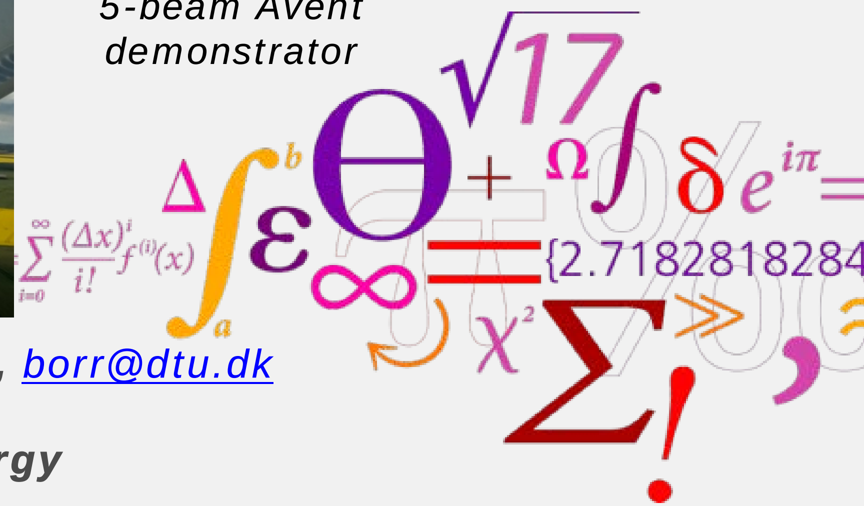
V infinity is found!

Near flow measu[...] with nacelle lidars: the futur[...] performance verification?

ZephIR Dual-Mode

5-beam Avent demonstrator



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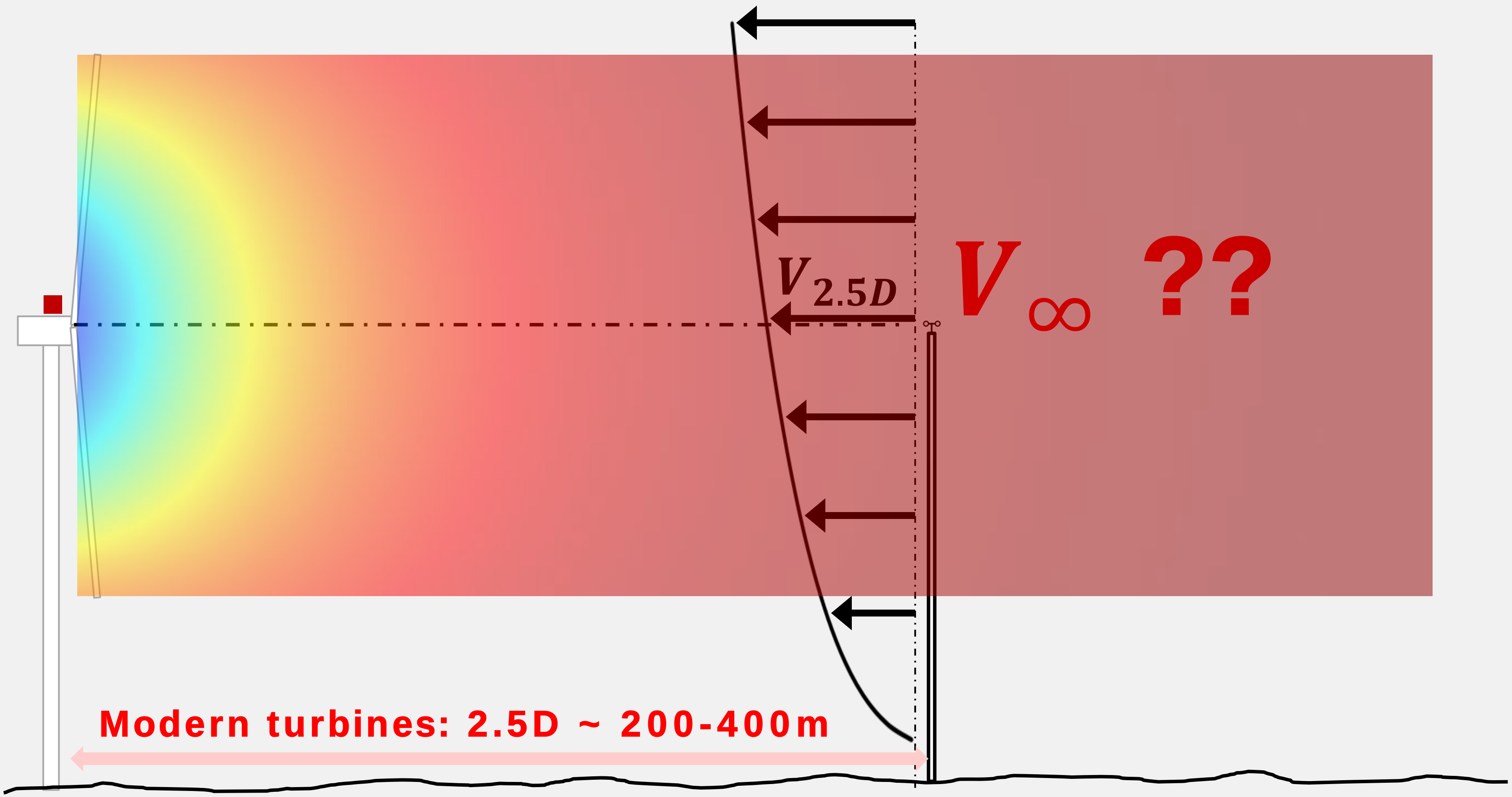
DTU Wind Energy
Department of Wind Energy

Innovation Fund Denmark
RESEARCH, TECHNOLOGY & GROWTH

Searching for free stream wind speed



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

Does this make it any easier?

Perdigão.
credit: N. Vasiljevic

- In complex terrain:
  - any ”free stream” wind speed idea?
  - site calibration? Maybe

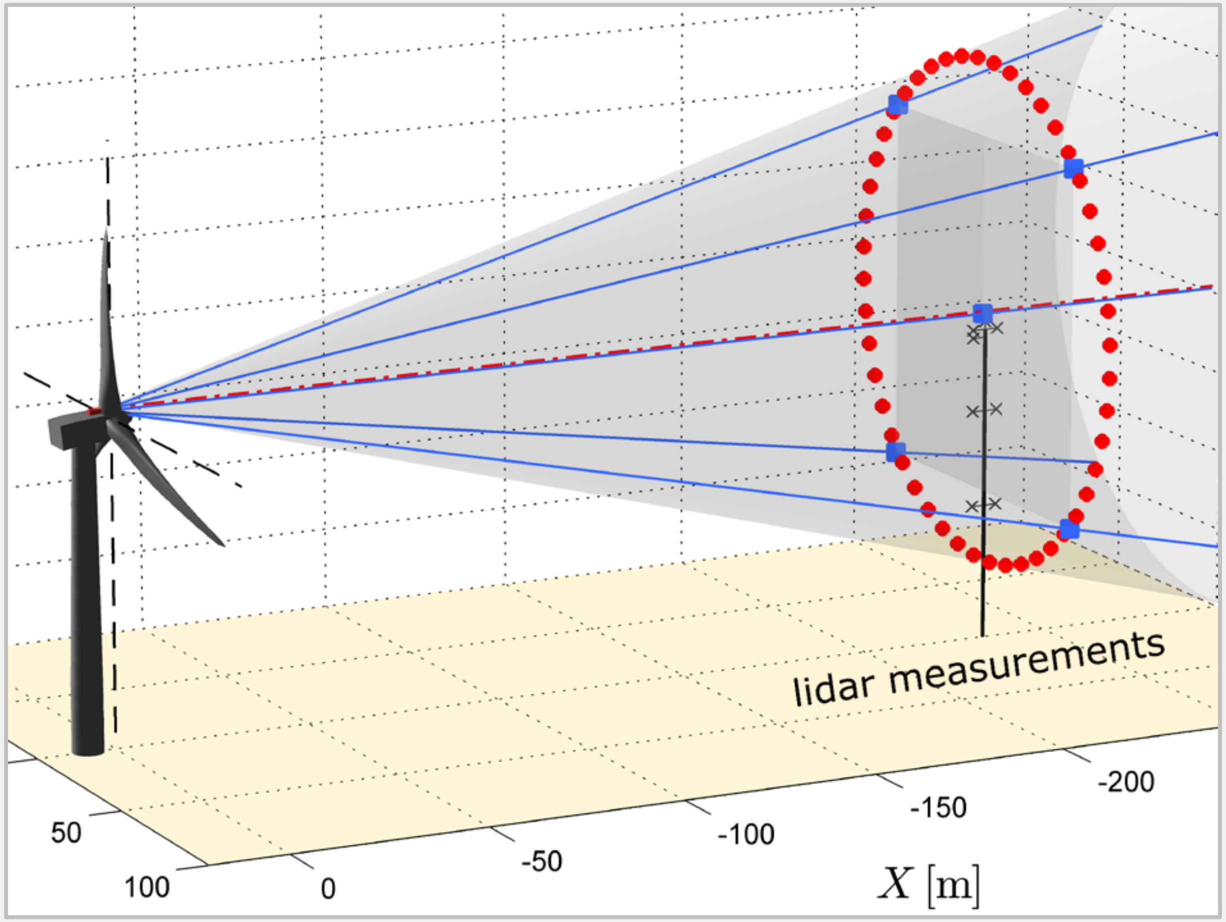
Does this make it any easier?

