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Analysis and results from the merged wake experiment

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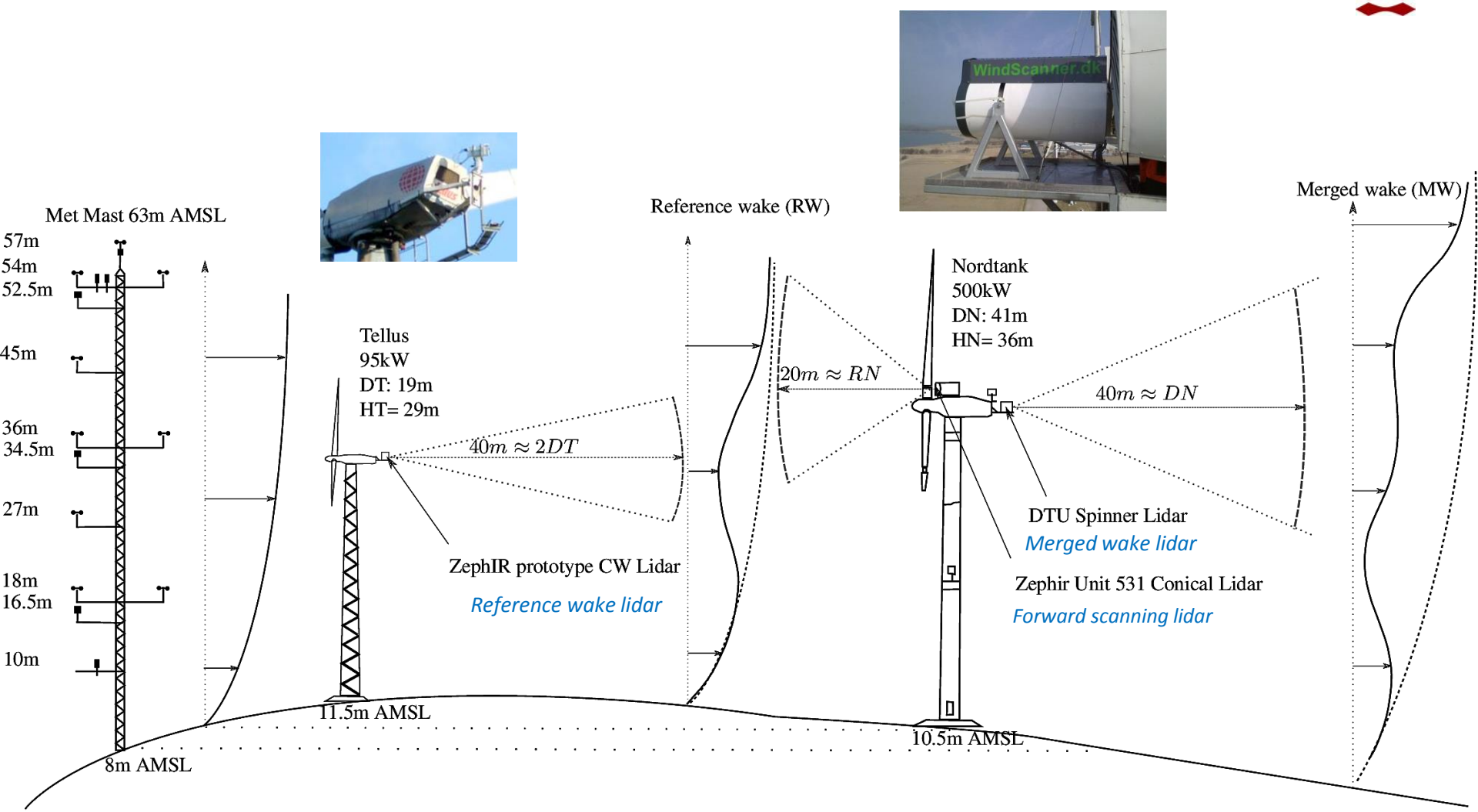
Motivation

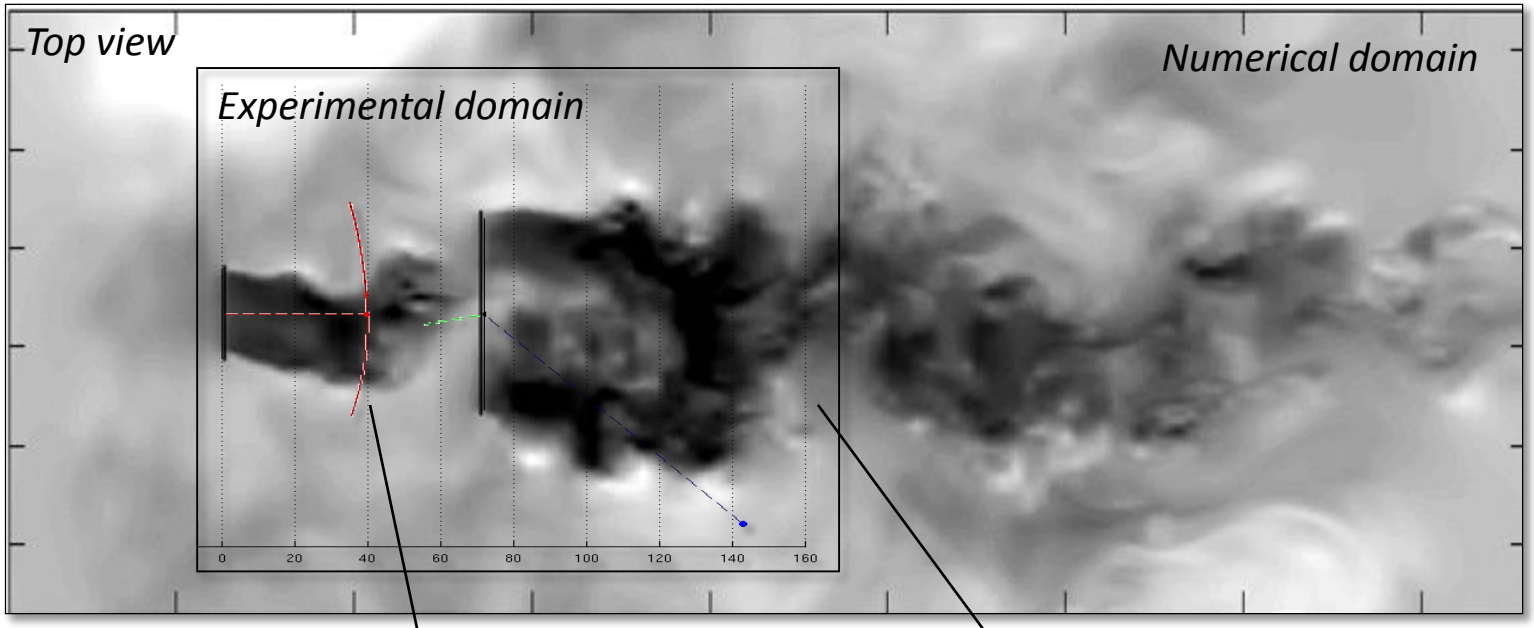
- Provide high resolution measurements of merged wake
- Assess performance of our CFD model / approach…
  - Neutral ABL wake interaction
  - Wake deficit, turbulence intensity, power and thrust.
- … Towards more realistic situation
  - EllipSys3D/HAWC2: wind turbine control
  - Atmospheric stability effects
- Use validated CFD models (and experimental results) to develop a simpler merged wake model
  - Parametric CFD study: spacing, rotor loading.
  - Extension of Dynamic Wake Meandering model in HAWC2.
  - Wind farm optimization toolbox

