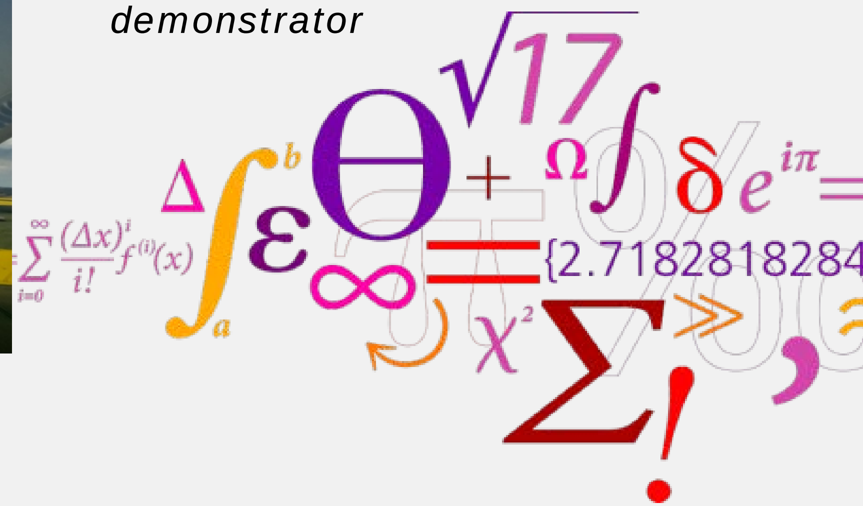
SWE Stuttgart Wind Energy @ Institute of Aircraft Design

DTU

Wind field reconstruction from nacelle-mounted profiling lidars for power performance

ZephIR Dual-Mode

5-beam Avent demonstrator



A. Borraccino, DTU Wind Energy

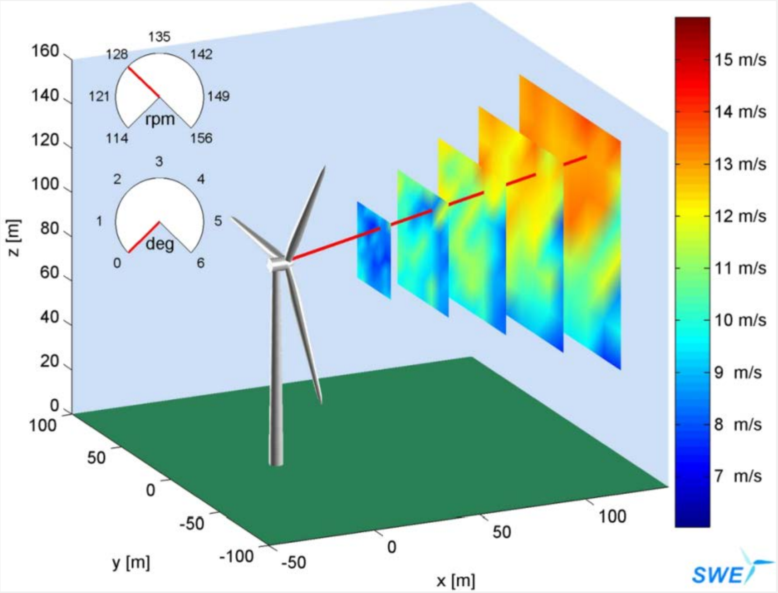
with the support of
D. Schlipf and F. Haizmann, SWE

DTU Wind Energy
Department of Wind Energy

Innovation Fund Denmark
RESEARCH, TECHNOLOGY & GROWTH

Nacelle-mounted lidars in WE: what for?

- Wind turbine control, incl. feed-forward ([Schlipf D.](#))

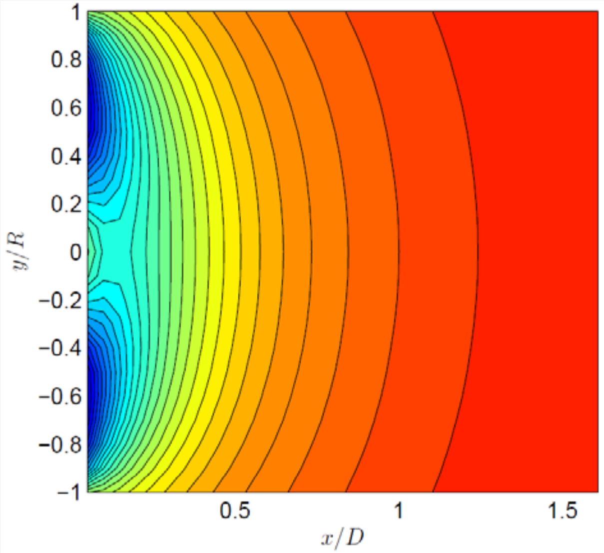


- Wakes measurements
- Yaw misalignment correction?
- **Power performance**: ([R. Wagner](#))
  to replace met. masts when
  - too expensive: offshore, complex sites
  - insufficient: wind spd at hub vs. REWS
  - free wind not measurable: decorrelation, no undisturbed sectors (offshore array, complex site, etc)

Unified Turbine Testing (UniTTe)

- **UniTTe: Unified Turbine Testing**
  - new methodology for power curve and loads assessment based on lidar near-flow measurements, i.e. close to the rotor, applicable in any type of terrain (radical change!)
  - basis for future standards (e.g. IEC 614100-12-1)

