Modelling Wind Turbine Inflow:

The Induction zone

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Co-supervisors:

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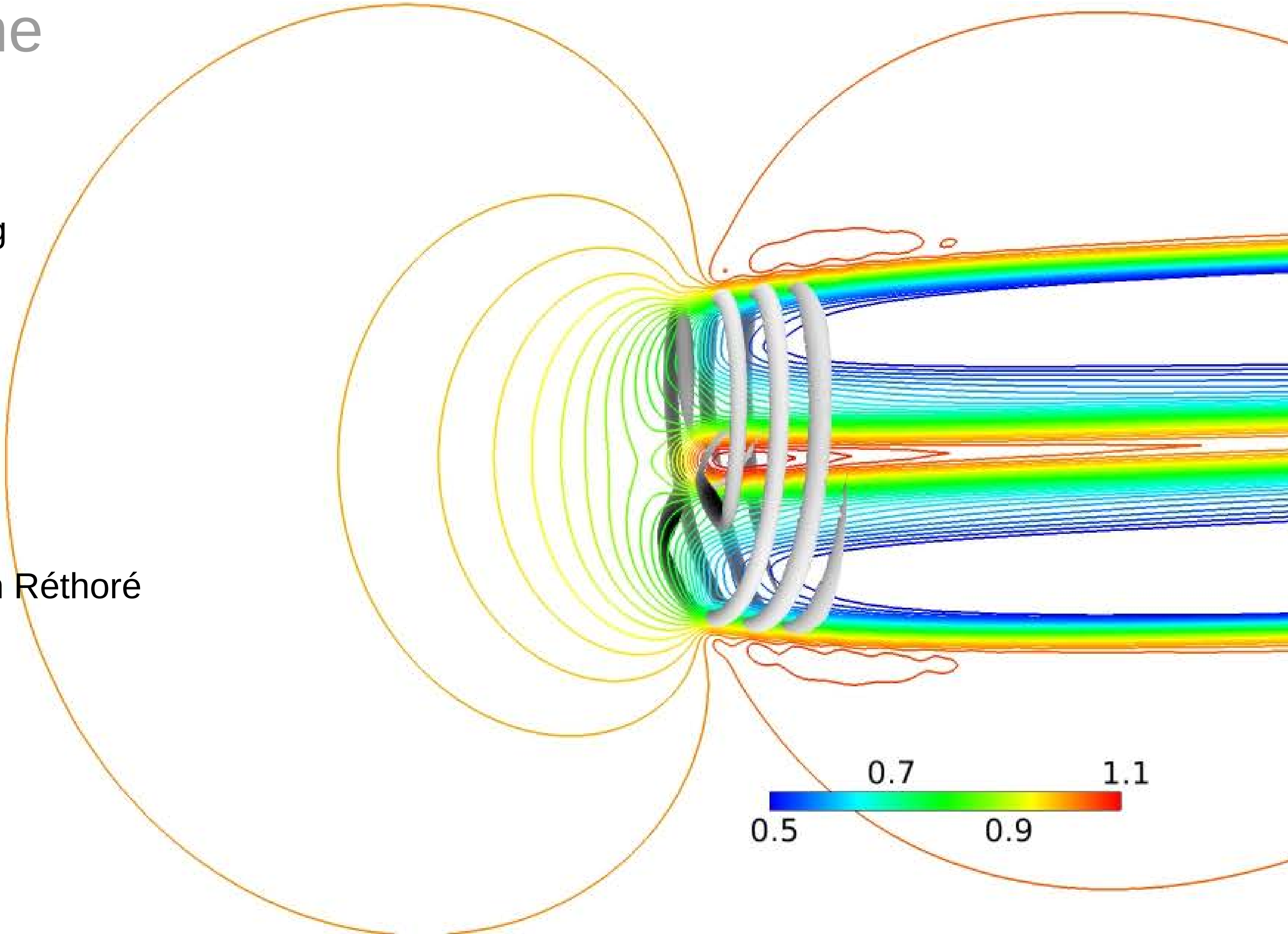


DTU Wind Energy
Department of Wind Energy

Why wind turbine inflow?

Inflow KE

$$\frac{1}{2}\rho V_{\infty}^{2} A$$

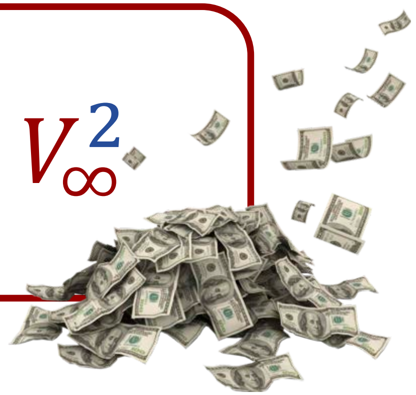
Why wind turbine inflow?

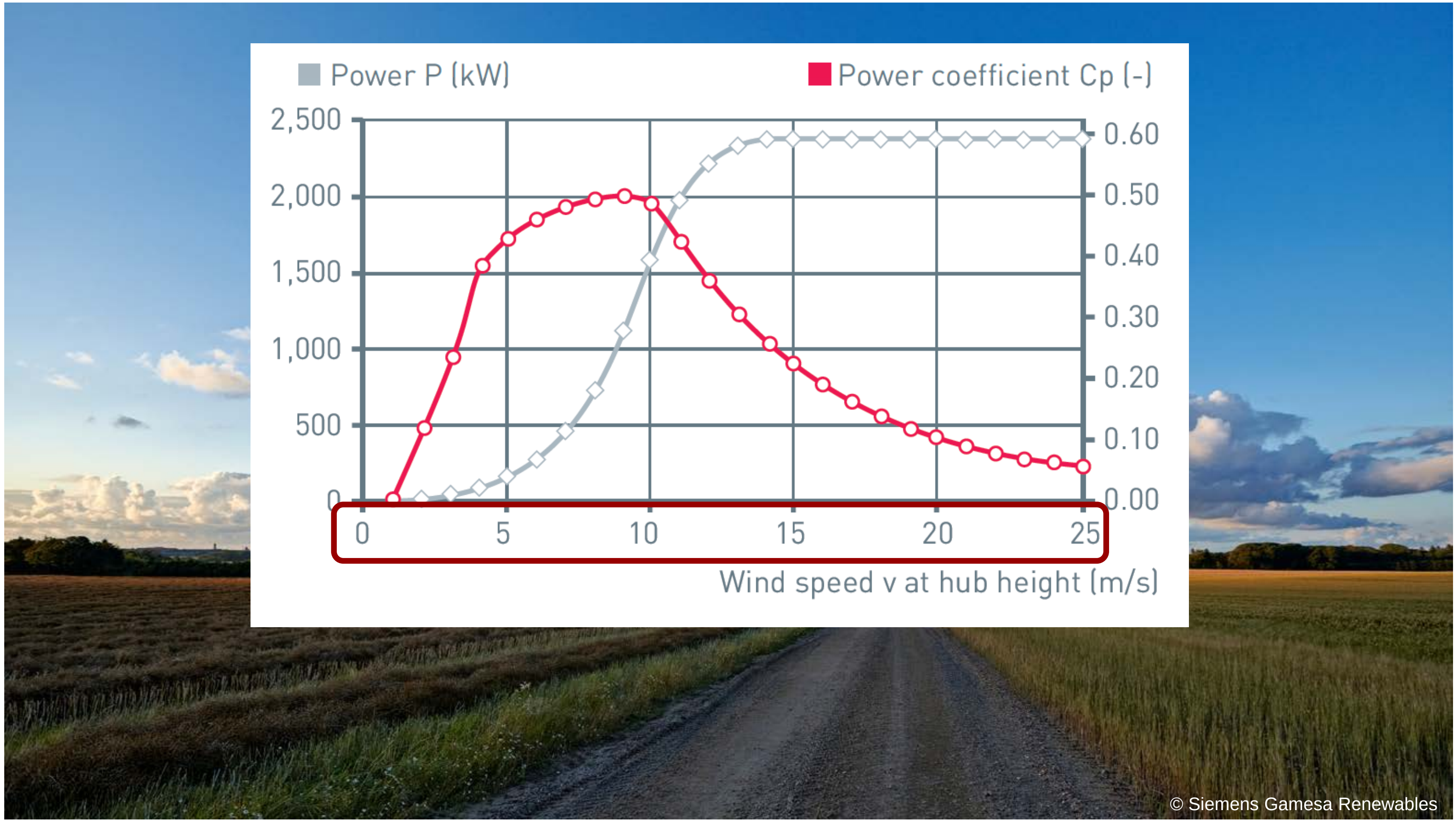
Power

$\propto V_\infty^3$

Blade Forces

$\propto V_\infty^2$





How do we get V_∞?

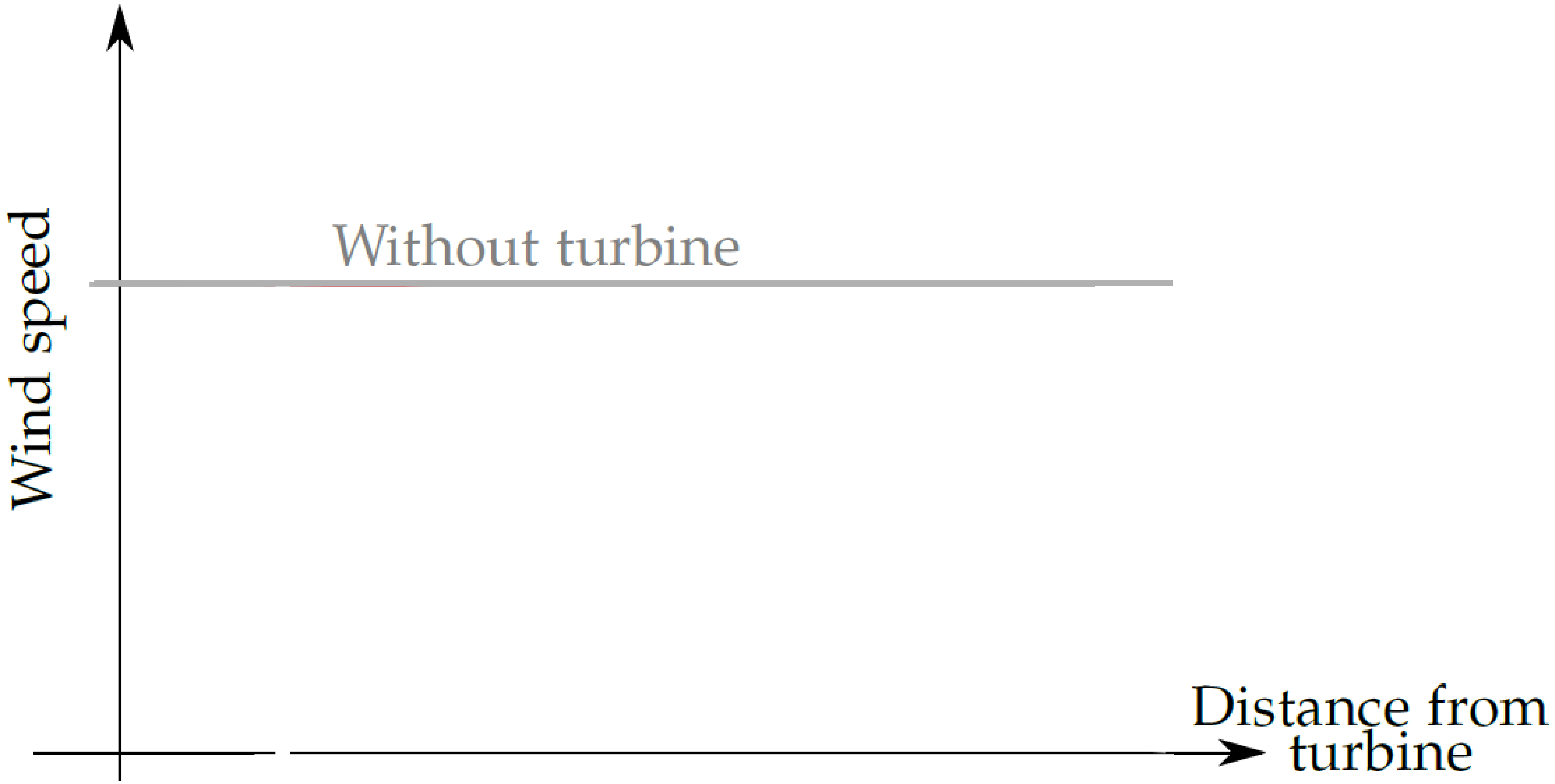
- Measure with:
  - Met mast
  - Lidar:
    - Ground-based
    - Hub mounted

But where do we find V_∞?

Decorrelation:

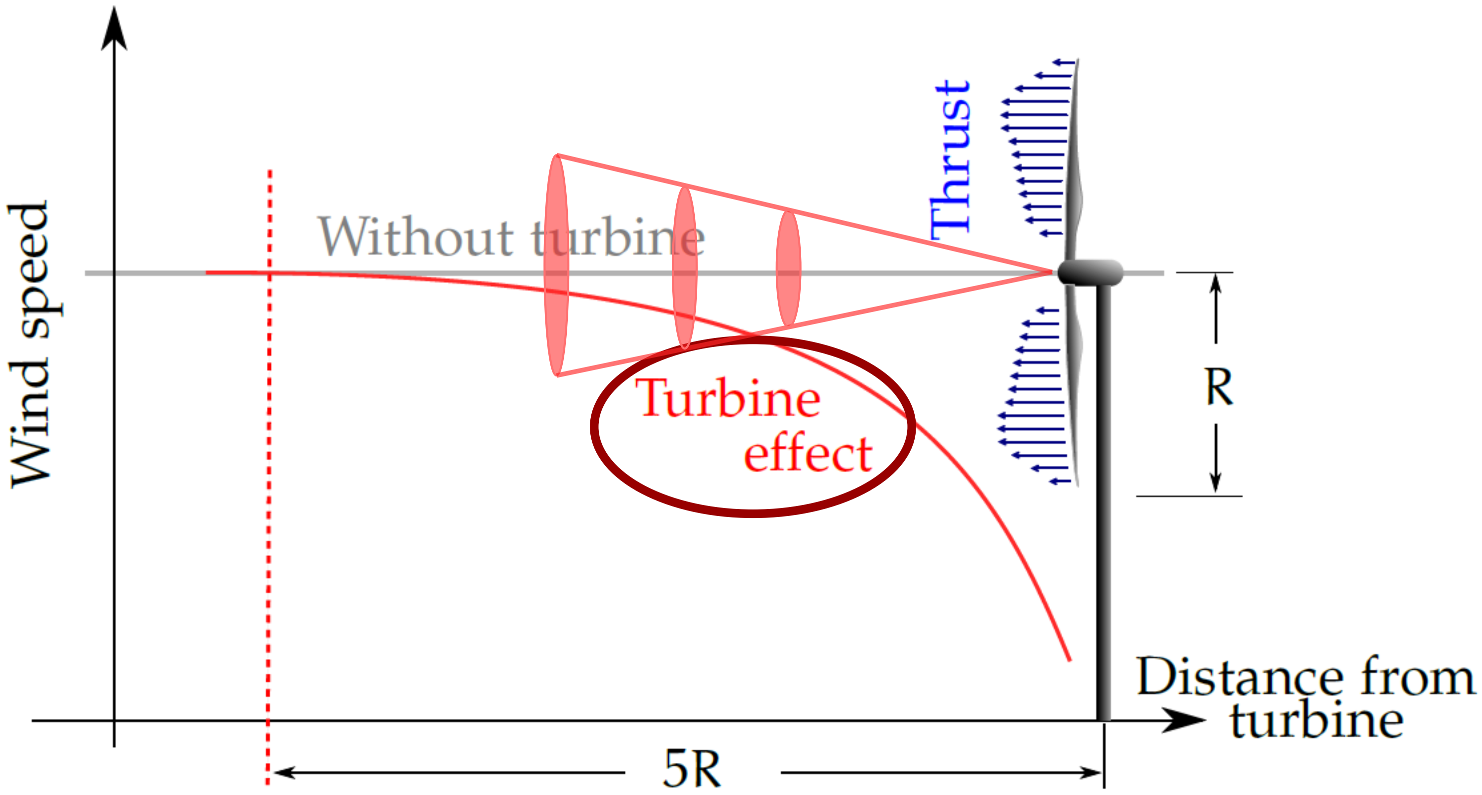
- Non-homogeneous wind field
- Move closer to the turbine