- Offshore:
  - mast expensive
  - free wind may not be measurable due to wakes

Power performance verification: nacelle-mounted lidars, the future?

- Several possibilities for lidar measurements:

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



Power performance verification: nacelle-mounted lidars, the future?

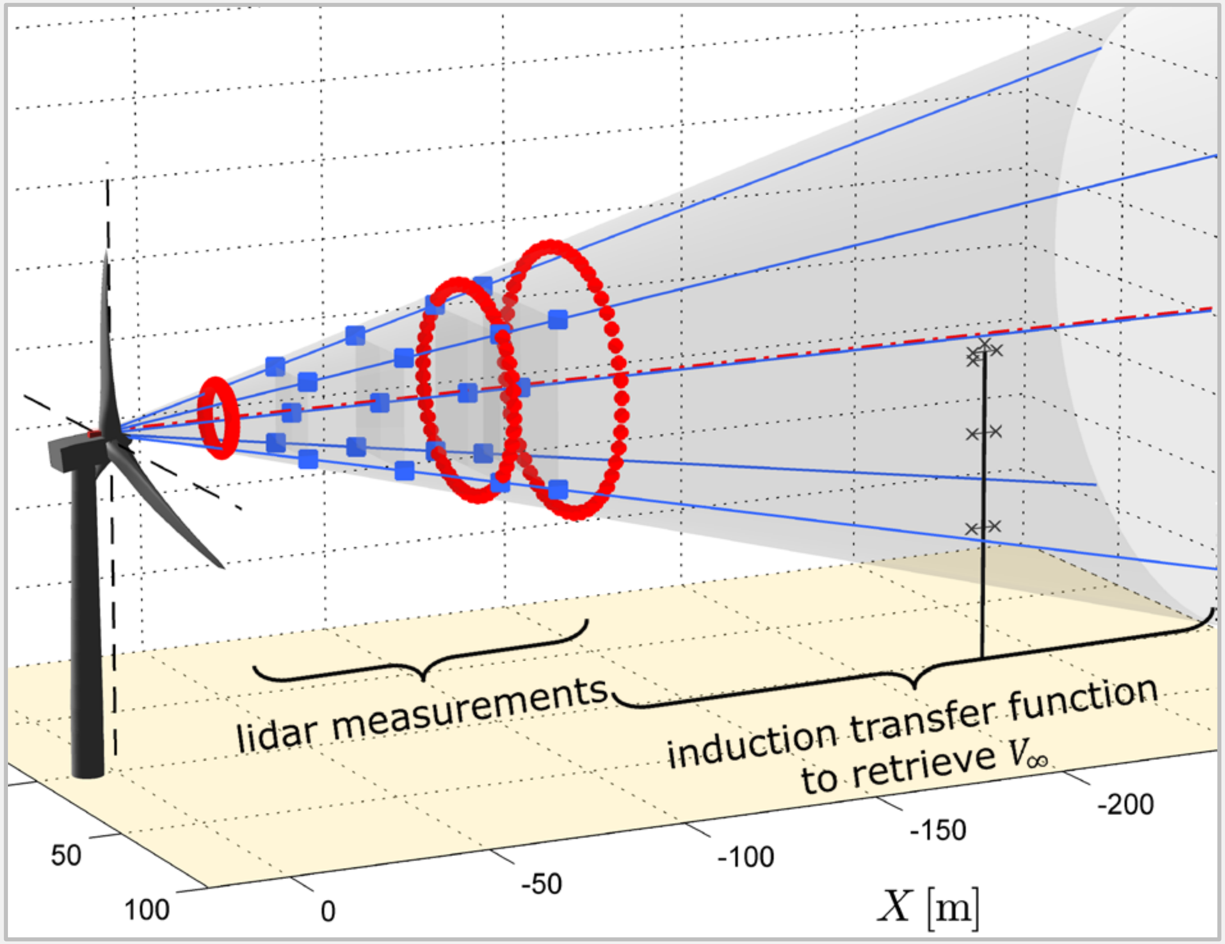
- Several possibilities for lidar measurements:

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

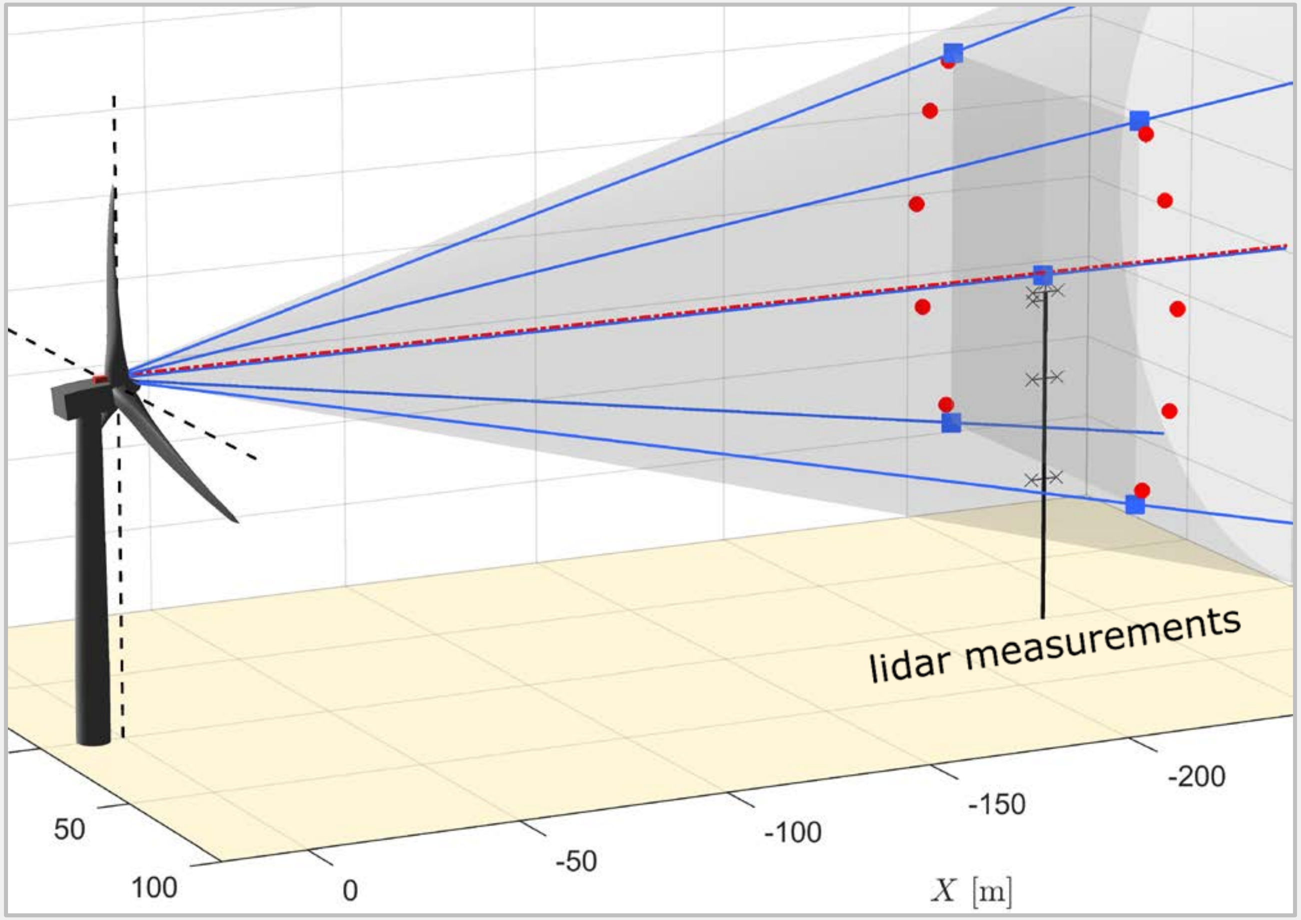
$$\frac{U(x)}{U_\infty} = 1 - a\left(1 + \frac{\xi}{\sqrt{1+\xi^2}}\right)$$

