Power curve measurement using V_∞ estimates from nacelle lidars

ZephIR Dual-Mode *5-beam Avent demonstrator*

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RESEARCH, TECHNOLOGY & GROWTH

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Power performance testing: where are we?

- New standards: IEC 61400-12-1:ed2 (2017)
- What's new?
  - – mast and/or RSD e.g. ground-based lidar
  - – hub height spd + shear measurement or rotor equivalent wind speed
  - – (somewhat) more thorough power curve uncertainty assessment

- But STILL
  - – no nacelle lidar (coming in IEC 61400-50-3)
  - – measurements between $\mathbf{2D_{rot}}$ and $\mathbf{4D_{rot}}$ from the turbine

In my PhD … the story

Link to thesis on DTU's site

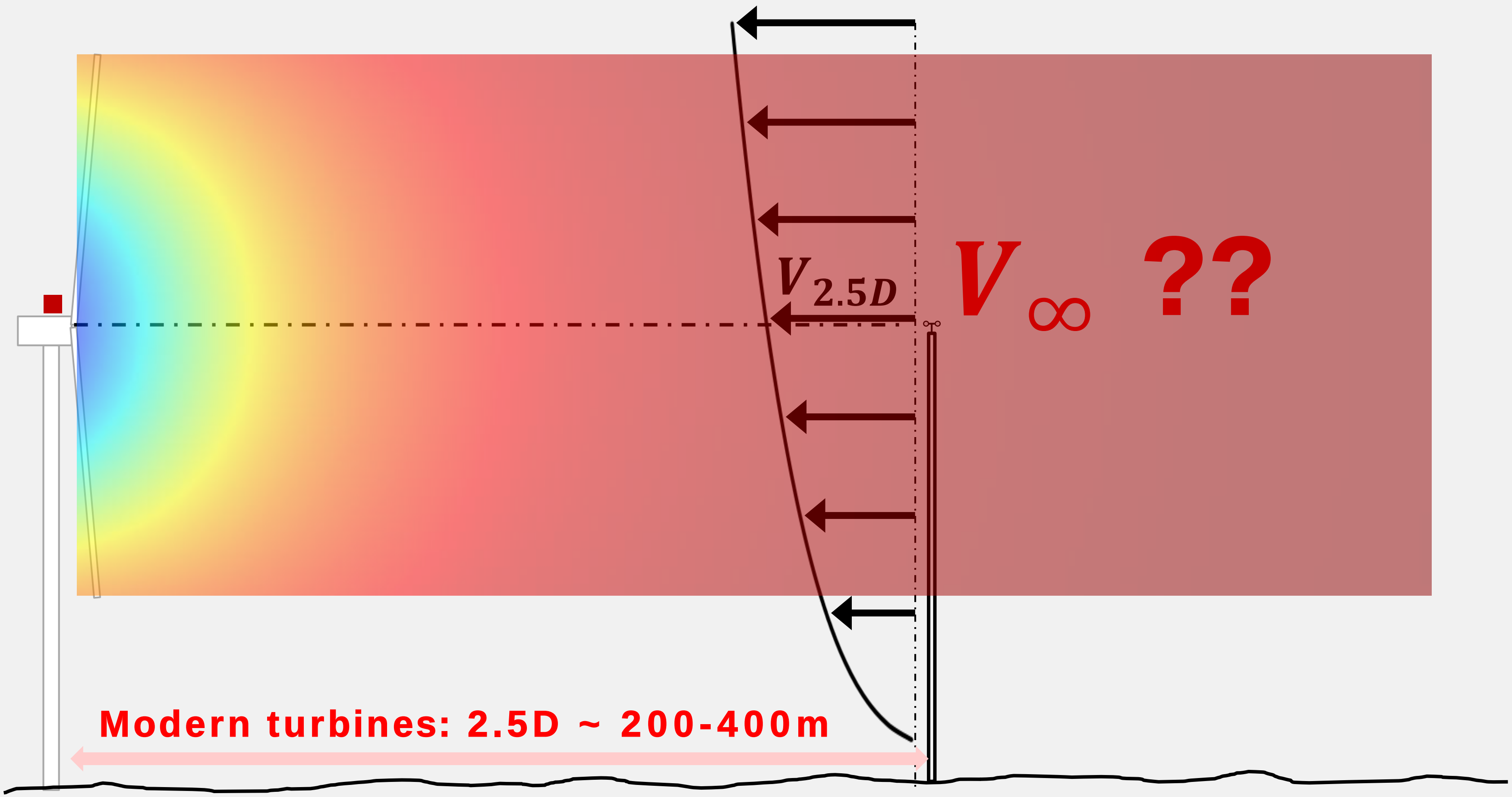
1) "Generic methodology for field calibration of nacelle-based wind lidars" (link)

2) "Wind field reconstruction from nacelle-mounted lidar short-range measurement" (link to WES)

3) Uncertainty propagation in WFR models (using Monte Carlo methods)

4) Applied to power perf.

Searching for free stream wind speed



- Decorrelation WSpeed / power
- H_{hub} speed sufficient?
- 2.5D not really free wind …

Model-fitting wind field reconstruction for power performance testing

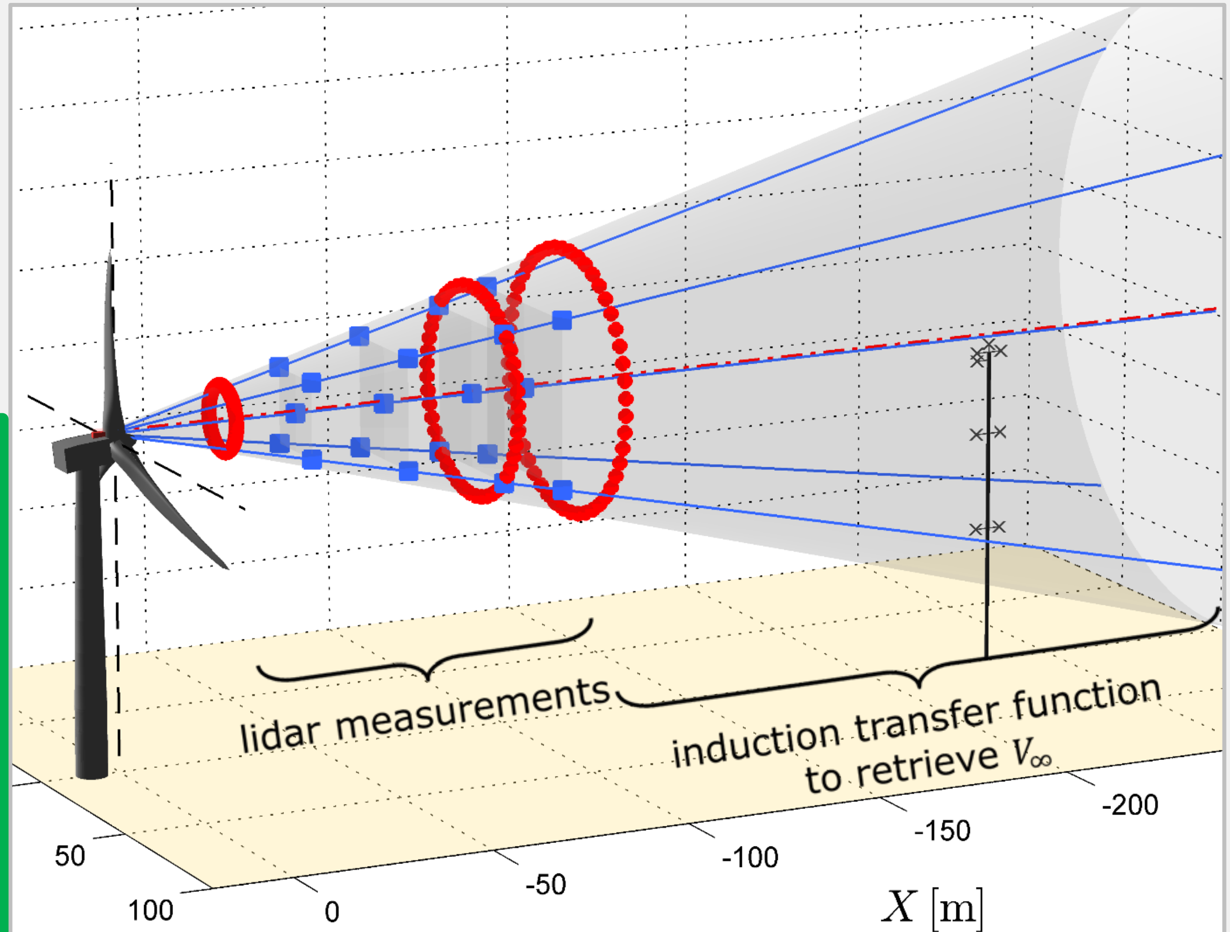
- Several possibilities for lidar measurements:

1) <u>2.5D distance</u>
   fitting wind speed + direction + shear to lidar-measured LOS velocities

2) <u>Multiple distances close to rotor</u>
   induction integrated in wind field reconstruction