Showstopper: The induction zone



Evolution of V_∞ + induction zone

Benefits of near-rotor measurements



UniTTe

Nacelle mounted lidars for power and loads assessment

- Improves wind speed – power/load correlation

Induction zone

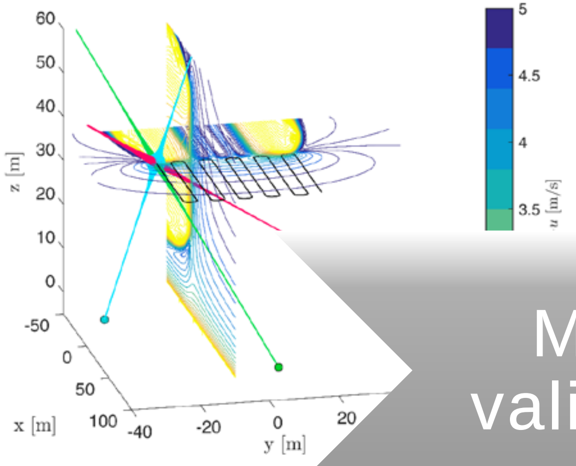
- Avoids building expensive met masts

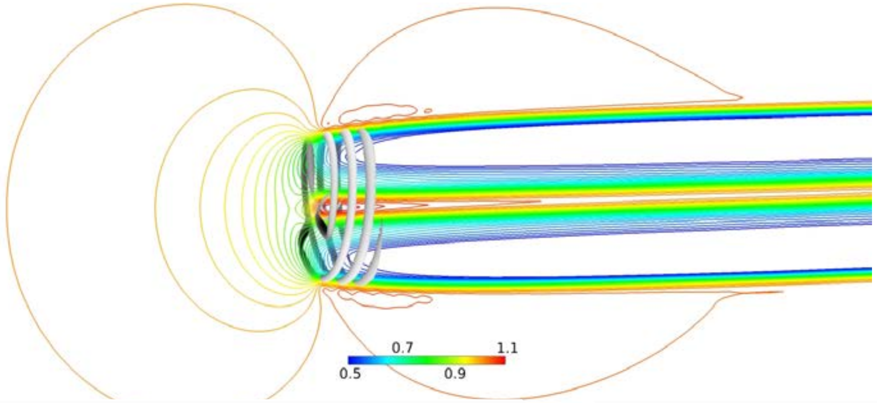
model

- Universal measurement procedure

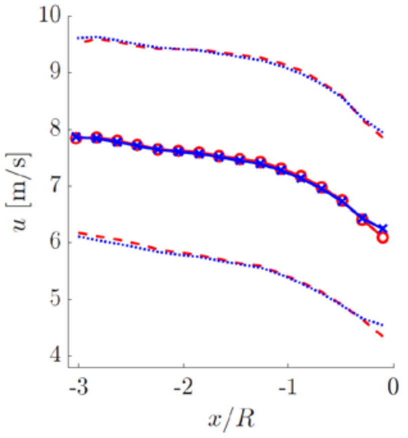
Modelling the induction zone

The quest for V_∞





Model validation → Physical parameters → Simple model



$$\tilde{u}(\tilde{x},\tilde{r},C_T) = 1 - \overbrace{a(C_T,\tilde{x})}^{\text{axial}}\,\underbrace{f(\epsilon)}_{\text{radial}}$$

Modelling the induction zone

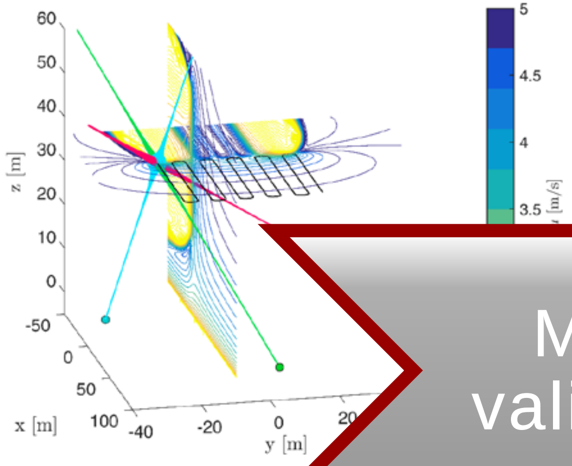
The quest for V_∞

Conferences:

Torque 2016

Wake Conference 2017

UNCECOMP 2017



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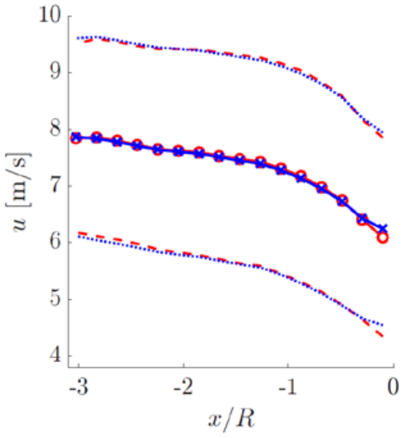
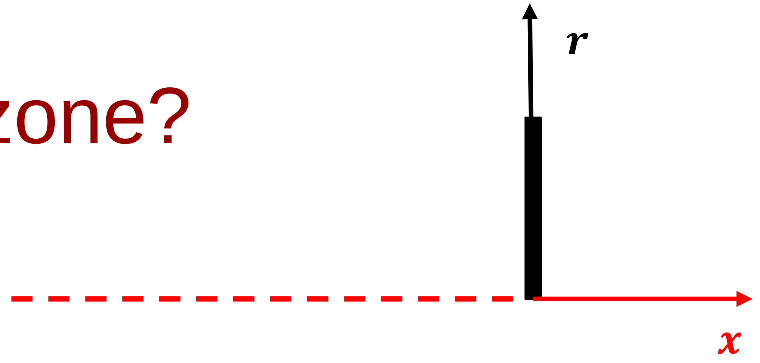


Meyer Forsting AR et al. *Validation of a CFD model with a synchronized triple-lidar system in the wind turbine induction zone.* Wind Energy. 2017;20:1481-1498.

Meyer Forsting AR, Troldborg N. *A finite difference approach to despiking in-stationary velocity data - tested on a triple-lidar.* Journal of Physics: Conference Series (Online). 2016

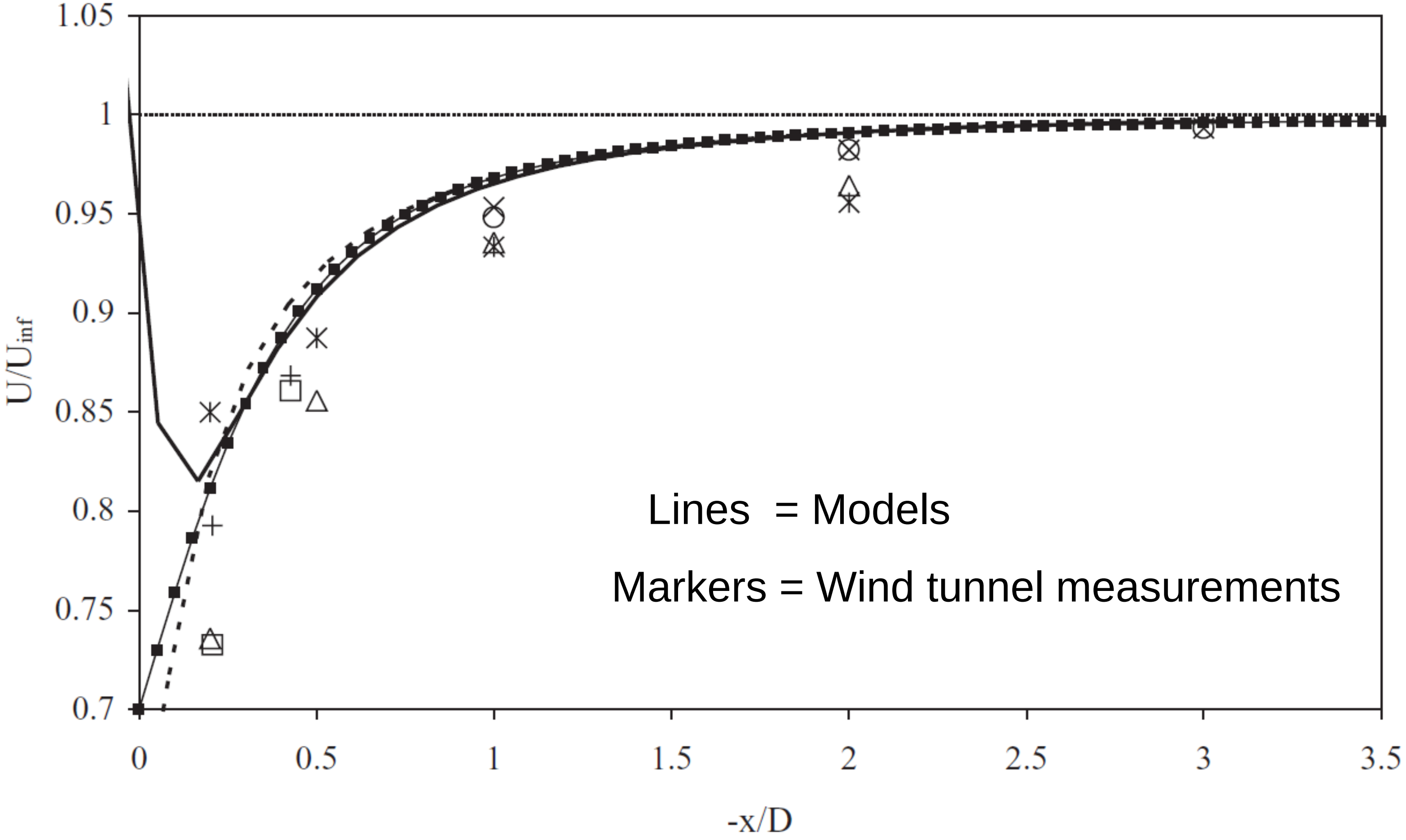
Meyer Forsting AR et al.: *Modelling lidar volume-averaging and its significance to wind turbine wake measurements*: Wake Conference 2017. Vol. 854. 2017.

Can we model the induction zone?

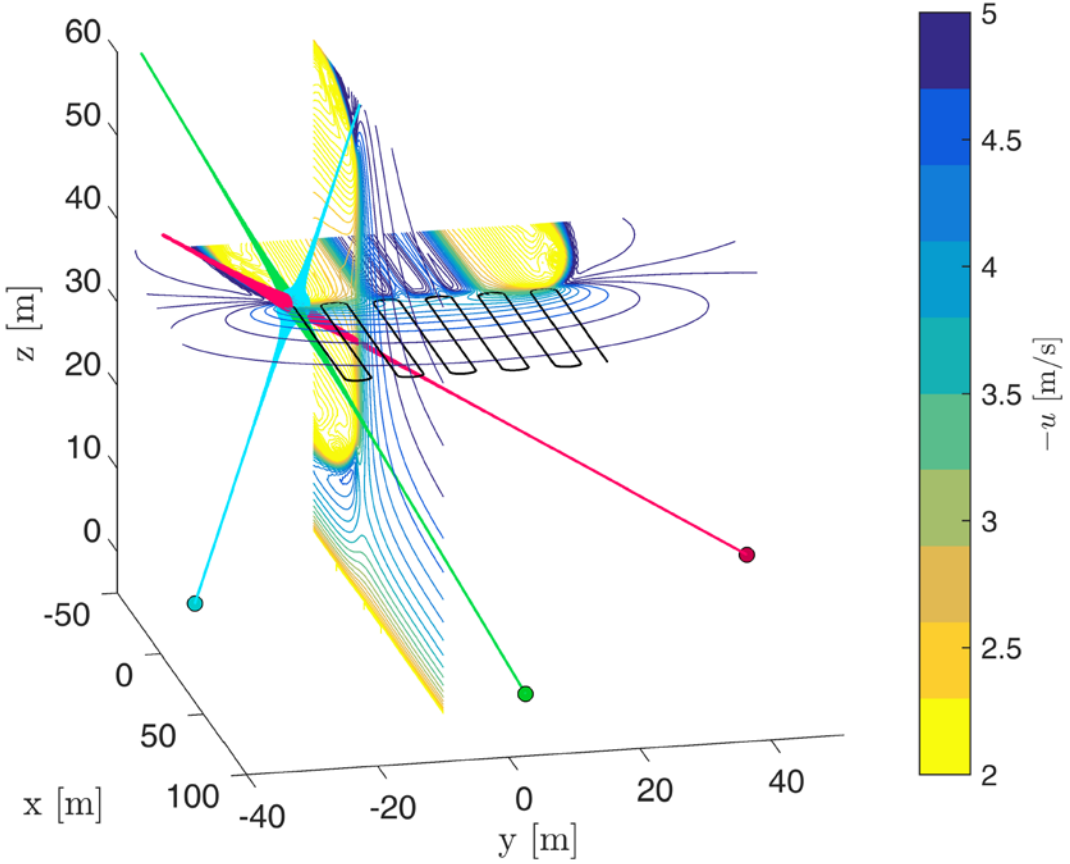


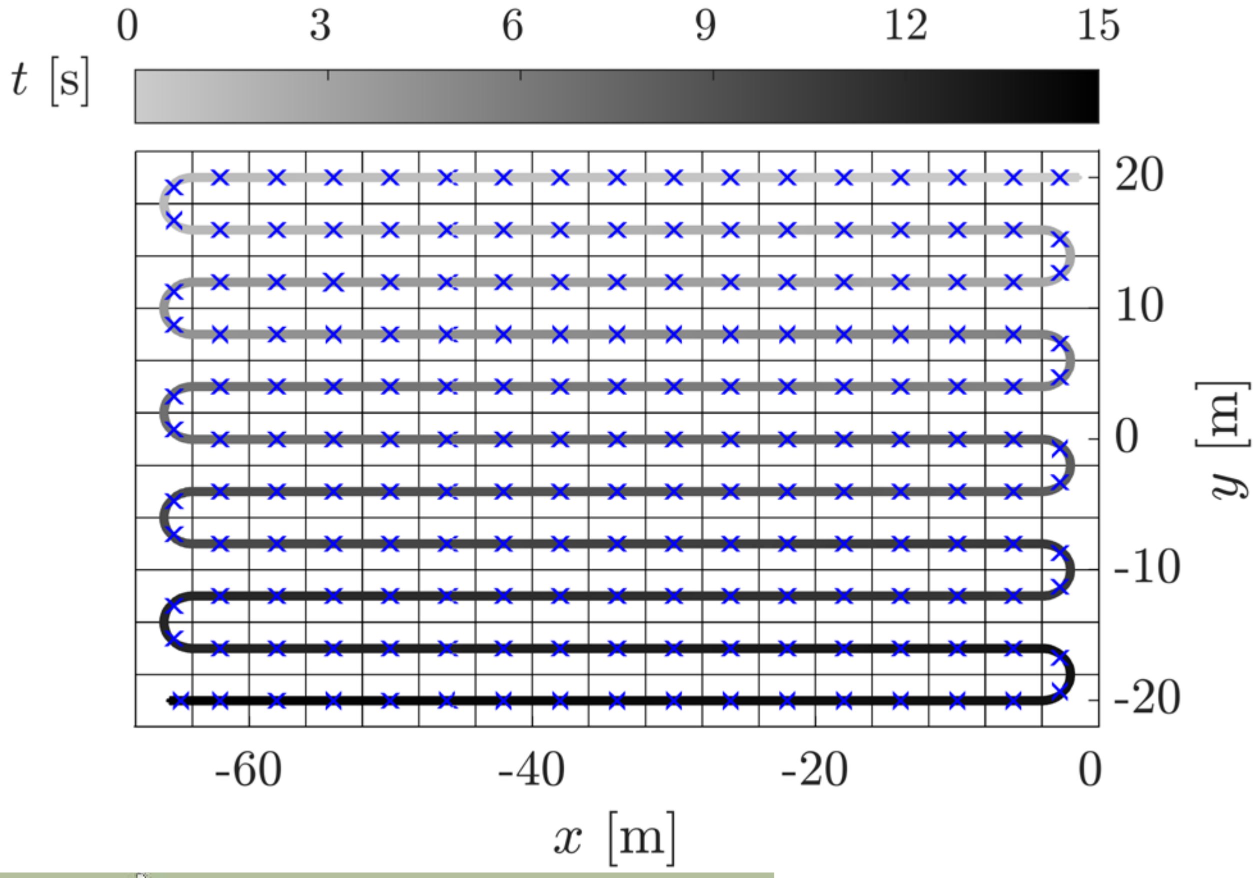
(Medici 2011)

(Simley 2016)