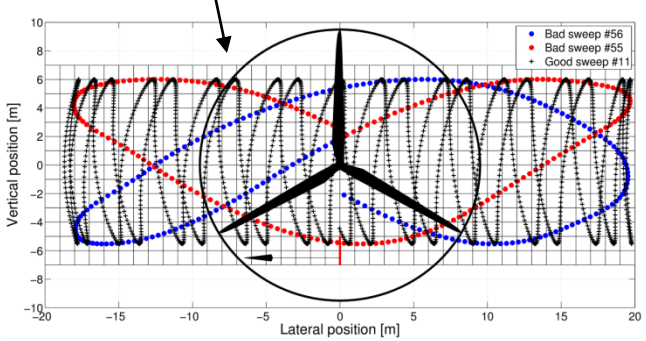
Experimental set up

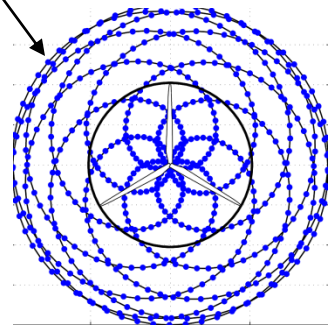


- Oct. 2012. to May 2013
- NTK sensor failure, optical cable damaged, over heating of spinner lidar, tilting mechanism failure, broken scanner (twice)
- 3.5 hours of merged wake measurements

Experimental analysis



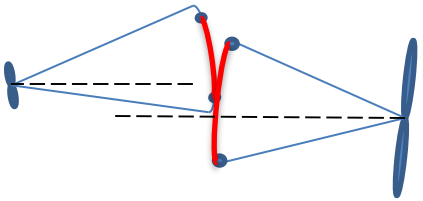




- high spatial and temporal resolution of the merged wake flow field
- detailed structure visualization
- .. and turbulence characteristics

Mutual validation exp. / num.

- **Key parameters to characterize experimentally**
  - Turbine yaw misalignments
  - Rotor relative positions (alignments with incoming wind)
  - Turbulence characteristics of incoming wind
  - Terrain, site roughness, atmospheric stability



- **But….**
  - Tellus turbine is not instrumented
    - No power, thrust force, rpm, azimuthal rotor position … (wake or not?)
    - Wake is deflected to the left systematically
  - Nordtank is well instrumented but questionable sensors
    - Yaw sensor offset when compare to mean direction by sonic
    - Strain gauges calibration for CT
  - Lidar malfunctions/limitations
    - Tilting mechanism failure of reference wake
    - Spatial and time resolution limitations

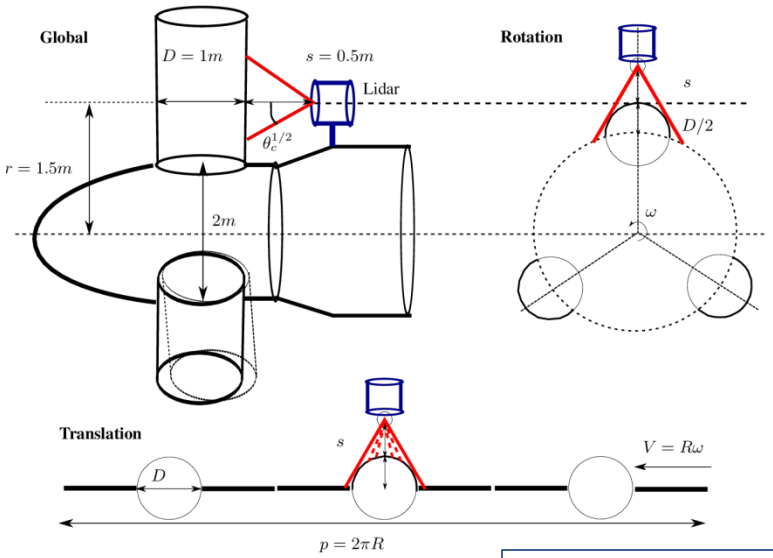
Experimental analysis: forward scanning lidar

