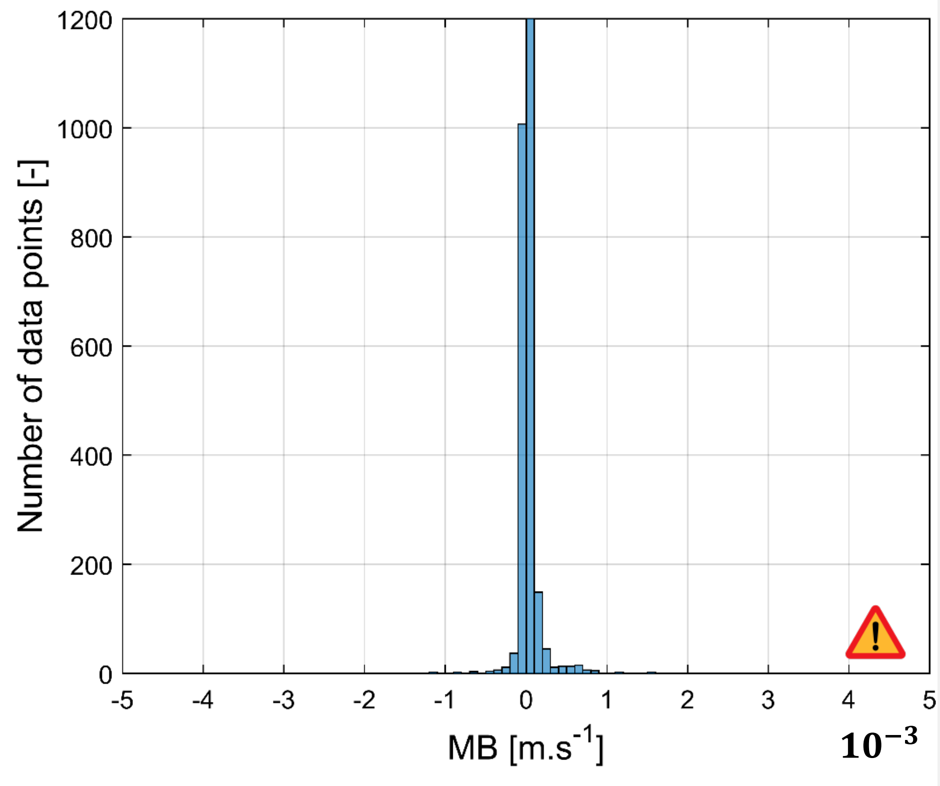



- **Computed stats:**
  - M: mean, N: normalised; F: fractional;
  - S: squared; R: root; SS: sum of squares
  - **MB**, ME, NMB, NME, MFB, MFE, SSE, MSE, **RMSE**, NMSE

# 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**

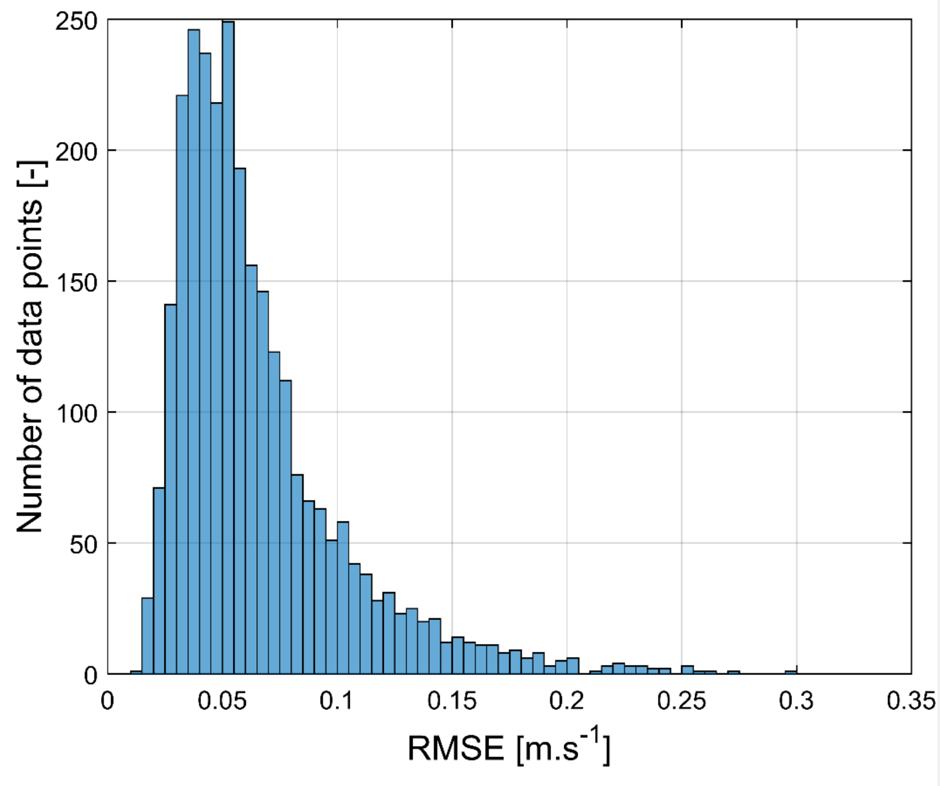
➔ MB show very low values;