The triple-lidar measurement campaign





Model validation

(Typical) validation approach

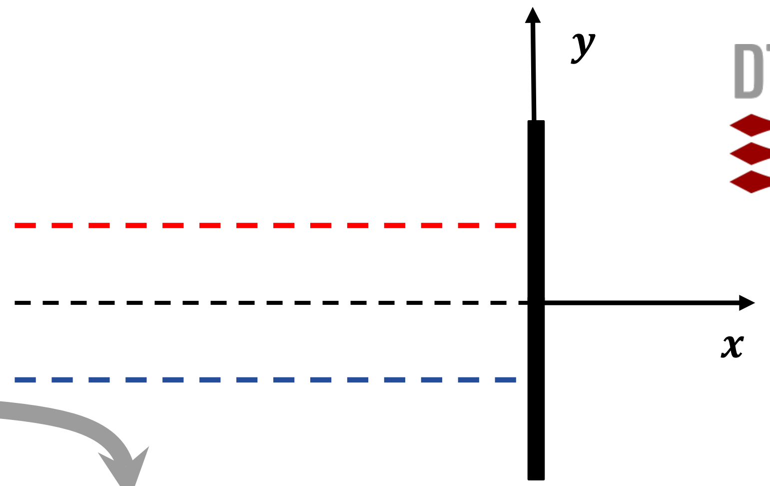
Model

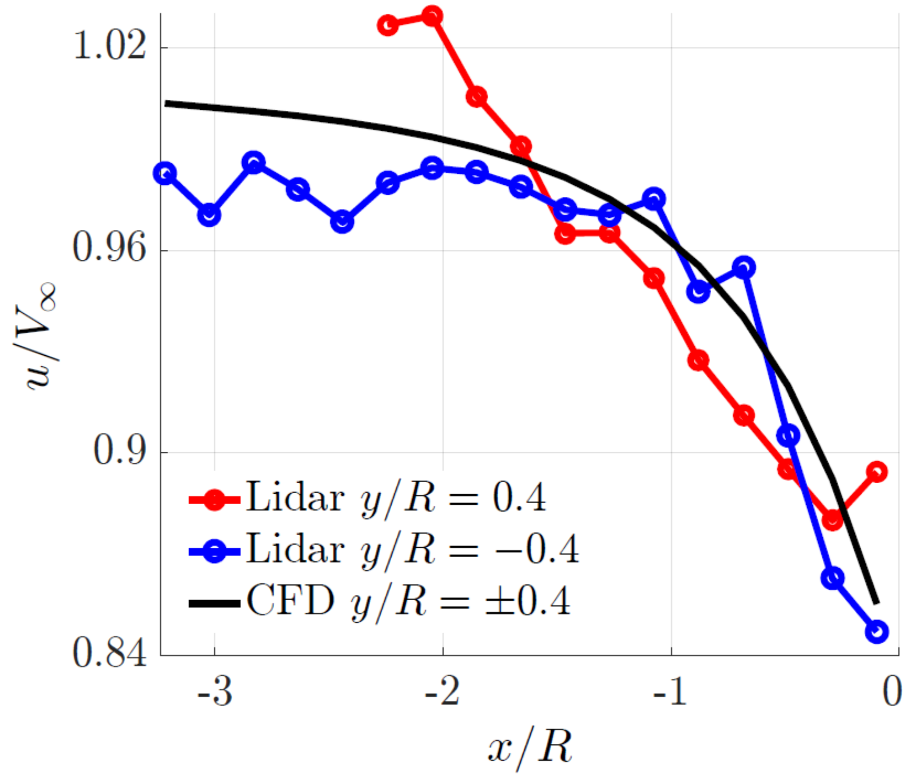
#	Date [dd/mm]	Start time [hh:mm]	$\bar{V}_\infty$ [m/s]	TI [%]	WD [°]
1	06/08	08:16	[illegible]	13.6	298
2	20/08	[illegible]	10.3	10.6	255
3	[illegible]	[illegible]	[illegible]	[illegible]	246
4	[illegible]	[illegible]	[illegible]	[illegible]	249
5	[illegible]	[illegible]	[illegible]	[illegible]	292
6	[illegible]	[illegible]	[illegible]	[illegible]	271
7	[illegible]	[illegible]	[illegible]	[illegible]	275
8	[illegible]	[illegible]	[illegible]	[illegible]	274
9	27/09	15:28	8.16	12.1	277
10	02/10	14:01	2.64	9.96	282

10 x 30 minute periods

1117 Horizontal planes

197 000 measurement points

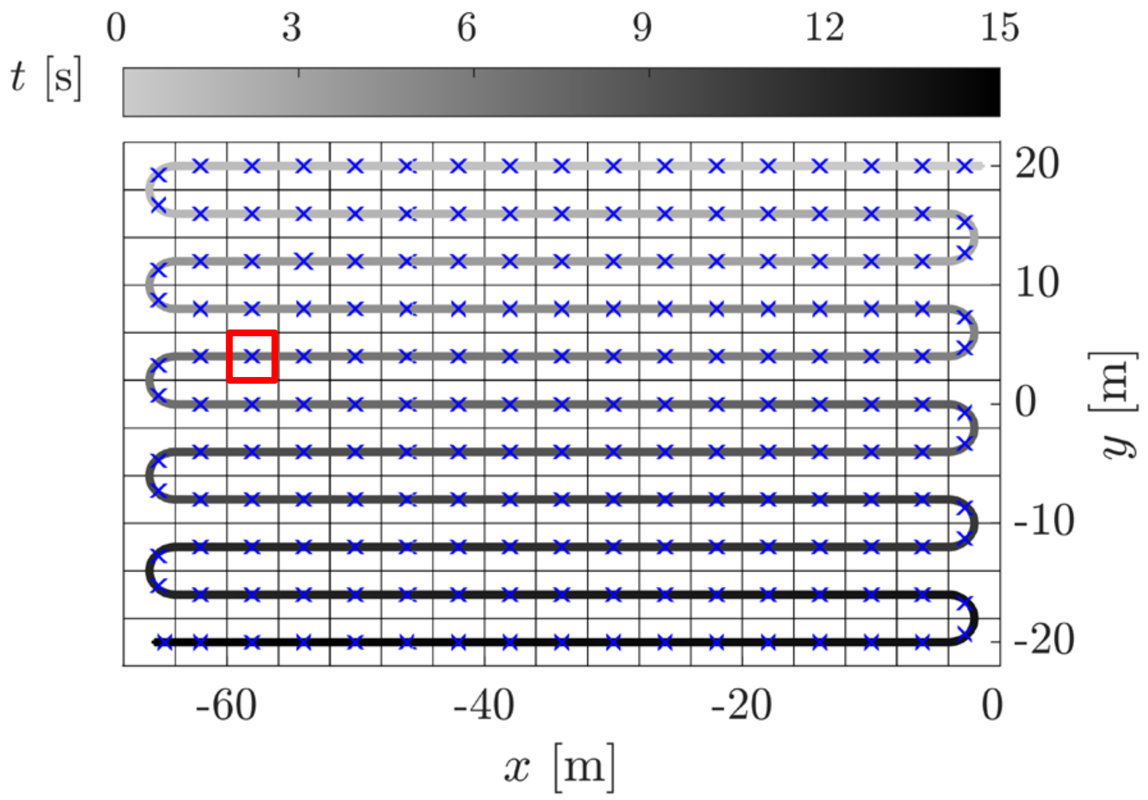




Model validation

Low sample size

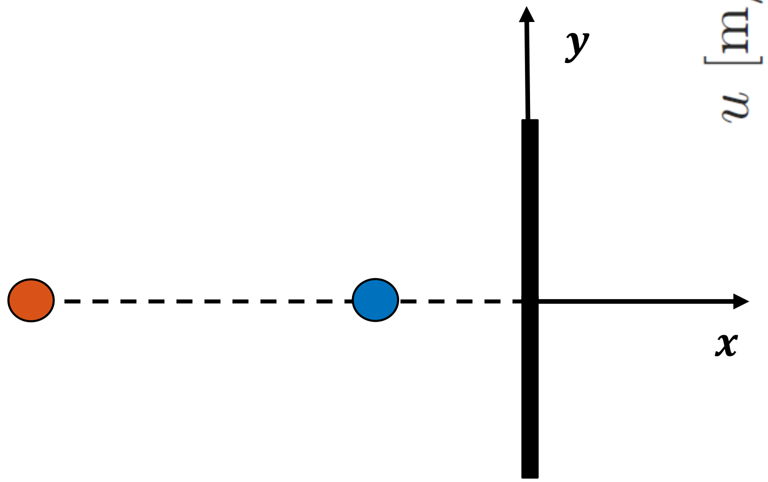
- 187 points per horizontal scan
- 15 seconds for one scan
- 30 min period = 120 points per grid cell

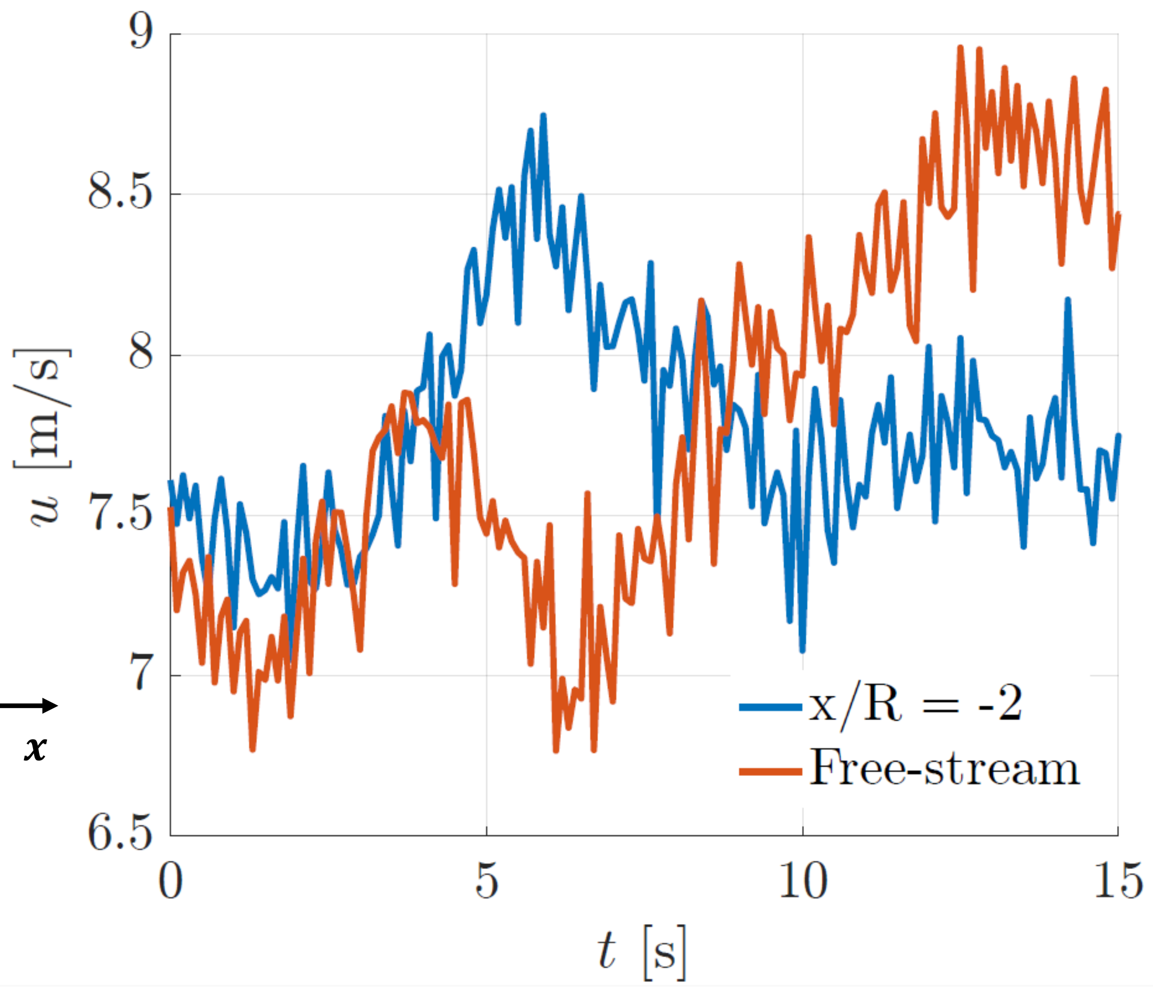


Triple-lidar uncertainties

Inflow variability

Free-stream estimate



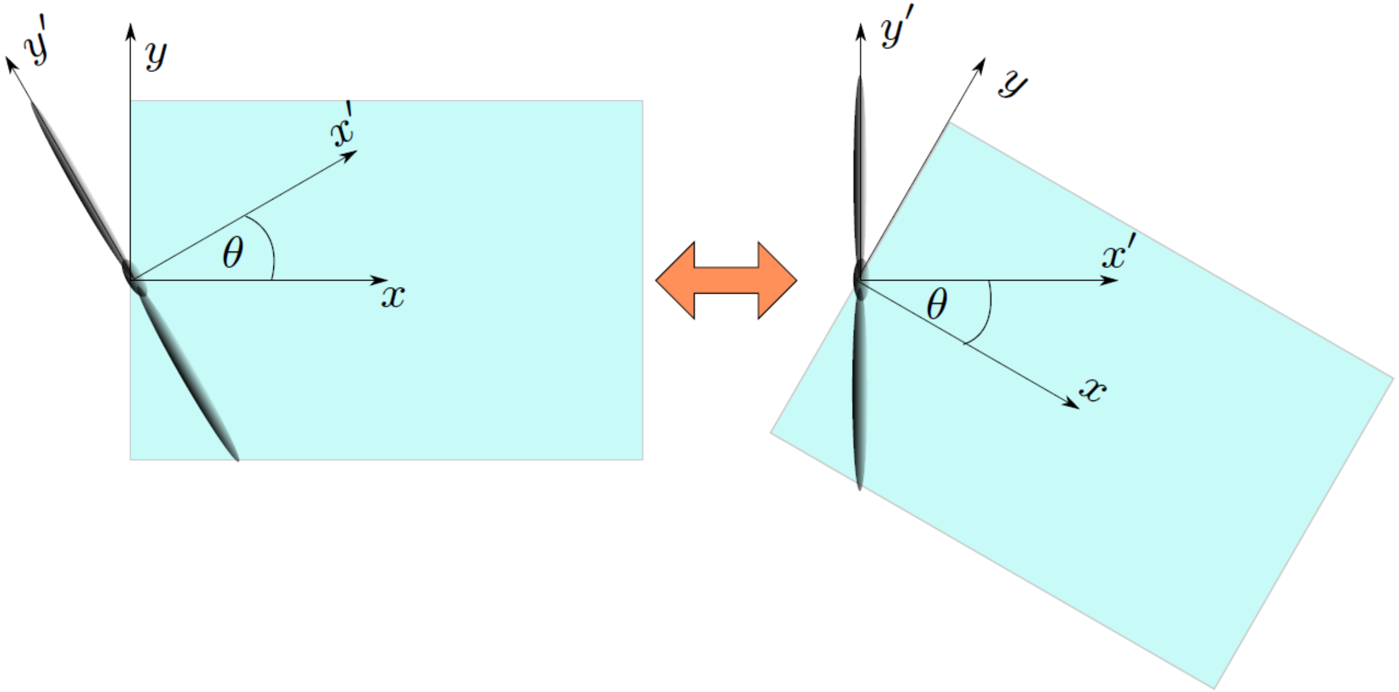


Model validation

Triple-lidar uncertainties

Free-yawing turbine + fixed measurement grid

Coordinate system mismatch



Triple-lidar uncertainties

Volume-averaging

Inflow variability

Spatio-temporal averaging

Free-stream estimate

Coordinate system mismatch

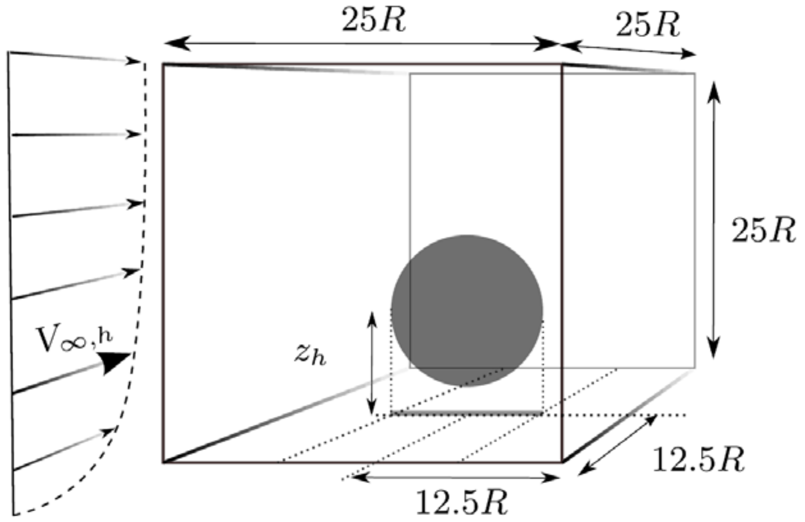
Measurement noise

Measurement location

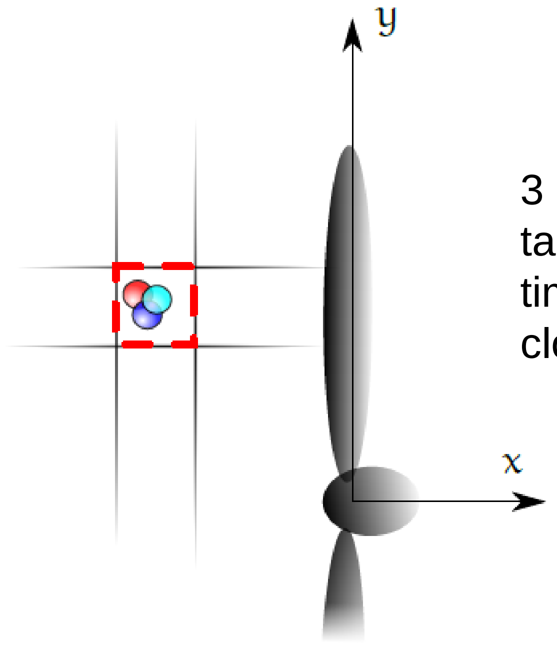
Model

EllipSys3D

- RANS
- Steady-state
- Actuator disc with airfoil data
- Log-law ie. neutral stability