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

$$a = \frac{1}{2}\left(1 - \sqrt{1 - C_t}\right)$$



Extrapolation of "true" free stream wind speed

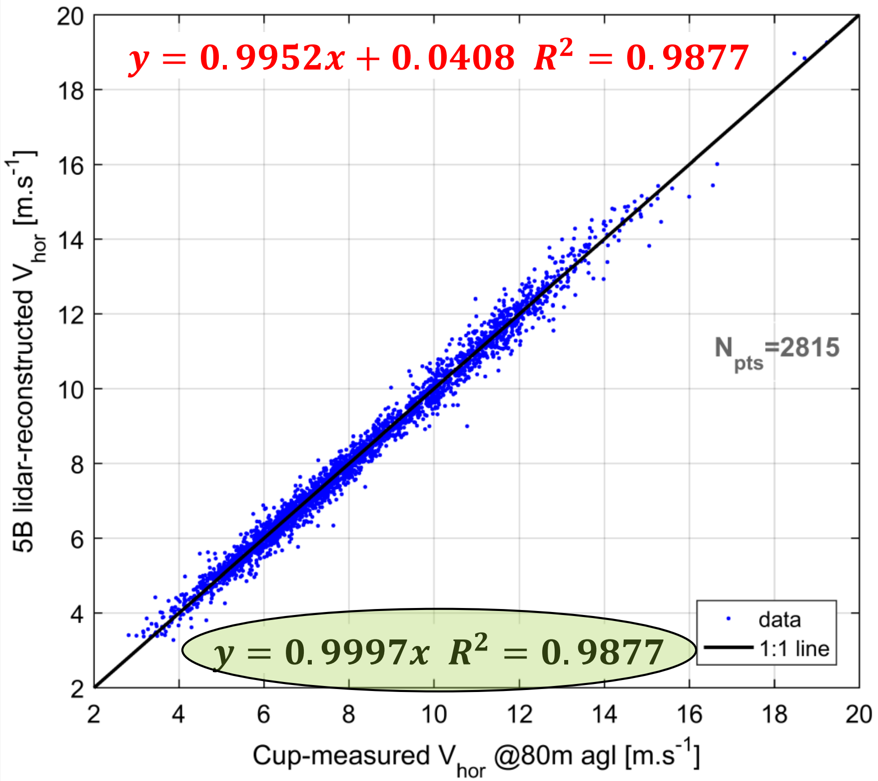
Lidar measurements @ multi-dist (near flow)

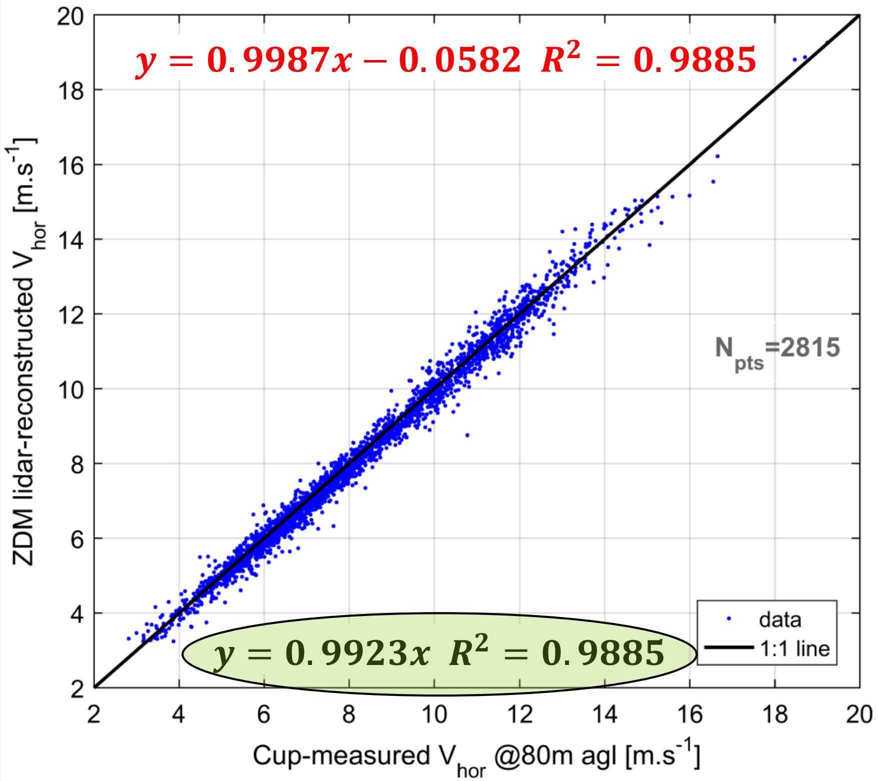
Mast comparison, Nørrekær Enge campaign, 7 months

5B-Demo: use the 5 LOS @[0.5; 0.75 ; 1.0 ; 1.15] D_{rot}

ZDM: use 6 pts @[0.3 ; 1.0 ; 1.25] D_{rot}

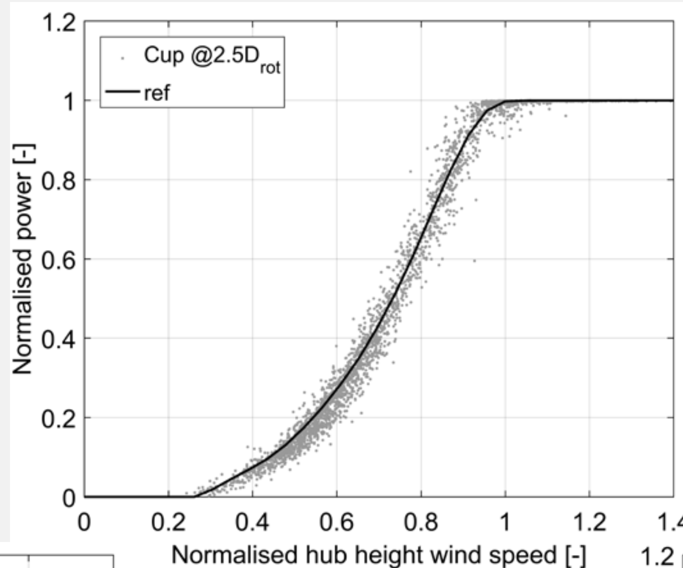
HWS estimated @hub height and @2.5D distance





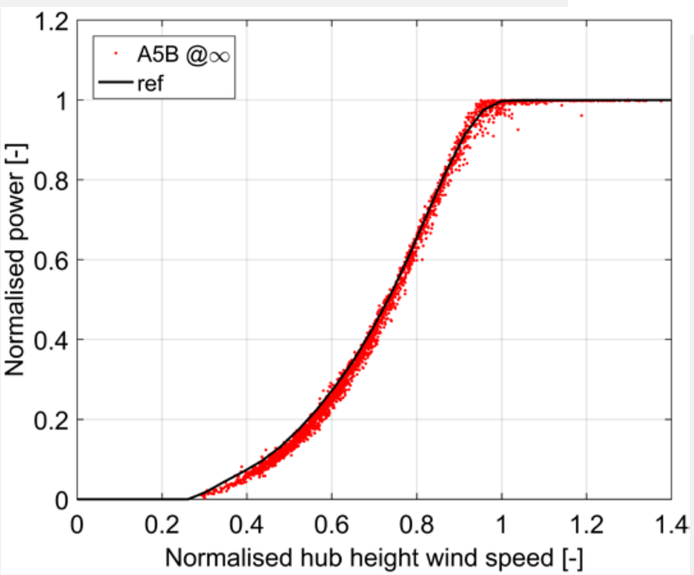
$$N_{points} = 2815$$

Measured power curves – 10-min data

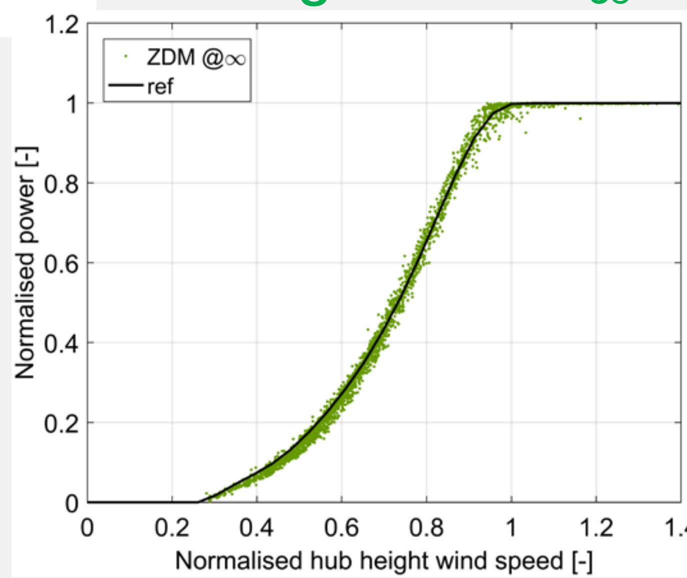


Mast, cup @H_{hub}

5B-Demo
using fitted $\mathbf{V}_\infty$



ZDM
using fitted $\mathbf{V}_\infty$



➔ Accurate

➔ & low scatter

power curves

can be measured ..