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



Case 1: lidar meas. @2.5D

5B-Demo: use the 5 pts **ZDM**: use 10 pts



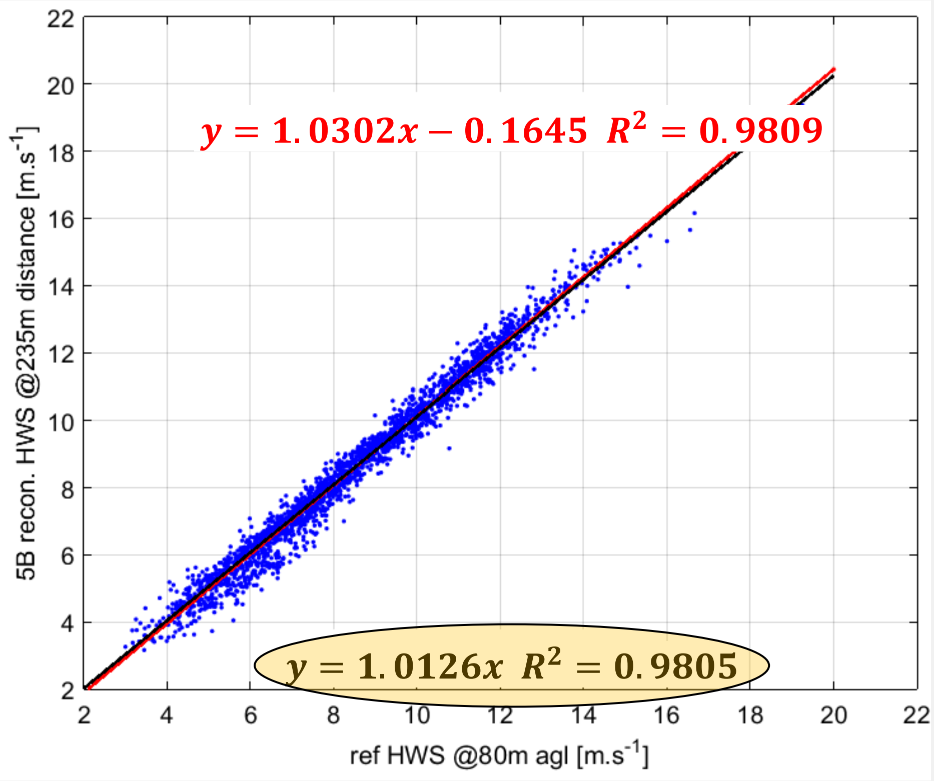
Case 1: lidar meas. @2.5D

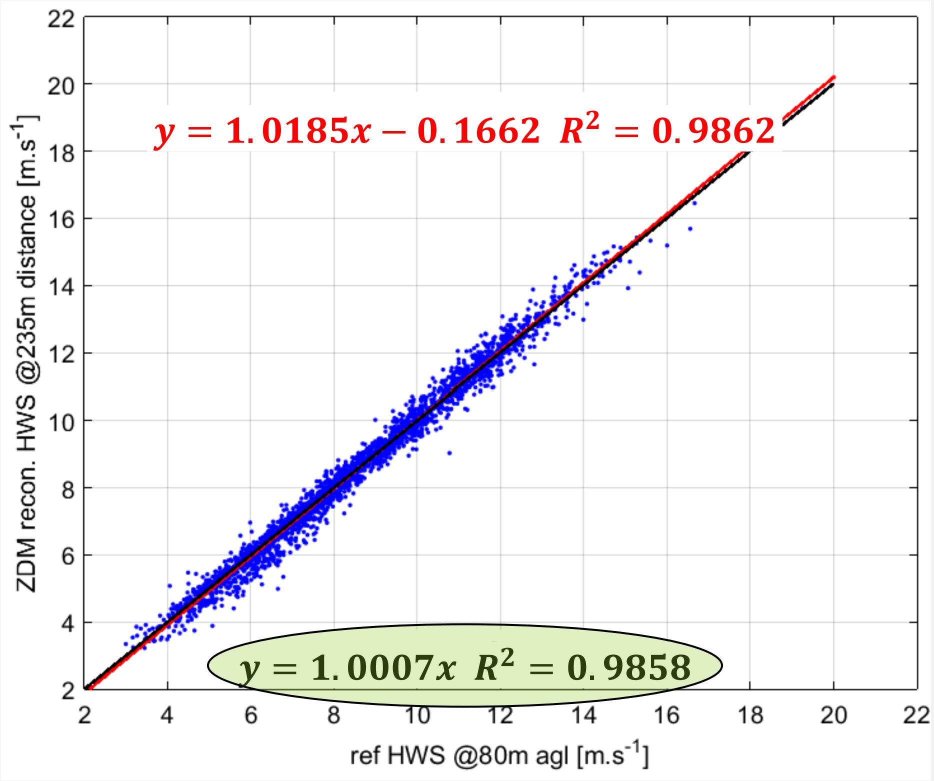
Mast comparison

5B-Demo: use the 5 pts

ZDM: use 10 pts

HWS estimated @hub height

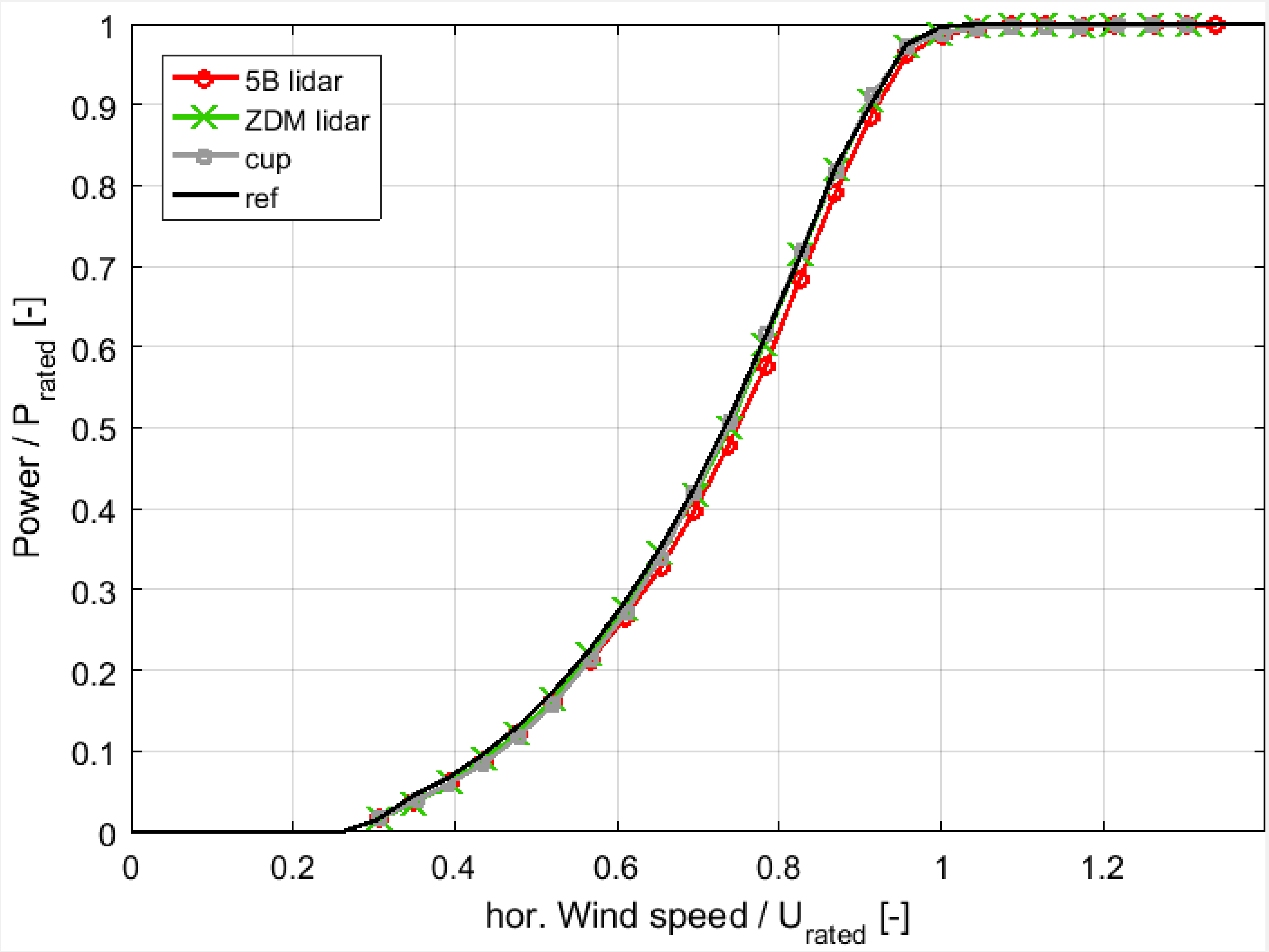