Stochastic validation approach

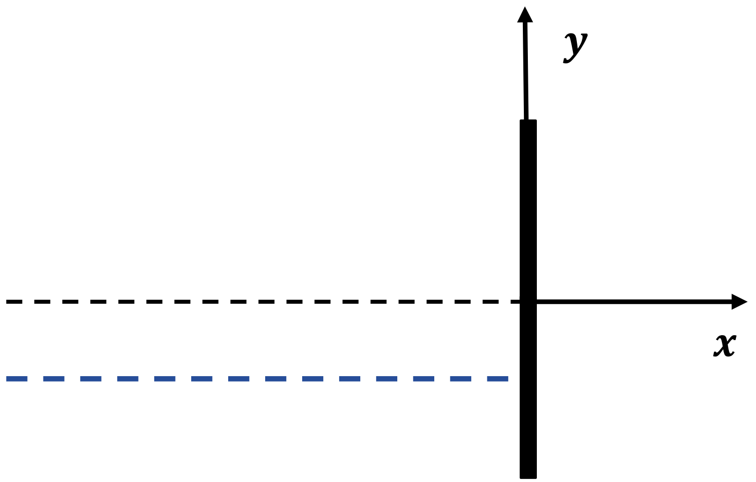


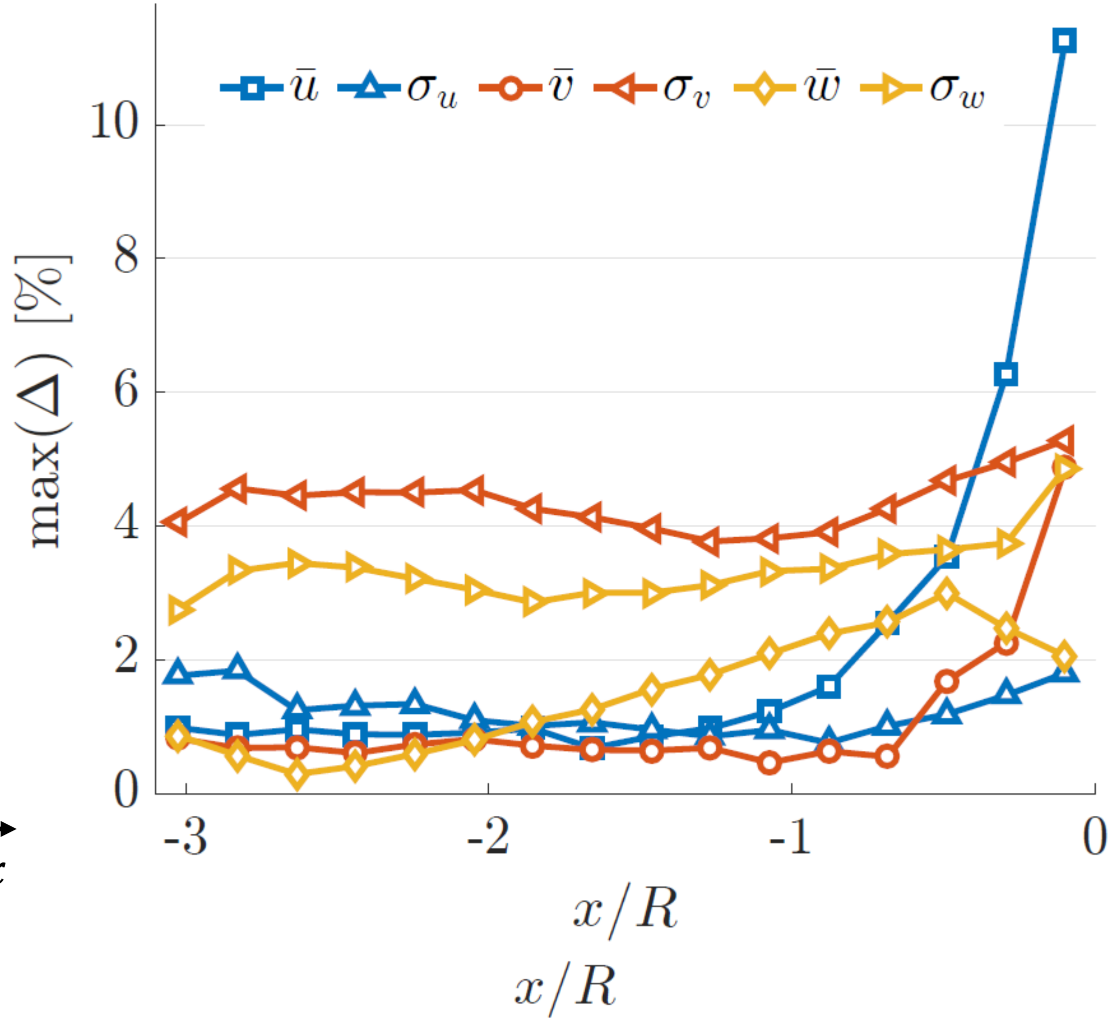
3 measurement points taken at different times/horizontal scans close to the rotor

Match boundary conditions

Stochastic validation

- 197 000 lidar measurements
- 8 measurement days
- All measurements used at once
- 14 CFD simulations



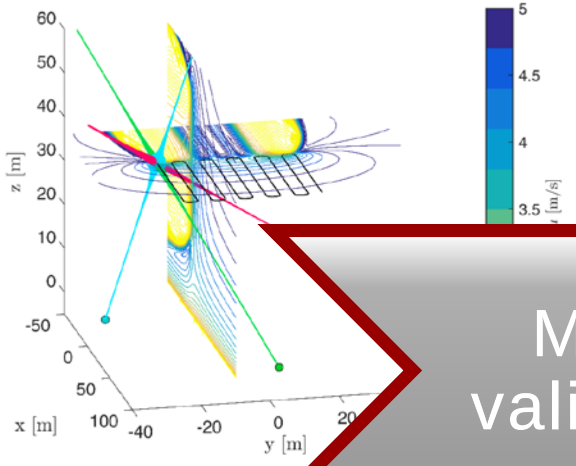


Modelling the induction zone

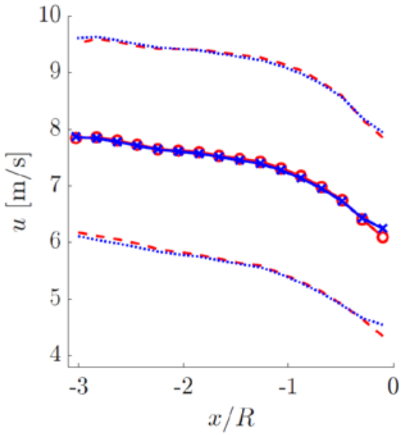
The quest for V_∞

”Any physical theory is always provisional: you can never prove it”

Stephen W. Hawking



Model validation → Physical parameters → Simple model



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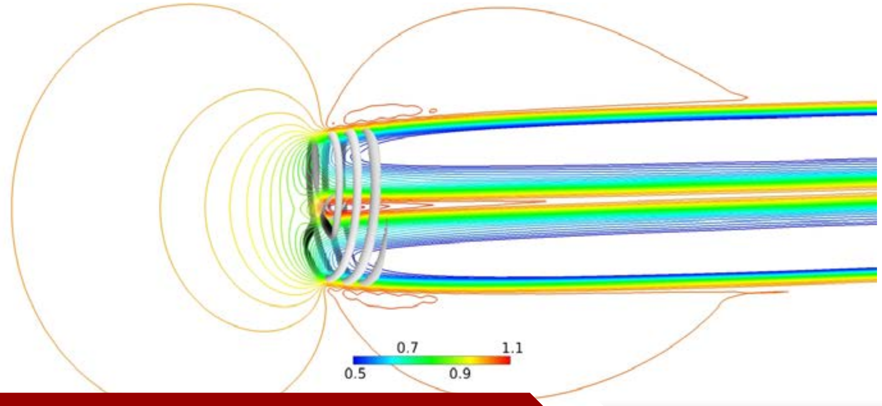


Conferences:
- Wake Conference 2015
- ECCOMAS 2016
- Torque 2016
- Wind Europe 2016
- WES 2017
- UNCECOMP 2017
- Wake Conference 2017

Model validation → **Physical parameters** → Simple model

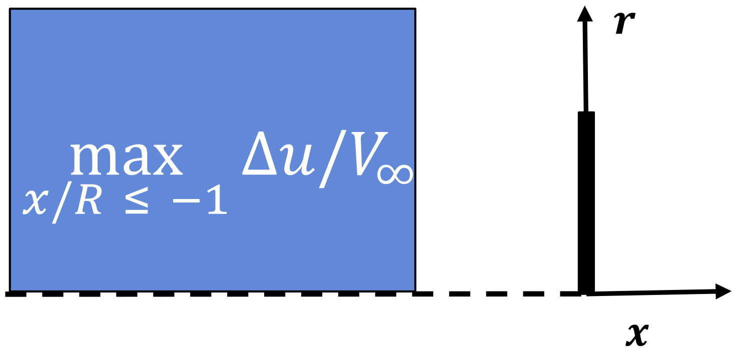
Nathan J, Meyer Forsting AR, Troldborg N, Masson C. *Comparison of OpenFOAM and EllipSys3D actuator line methods with (NEW) MEXICO results:* Paper. In Wake Conference 2017 .

Meyer Forsting AR, Bechmann A, Troldborg N. *A numerical study on the flow upstream of a wind turbine on complex terrain*. Journal of Physics: Conference Series (Online). 2016;753.

Meyer Forsting AR, Troldborg N, Gaunaa M. The flow upstream of a row of aligned wind turbine rotors and its effect on power production. Wind Energy. 2017;20(1):63–77.

Mirzaei M, Meyer Forsting AR, Troldborg N. *Dynamics of the interaction between the rotor and the induction zone.* Journal of Physics: Conference Series (Online). 2016;753.