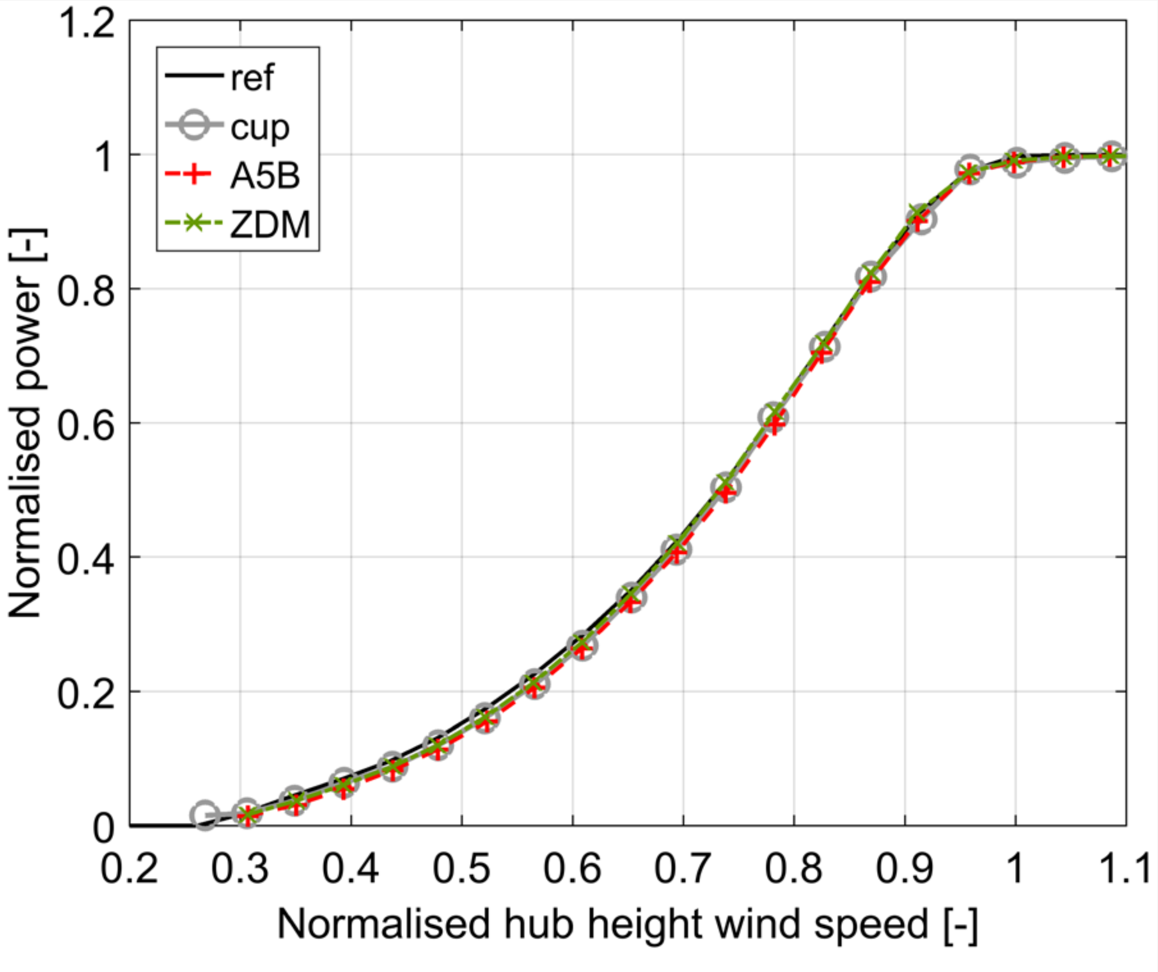
Using nacelle lidar measurements close to turbine rotor!

Measured power curves – binned data

5B-Demo
using fitted $\mathbf{V}_\infty$

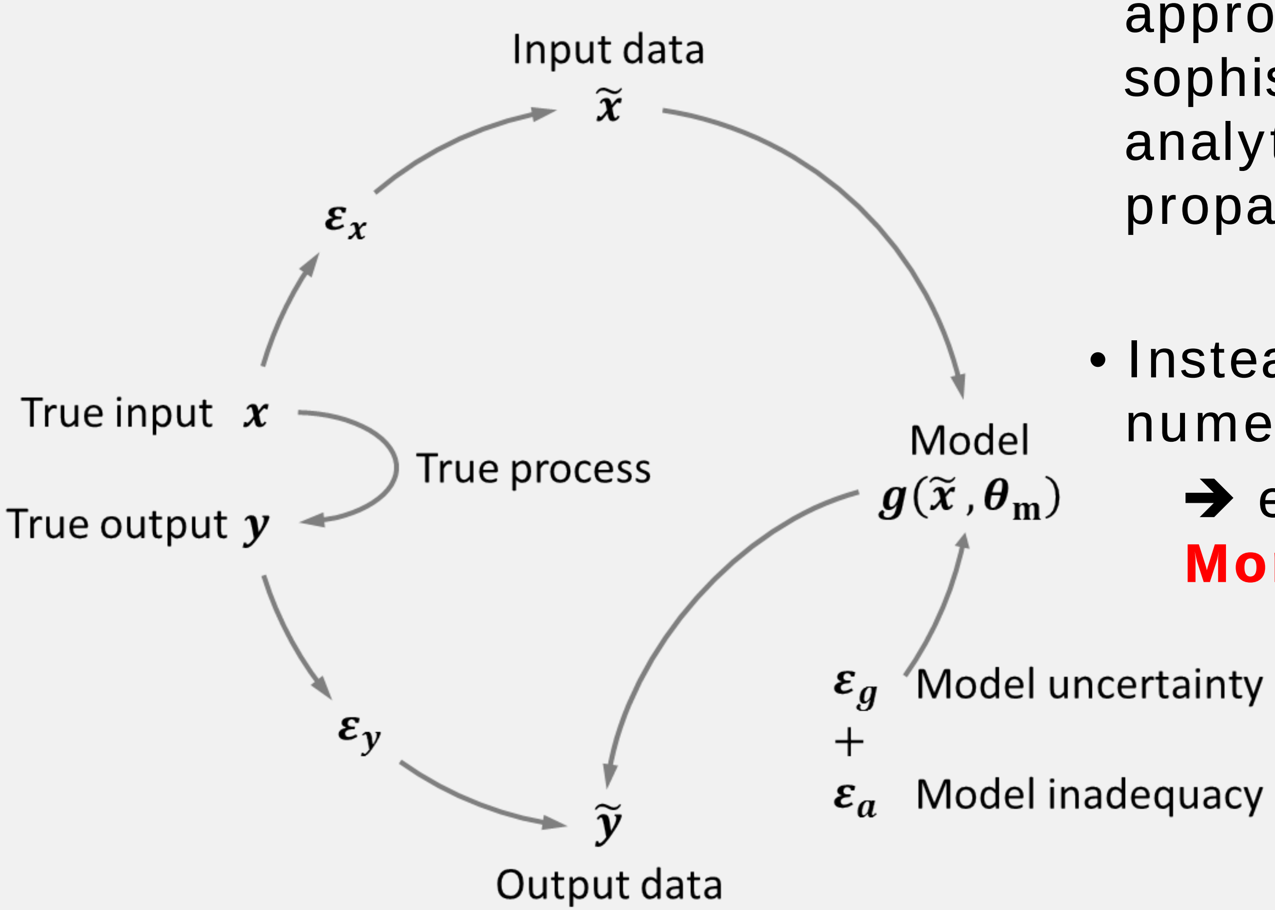
Mast, cup
@H_{hub}

ZDM
using fitted $\mathbf{V}_\infty$



Uncertainty quantification in WFR models

- **Models are always wrong**
  ➔ framework for UQ



- The model-fitting WFR approach is too sophisticated for using analytical uncertainty propagation (“GUM”)