$N_{points} = 2563$

Case 1: lidar meas. @2.5D

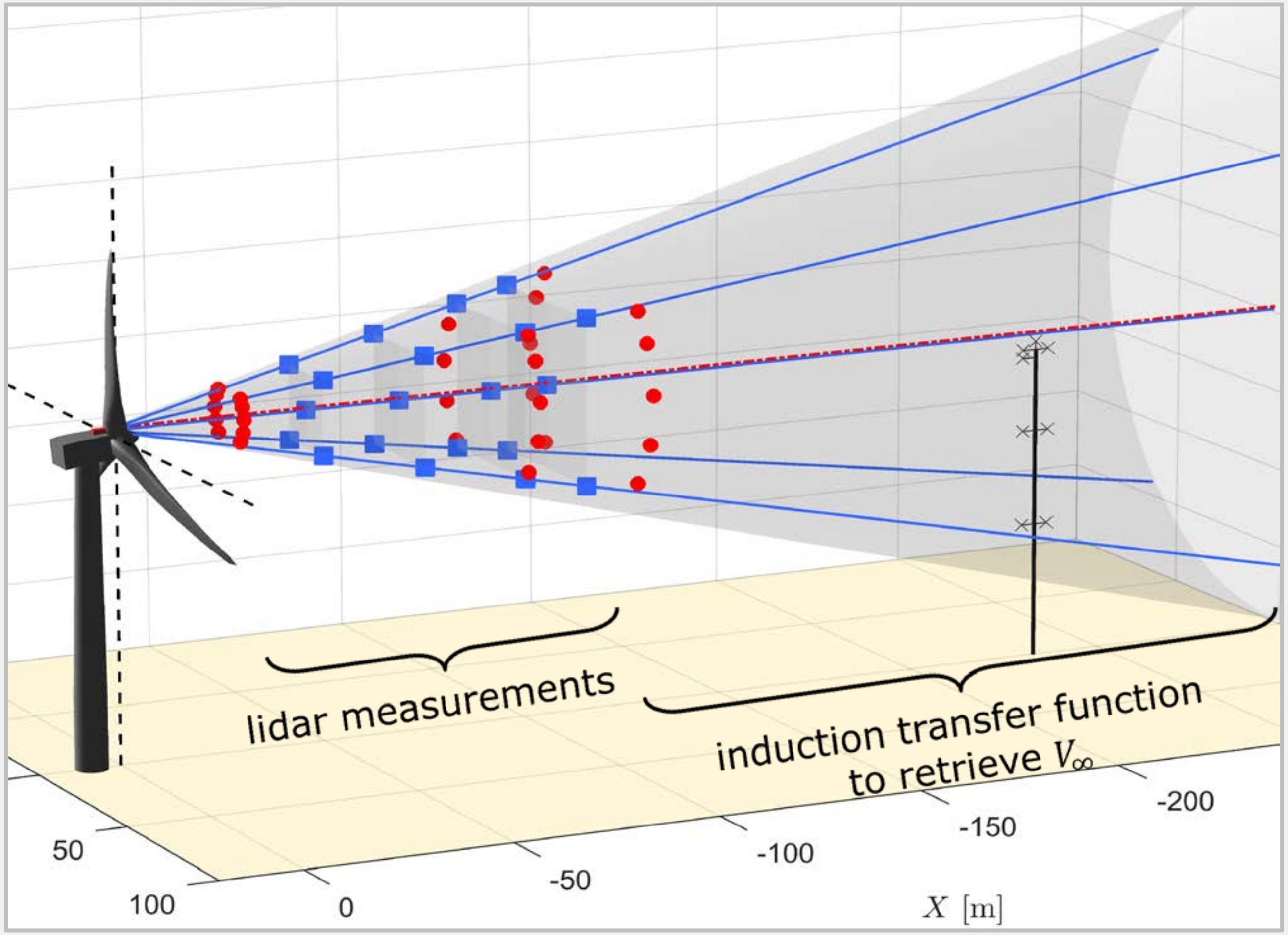
Power curves



Case 2: lidar meas. @ multiple distances close to rotor

5B-Demo : use the 5 pts @[0.5 0.75 1.0 1.15] D

ZDM: use 10 pts @[0.3 1.0 1.25] D



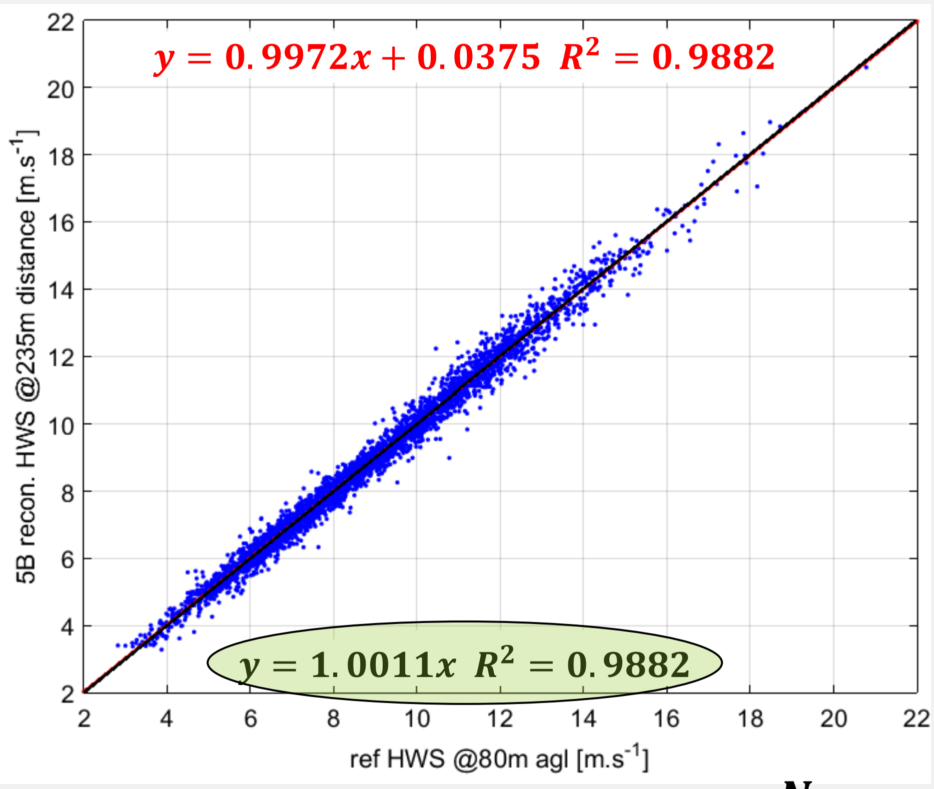
Case 2: lidar meas. @ multi-dist (near flow)