Physics of the induction zone

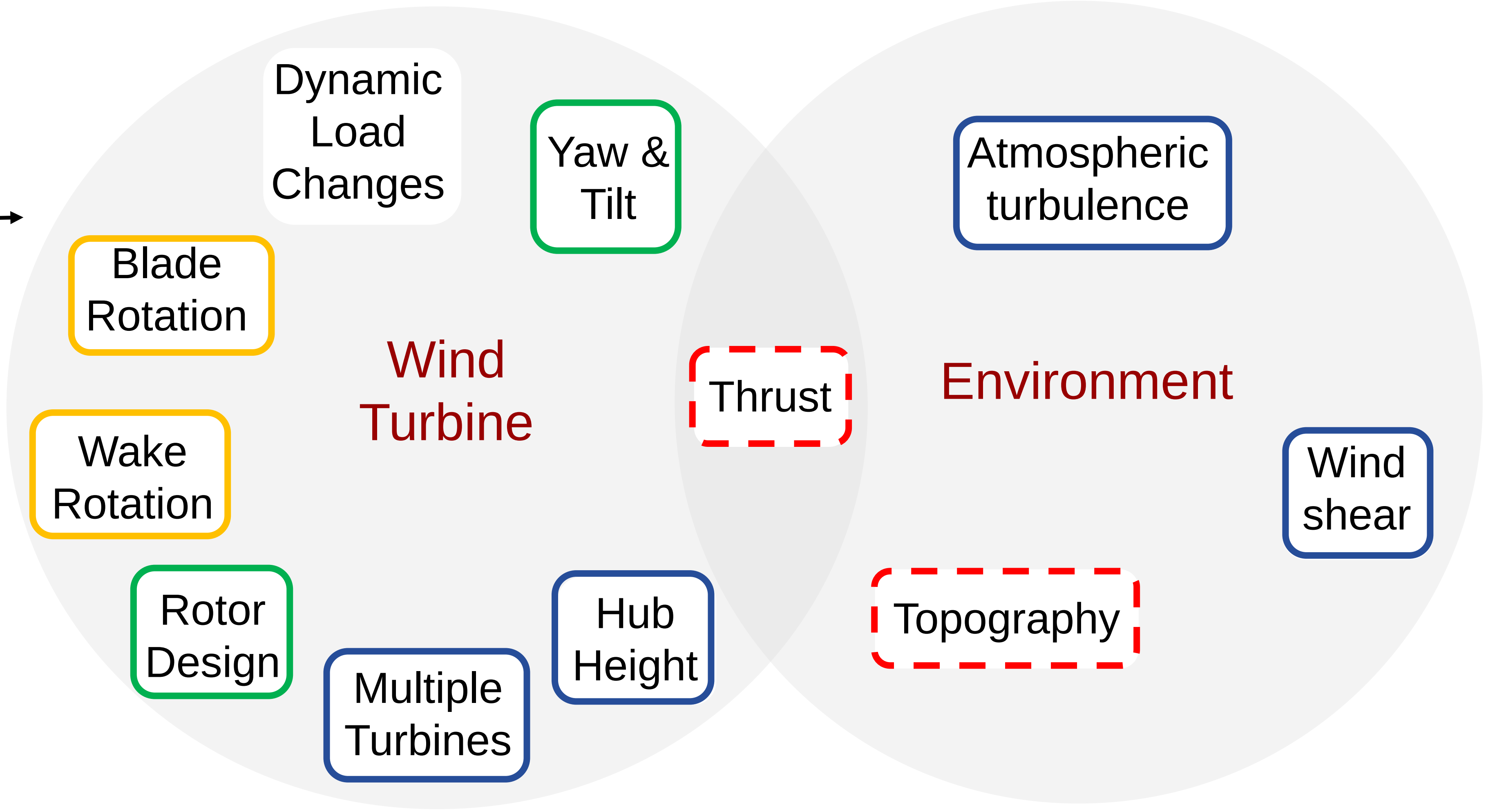


$\le 0.5\ \%$

$\le 1.0\ \%$

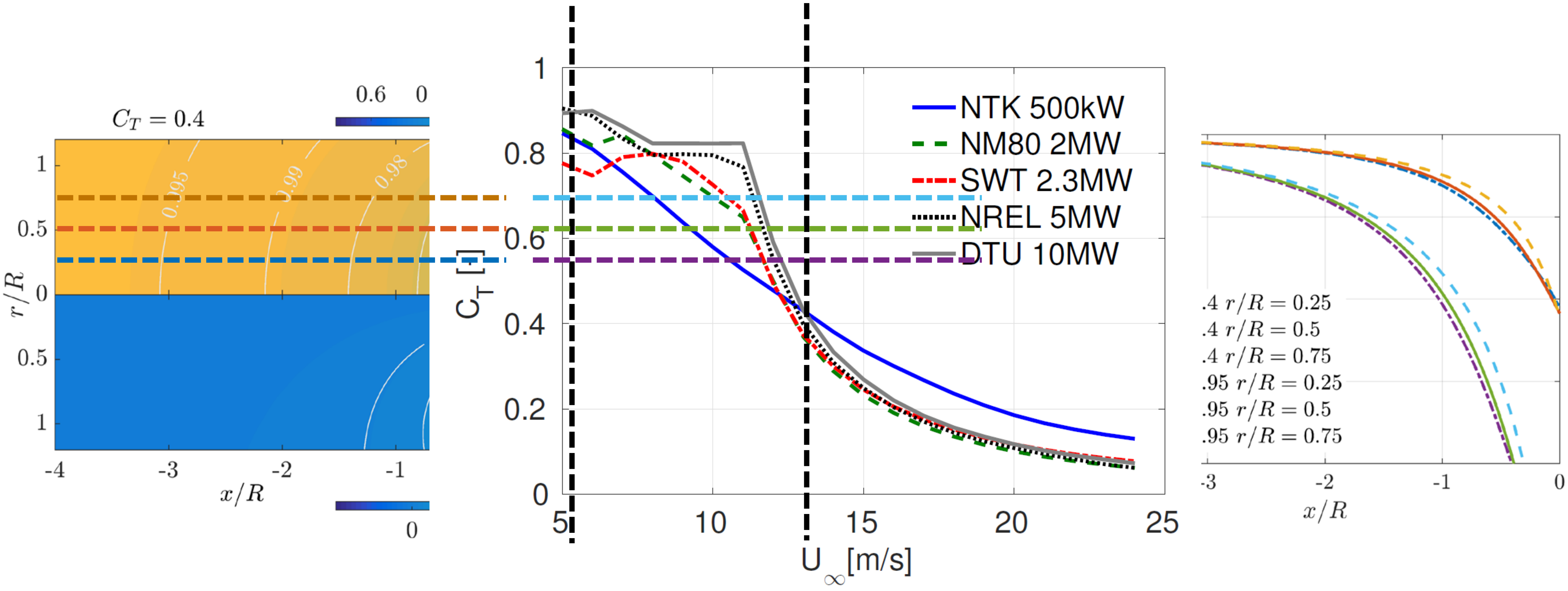
$\le 2.0\ \%$

$> 2.0\ \%$



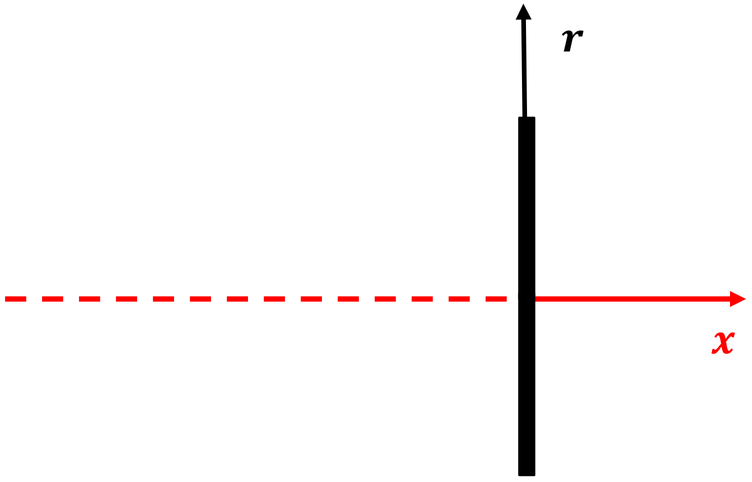
Physical parameters

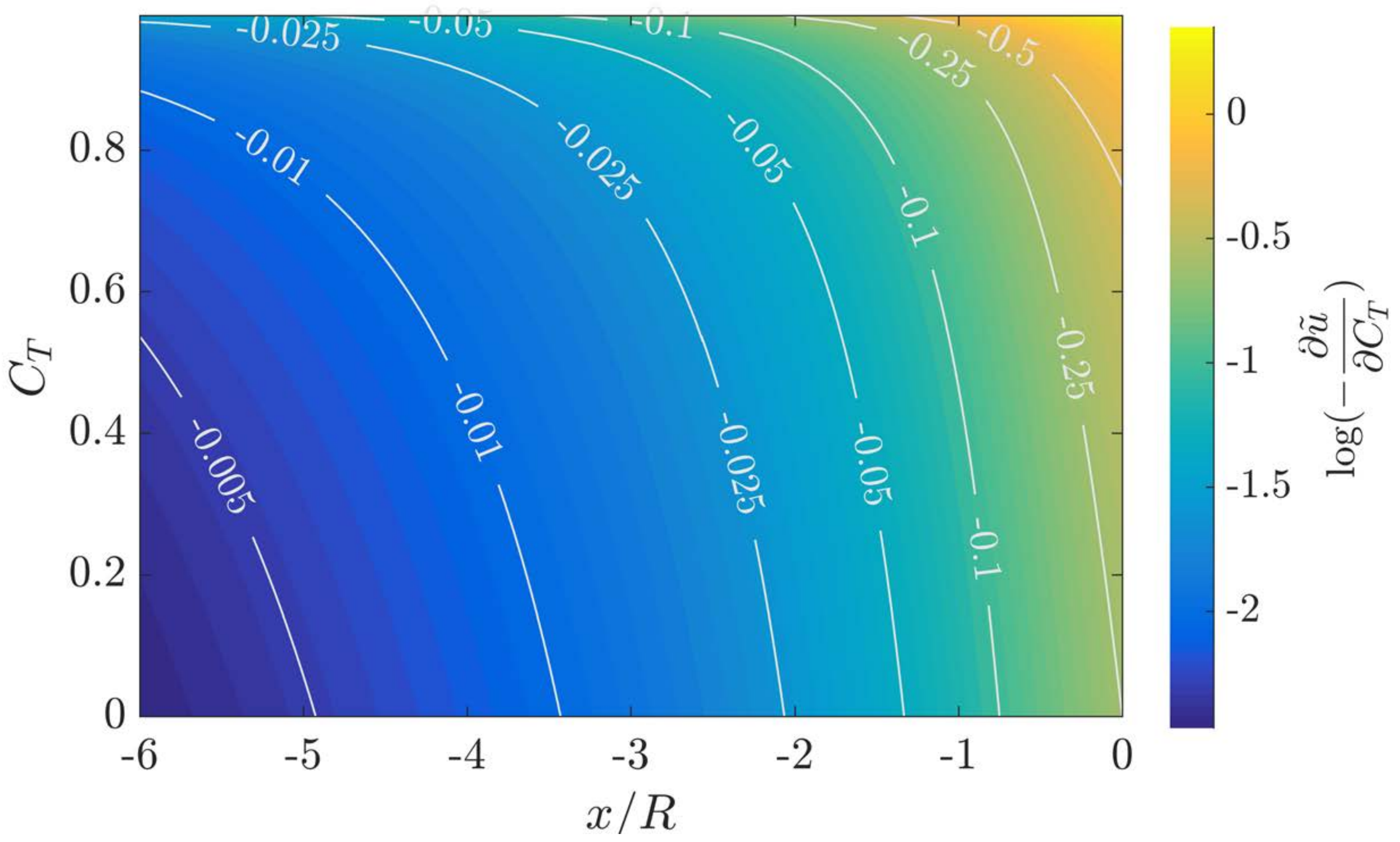
Thrust



Thrust

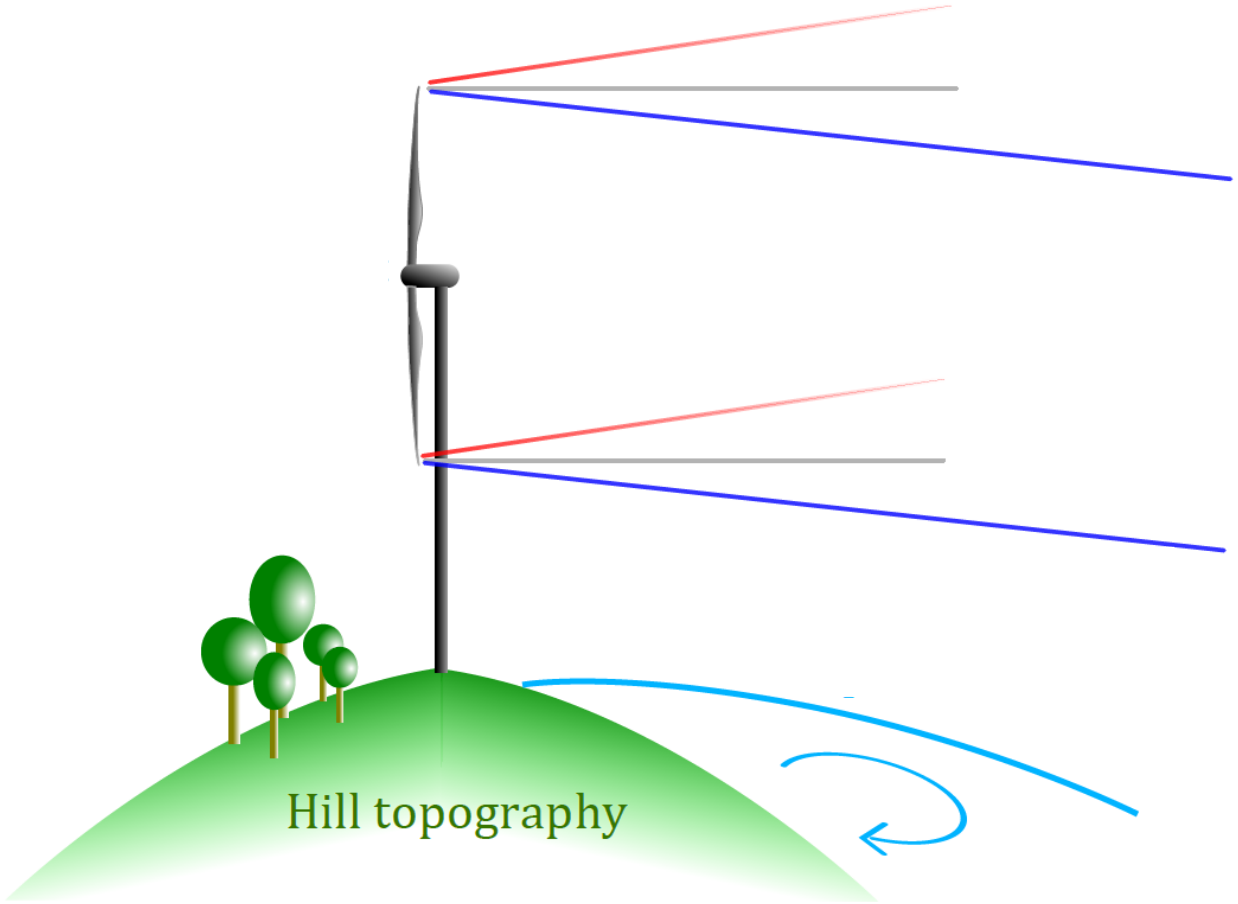
Velocity response to a change in thrust coefficient $\frac{\partial u}{\partial C_T}$





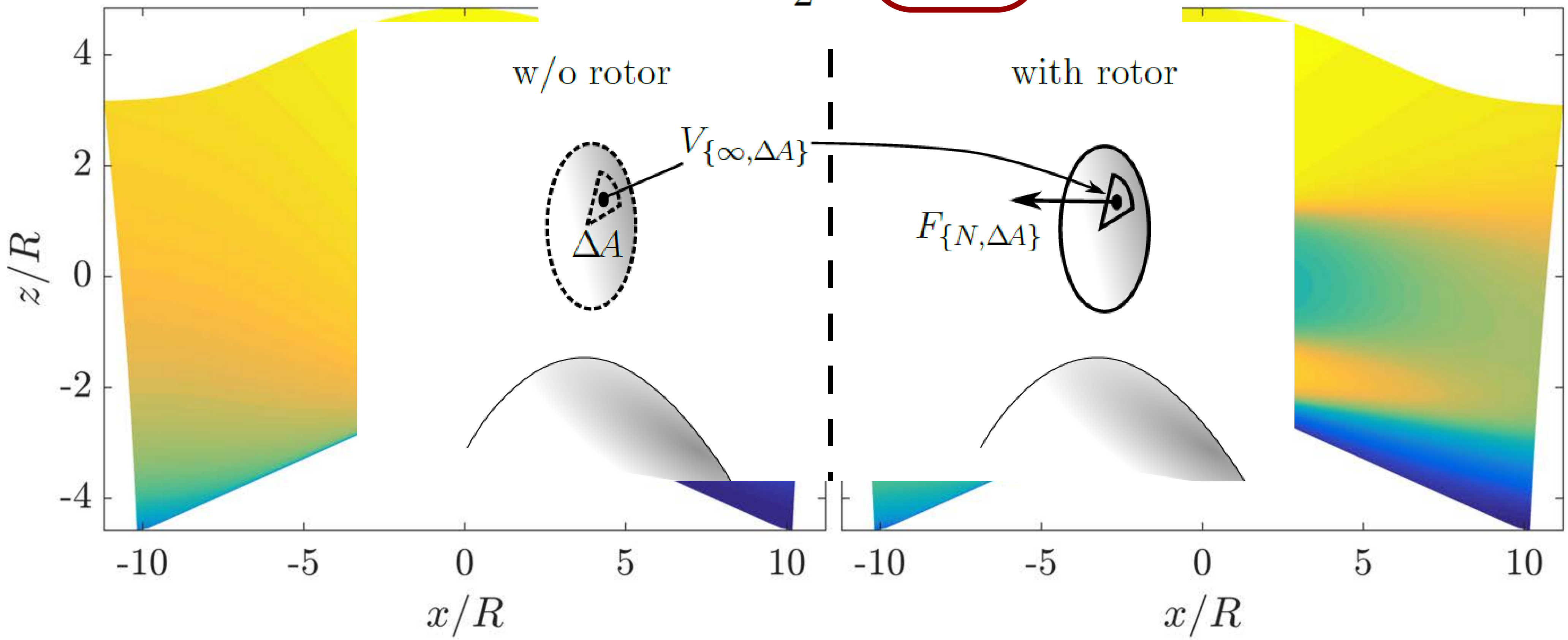
Physical parameters

Topography

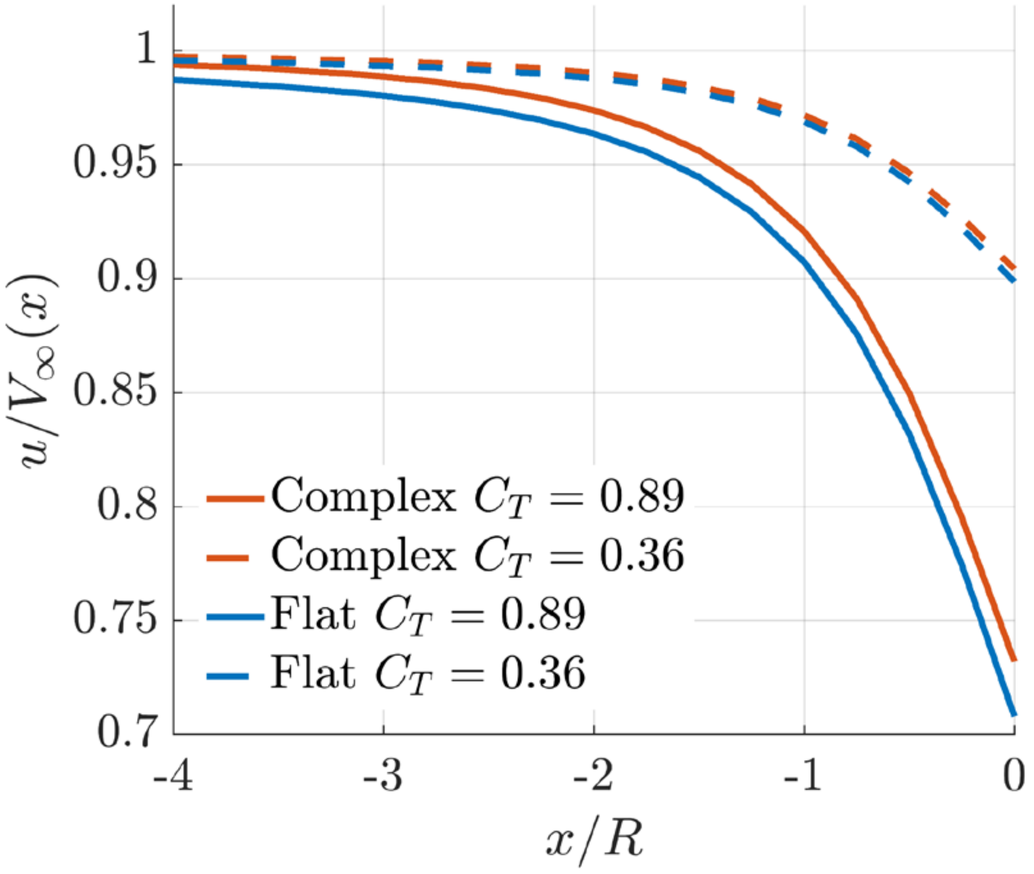


Topography

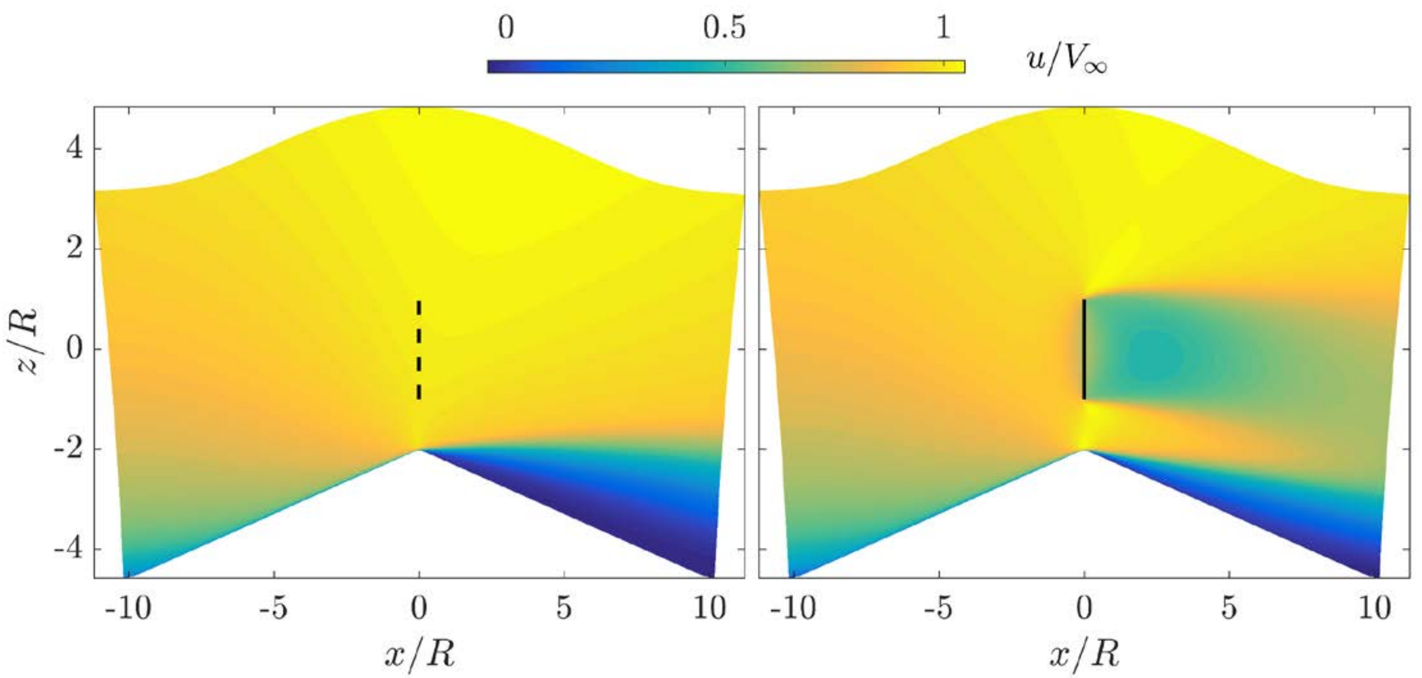
$$F_{\{N,\Delta A\}} = \frac{1}{2}\rho_\infty V^2_{\{\infty,\Delta A\}} C_T \Delta A \quad V_\infty$$