Numerical modelling of turbine inflow: induction ‘transfer’ function



Measurement campaigns: calibration + simple & complex terrain

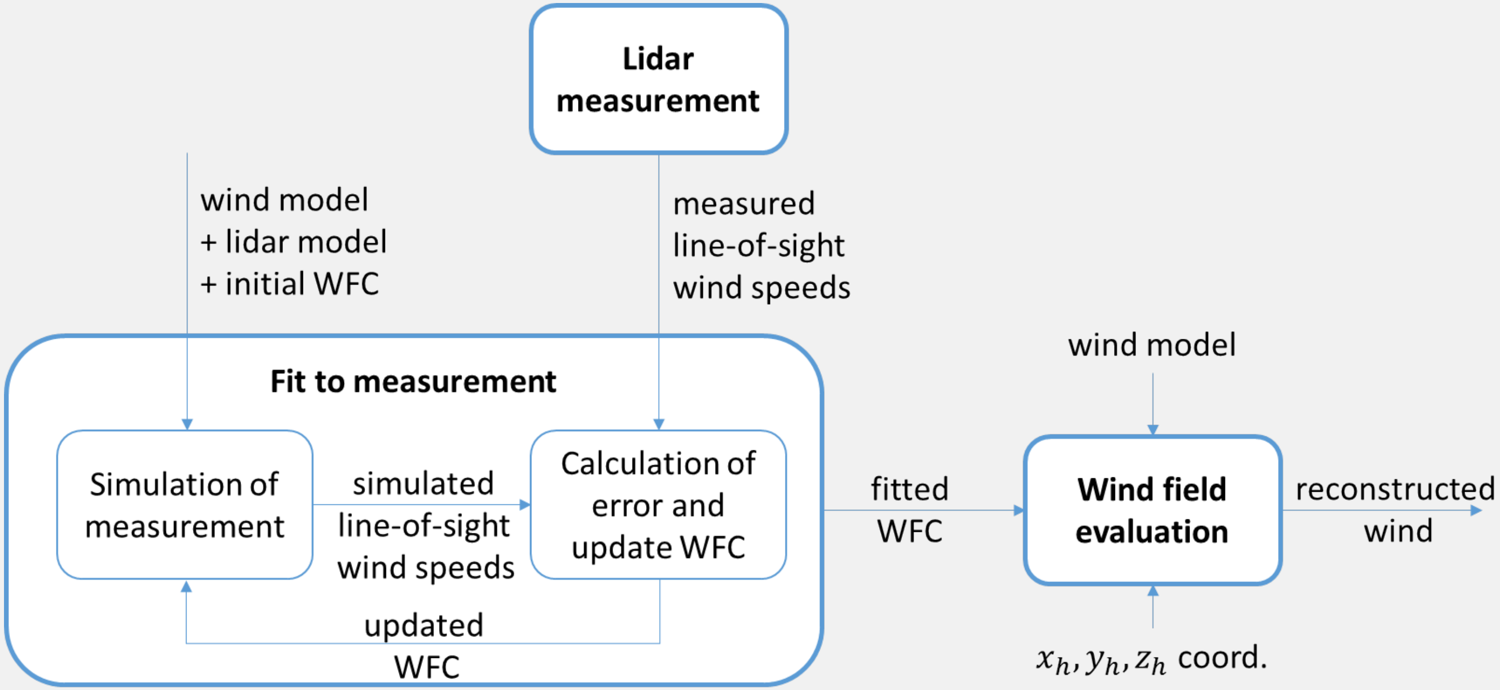
Model-based wind field reconstruction

- **Doppler wind LiDaRs do not…**

…measure wind speed, wind direction, shear, …

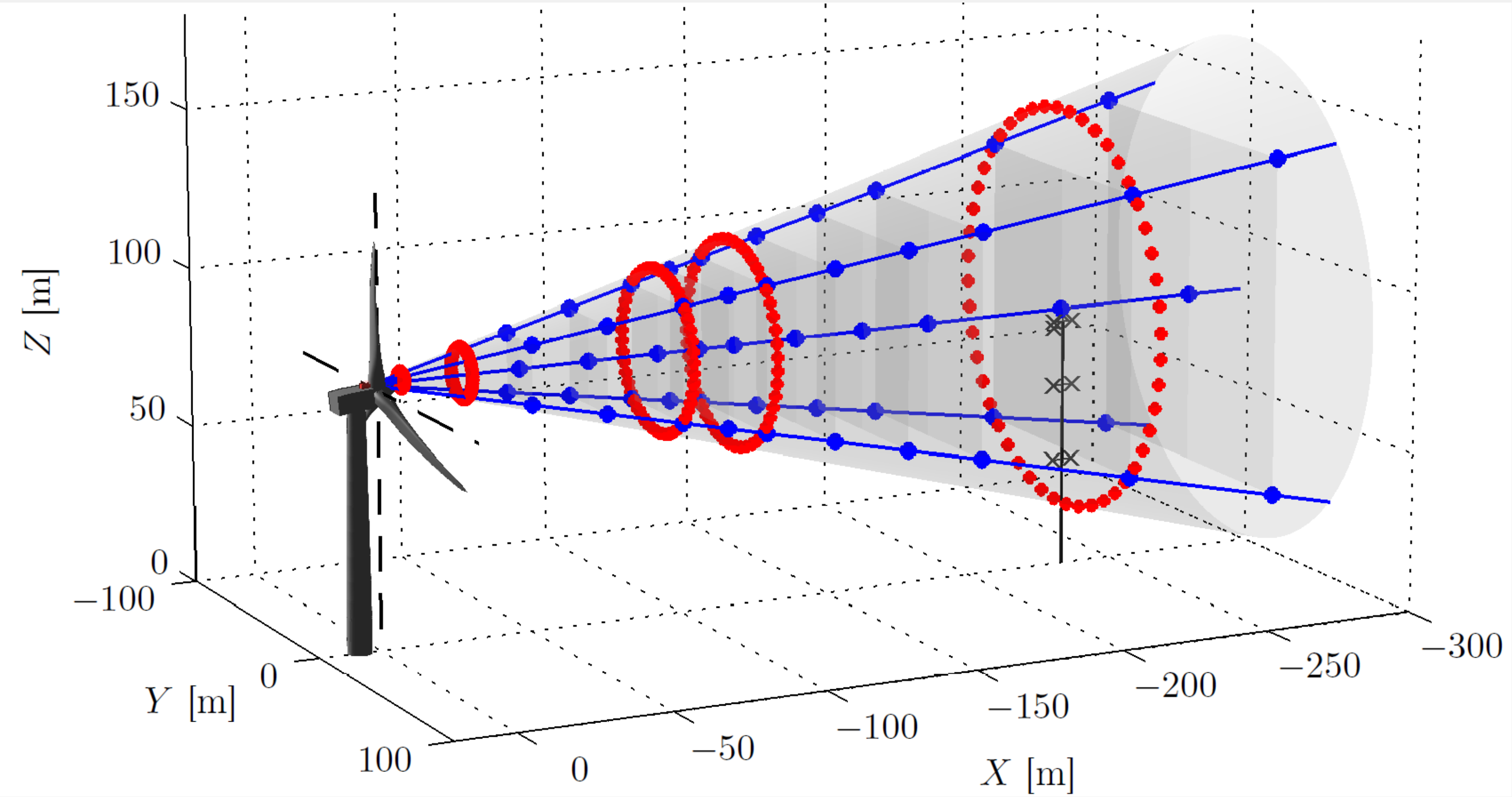
see Hardesty, 1987 (wonderful description of lidar principles)