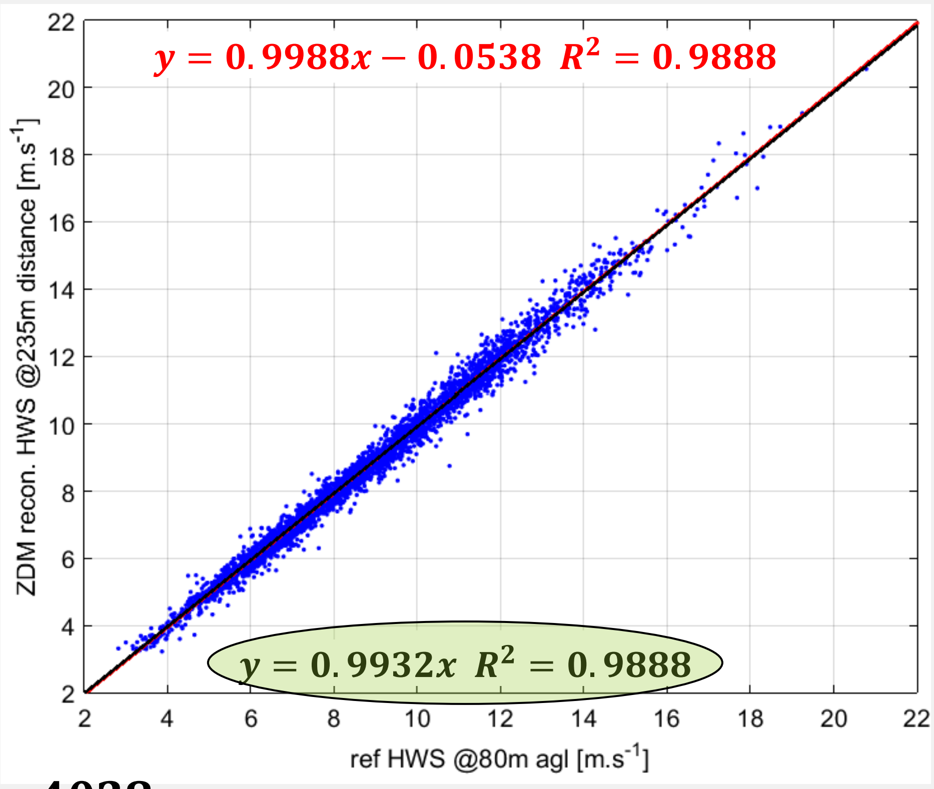
Mast comparison

5B-Demo: use the 5 pts @[0.5 0.75 1.0 1.15] D

ZDM: use 10 pts @[0.3 1.0 1.25] D

HWS estimated @hub height and @2.5D distance

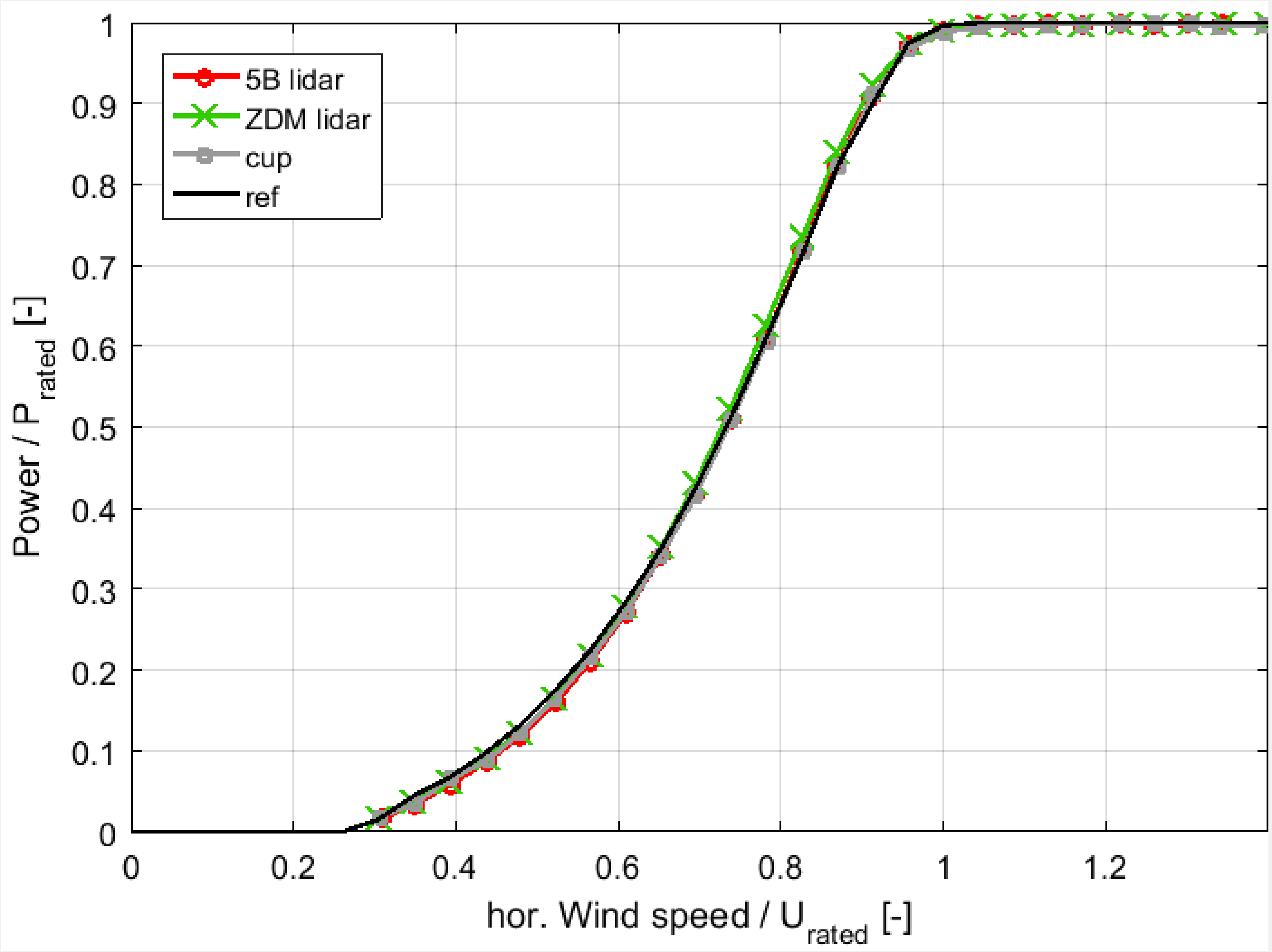




$$N_{points} = 4028$$

Case 2: lidar meas. @ multi-dist (near flow)

Power curves



AEP results

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

Lidar measurements	@2.5 D (case 1)			@multiple distances (case 2)		
Rayleigh avg wind speed	6 m/s	8 m/s	10 m/s	6 m/s	8 m/s	10 m/s
Avent 5-Beam demonstrator lidar	Wspeed difference: +1.2%			Wspeed difference: +0.1%		
	-2.0%	-1.6%	-1.2%	-0.4%	-0.1%	+0.0%
Zephir Dual Mode lidar	Wspeed difference: +0.1%			Wspeed difference: -0.7%		
	+0.4%	+0.2%	+0.1%	+2.0%	+1.3%	+0.9%

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

Take-aways

- **V_∞ is found!** The solution: measurements close to rotor, within the induction zone, at multiple distances, e.g. with nacelle lidars

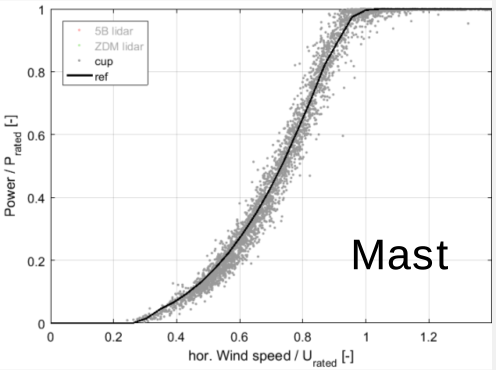
- Wind Field Reconstruction algo. provide estimates comparable classic mast instrumentation ($< 1\%$ difference)

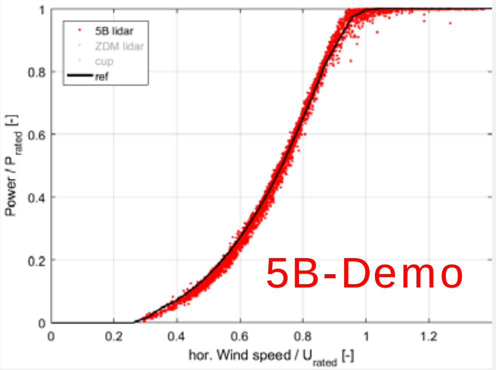
- Power curves in flat terrain verified accurately, reduced scatter (as usual with nacelle lidars)

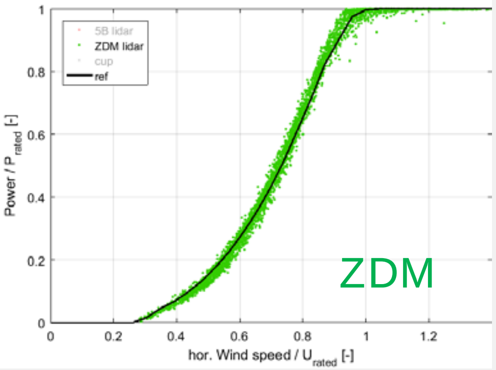
  ➔next generation of IEC61400-12-1 standards? (NWIP)

- **Further work** :
  - Two-dimensional induction? (ongoing)
  - Adaptation and testing of method in complex terrain (campaign in Hill of Towie, Zephir DM+4-beam Wind Iris)
  - Uncertainty assessment of Wind Field Characteristics: speed, direction, shear, induction factor / Ct, ...