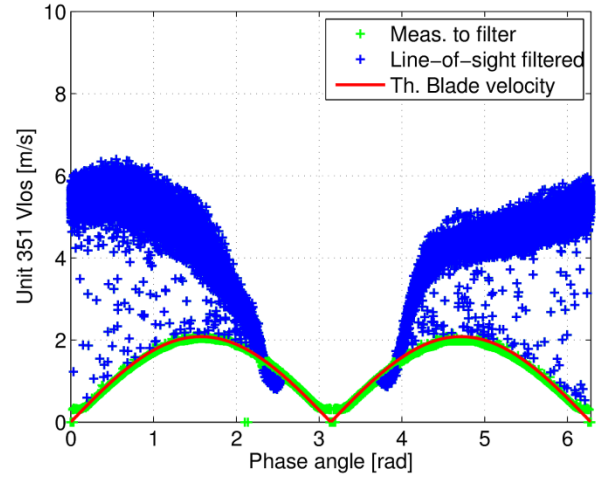
Unit 351 prototype

- Scanning through the Nordtank rotor
- Conical pattern
- 48.8 Hz, sweep time 1s
- Blade passage filtering required

Experimental analysis: forward scanning lidar

Geometrical model for blade discarding





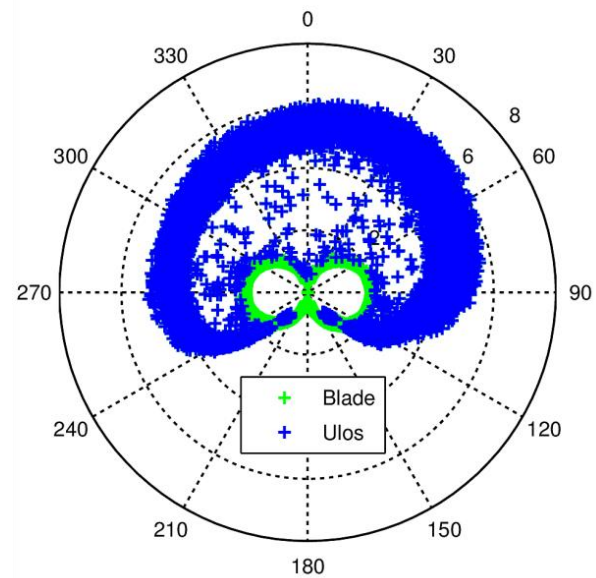
Conical scanning lidar: $$U_{los} = |a\cos(\phi - b) + c|$$

Horizontal velocity $$V = a/\sin\theta_c \equiv R\omega = 4.12m/s$$

No vertical velocity $$W = -c/\cos\theta_c = 0$$

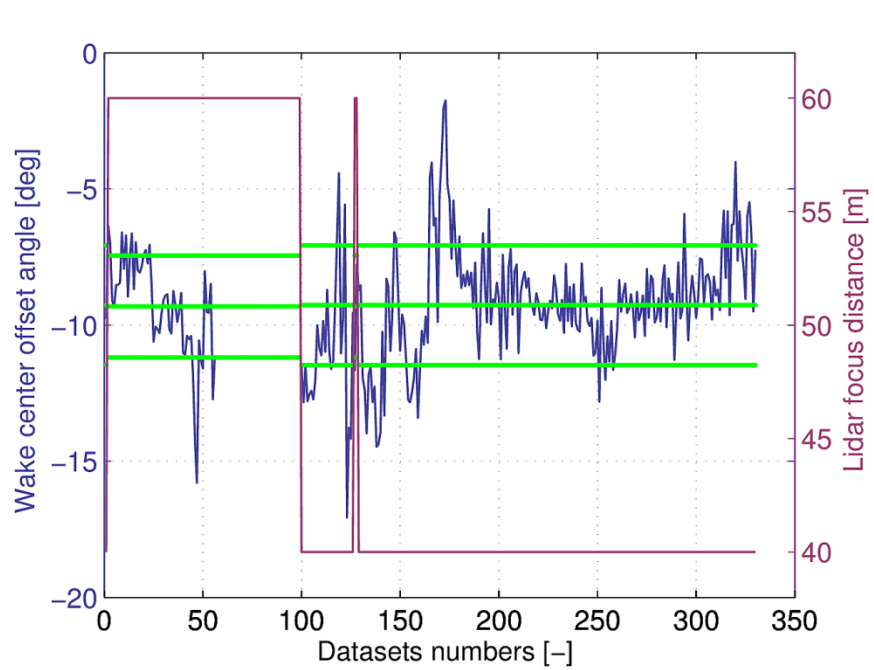
Azimuth parallel to wind $$B = b = \pm 90^\circ$$

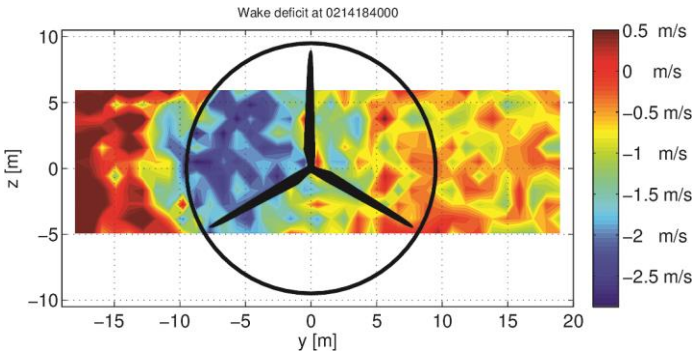
Blade : $$U_{los} = |2.08\cos(\phi - \pi/2)|$$



Experimental analysis: yaw misalignment

- Wake systematically located to the left:
  Yaw or lidar mounting offset?





	FC=40m, 2D	FC=60m, 3D
χ_t	-9.26deg	-9.31deg
y_o	-6.53m	-9.85m
$\sigma\chi_o$	2.1 deg	1.9deg

- constant angle of -9.3deg in near wake
- assumed to be constant yaw error
- de-calibration of wind vane ?