- Instead we can use numerical techniques:
  ➔ e.g.
  Monte Carlo methods

Monte Carlo UQ results for combined wind-induction WFR model

$U(V_\infty)$ $U(\theta_r)$ $U(\alpha_{exp})$ $U(a_{ind})$

vs spd V_∞

vs relative dir. θ_r

vs shear exponent α_{exp}

vs induction factor a_{ind}

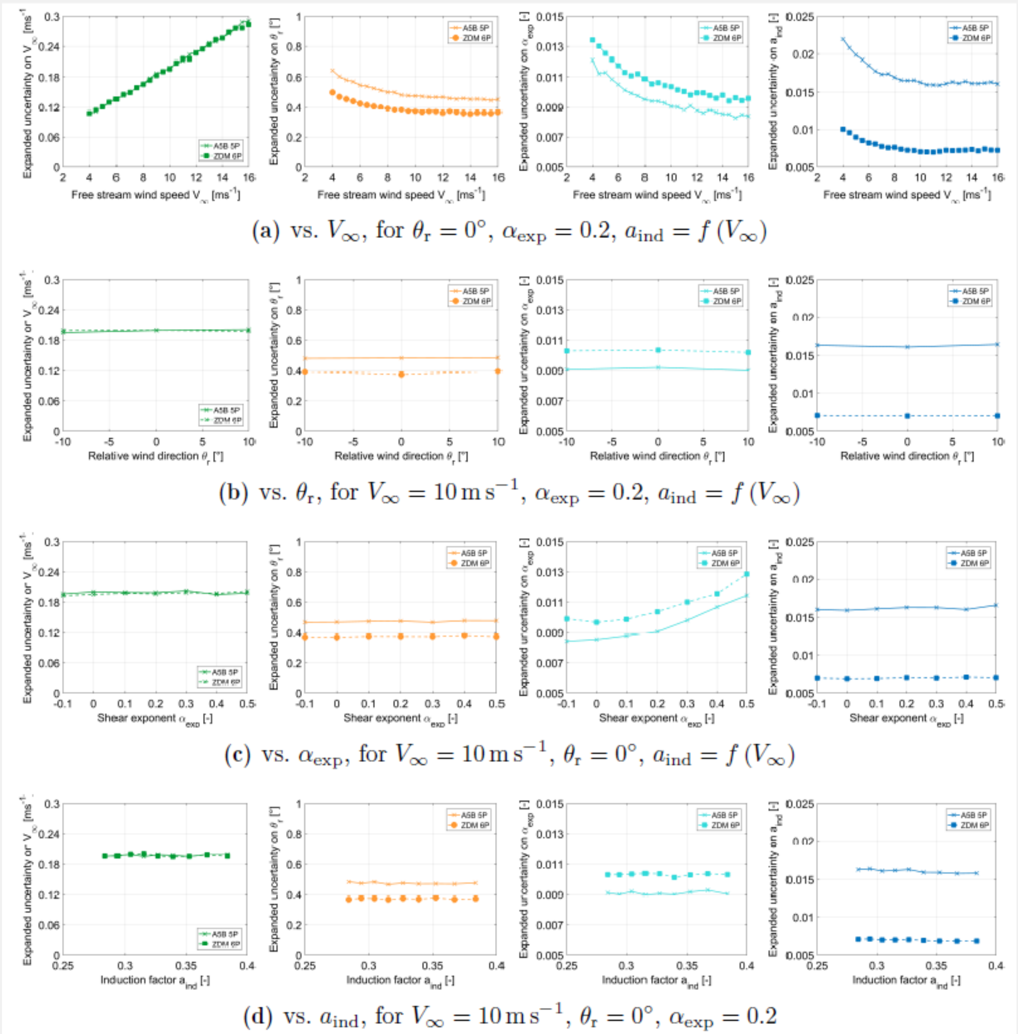
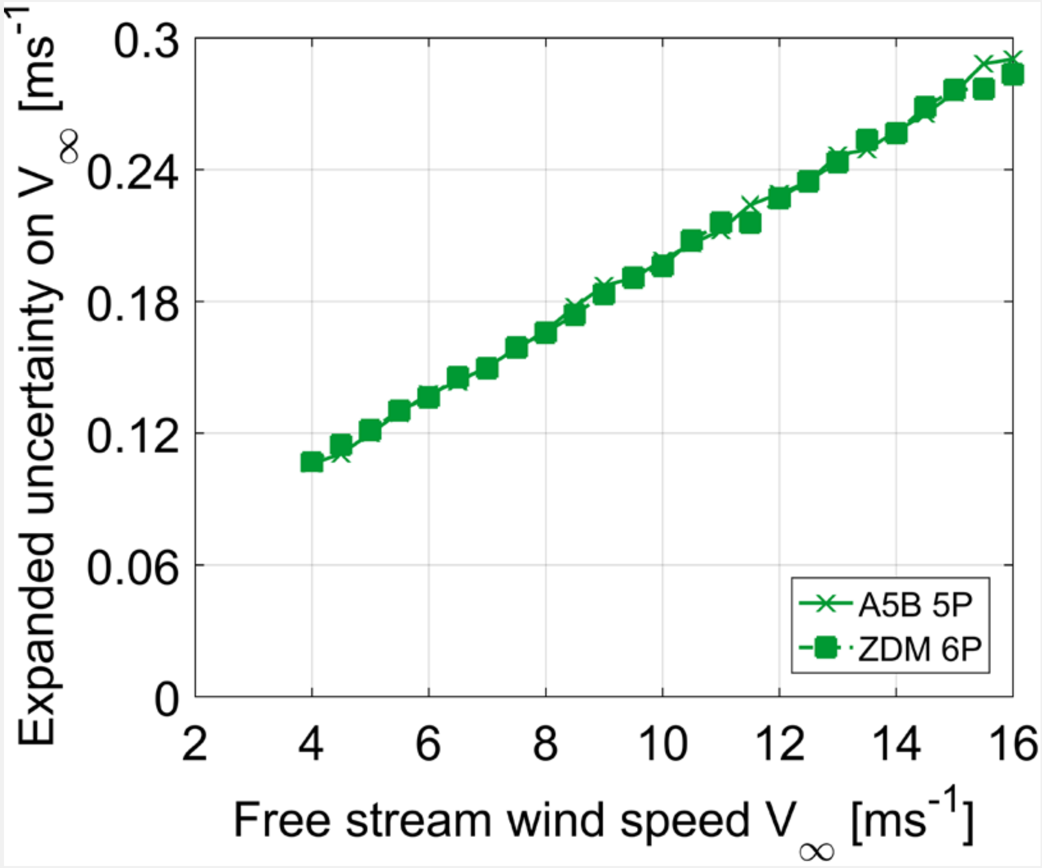


Figure 4.11: Profiling nacelle lidars MC results: expanded uncertainties U_{V_H}, U_{θ_r}, $U_{\alpha_{exp}}$, $U_{a_{ind}}$ as a function of V_H, θ_r, α_{exp} and a_{ind}.

Monte Carlo UQ results for combined wind-induction WFR model



Conclusion

the model uncertainty on V_∞ estimated by the nacelle lidars is negligibly different from the wind speed uncertainty of the reference anemometer used during the LOS velocity calibration campaign

Power curve uncertainty assessment (1/4)

- The **procedure is based on the new standards** IEC 61400-12-1:ed2 (2017)

➔with some deviations:
no “method” uncertainty considered (related to REWS, and shear, veer, TI normalisation, etc)

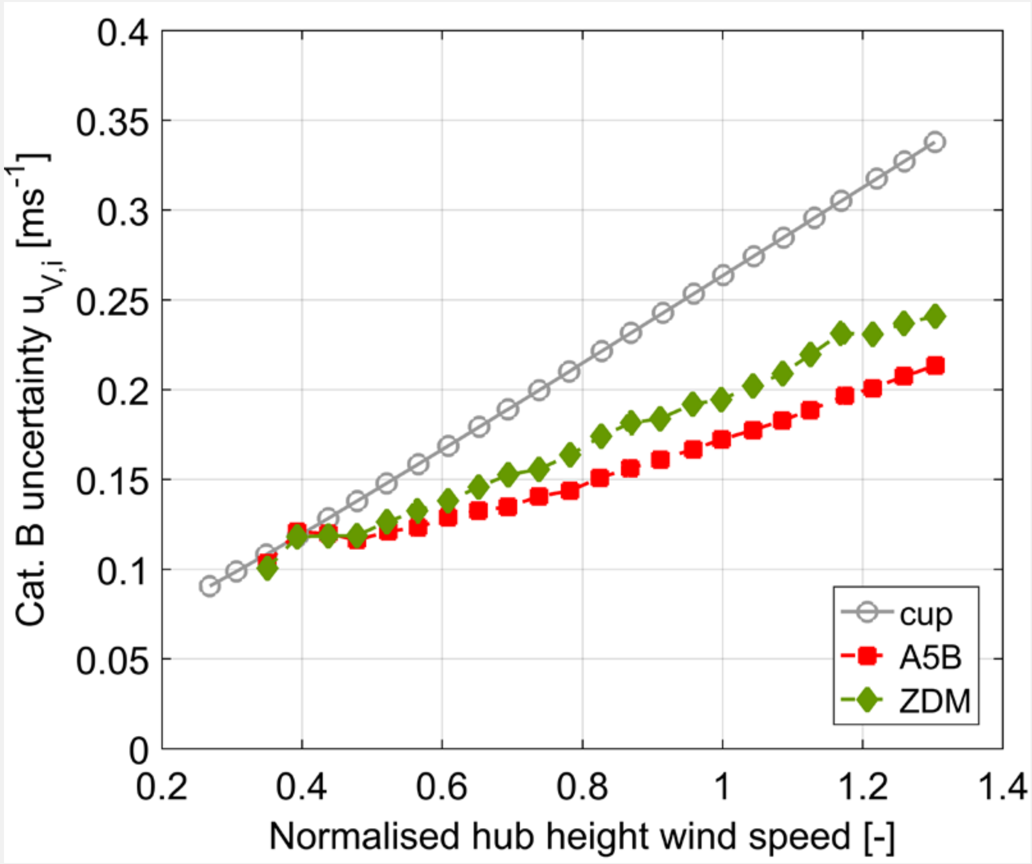
- Method to estimate the cat. B wind speed unc. for the lidars combines the **model uncertainty (Monte Carlo) with fitting residuals** (inadequacy)

- **The “flow distortion uncertainty”**

➔2% for the cup (no site cal, default IEC for 2.5D dist)

➔1% for the lidars: fair enough since measurements taken close to the rotor (about $1D_{rot}$)