Thanks for your attention!







More info:

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

Acknowledgements

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

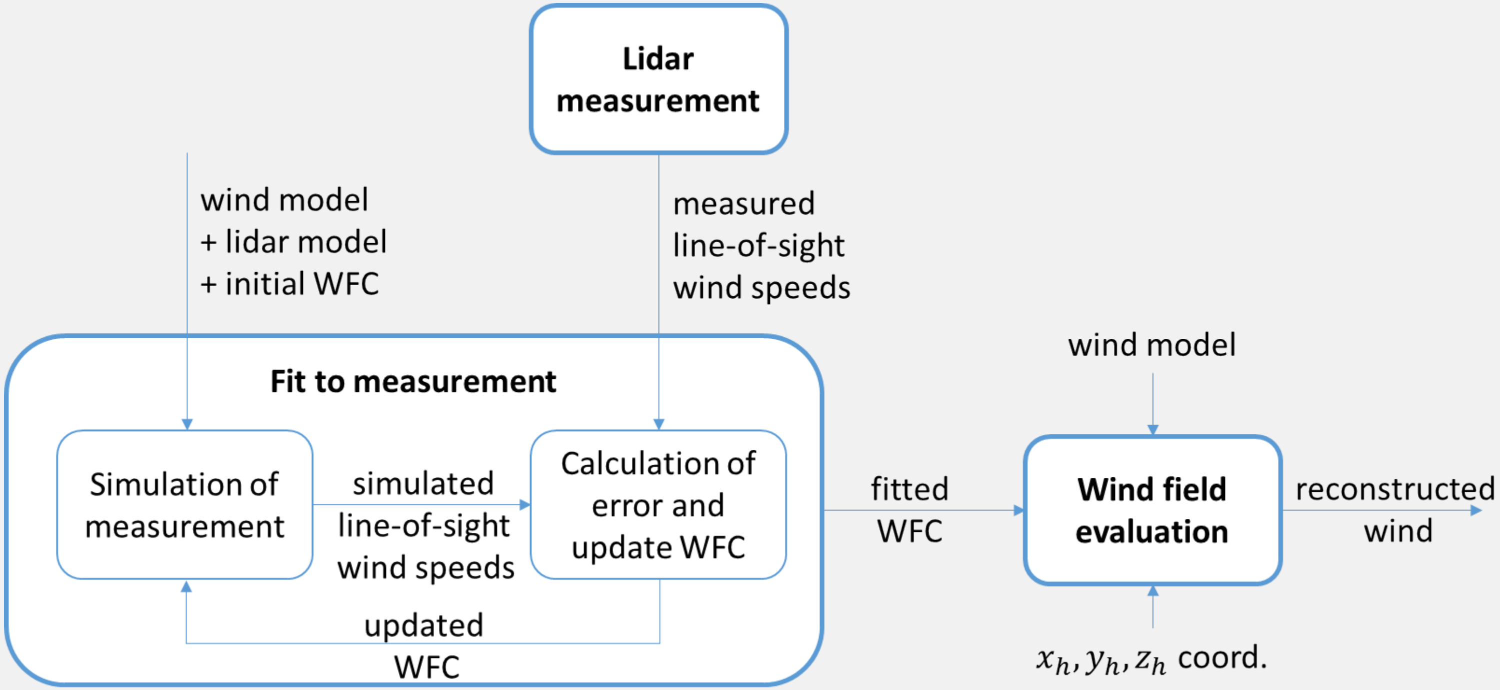
Model-based wind field reconstruction

- **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)



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	U	V	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
Inhomogeneous 2D + linear V shear	$U_w = v_0 + \delta_V \cdot (z_W - z_{hub})$ $\leftrightarrow U_I = f(z)$	$V_w = 0 \ \leftrightarrow V_I = V$	$W_w = 0 \ \leftrightarrow W_I = 0$	Yaw misalignment $\alpha_H = cst$
Inhomogeneous 2D + linear V shear + linear V veer	$U_w = v_0 + \delta_V \cdot (z_W - z_{hub})$ $\leftrightarrow U_I = f(z)$	$V_w = 0 \ \leftrightarrow V_I = f(z)$	$W_w = 0 \ \leftrightarrow W_I = 0$	Yaw misalignment $\alpha_H = f(z)$
Inhomogeneous 2D + power law shear	$\boldsymbol{U_w = v_0 ({}^{z_w}/_{z_{hub}})^{\alpha_{exp}}}$ $\boldsymbol{\leftrightarrow U_I = f(z)}$	$\boldsymbol{V_w = 0 \ \leftrightarrow V_I = V}$	$\boldsymbol{W_w = 0 \ \leftrightarrow W_I = 0}$	**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}