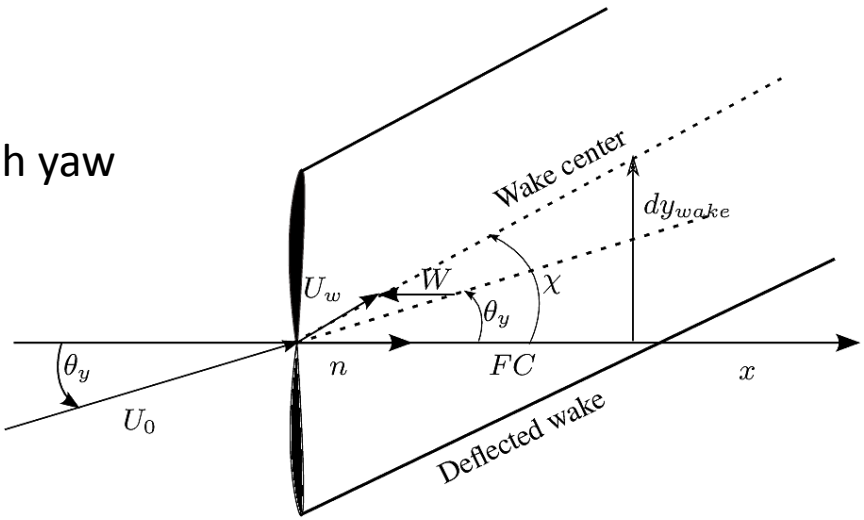
Experimental analysis: yaw misalignment

- Yaw sensor missing
- Theory based on vortex cylinder model
- Relates the measured wake skew angle with yaw

$$\chi = (0.6a + 1)\theta_{yaw}{}^{*}$$

$$\chi = (0.3CT + 1)\theta_{yaw}{}^{**}$$

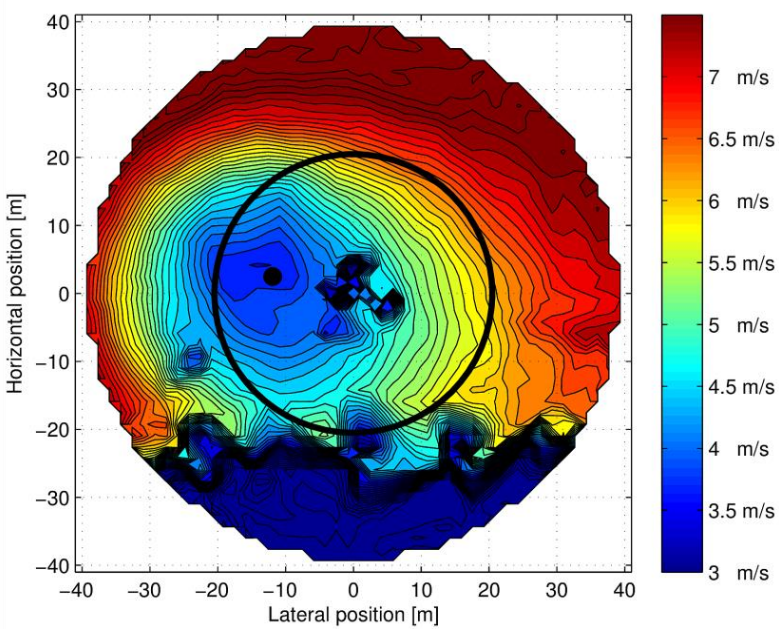
Tellus: BEM
Nordtank: measured by strain gauges



- Using sensor

$$\chi_m = -8.46^\circ$$
$$\theta_{yaw,\chi_m} = -7.01^\circ$$
$$\theta_{yaw,sensor} = -7.25^\circ$$

Yawed wake case: streamwise wake velocity

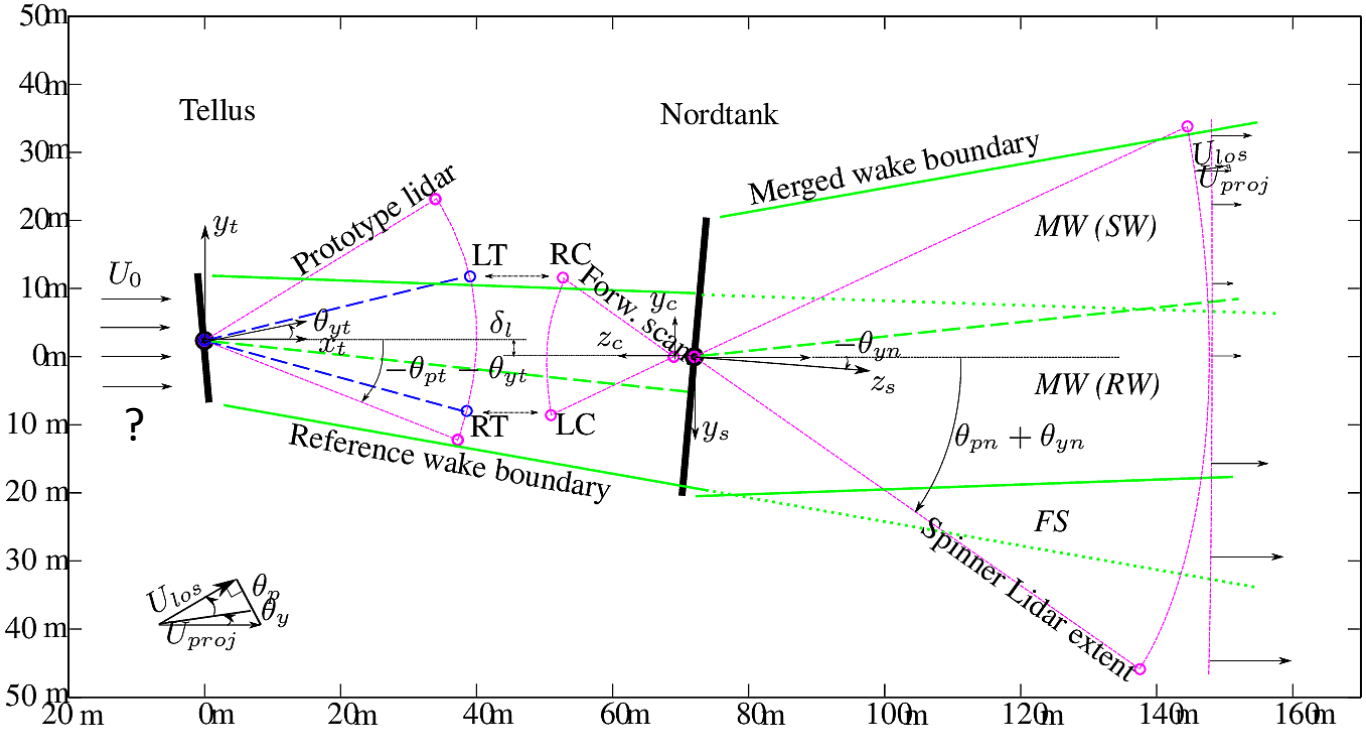


* Wagenaar, J. W., & Schepers, J. G. (2012). Controlling Wind in ECN ' s Scaled Wind Farm, (APRIL), 16–19.