Power curve uncertainty assessment (2/4) cat. B wind speed uncertainty



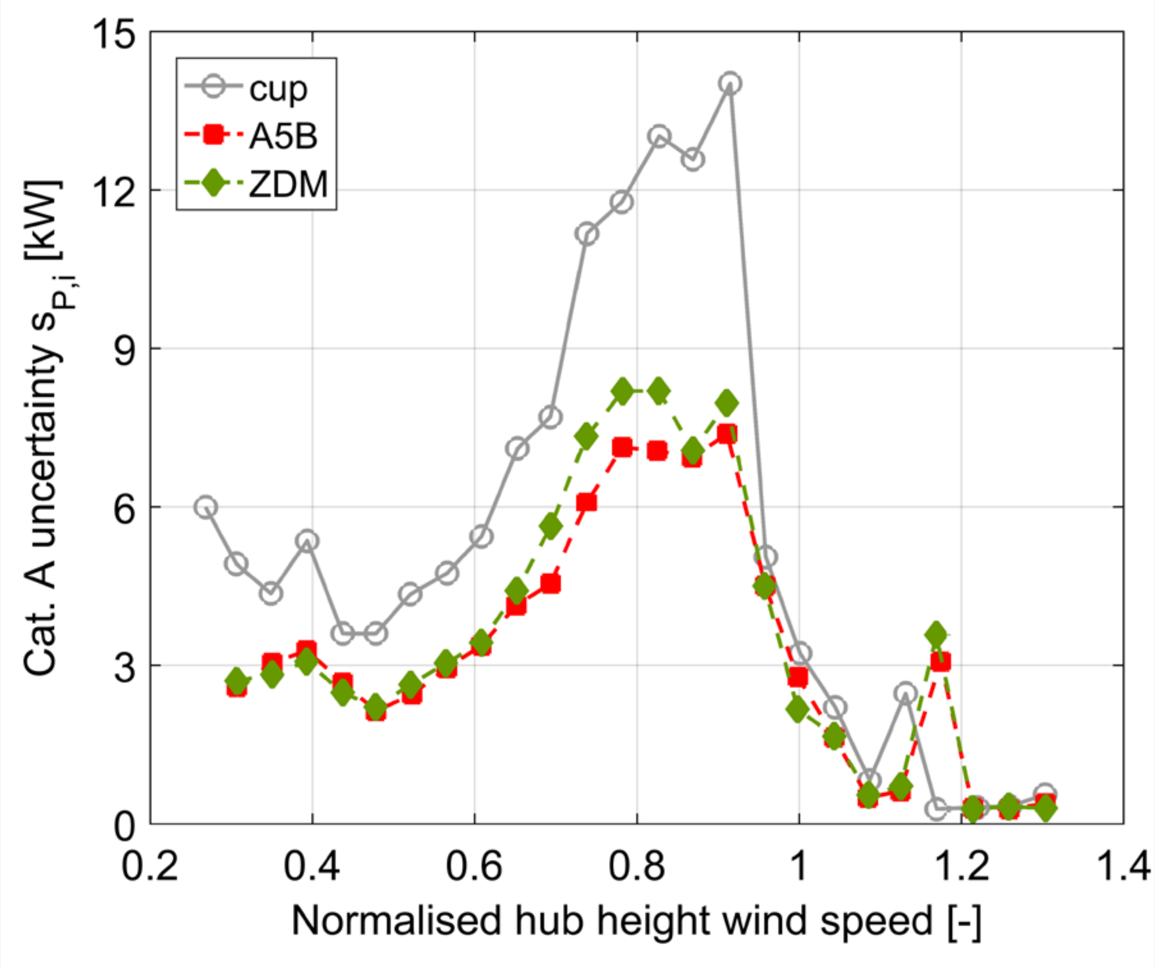
- The reduction of combined wind speed uncertainty is "artificial" since due to the different flow distortion uncertainty value

➔ need for finer quantification of this component in standards

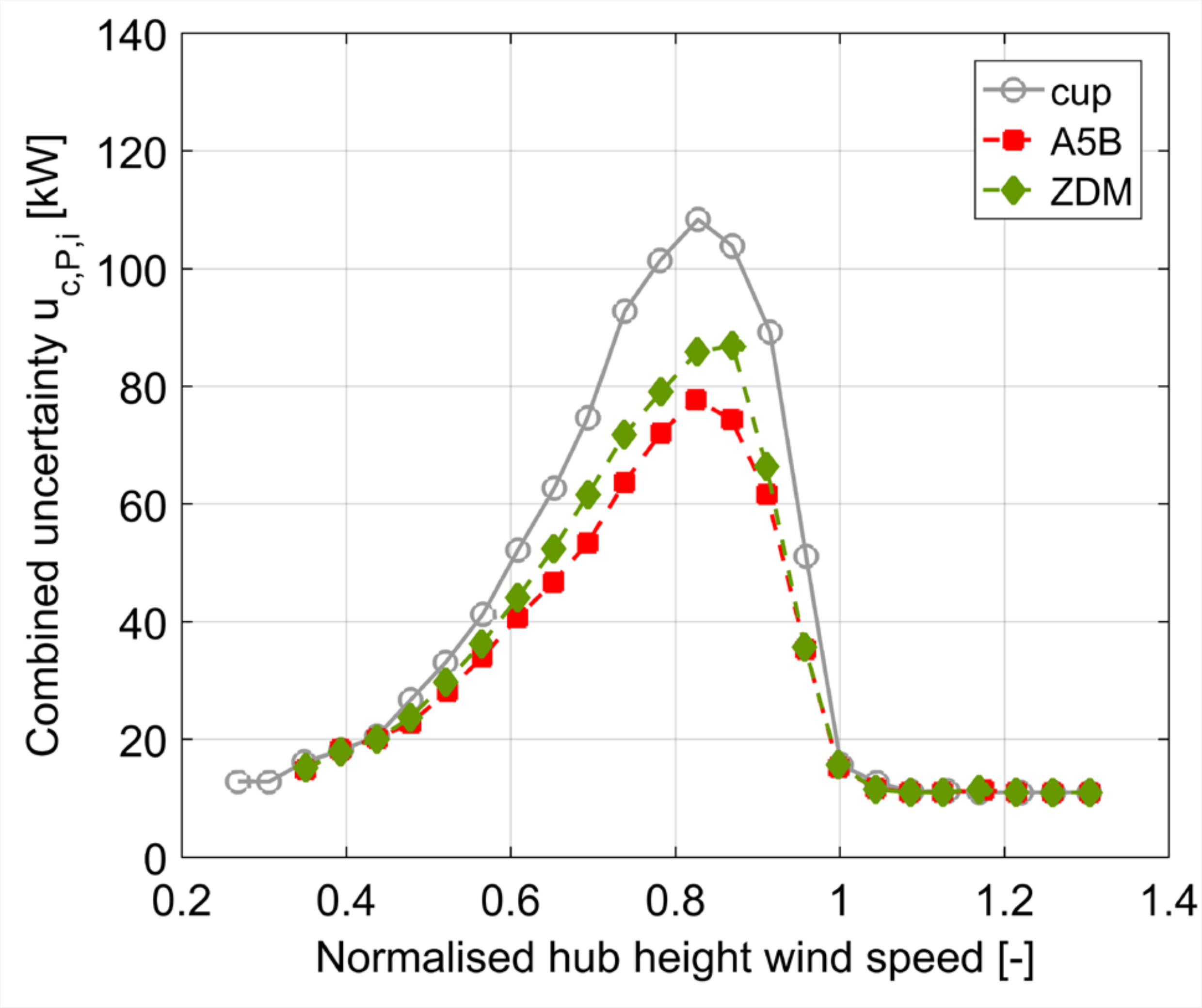
- Fitting residuals slightly higher for ZDM than 5B-Demo explain the difference

Power curve uncertainty assessment (3 / 4)
cat. A power uncertainty

Lower scatter for the measured power curves with the lidars ➔ lower cat. A uncertainty on power output



Power curve uncertainty assessment (4/4)
combined power curve uncertainty (k=1)



Take-aways

V_∞ is found!

- The solution: measurements close to rotor, within the induction zone, at multiple distances, e.g. with nacelle lidars

  ➔ ***no need for more powerful lasers!***

- **Wind Field Reconstruction** algo. provide estimates comparable to classic mast instrumentation ($< 1\%$ difference)

- **Power curves** in flat terrain verified accurately, reduced scatter (as usual with nacelle lidars)

  ➔extinction of the "met. mast species" is coming... the dinosaurs of wind measurements

  ➔next generation of IEC standards work ongoing (-50-3)

  ➔some studies on PCurve uncertainty assessment desirable

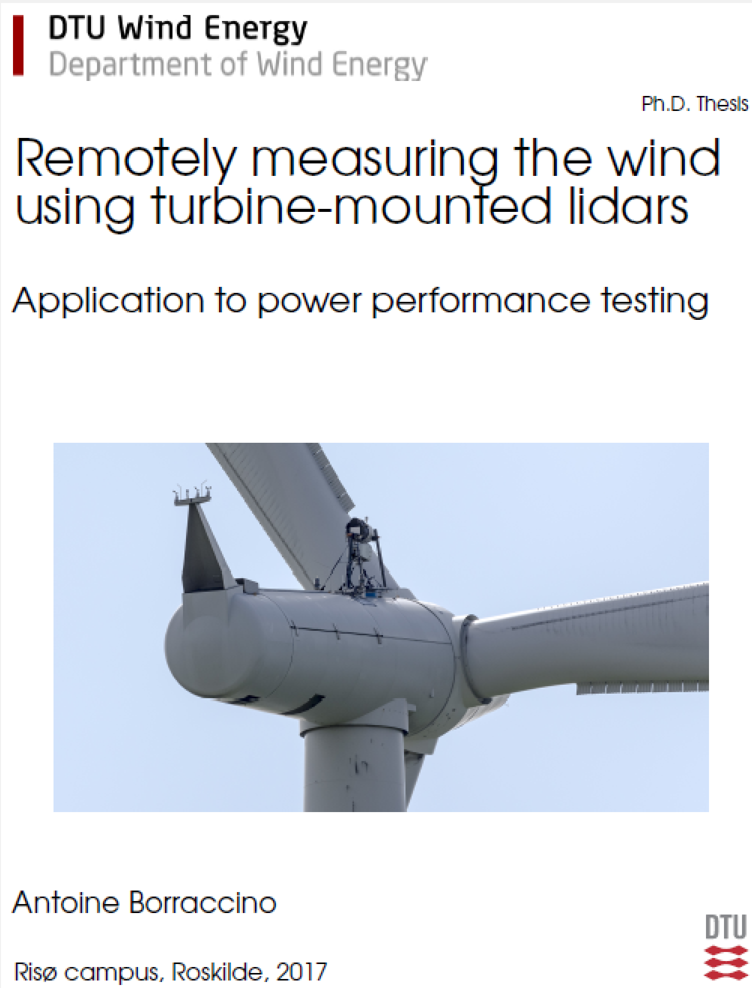
Coming soon in UniTTe:

- Complex terrain: demonstration of nacelle lidar short-range measurement technique in two campaigns

  ➔ Hill Of Towie, Scotland (*RES*), **ZDM** & **4-beam Wind Iris**

  ➔ Ogorje, Croatia (*Akuo Energy*), with a 4-beam Wind Iris

Thanks for your attention!