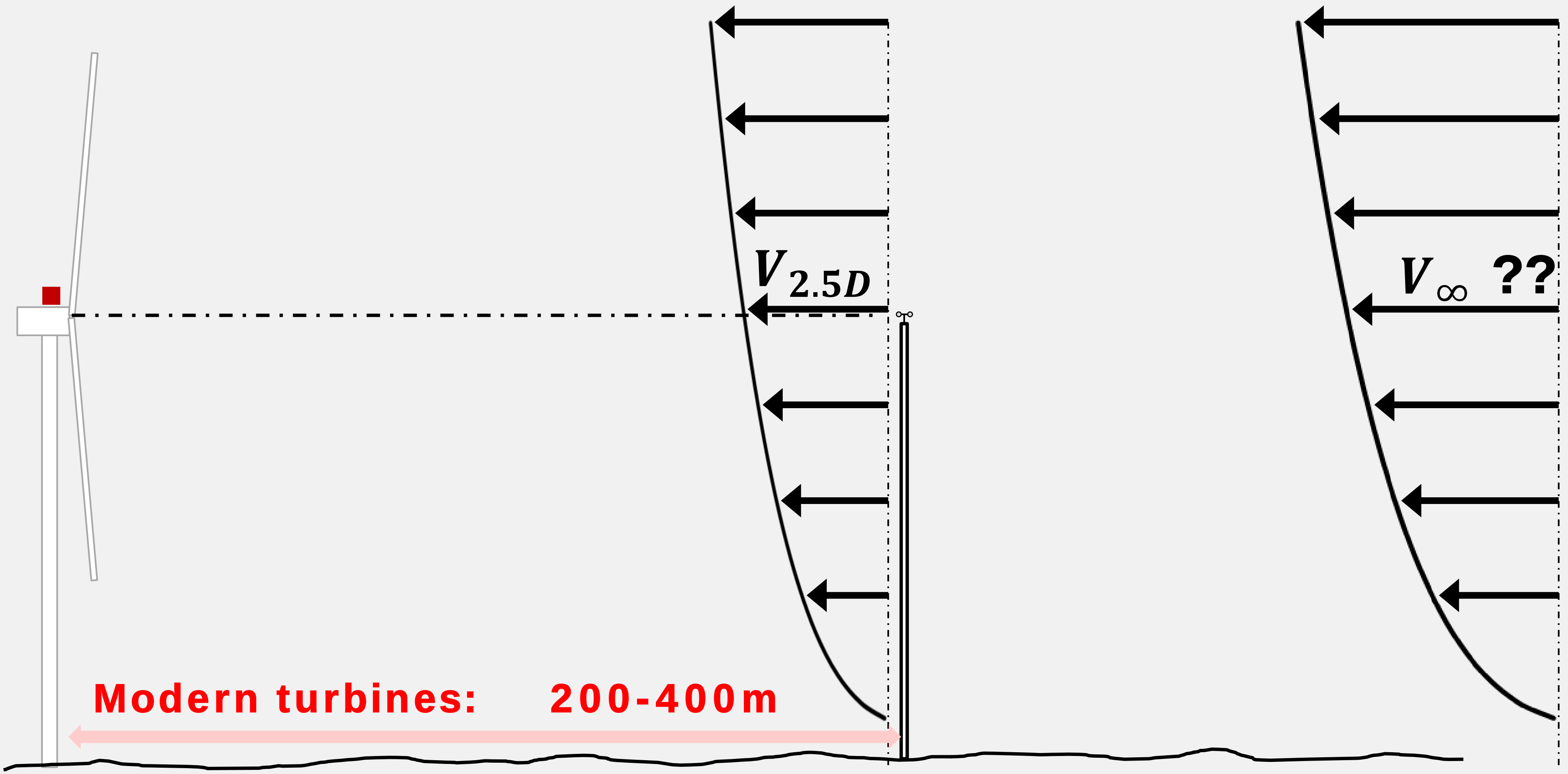
Model-based wind field reconstruction

- **Wind models**

Model name	***U***	***V***	***W***	**comment**
Homogeneous 2D	$U_w = cst \quad \leftrightarrow U_I = U$	$V_w = 0 \;\; \leftrightarrow V_I = V$	$W_w = 0 \;\; \leftrightarrow W_I = 0$	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
Inhomogeneous 2D + linear V shear	$U_w = v_0 + \delta_V \cdot (z_W - z_{hub})$ $\leftrightarrow U_I = f(z)$	$V_w = 0 \;\; \leftrightarrow V_I = V$	$W_w = 0 \;\; \leftrightarrow W_I = 0$	Yaw misalignment $\alpha_H = cst$
Inhomogeneous 2D + linear V shear + linear V veer	$U_w = v_0 + \delta_V \cdot (z_W - z_{hub})$ $\leftrightarrow U_I = f(z)$	$V_w = 0 \;\; \leftrightarrow V_I = f(z)$	$W_w = 0 \;\; \leftrightarrow W_I = 0$	Yaw misalignment $\alpha_H = f(z)$
Inhomogeneous 2D + power law shear	$U_w = v_0 (^{z_w}/_{z_{hub}})^{\alpha_{exp}}$ $\leftrightarrow U_I = f(z)$	$V_w = 0 \;\; \leftrightarrow V_I = V$	$W_w = 0 \;\; \leftrightarrow W_I = 0$	Yaw misalignment $\alpha_H = cst$
Inhomogeneous 2D + power law shear + induction model	$\boldsymbol{U_w = f(x,z)}$ $\boldsymbol{\leftrightarrow U_I = f(x,z)}$	$\boldsymbol{V_w = 0}$ $\boldsymbol{\leftrightarrow V_I = f(x,z)}$	$\boldsymbol{W_w = 0 \;\; \leftrightarrow W_I = 0}$	**1D Biot-Savard for induction fct**

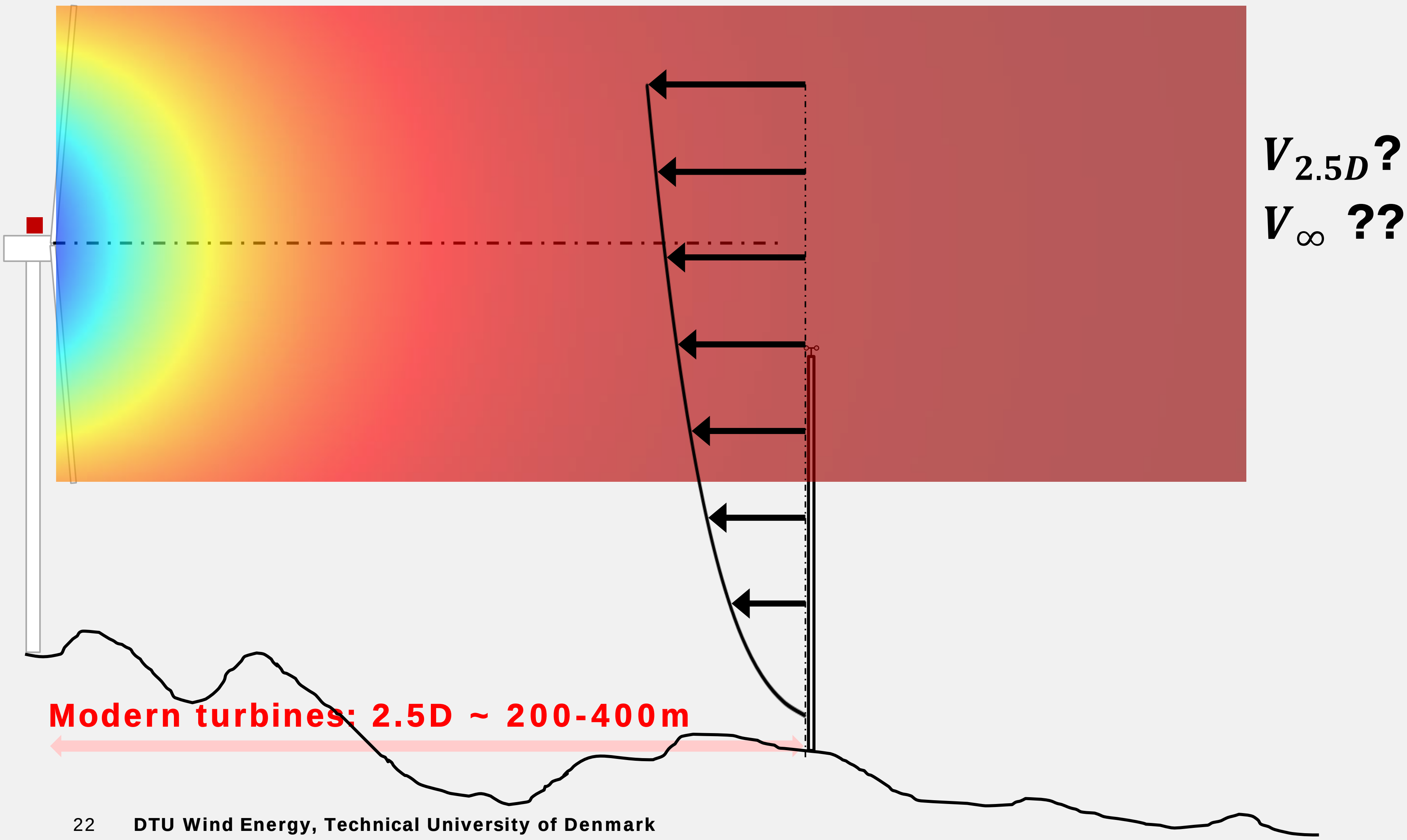
→ fitted wind characteristics are: free stream HWS U_∞ , yaw misalignment α_H, shear exponent α_{exp}, induction factor a.

Power performance verification: "standard" procedure, what's the problem?