** D. Micallef, "MEXICO Data Analysis, Stage V – Investigation of the Limitations of Inverse Free Wake Vortex Codes on the Basis of the MEXICO Experiment", TUDelft/University of Malta

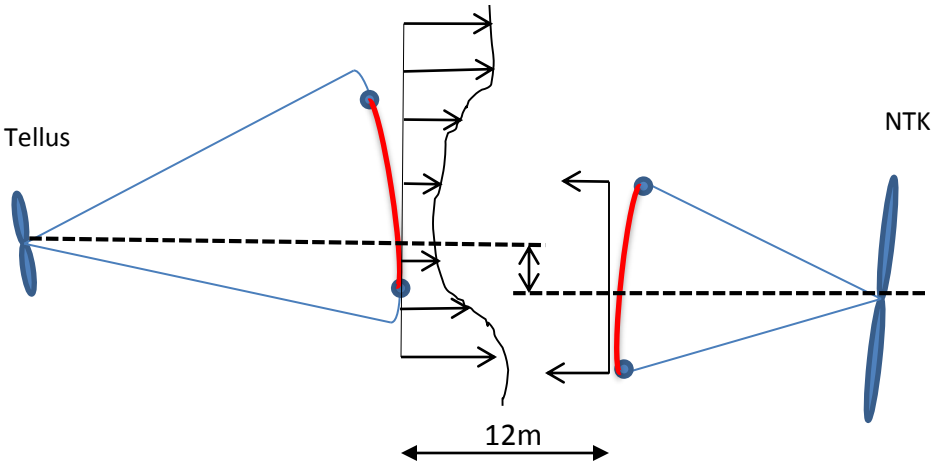
Experimental analysis: merged wake test case

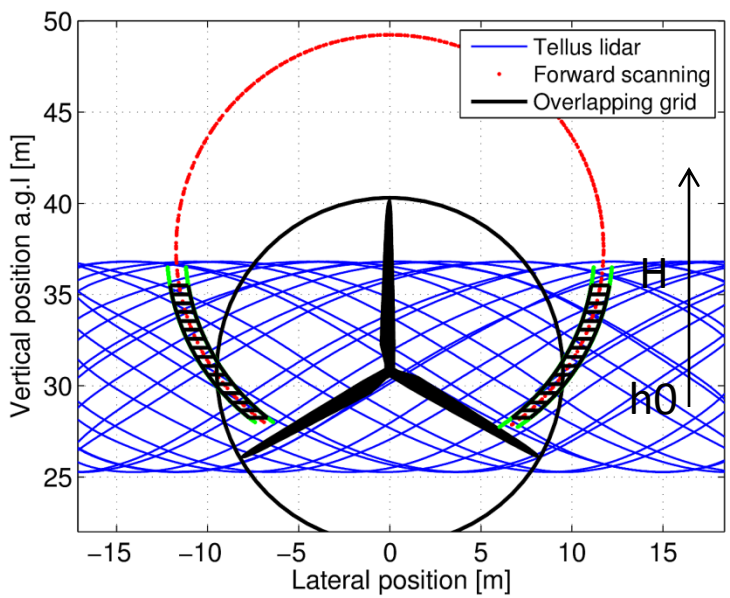
- selected time series
- asymmetric flow: different rotor size, Tellus systematic yaw
- alignment: sonic measurement and theoretical alignment (Google Earth)

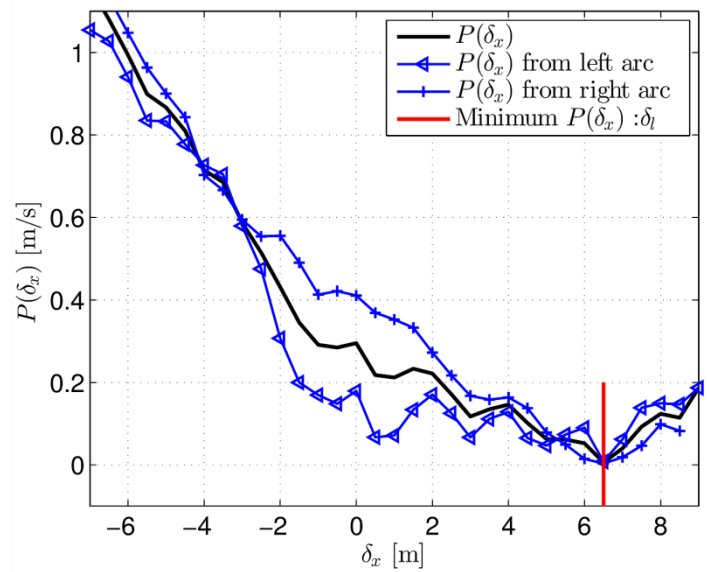


Experimental analysis: turbine lateral displacement

- cross correlation between reference wake and forward scanning lidar
- assume stream wise correlation of the wind speed: no NTK induction