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



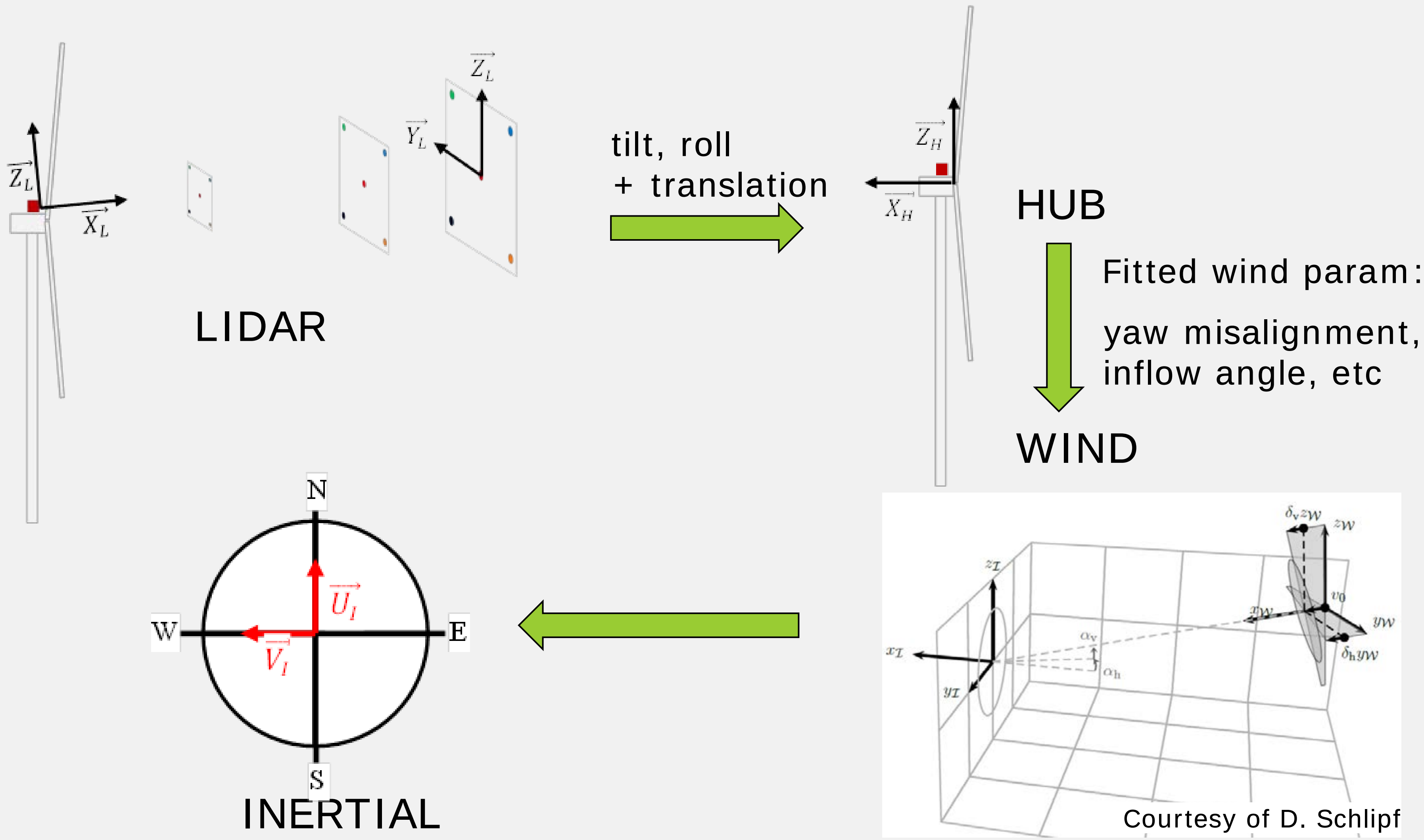
Nørrekær Enge campaign (NKE), 7 months

- Two nacelle lidars:
  Avent 5-beam (5B) **in blue**, ZephIR Dual Mode (ZDM) **in red**
- IEC compliant mast + SCADA + full loads



Model-based wind field reconstruction

- **Coordinate systems**



Courtesy of D. Schlipf

Model-based wind field reconstruction

- **Modelling the wind field**
  - choose a wind model that fits the application & site characteristics
  - the reconstruction should be performed either in the WIND coordinate systems or in the HUB
- **For power performance: static models**
  - i.e. no time dependency
  - use 10-min averages of:
    - LOS velocities
    - inclinometers readings
  - use knowledge of the trajectory (opening angles, ranges config) and of lidar position

Model-based wind field reconstruction

- **Wind models**

Model	$\boldsymbol{U}$	$\boldsymbol{V}$	$\boldsymbol{W}$	comment
Homogeneous 2D	$U_w = cst \quad \leftrightarrow U_I = U$	$V_w = 0 \ \leftrightarrow V_I = V$	$W_w = 0 \ \leftrightarrow W_I = 0$	Does not depend on X, Y, Z
Homogeneous 3D	$U_w = cst \quad \leftrightarrow U_I = U$	$V_w = 0 \ \leftrightarrow V_I = V$	$W_w = 0 \ \leftrightarrow W_I = W$	Does not depend on X, Y, Z

- Assumption of flow homogeneity
  - ➔ typically used by ground-based lidars (VAD, DBS) in flat terrain
  - ➔ not making much sense for lidars in nacelle mode because of variations with heights a.g.l. (shear, veer, etc.)

Model-based wind field reconstruction

- **Wind models**

Model	U	V	W	comment
Homogeneous 2D	$U_w = cst \quad \leftrightarrow U_I = U$	$V_w = 0 \quad \leftrightarrow V_I = V$	$W_w = 0 \quad \leftrightarrow W_I = 0$	Does not depend on X, Y, Z
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Inhomogeneous 2D + linear V shear	$U_w = v_0 + \delta_V \cdot (z_W - z_{hub})$ $\leftrightarrow U_I = f(z)$	$V_w = 0 \quad \leftrightarrow V_I = V$	$W_w = 0 \quad \leftrightarrow W_I = 0$	Yaw misalignment $\alpha_H = cst$
Inhomogeneous 2D + linear V shear + linear V veer	$U_w = v_0 + \delta_V \cdot (z_W - z_{hub})$ $\leftrightarrow U_I = f(z)$	$V_w = 0 \quad \leftrightarrow V_I = f(z)$	$W_w = 0 \quad \leftrightarrow W_I = 0$	Yaw misalignment $\alpha_H = f(z)$
Inhomogeneous 2D + power law shear	$\boldsymbol{U_w = v_0 (z_w / z_{hub})^{\alpha_{exp}}}$ $\boldsymbol{\leftrightarrow U_I = f(z)}$	$\boldsymbol{V_w = 0 \quad \leftrightarrow V_I = V}$	$\boldsymbol{W_w = 0 \quad \leftrightarrow W_I = 0}$	**Yaw misalignment** $\boldsymbol{\alpha_H = cst}$