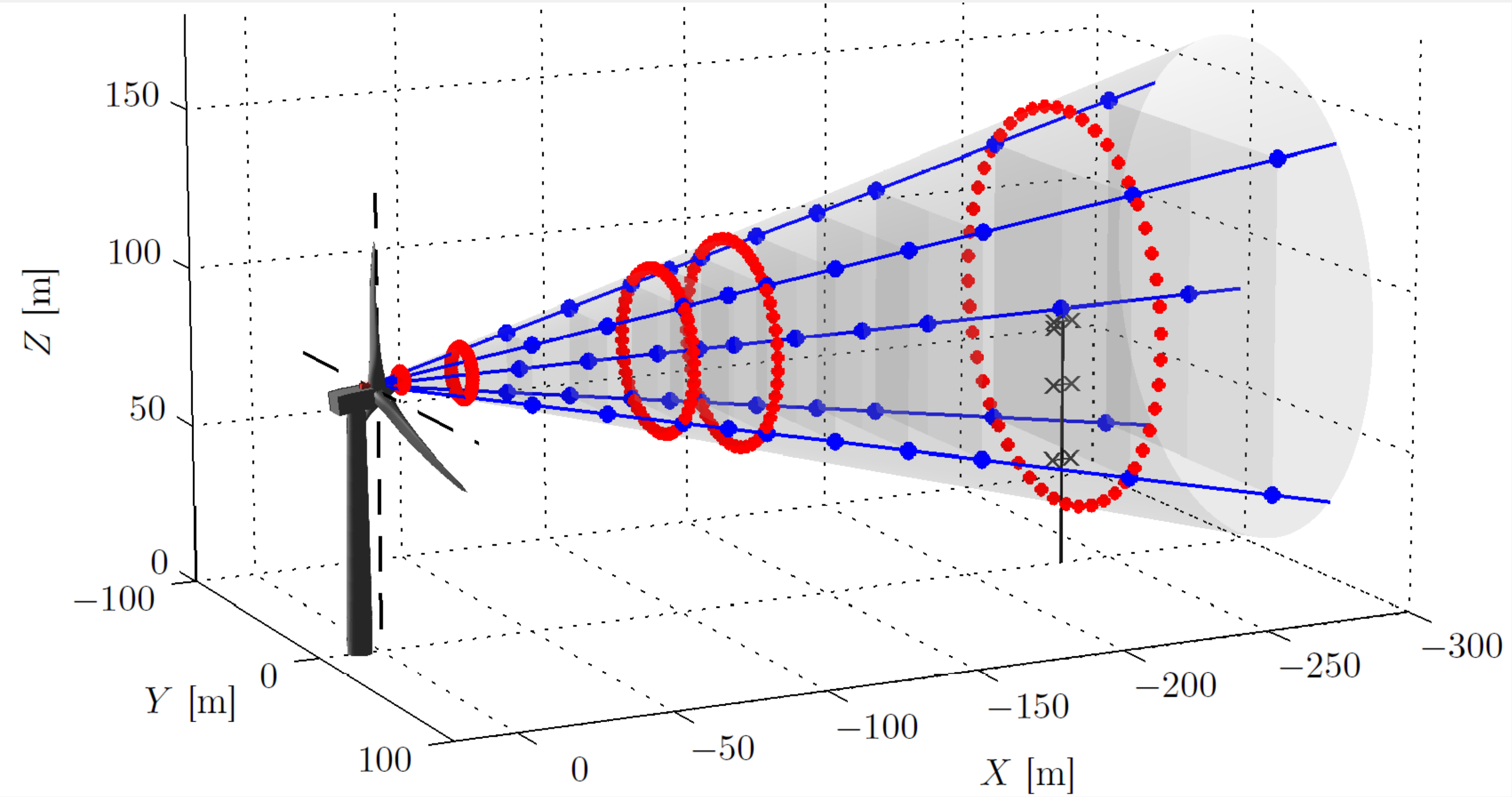
- Decorrelation WSpeed / power
- H_{hub} speed insufficient?
- 2.5D not really free wind …
- Too expensive: e.g. offshore

Power performance verification: “standard” procedure, what’s the problem?



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



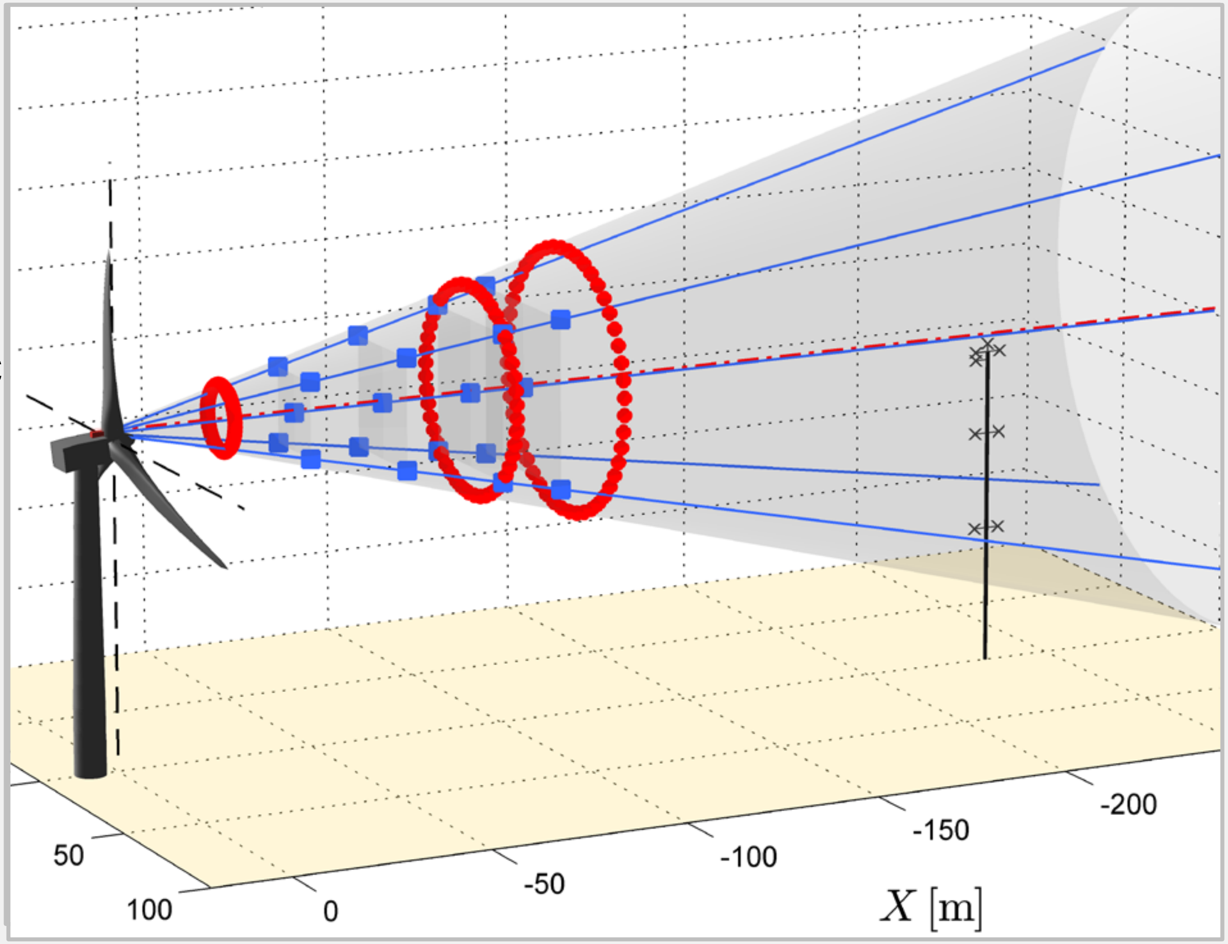
Power performance verification: nacelle-mounted lidars, the future?

- Several possibilities for lidar measurements:

1) 2.5D distance
   incl. shear

2) 1D distance (only)
   + correct with induc
   transfer function

3) Multiple distances
   from 0.5 to 1.5D
   induction integrated
   in wind field
   reconstruction

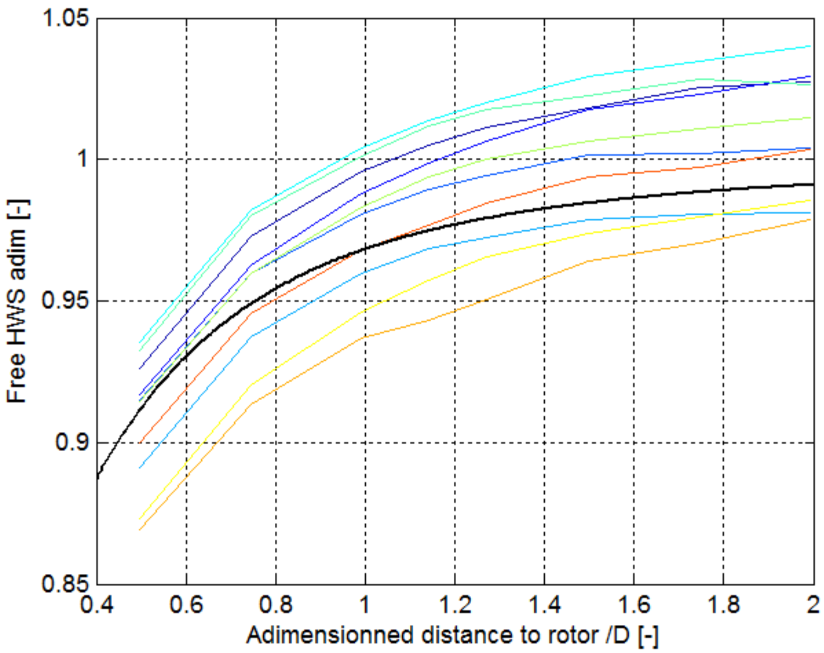


A simple induction model

- **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