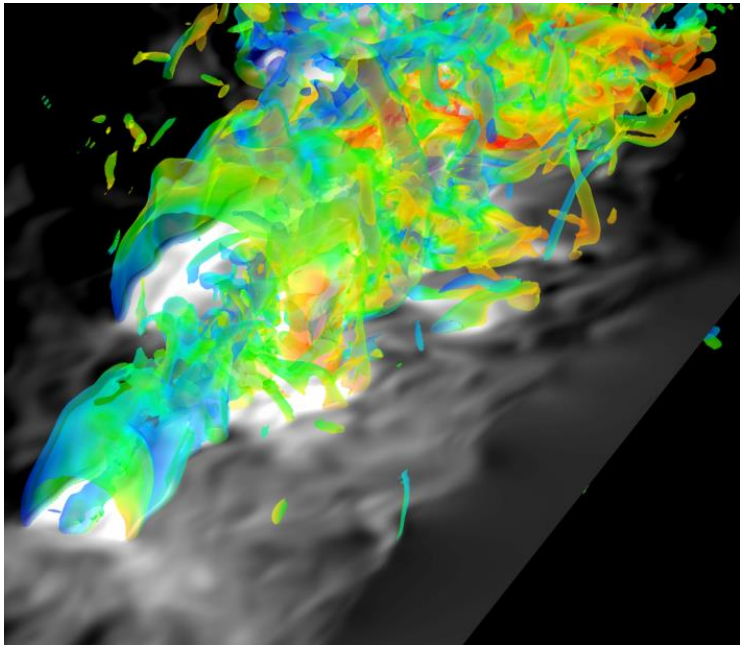


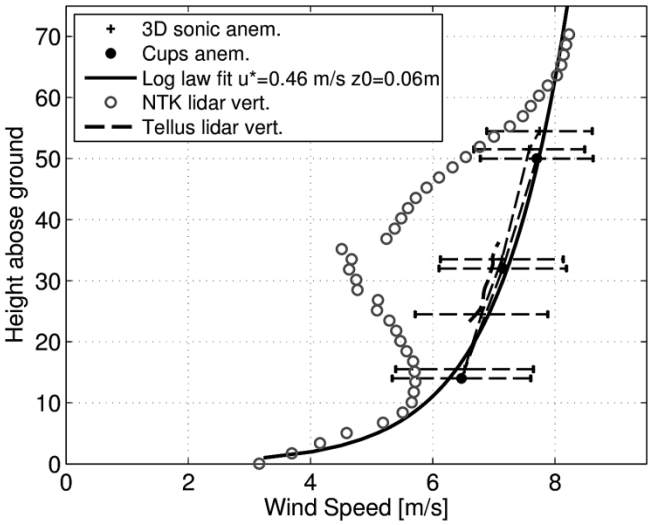


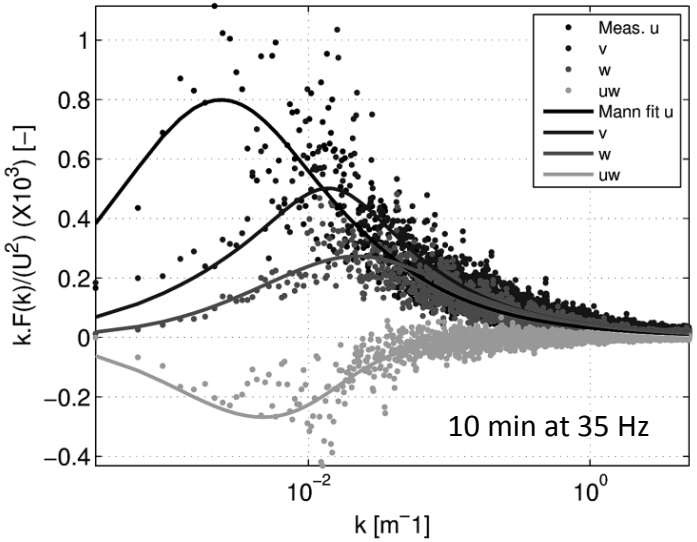
$$P(\delta_x) = \frac{1}{H}\sum_{i=h_0}^{H}\left[|(U_{l-RW}h(i) - U_{l-FW}h(i))| \quad |(U_{r-RW}h(i) - U_{r-FW}h(i))|\right]$$

Numerical work: methodology

- EllipSys3D LES
- Actuator Disk, airfoil data, fixed yaw
- Log law inlet: best fit
- Turbulence: Mann spectral tensor fit
- Neutral ABL
- 19.9 million cells Cartesian mesh, 60 cells per D