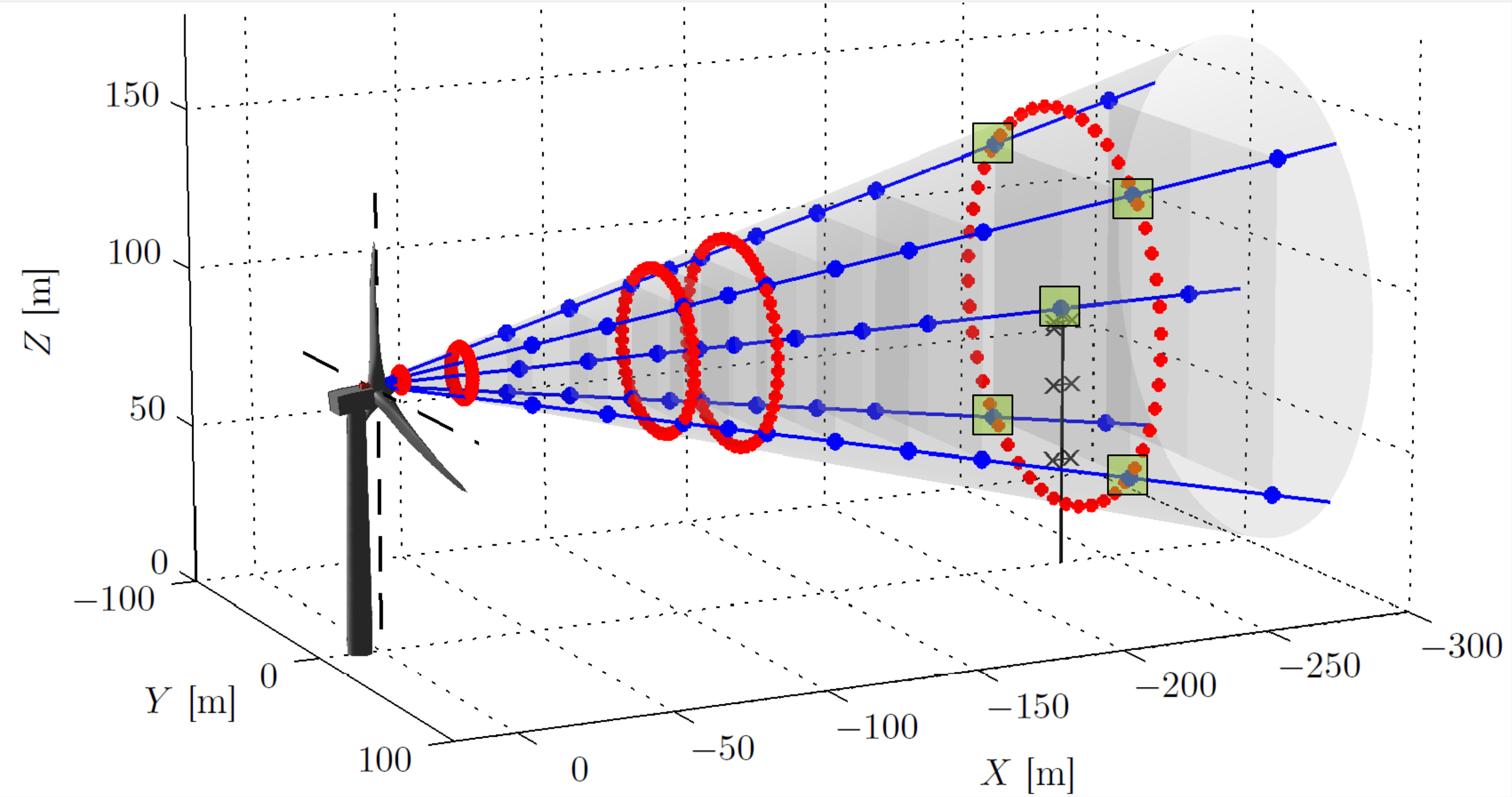
→ fitted wind characteristics are:

- o HWS v_0
- o yaw misalignment α_H (relative wind dir)
- o shear exponent α_{exp}

Results: Inhomogeneous 2D with shear exp

5B: use all 5 pts | **ZDM: use 4 pts in square**

Free sector [110; 219]° ; **@2.5 D_{rot}** ; HWS estimated @hub



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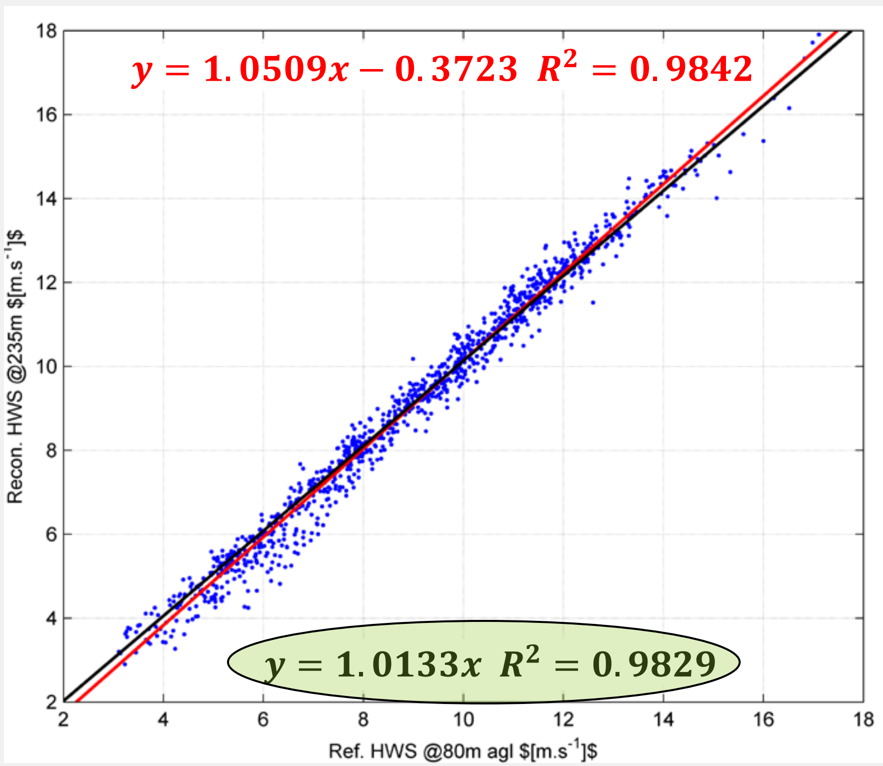
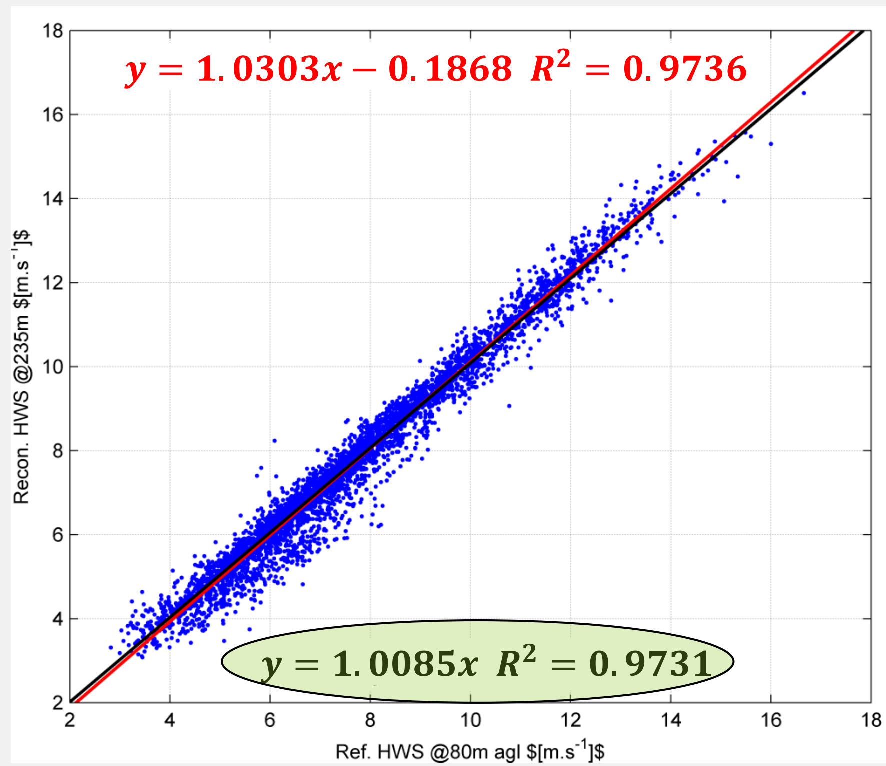
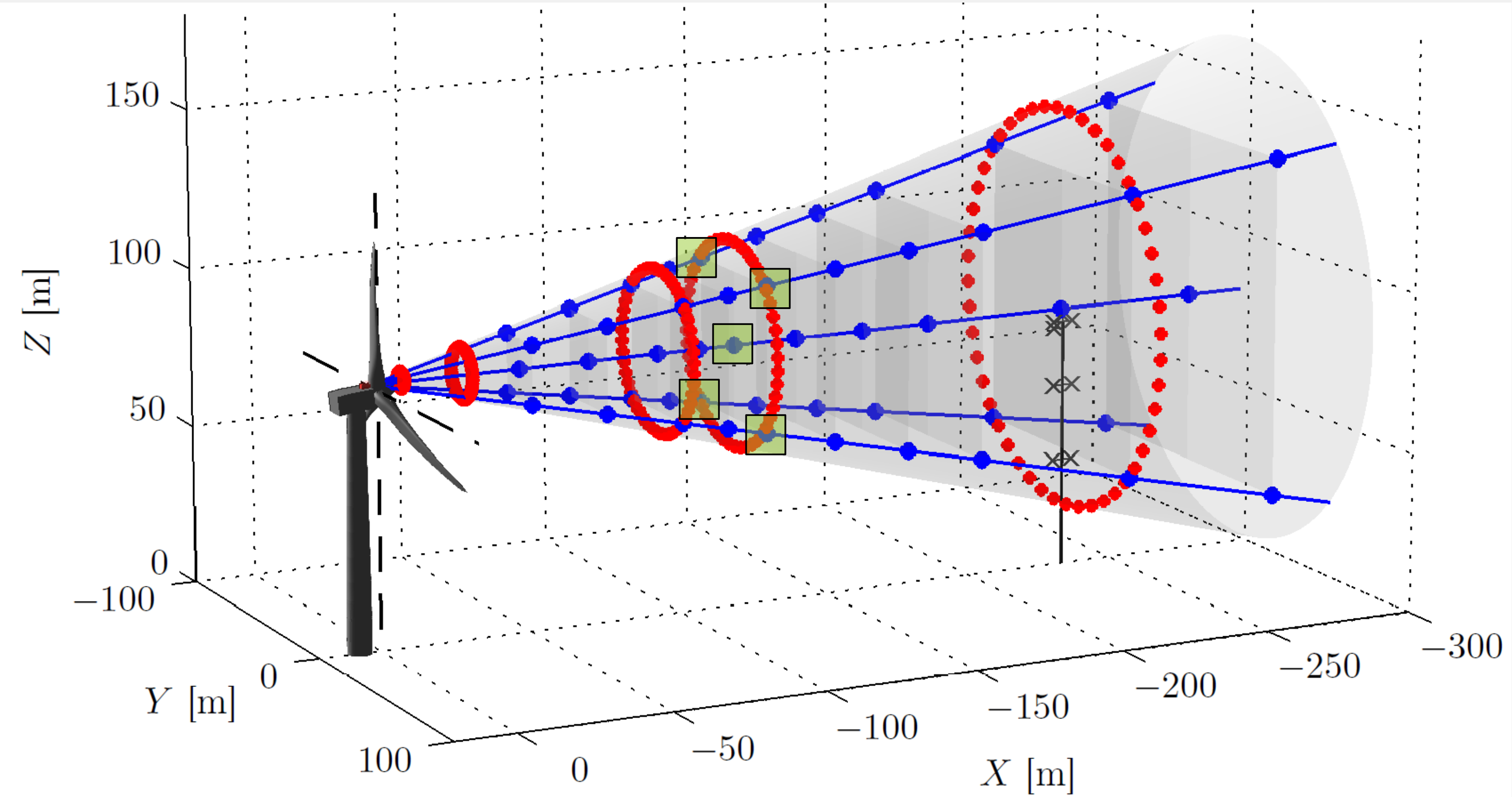