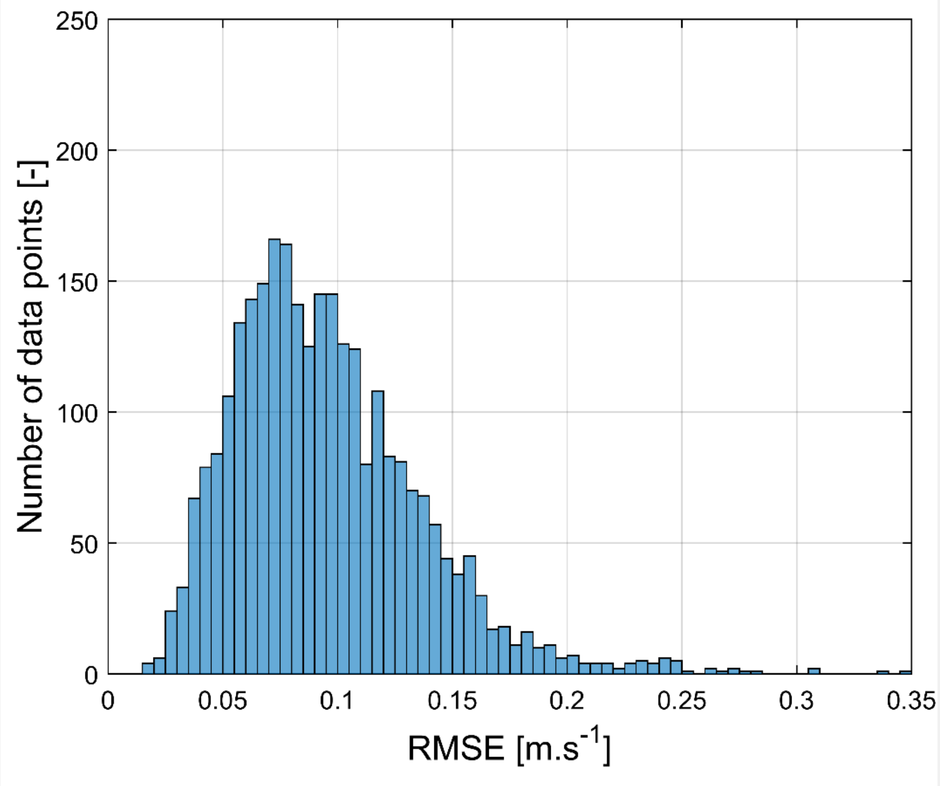
➔ Histogram centered on zero: the used model is “unbiased”