Topography

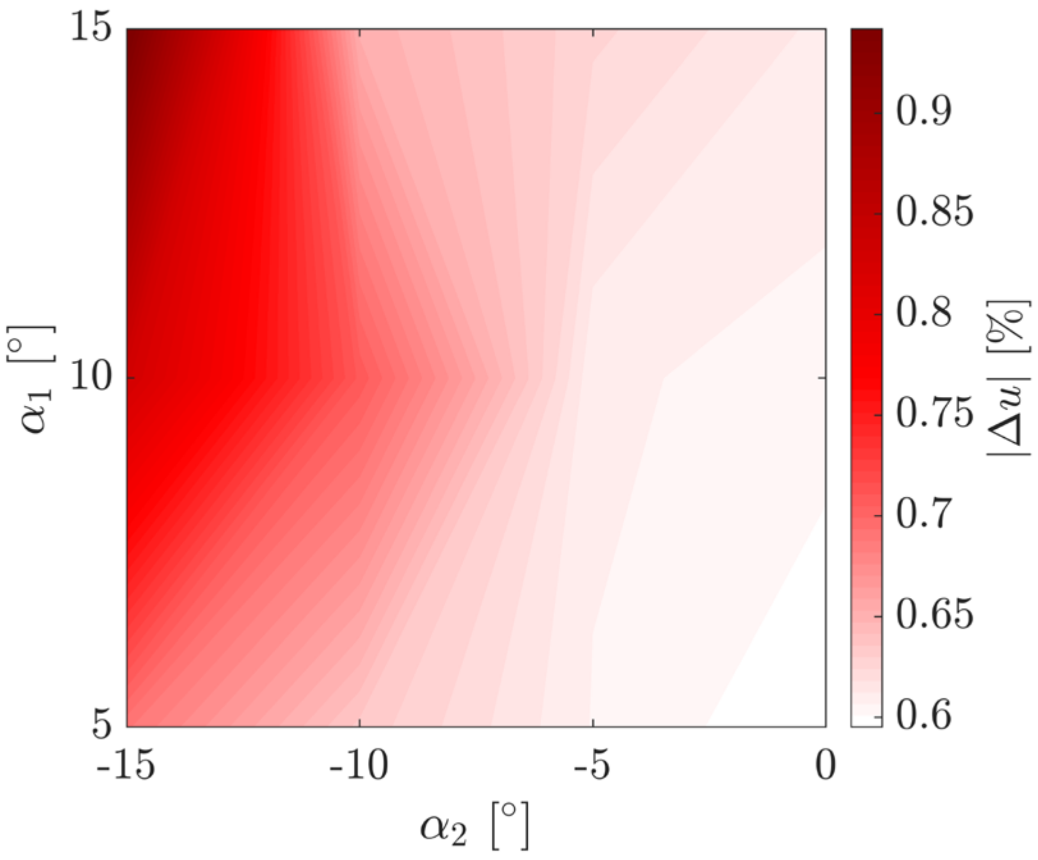


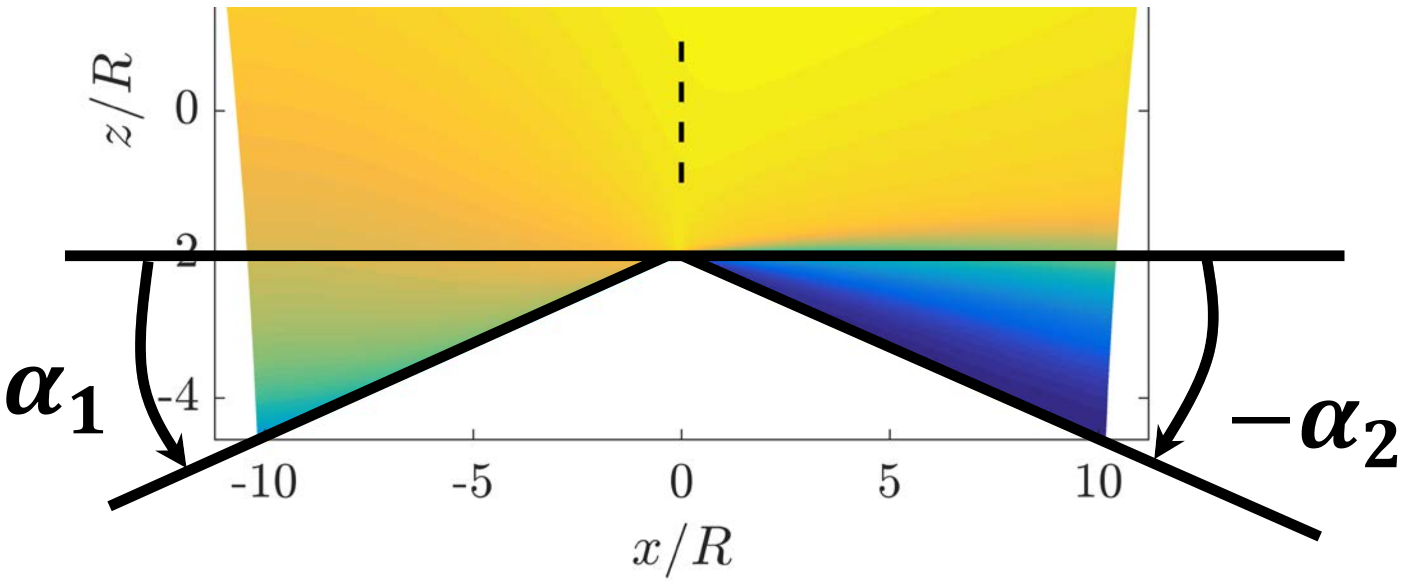
1
0.95
0.9
0.85
0.8
0.75
0.7
$u/V_\infty(x)$
-4
-3
-2
-1
0
x/R
Complex $C_T = 0.89$
Complex $C_T = 0.36$
Flat $C_T = 0.89$
Flat $C_T = 0.36$



0
0.5
1
u/V_∞
4
2
0
-2
-4
z/R
-10
-5
0
5
10
x/R
-10
-5
0
5
10
x/R

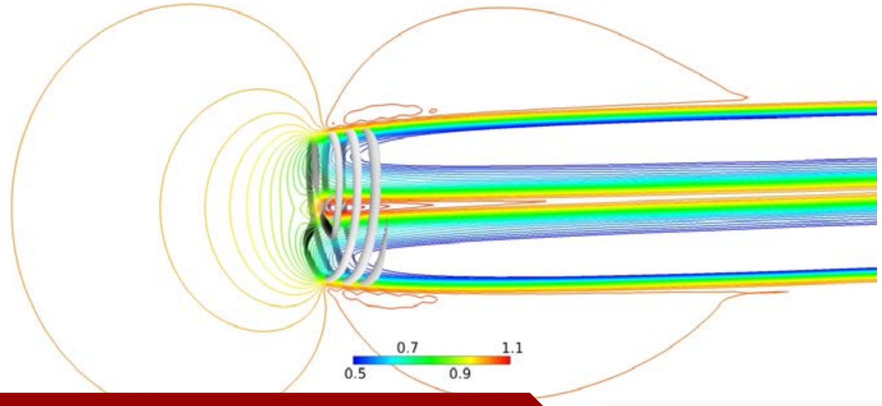
Topography


15
10
5
α_1 [°]
-15
-10
-5
0
α_2 [°]
0.9
0.85
0.8
0.75
0.7
0.65
0.6
$|\Delta u|$ [%]


z/R
0
-2
-4
-10
-5
0
5
10
x/R
α_1
$-\alpha_2$

Modelling the induction zone

The quest for V_∞



Model validation → **Physical parameters** → Simple model

Modelling the induction zone

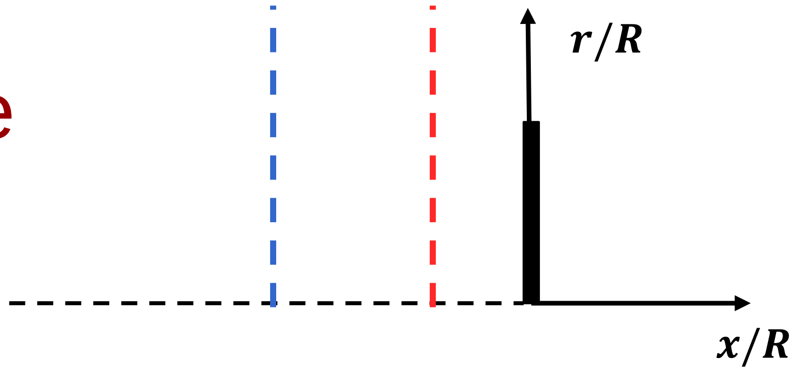
The quest for V_∞

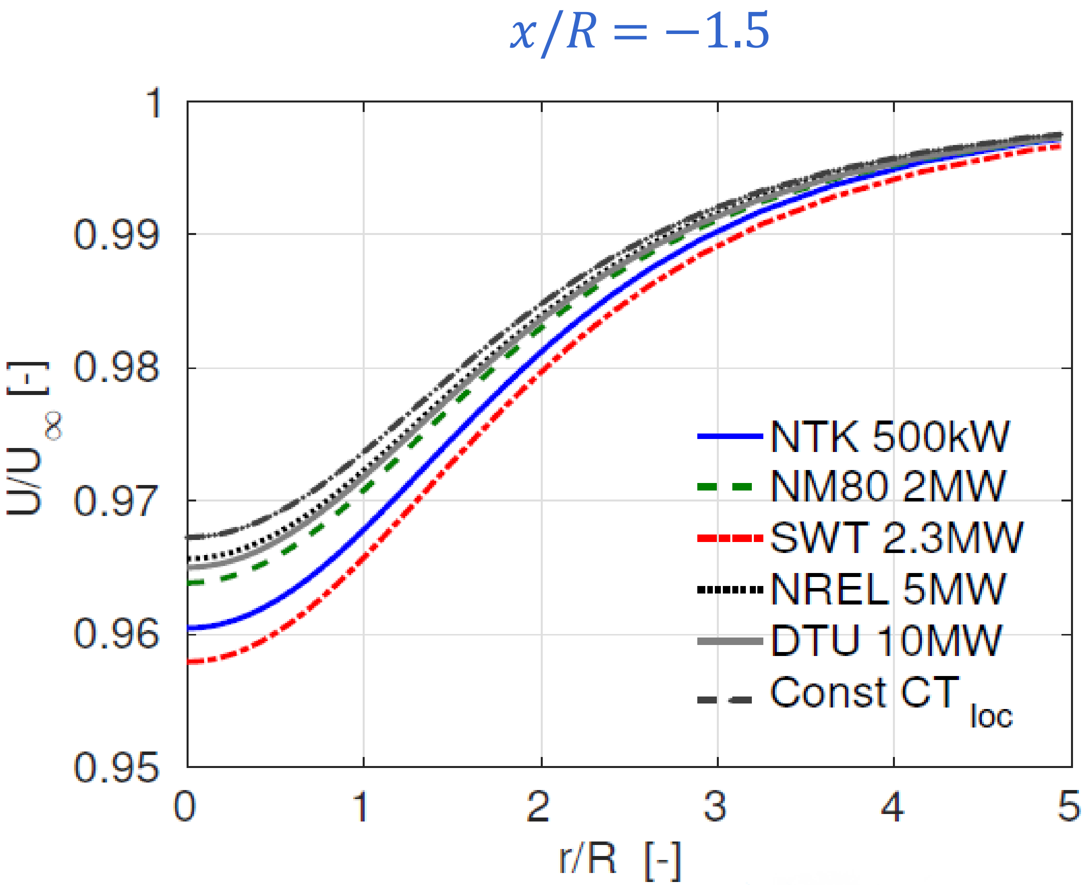
Troldborg N, Meyer Forsting AR. Wind Energy. 2017. *A simple model of the wind turbine induction zone derived from numerical simulations.*

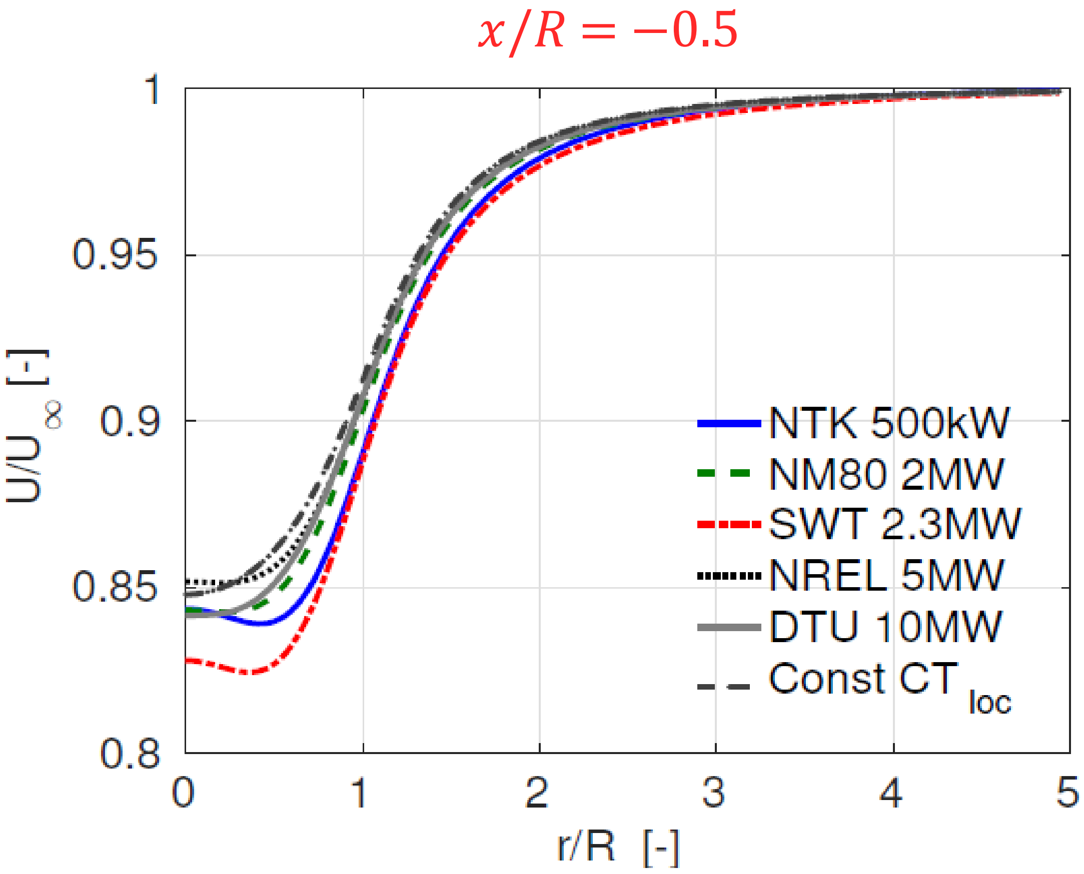
Branlard, ESP; Meyer Forsting, AR: *Using a cylindrical vortex model to assess the induction zone in front of aligned and yawed rotors.* Proceedings of EWEA 2015.

$$\tilde{u}(\tilde{x},\tilde{r},C_T) = 1 - \overbrace{a(C_T,\tilde{x})}^{\text{axial}}\,\underbrace{f(\epsilon)}_{\text{radial}}$$