Results: Inhomogeneous 2D with shear exp

5B: use all 5 pts **ZDM: use 4 pts in square**

Free sector [110; 219]° ; **@1.0 D_{rot}** ; HWS estimated @hub



Results: Inhomogeneous 2D with shear exp

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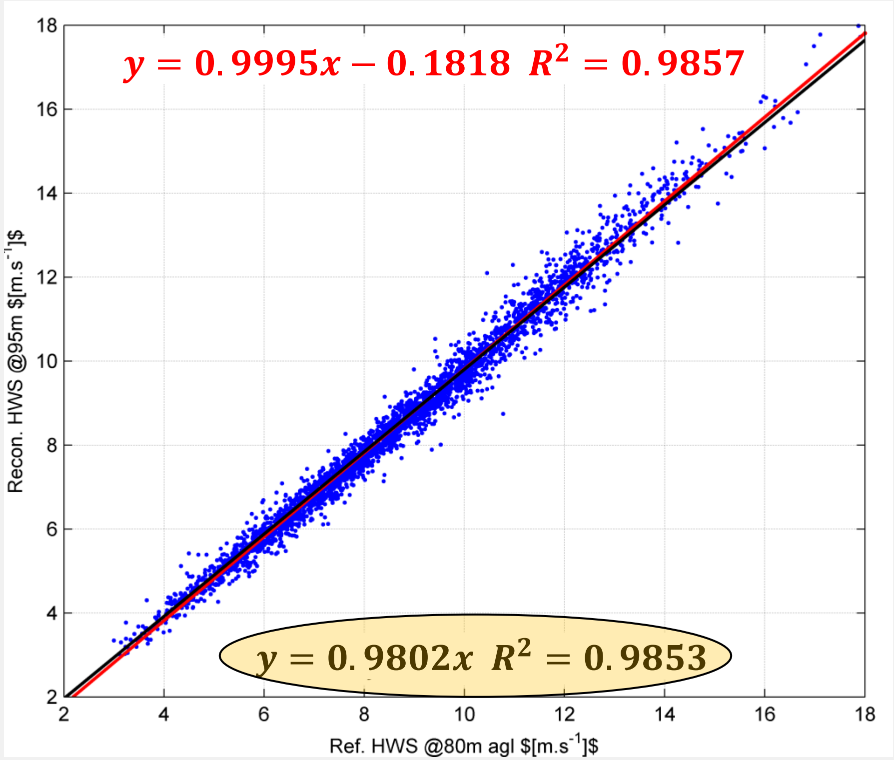
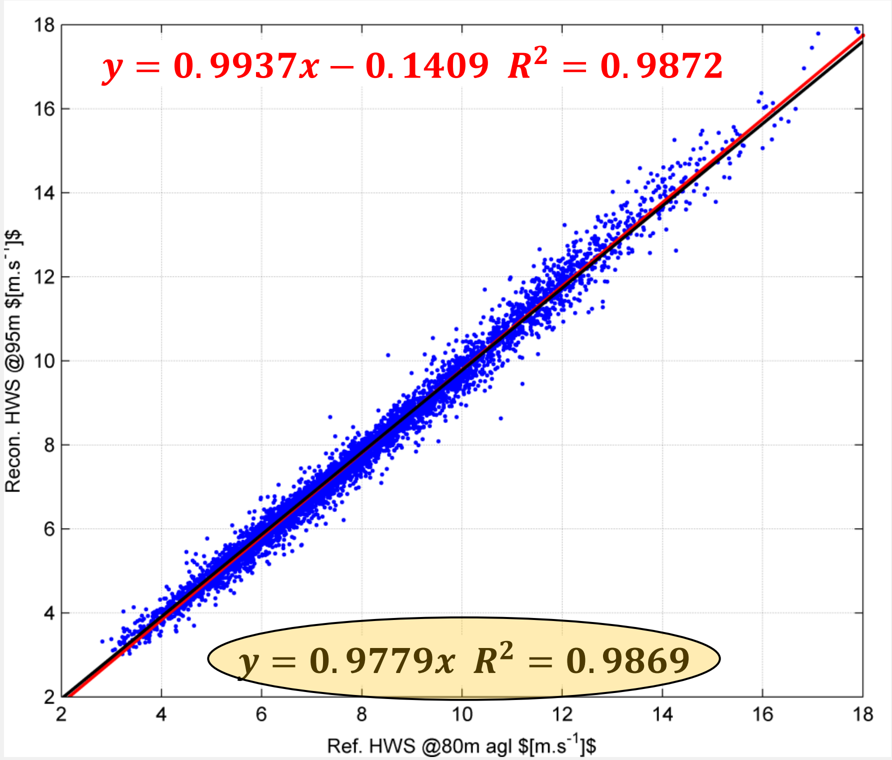
Free sector [110; 219]° ; **@1.0 D_{rot}** ; HWS estimated @hub