DTU Wind Energy
Department of Wind Energy

Ph.D. Thesis

Remotely measuring the wind using turbine-mounted lidars

Application to power performance testing

Antoine Borraccino

Risø campus, Roskilde, 2017

More info:

- website www.unitte.dk
- contact borr@dtu.dk

Acknowledgements

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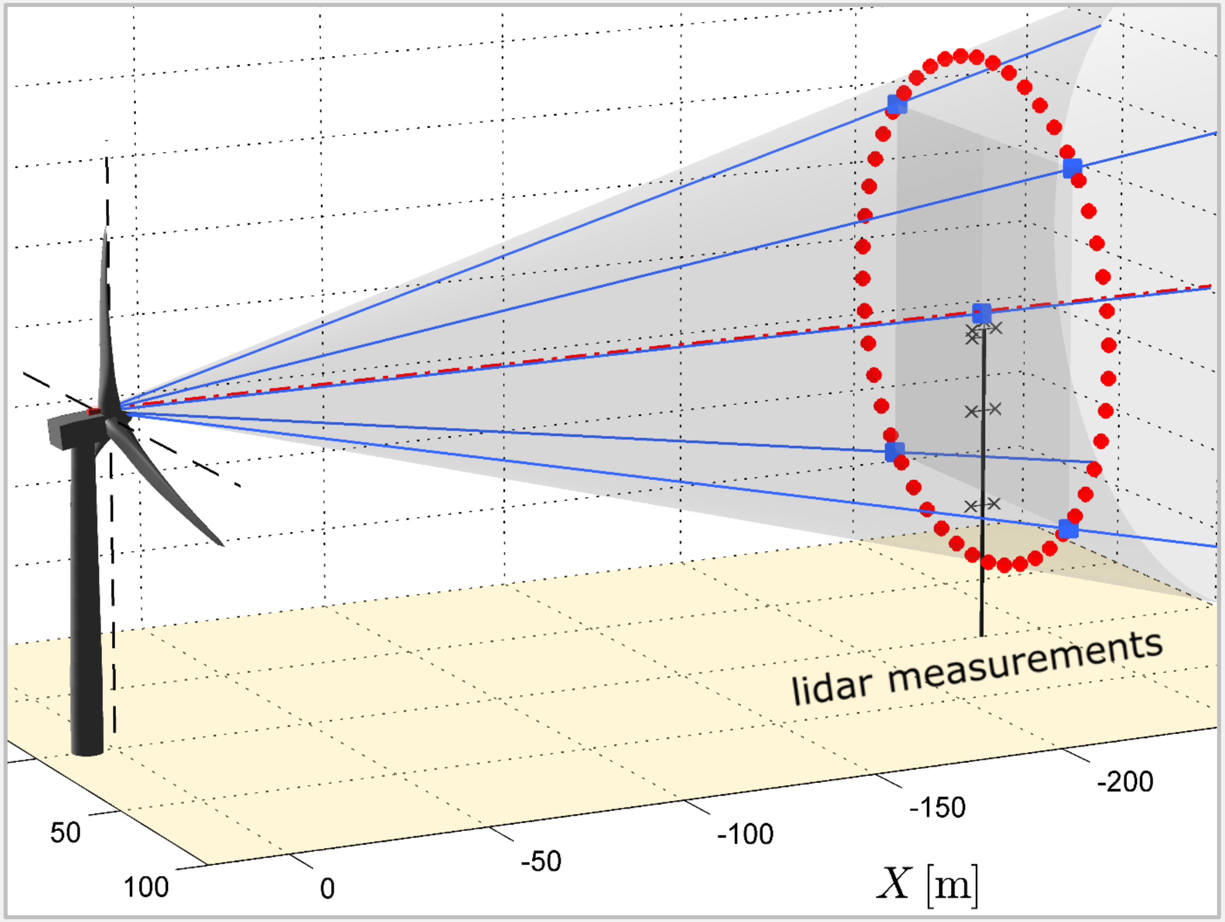
Model-fitting Wind Field Reconstruction for power performance testing

- Several possibilities for lidar measurements:

1) <u>2.5D distance</u>
   fitting wind speed + direction + shear to lidar-measured LOS velocities

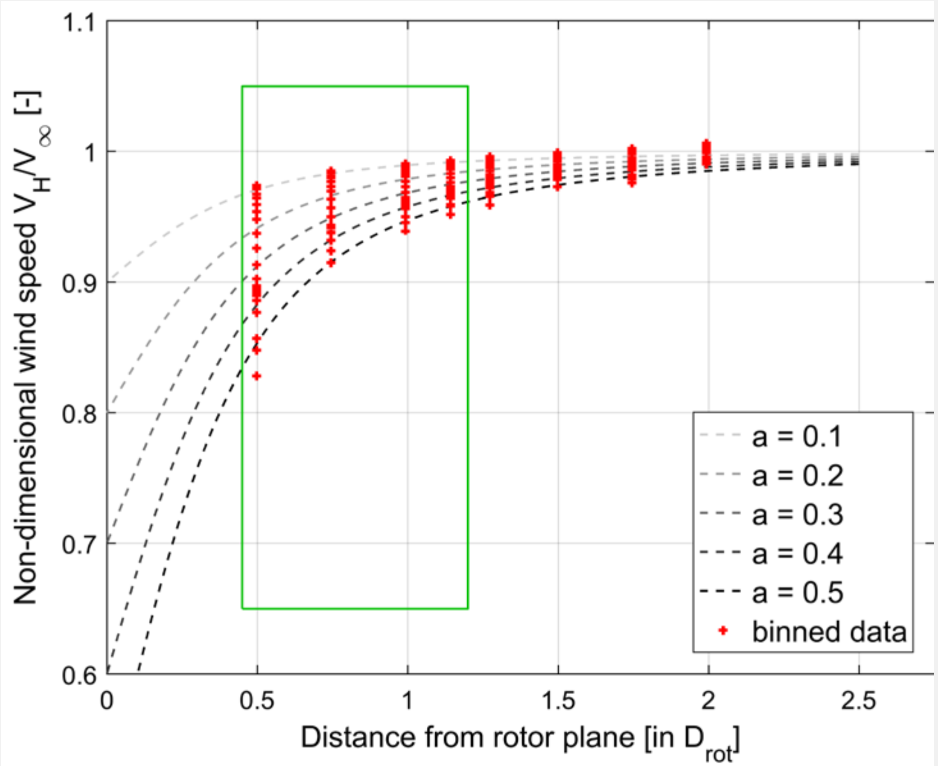


Wind speed evolution within the induction

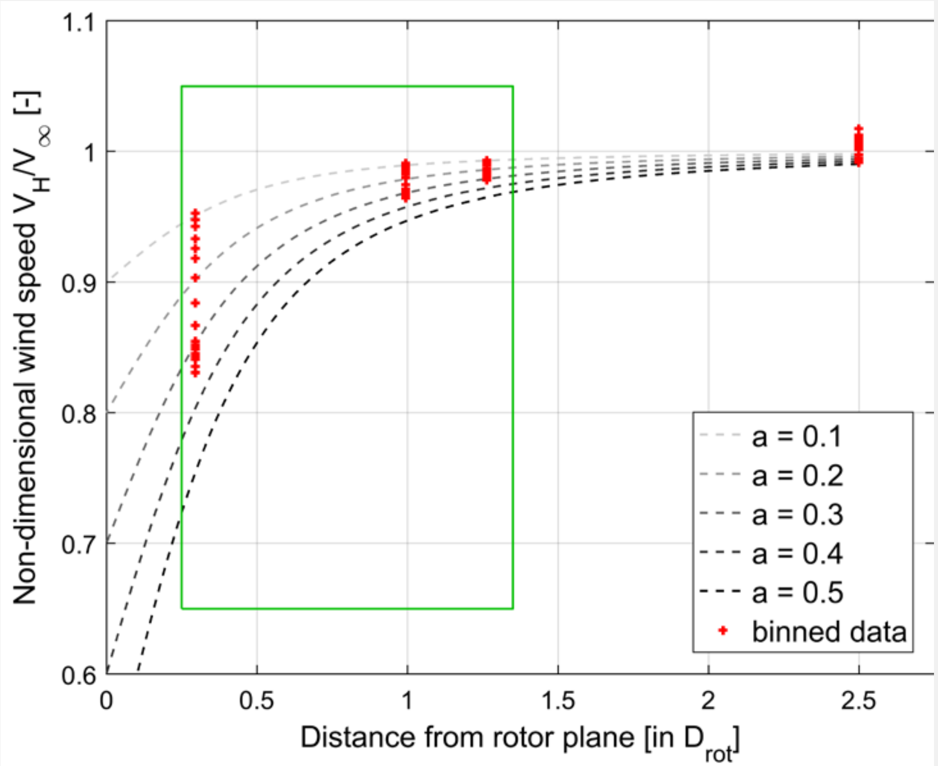
Process:

1) lidar-estimated H_{hub} speed @each distance adimensionned by lidar-estimated $\mathbf{V}_\infty$ (for each 10min period)
2) Averaging of non-dimensional spd by $\mathbf{V}_\infty$ bins of 0.5 ms^{-1}

5B-Demo



ZDM

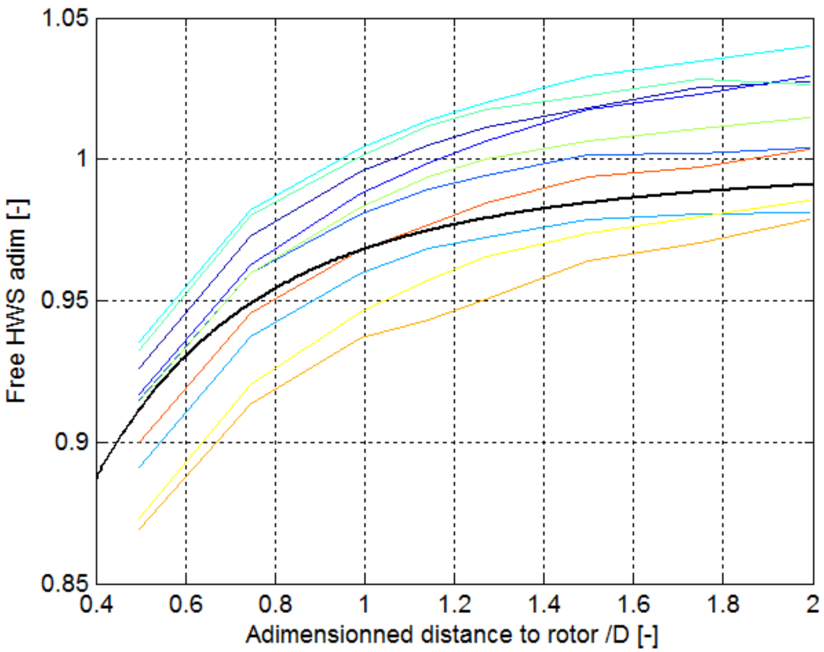


A simple induction model

- **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_∞

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

- **What does the induction looks like in NKE?**



Black: theoretical, $a = 0.3$

Colored lines: different 10min periods

➔Fitting a and U_∞ should be possible

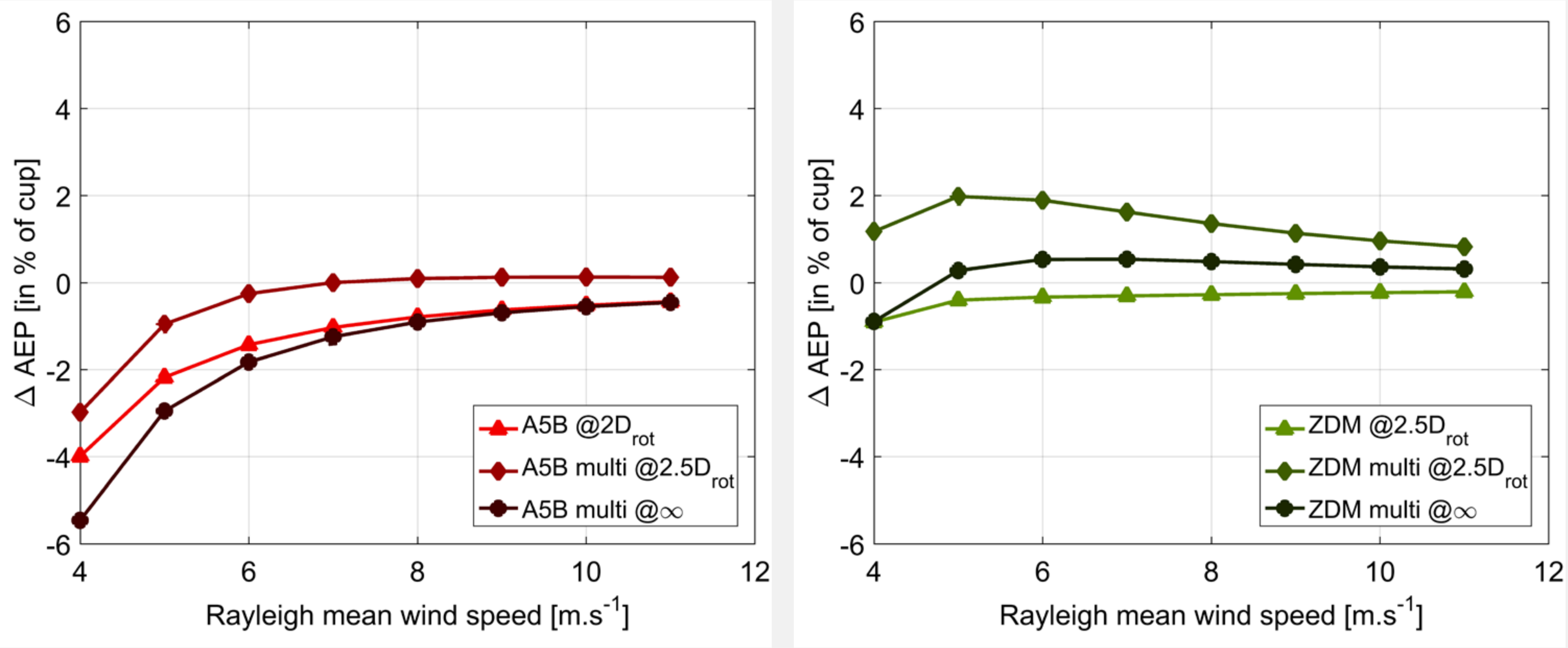
AEP results

- IEC -12-1 methodology
- extrapolated AEPs
- 0.5 m/s bin width
- Relative difference in % of cup-based AEP
- Rayleigh avg speed = 8 m/s

Lidar measurements	**@2D (5B-Demo) @2.5 D ZDM)** (case 1)	**multiple distances @ ∞** (case 2)
Avent 5-Beam demonstrator lidar	Wspeed difference: +0.59%	Wspeed difference: +0.52%
	-0.8%	-0.9%
Zephir Dual Mode lidar	Wspeed difference: +0.32%	Wspeed difference: -0.27%
	-0.3%	+0.5%

➔AEP estimations as good with the "multi-distances" method as with the 2.5D (<1.5% difference)

AEP results



Δ AEP [in % of cup]
Rayleigh mean wind speed [m.s^{-1}]
A5B @2D$_{rot}$
A5B multi @2.5D$_{rot}$
A5B multi @∞
ZDM @2.5D$_{rot}$
ZDM multi @2.5D$_{rot}$
ZDM multi @∞