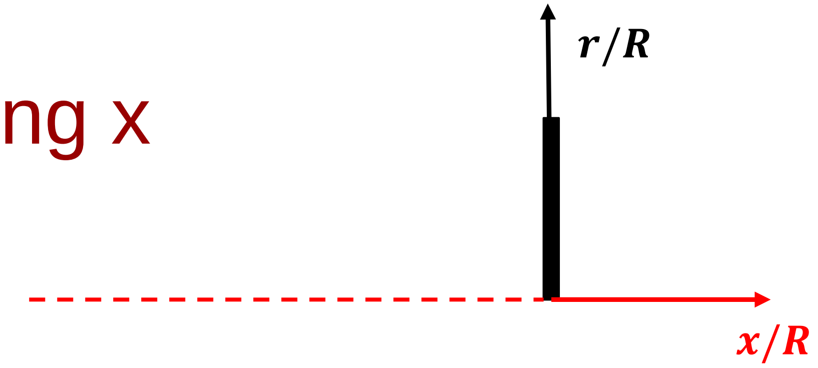
Universal induction zone

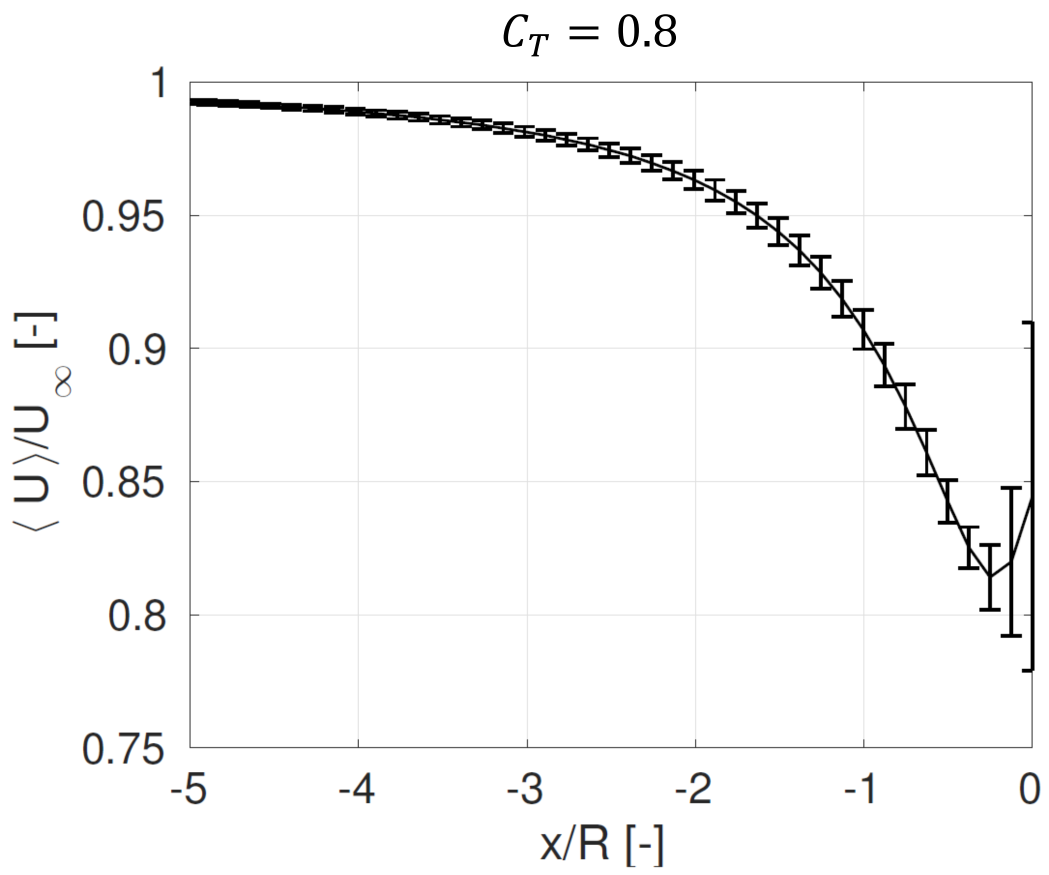


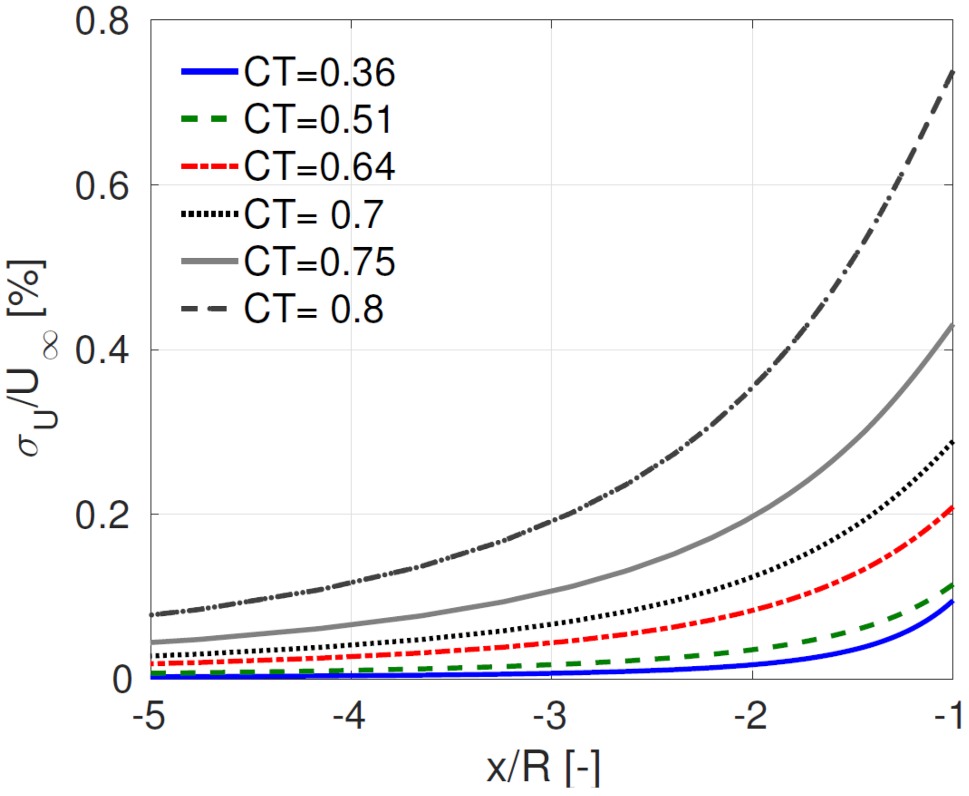




Axial induction behaviour along x

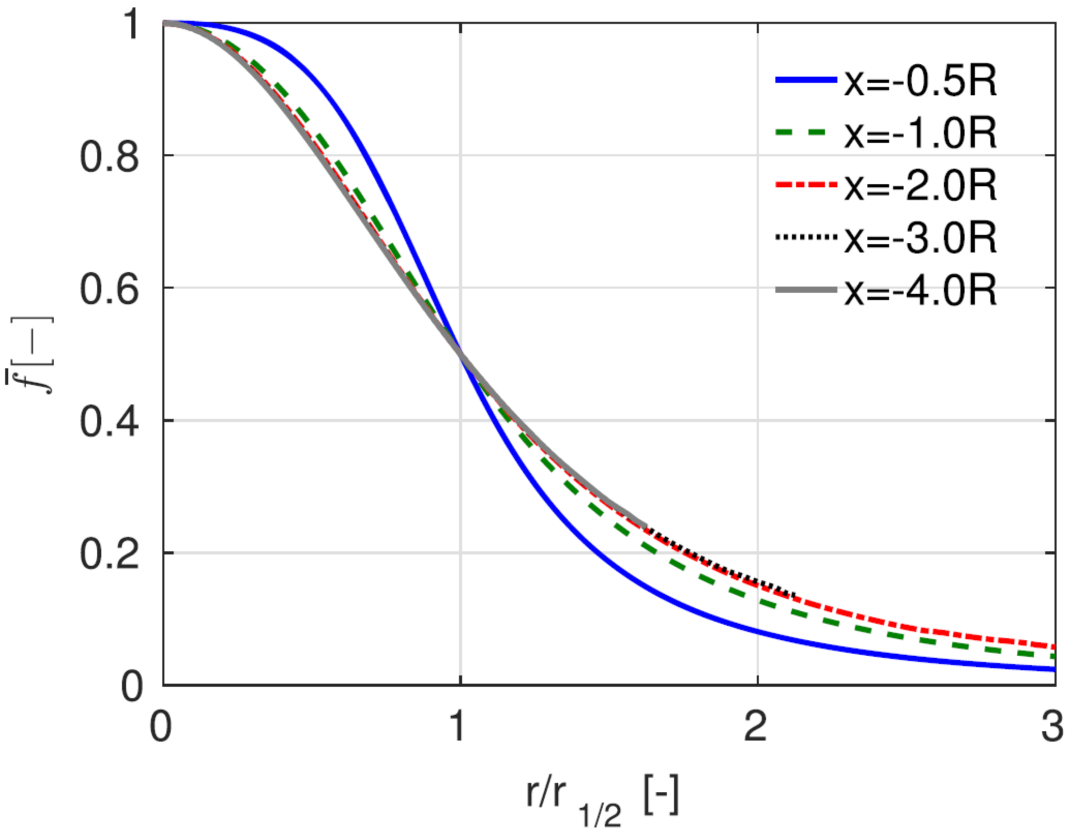


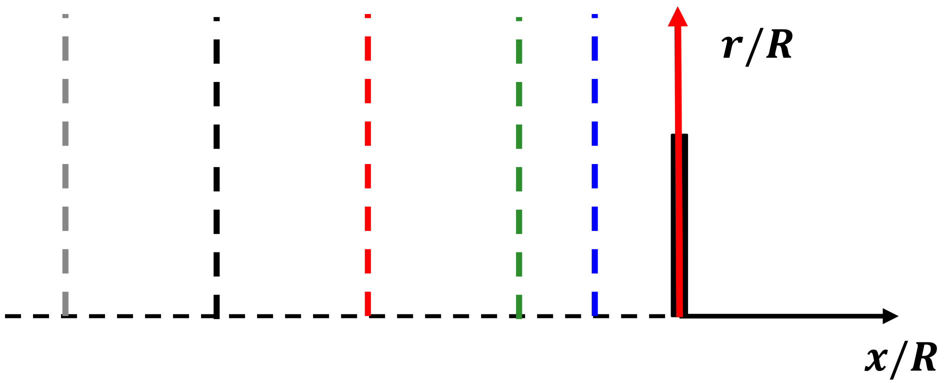




Axial induction behaviour along r

Normalised averaged RANS profiles

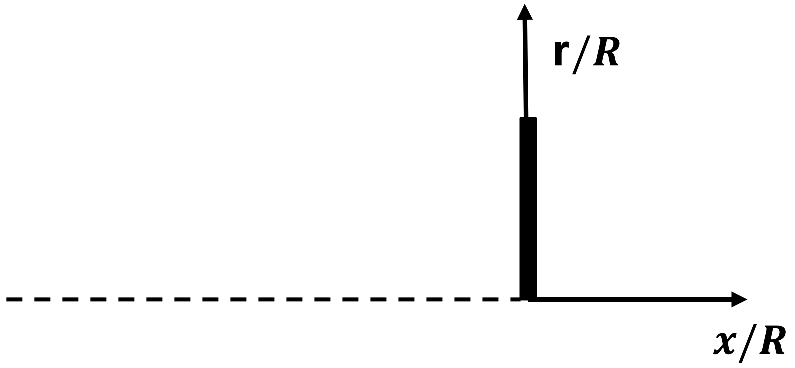


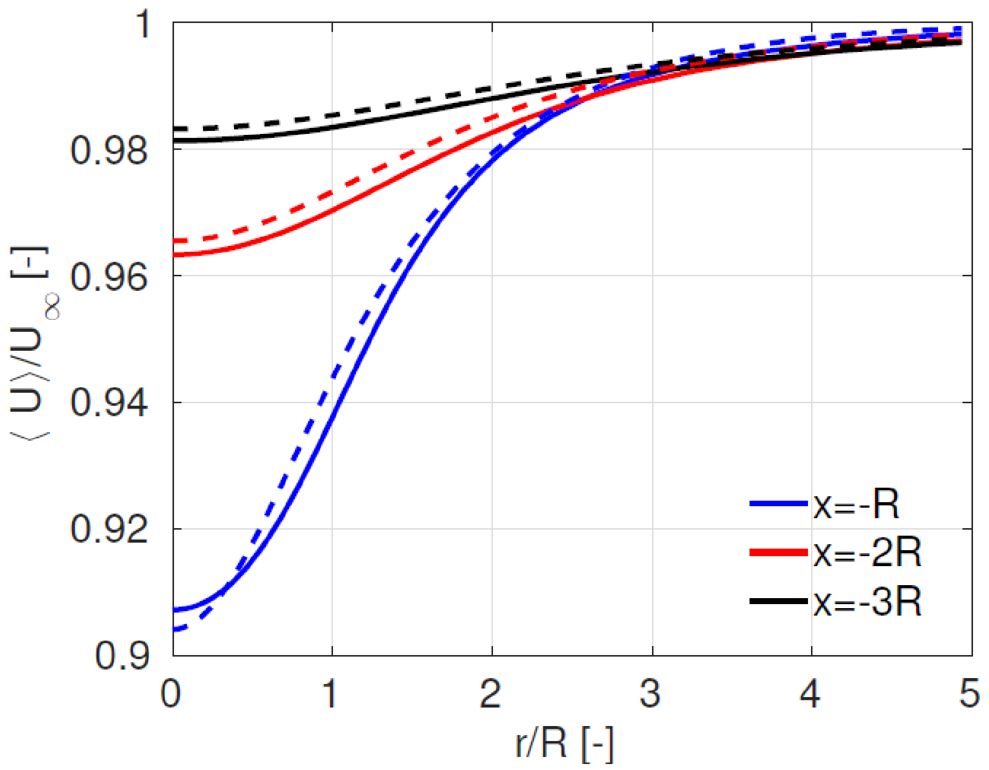


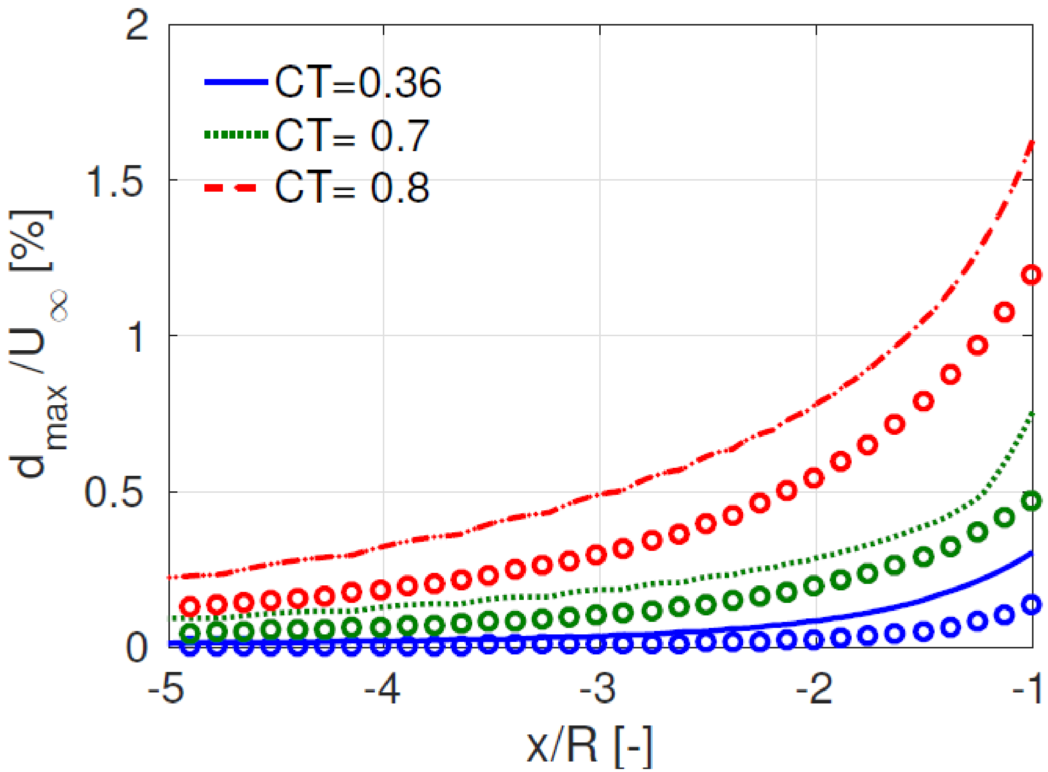
Simple model

Simple vs CFD

$$\tilde{u}(\tilde{x},\tilde{r},C_T) = 1 - \overbrace{a(C_T,\tilde{x})}^{\text{axial}}\underbrace{f(\epsilon)}_{\text{radial}}$$