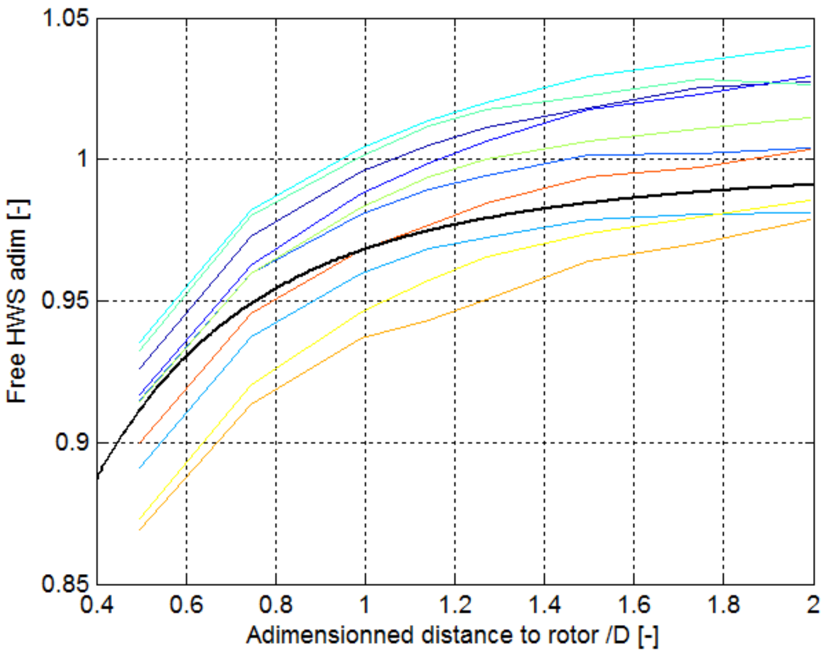
less scatter, wind speed deficit of ~2% ➔ can we correct this?

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

Model-based wind field reconstruction

- **Wind models**

Model name	U	V	W	**comment**
Homogeneous 2D	$U_w = cst \quad \leftrightarrow U_I = U$	$V_w = 0 \quad \leftrightarrow V_I = V$	$W_w = 0 \quad \leftrightarrow W_I = 0$	Does not depend on X, Y, Z
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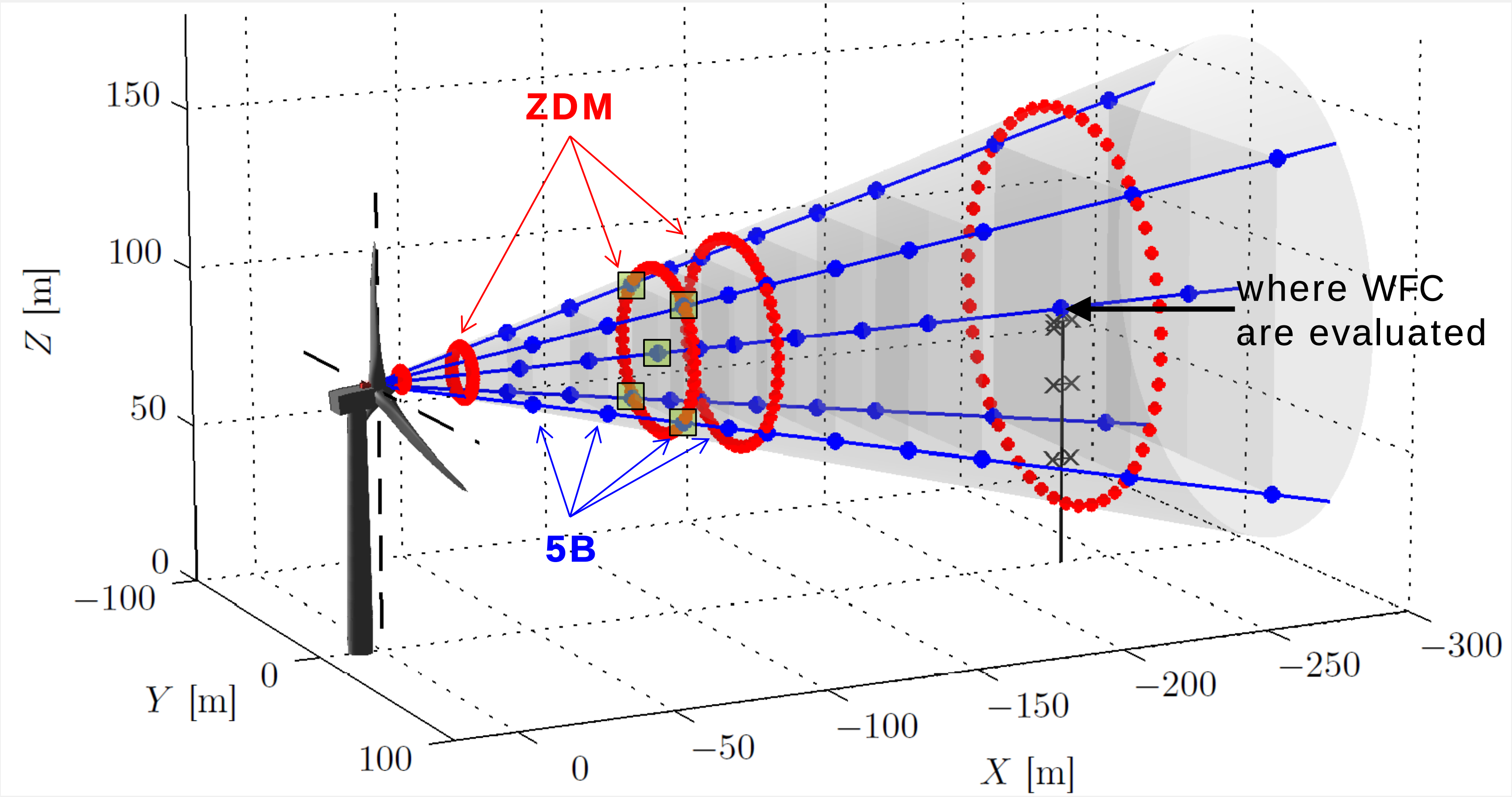
Inhomogeneous 2D + linear V shear	$U_w = v_0 + \delta_V \cdot (z_W - z_{hub})$ $\leftrightarrow U_I = f(z)$	$V_w = 0 \quad \leftrightarrow V_I = V$	$W_w = 0 \quad \leftrightarrow W_I = 0$	Yaw misalignment $\alpha_H = cst$
Inhomogeneous 2D + linear V shear + linear V veer	$U_w = v_0 + \delta_V \cdot (z_W - z_{hub})$ $\leftrightarrow U_I = f(z)$	$V_w = 0 \quad \leftrightarrow V_I = f(z)$	$W_w = 0 \quad \leftrightarrow W_I = 0$	Yaw misalignment $\alpha_H = f(z)$
Inhomogeneous 2D + power law shear	$U_w = v_0 (z_w / z_{hub})^{\alpha_{exp}}$ $\leftrightarrow U_I = f(z)$	$V_w = 0 \quad \leftrightarrow V_I = V$	$W_w = 0 \quad \leftrightarrow W_I = 0$	Yaw misalignment $\alpha_H = cst$
Inhomogeneous 2D + power law shear + induction model	$\boldsymbol{U_w = f(x,z)}$ $\boldsymbol{\leftrightarrow U_I = f(x,z)}$	$\boldsymbol{V_w = 0}$ $\boldsymbol{\leftrightarrow V_I = f(x,z)}$	$\boldsymbol{W_w = 0 \quad \leftrightarrow W_I = 0}$	**1D Biot-Savard for induction fct**