# 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**

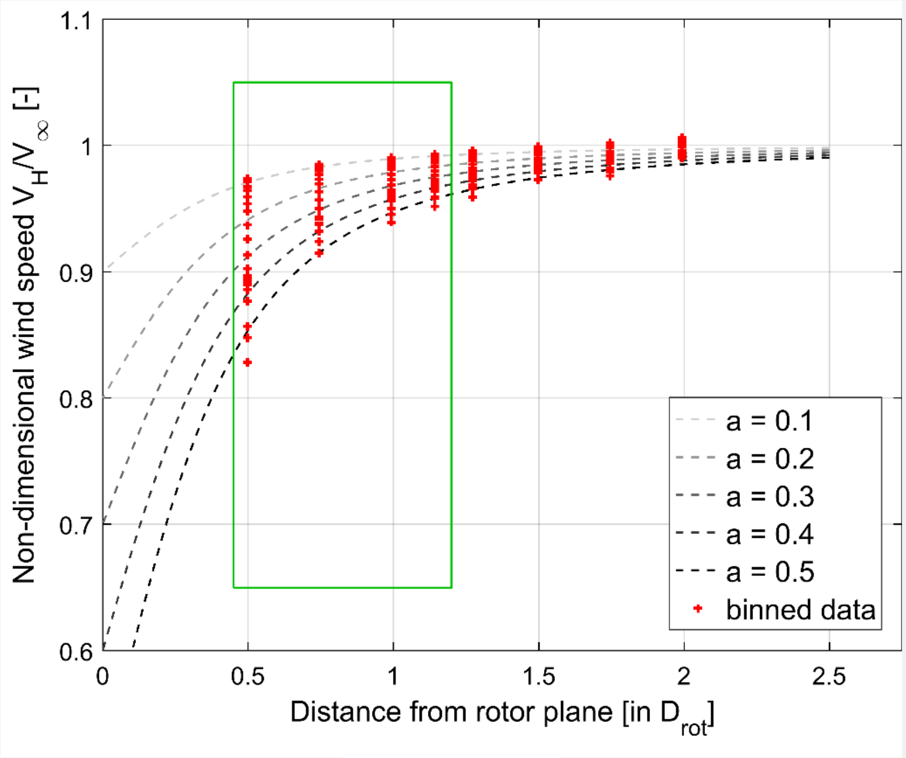
➔ RMSE values between 0 and 0.25 m/s

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

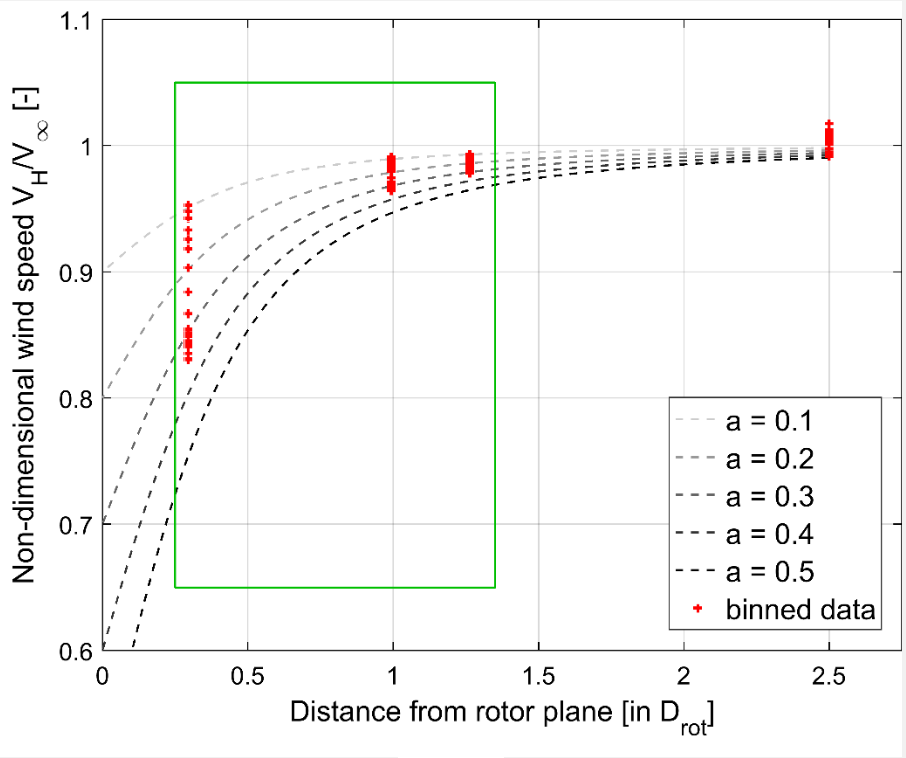
# A simple induction model

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

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




**5B-demo**




**ZDM**

# Simple induction models

- **One- or two- dimensional?**