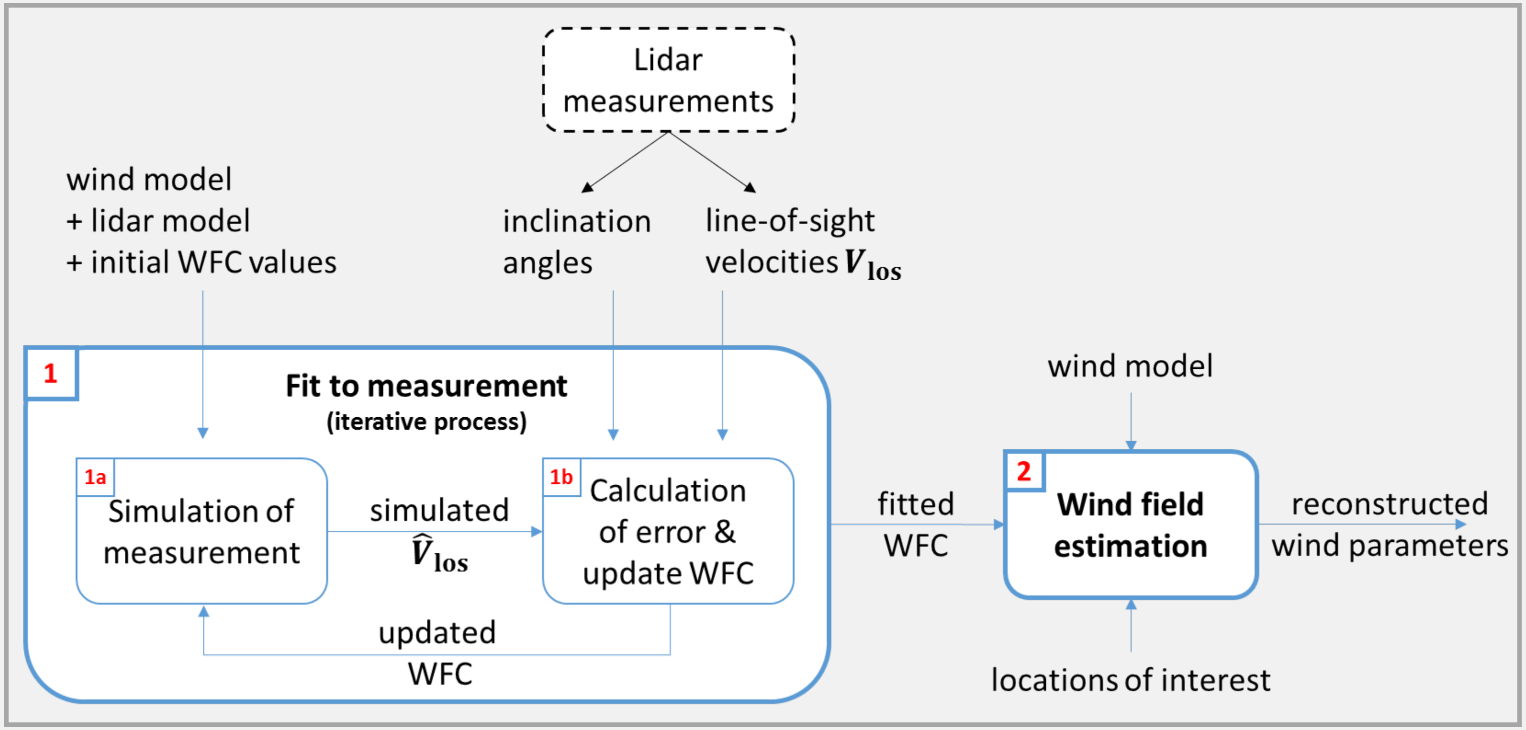
Model-based wind field reconstruction

- **Doppler wind LiDaRs do not…**

…measure wind speed, wind direction, shear, …

see Hardesty, 1987 (wonderful description of lidar principles)

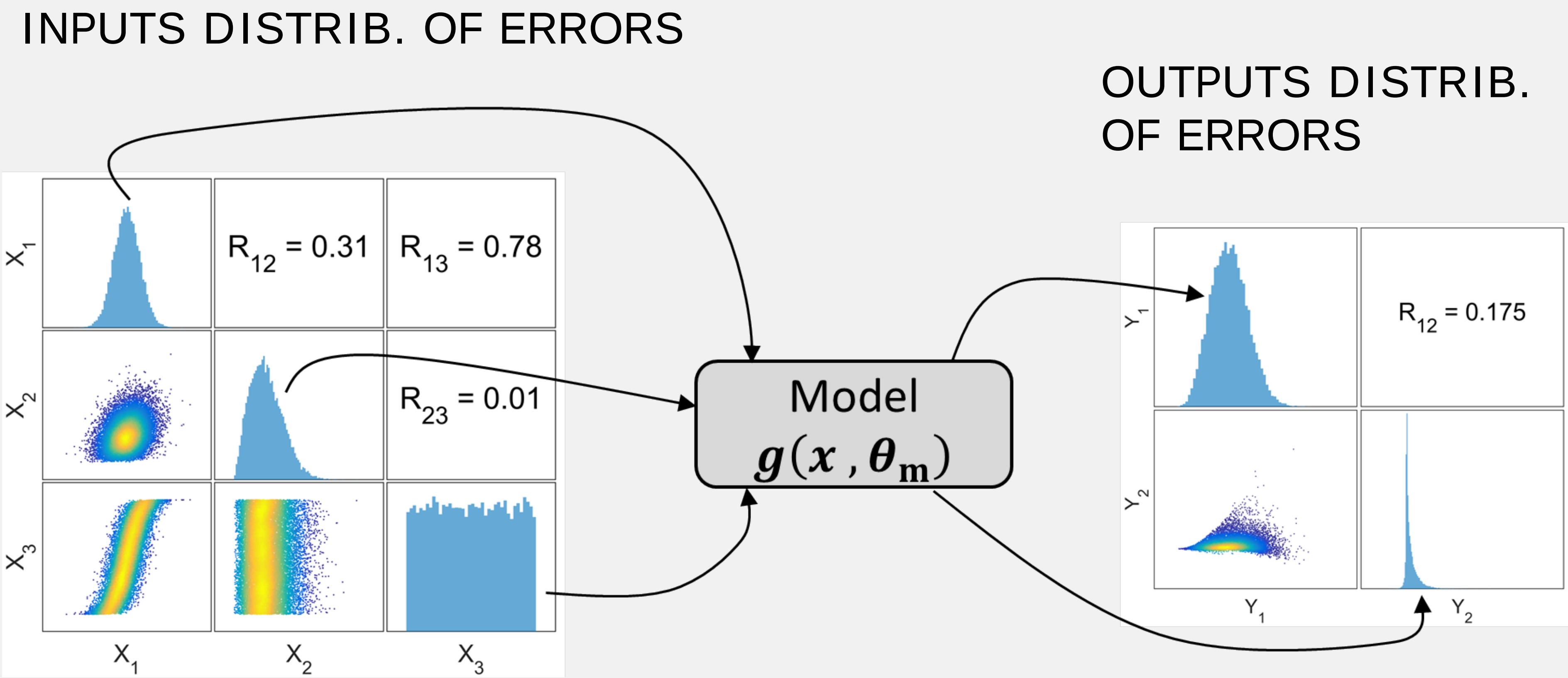
- **They:**
  - only measure LOS velocities
  - estimate/reconstruct wind field characteristics (WFC)



Does this make it any easier?

- In complex terrain:
  - any ”free stream” wind speed idea?
  - site calibration? Maybe
- Offshore:
  - mast expensive
  - free wind may not be measurable due to wakes

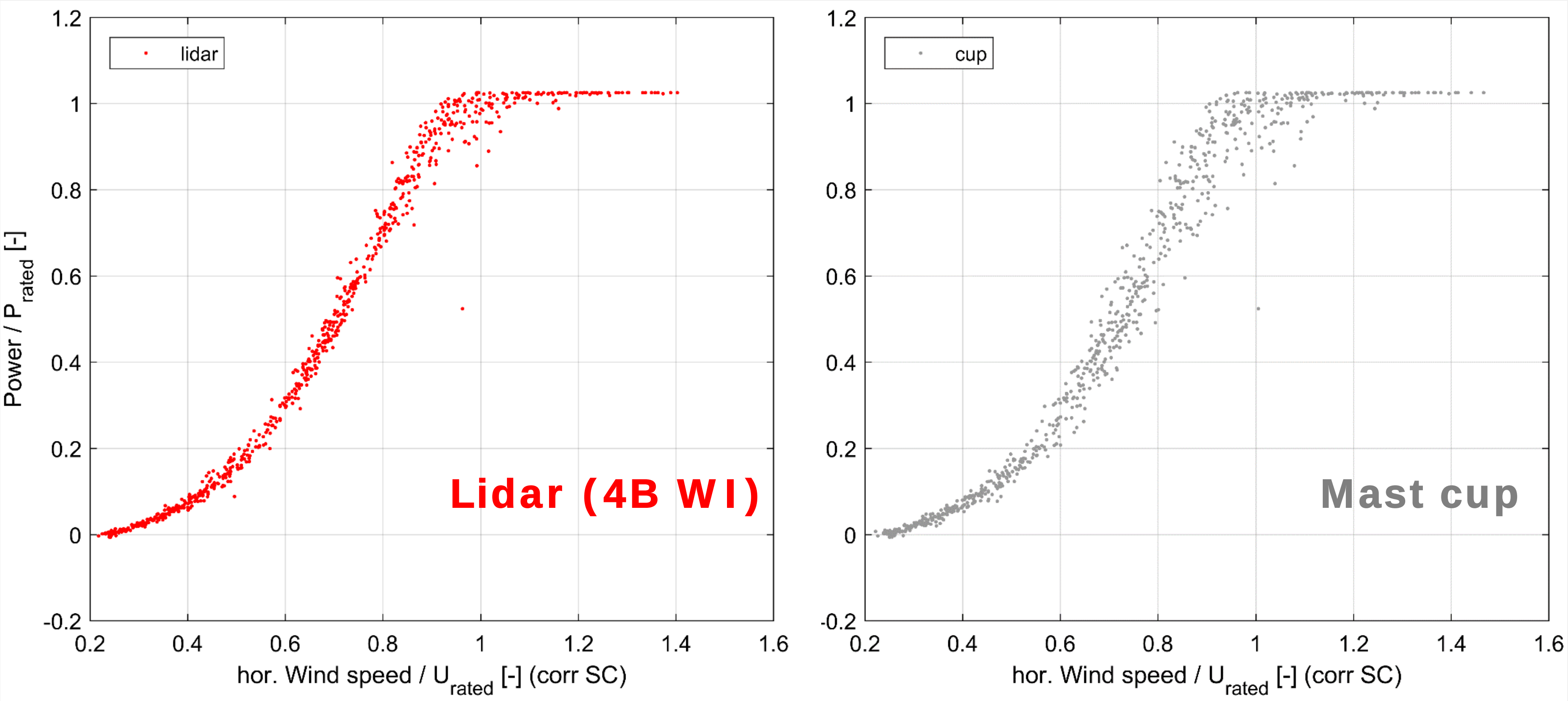
Monte Carlo methods in brief
(dummy example)



Power curve in complex terrain wind-induction model @4 dist

scatter

- Mast: top cup wind spd, corrected with SC (experimental)
- Lidar: free stream wind spd V_∞, no correction



→ **Clear scatter reduction in lidar PCurve**

Power curve in complex terrain wind-induction model @4 dist

binned

- Mast: top cup wind spd, corrected with SC (experimental)
- Lidar: free stream wind spd V_∞, no correction