→ fitted wind characteristics are: free stream HWS U_∞ , yaw misalignment α_H, shear exponent α_{exp}, induction factor a.

Results: 'free' wind speed based on near flow measurements

5B: use all 5 pts + 4 dist. (0.5 to 1.1D)

ZDM: use 4 pts in square + 3 dist. (0.3 to 1.2D)



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+ 4 dist. (0.5 to 1.1D)

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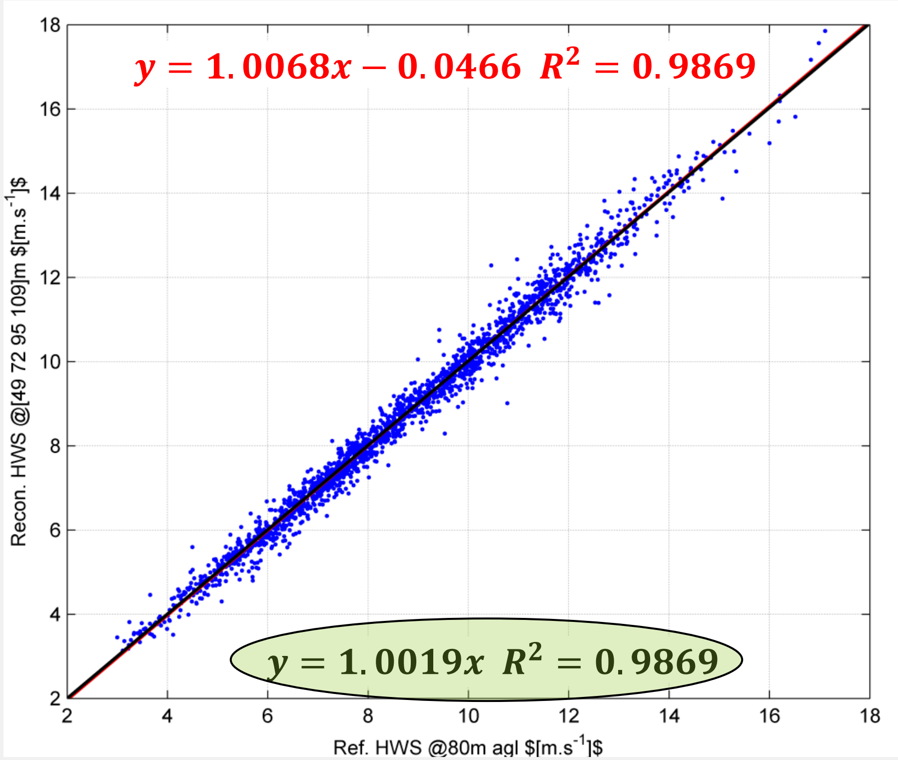
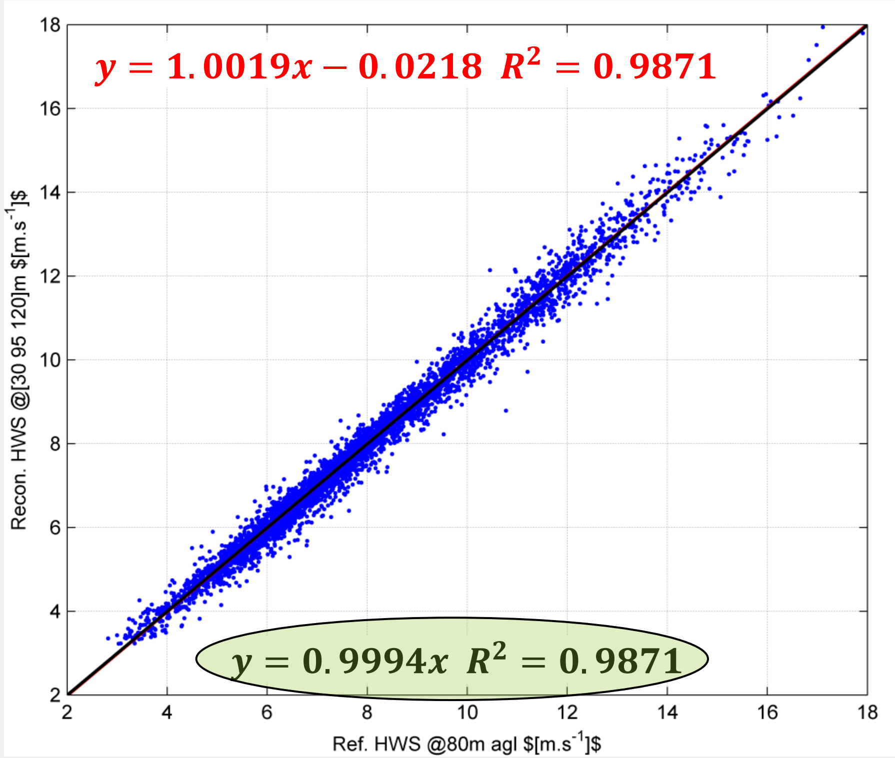
Free sector [110; 219]° ; **HWS estimated @H_{hub} & 2.5 D_{rot}**