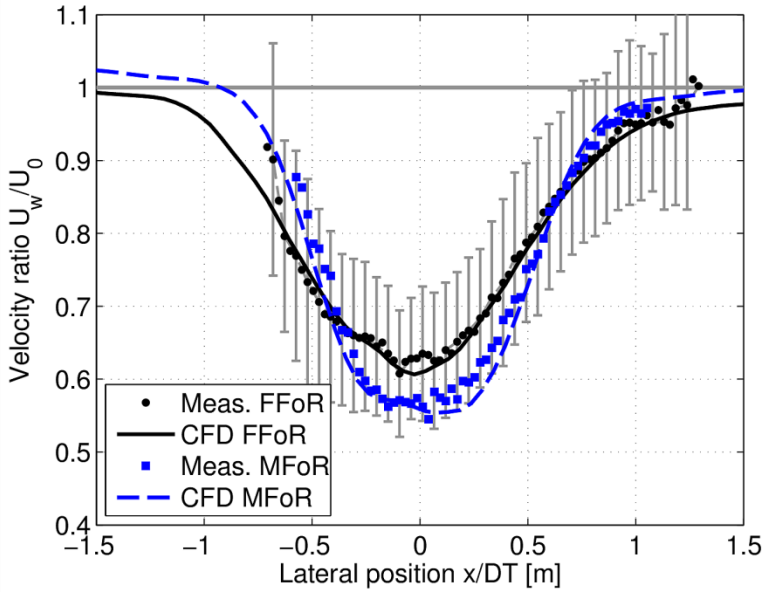


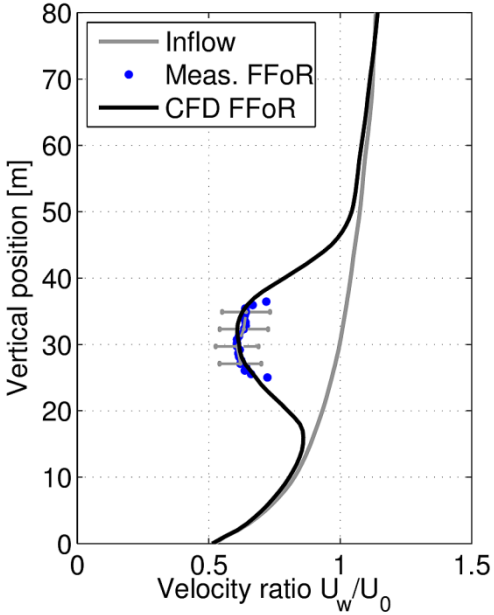




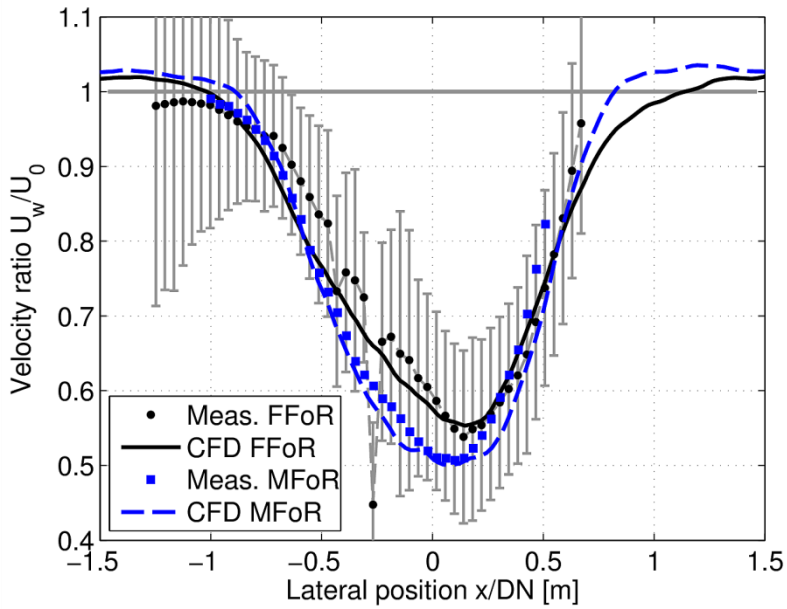
Numerical work: Normalized velocity

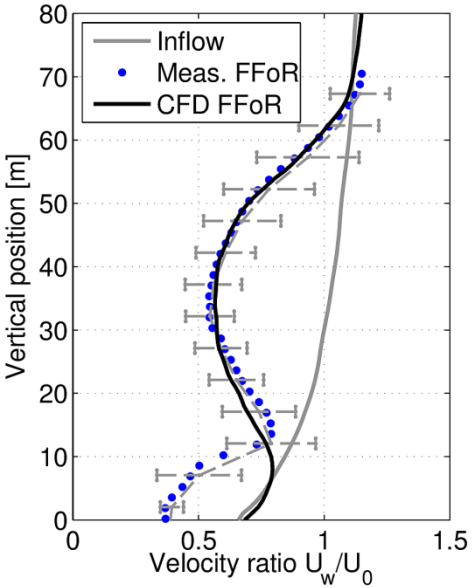
Ref. Wake





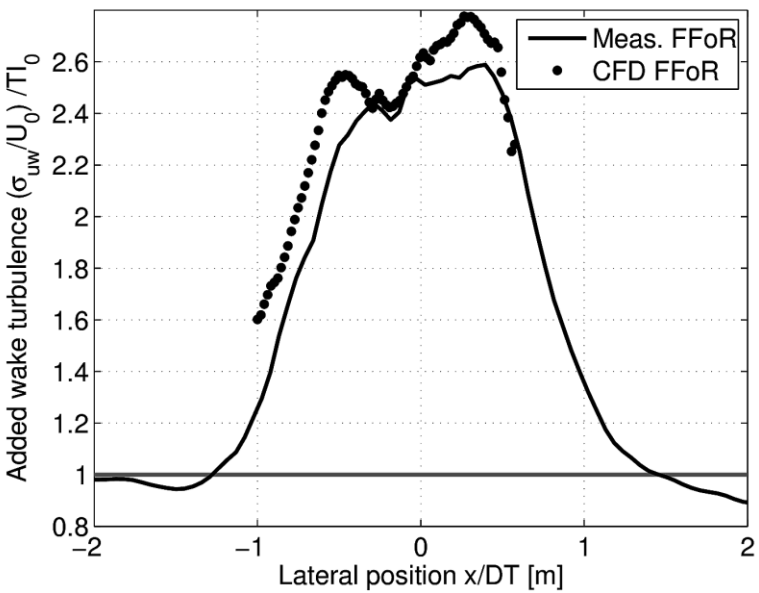
Merged Wake

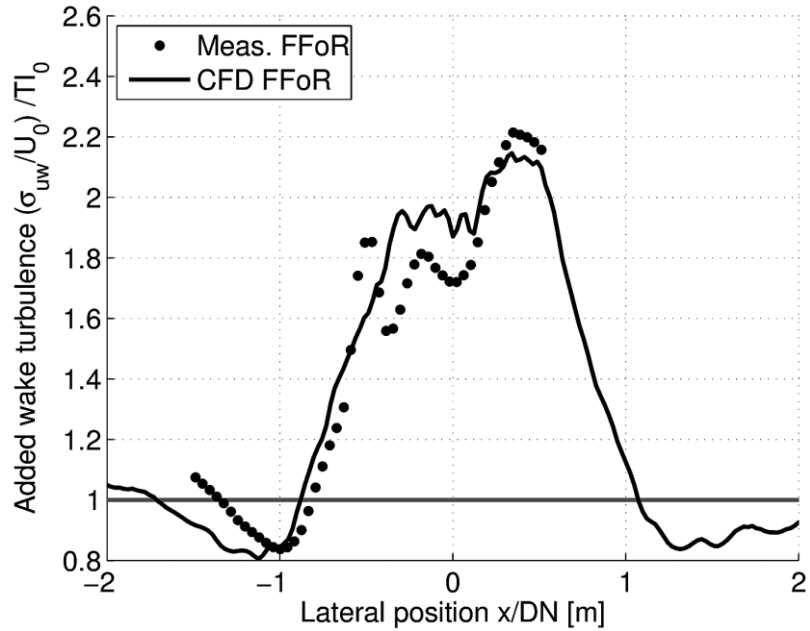




Numerical work: added wake turbulence

Added wake turbulence: $$TI_u = \frac{\sigma\tilde{u}}{\bar{\tilde{u}}} / TI_{u0}$$