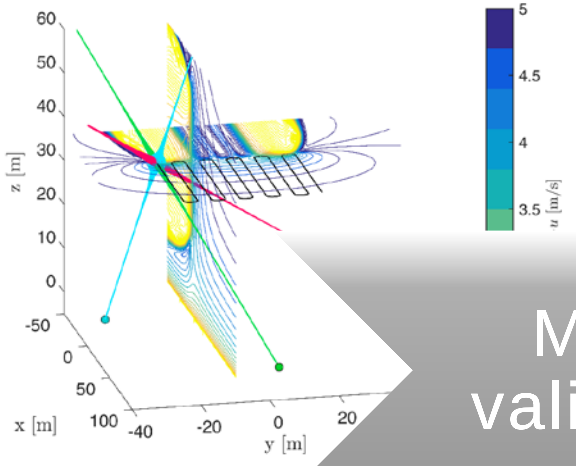


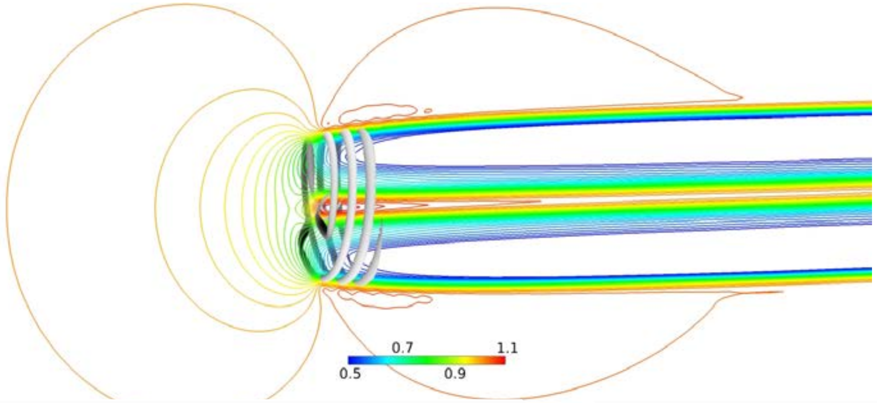




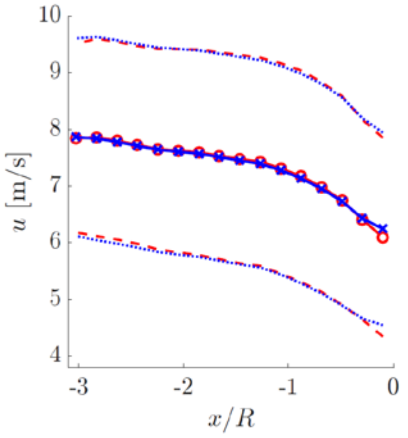
Modelling the induction zone

The quest for V_∞





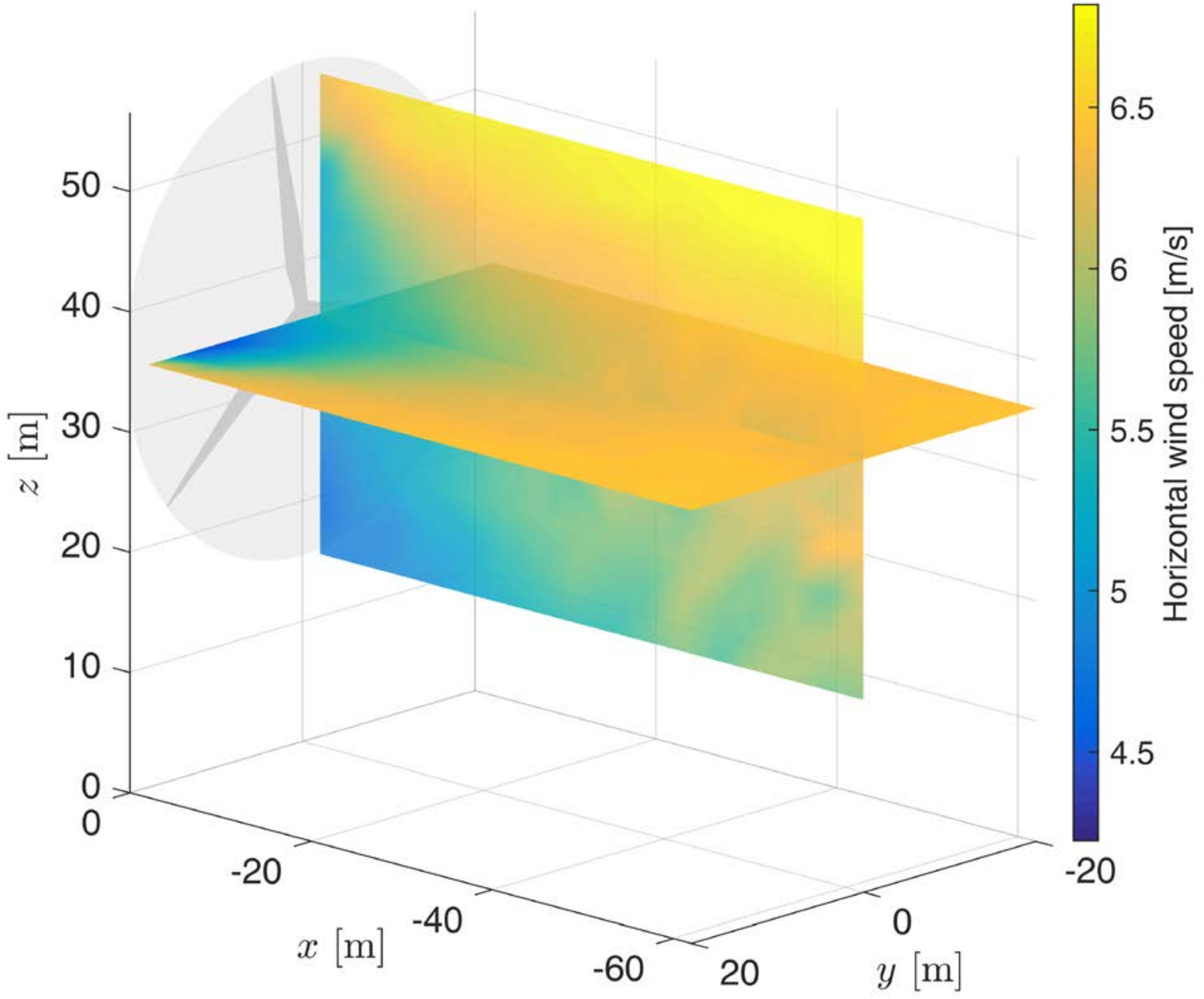
Model validation → Physical parameters → Simple model



$$\tilde{u}(\tilde{x},\tilde{r},C_T) = 1 - \overbrace{a(C_T,\tilde{x})}^{\text{axial}}\,\underbrace{f(\epsilon)}_{\text{radial}}$$

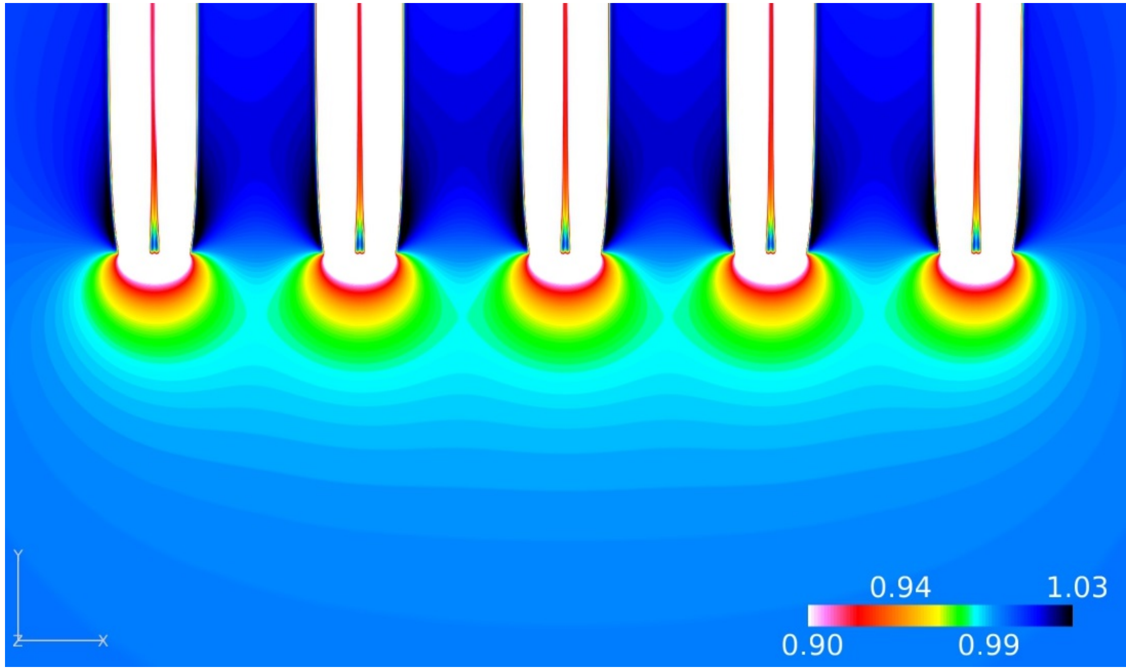
Conclusions

- Validated CFD model with a novel stochastic approach
- Induction zone independant of physical parameters except for the thrust coefficient and topography
- Possible to describe the axial induction with a simple model



Open Questions

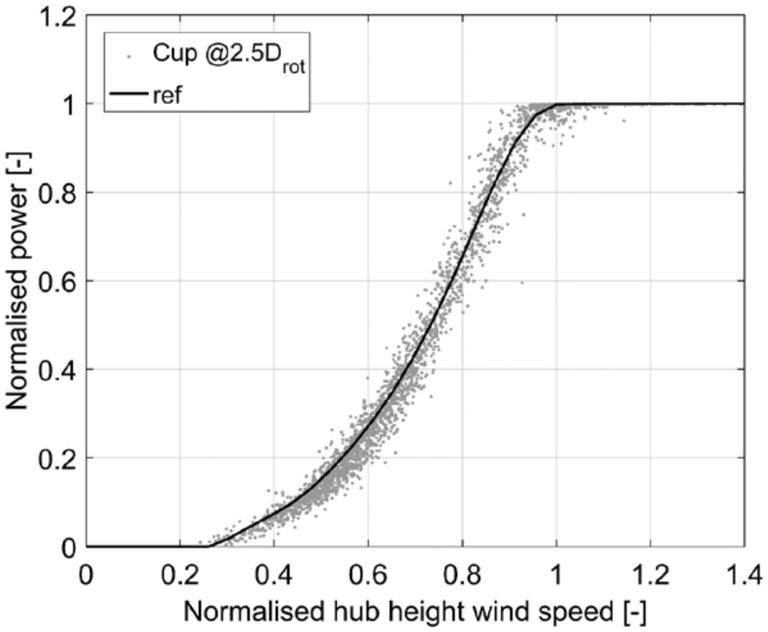
	Possible Impact
• Wind farm effects	0.5%
• Dynamic load changes	3.0%
• Turbulence evolution	1.0%
• Complex terrain	5.0%

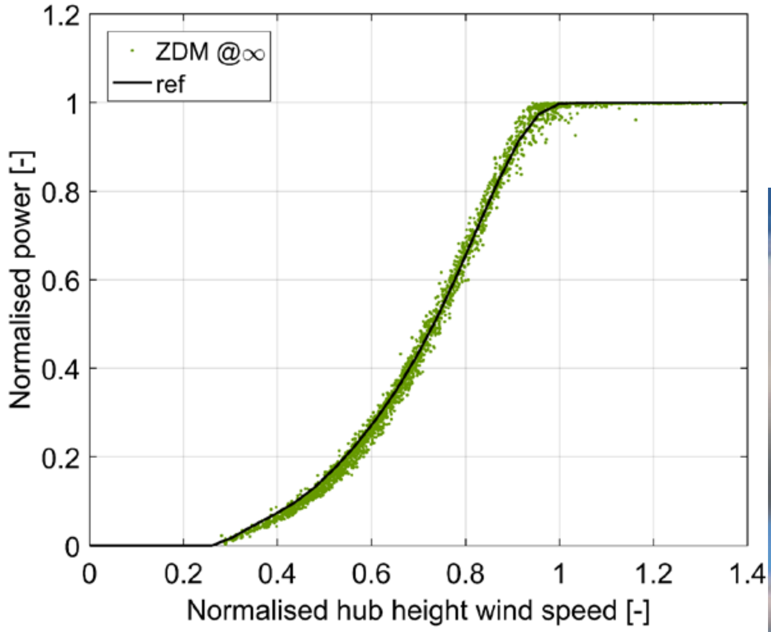


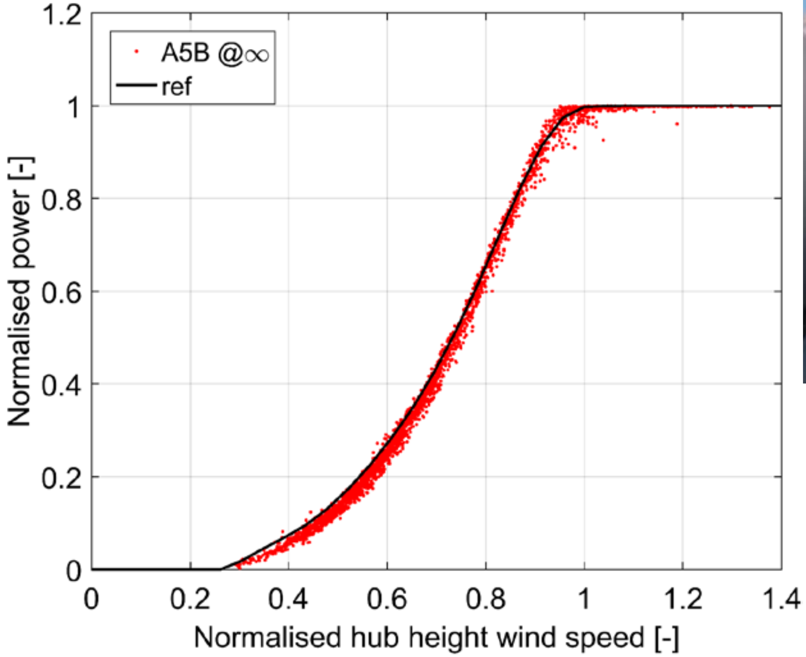
Outlook

- Continuing simple model validation
- Simple radial velocity model
- Complex terrain:
  - Model validation
  - Include complex physics
  - Model sensitivity

Outlook







Credit: Antoine Borraccino

Innovation Fund Denmark

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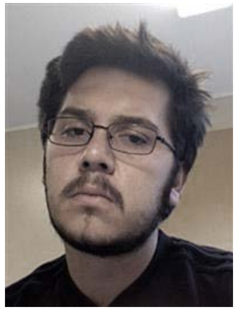
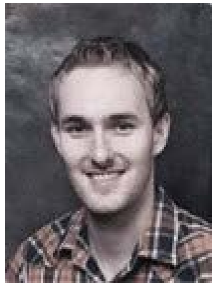
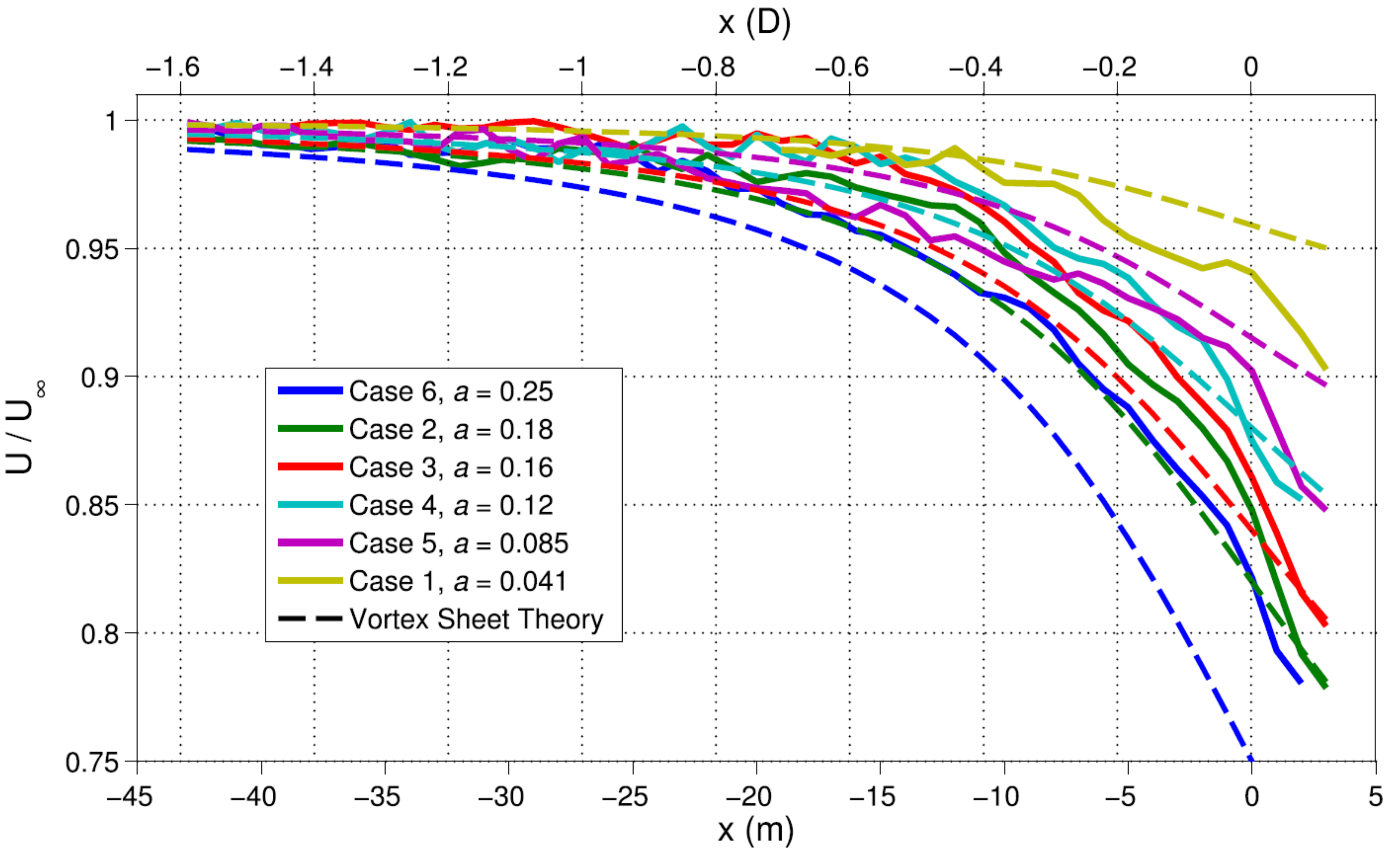



Can we model the induction zone?

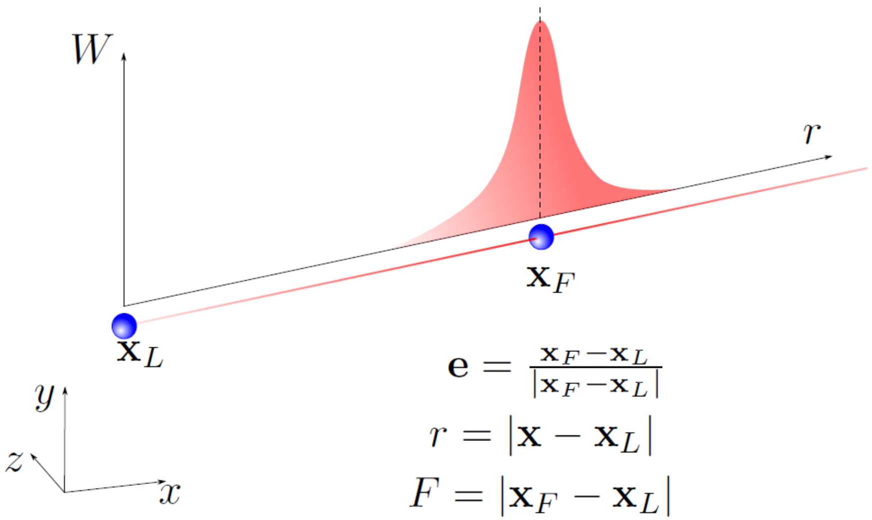
(Simley 2016)



Triple-lidar uncertainties

Volume-averaging

Spatio-temporal averaging



$$\mathbf{e} = \frac{\mathbf{x}_F - \mathbf{x}_L}{|\mathbf{x}_F - \mathbf{x}_L|}$$

$$r = |\mathbf{x} - \mathbf{x}_L|$$

$$F = |\mathbf{x}_F - \mathbf{x}_L|$$