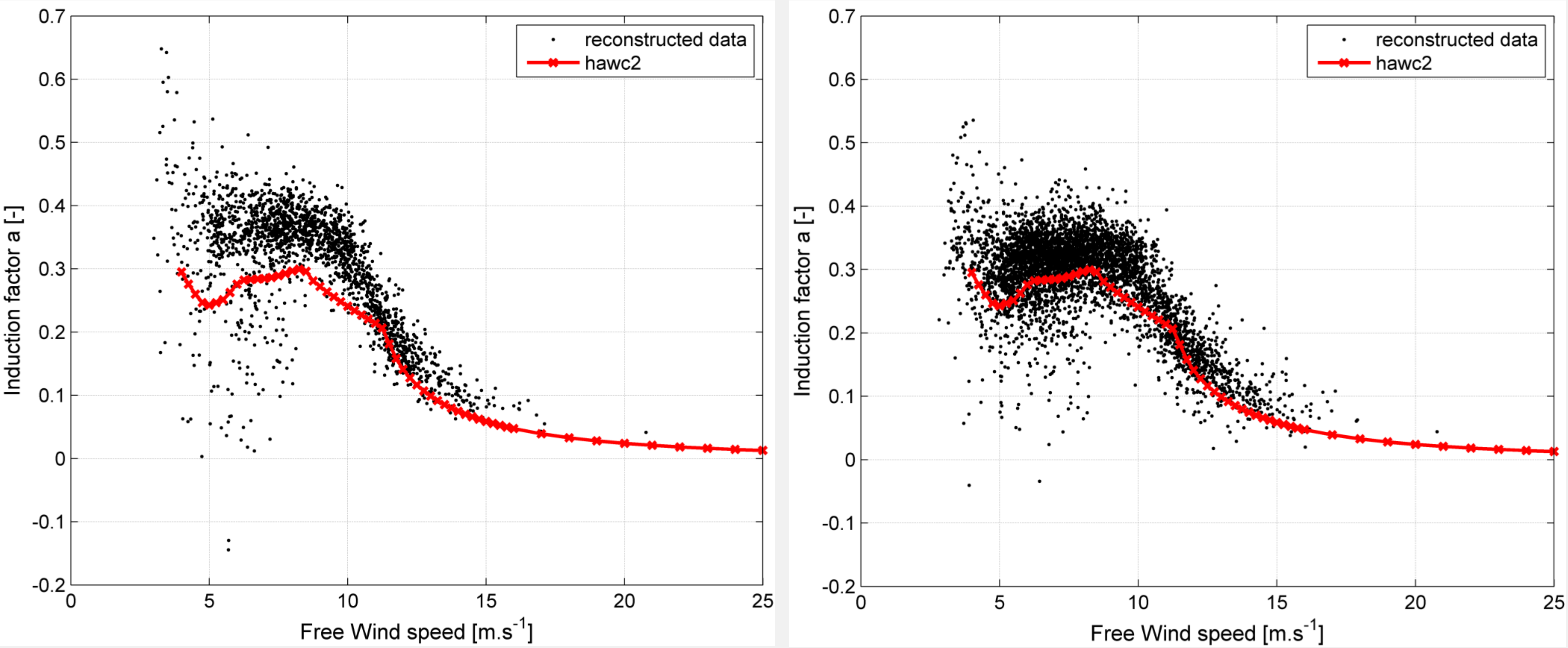


Induction factor?

Estimated as part of the outputs of the induction model

➔ can even be considered a lidar-estimation of thrust coeff.

Induction factor vs. free stream wind speed
(5B left, ZDM right)



Conclusions

- Model-based wind field reconstruction provides estimations of wind characteristics comparable with classic anemometry

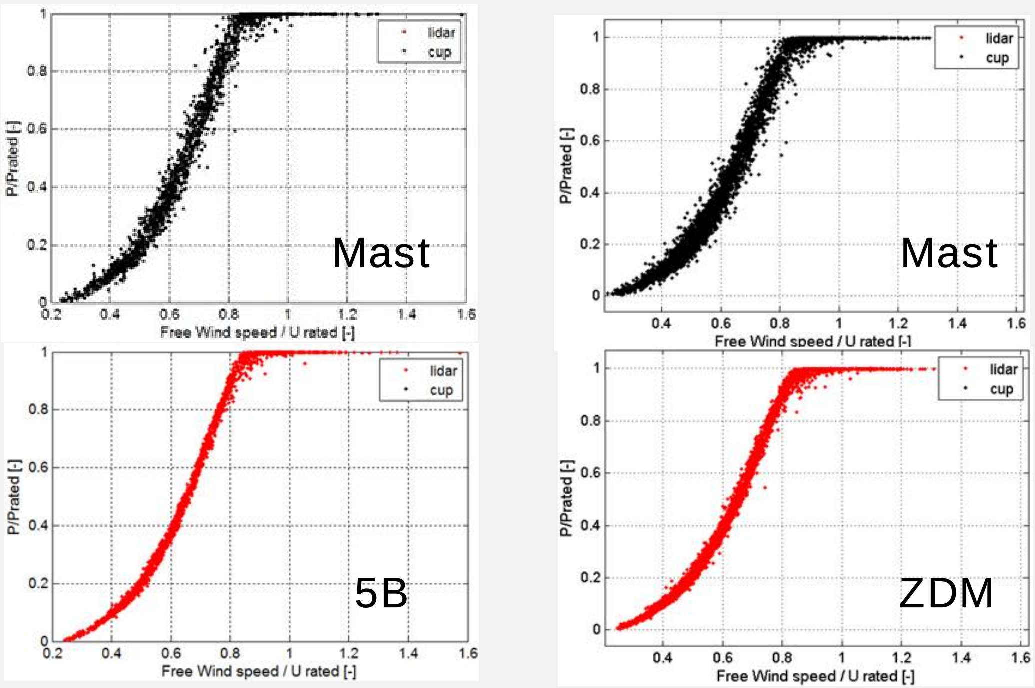
- Integrating an induction model is possible (same for wakes?)

- Combined with near-flow measurements, the method allows robust estimation of ‘free stream’ wind

- **Questions & further work:**
  1. How to adapt the models to complex terrain? Same?
  2. Should the induction function be made 2-dimensional?
  3. Quantify uncertainties on wind characteristics estimates using calibrated LOS velocity measurements

- Preliminary power curves show reduced scatter and high accuracy

Thanks for your attention!



More info:

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

Acknowledgements

This work was performed inside the UniTTe project (www.unitte.dk) which is financed by Innovation Fund Denmark.

Thanks to David Schlipf, Florian Haizmann and all SWE for the good collaboration that made this work possible.