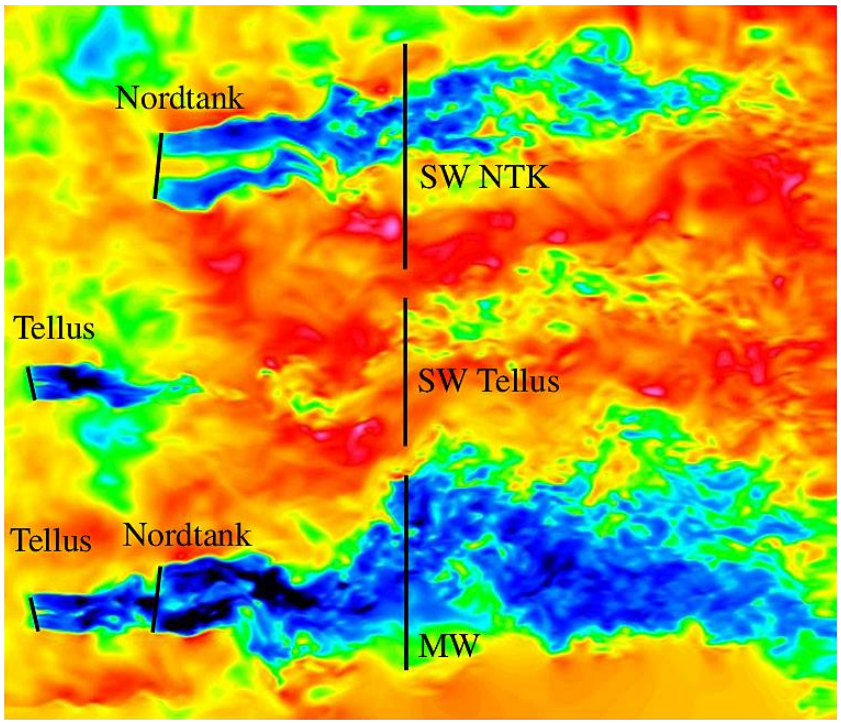


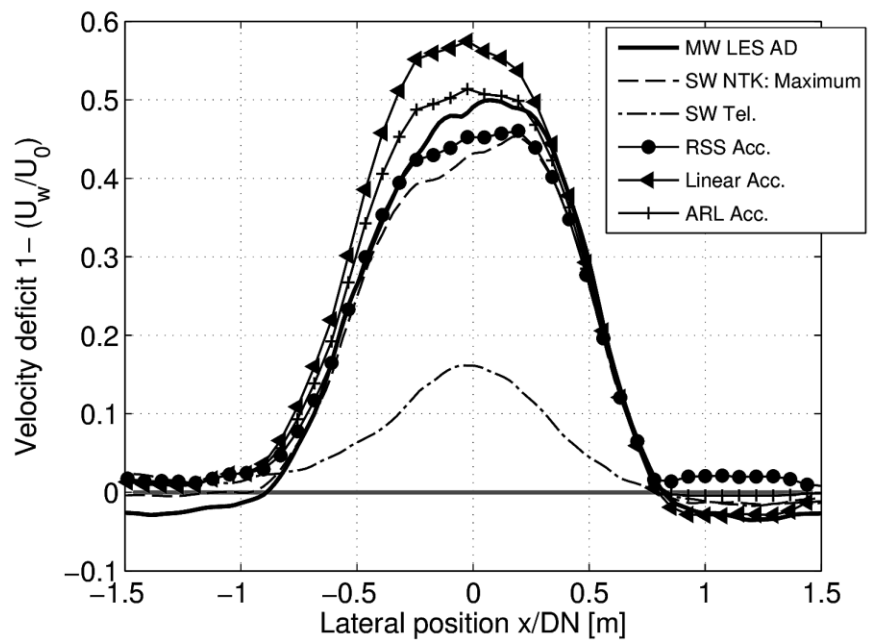
	Simulated	Measured	Design
Nordtank Elec. power [kW]	86.0 kW	81.8 kW	137.2 kW
Thrust [kN]	28.9 kN	25.4 kN	31.9kN
Tellus Elec. power [kW]	26.2 kW	-	24.7 kW
Thrust [kN]	5.9 kN	-	6.8 kN

Without Tellus upstream

Numerical work: wake accumulation

- CFD model used for wake accumulation investigation
  - nearest (dominant) wake (in DWM)
  - *linear* summation of wakes
  - *root-sum-square (quadratic)* summation of wakes
  - *average* of *linear* and *root-sum-square* summation (ARL)





- ARL closest to simulated MW profile in this particular case
- Pitch Vs Stall regulated? Deep array effect?

Conclusion

- New post processing techniques developed.
- EllipSys3D LES AD neutral ABL in yawed turbine: very good agreement.
- Impact of atmospheric stability currently investigated (exp., num.)

Future work:

- CFD based parametric study
    - LES (expensive), RANS
    - Vortex method: Omnivor/ HAWC2
    - Validation & extension of HAWC2/DWM, multiple wakes and deep array
- Experimental work:
    - use of high speed lidar recordings for characterization of single wake turbulence