

Single Wake Meandering, Advection and Expansion

An analysis using a pulsed lidar and CFD LES-ACL simulations

Presenter: Ewan Machefaux, DTU Wind Energy

Co-authors

Gunner Larsen, DTU Wind Energy

Niels Troldborg, DTU Wind Energy

Andreas Rettenmeier, University of Stuttgart - Wind Energy Dept. (SWE)

1- Project outline

Goals:

- Study of the single wake dynamics
 - **Meandering:** wake motions governed by large scale turbulent structure in the atmosphere
 - **Advection:** speed of the wake downstream transportation
 - **Expansion:** increase in radial extend of the wake deficit caused by small scale turbulent diffusion, pressure recovery and meandering

Methods:

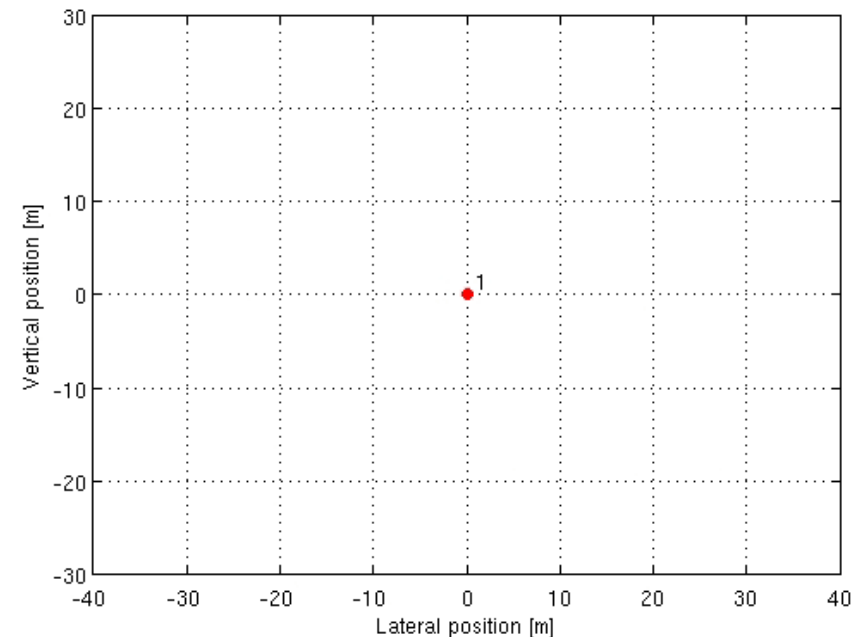
- Experimental and numerical study
 - Measured wake meandering against model predictions (DWM)
 - Measured expansion against EllipSys3D simulations and other engineering models
 - Calibrate the advection velocity of the DWM model

2 – Experimental approach: set up



- Cartesian pattern of 7X7 points
- 2 half-opening angle tested: 8.5deg and 16.7deg
- Sweep time ≈ 7.8 sec

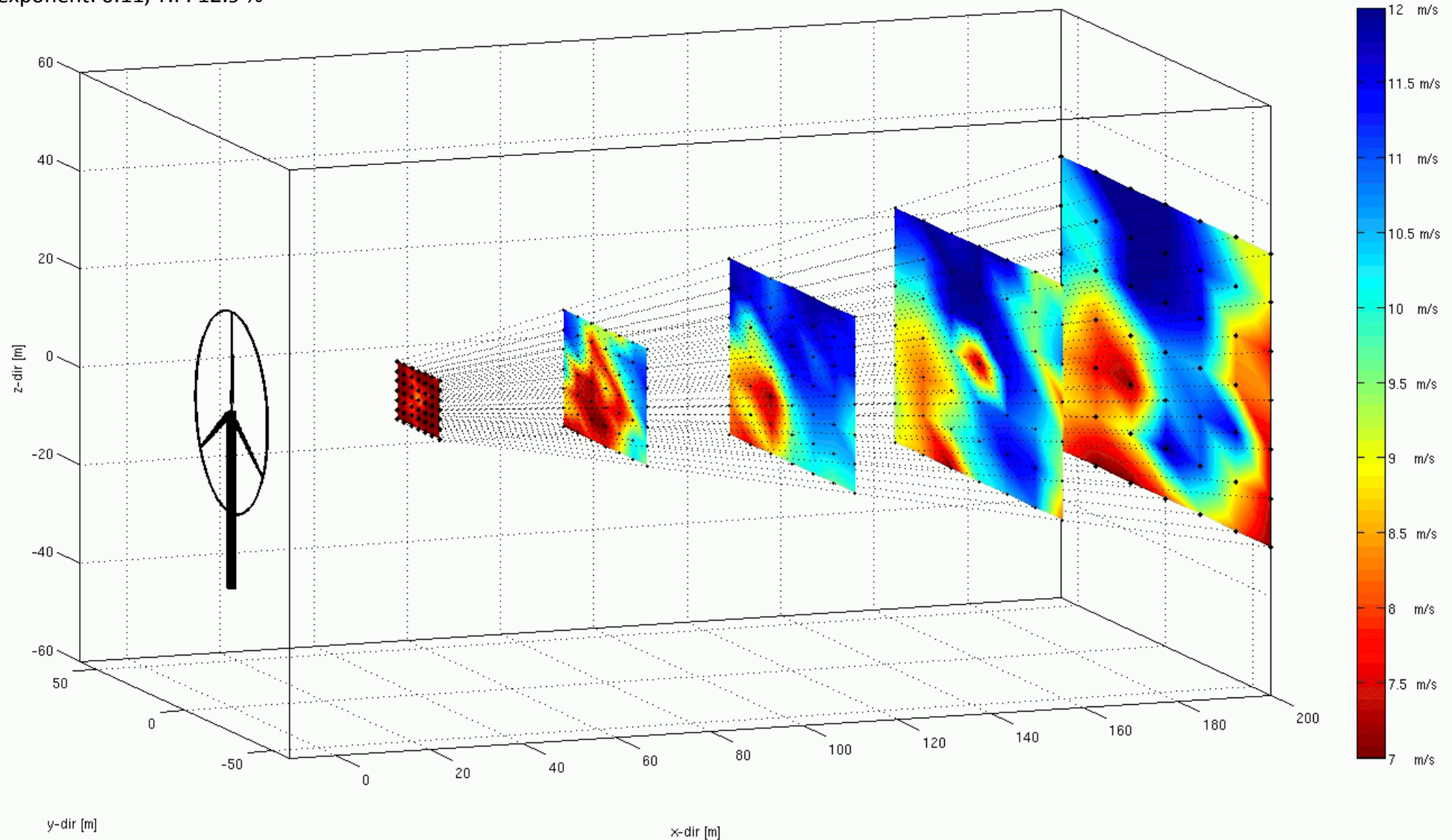
- June to November 2009, DTU Risø Campus
- WindCube pulsed lidar WLS7, developed and adapted at SWE
- 5 simultaneous cross section scanning at $\approx 1D$, 2D, 3D, 4D and 5D



2 – Experimental approach: wake resolving

Unfiltered line-of-sight velocities,
Average free stream velocity: 12.4 m/s, shear
exponent: 0.11, T.I : 12.9 %

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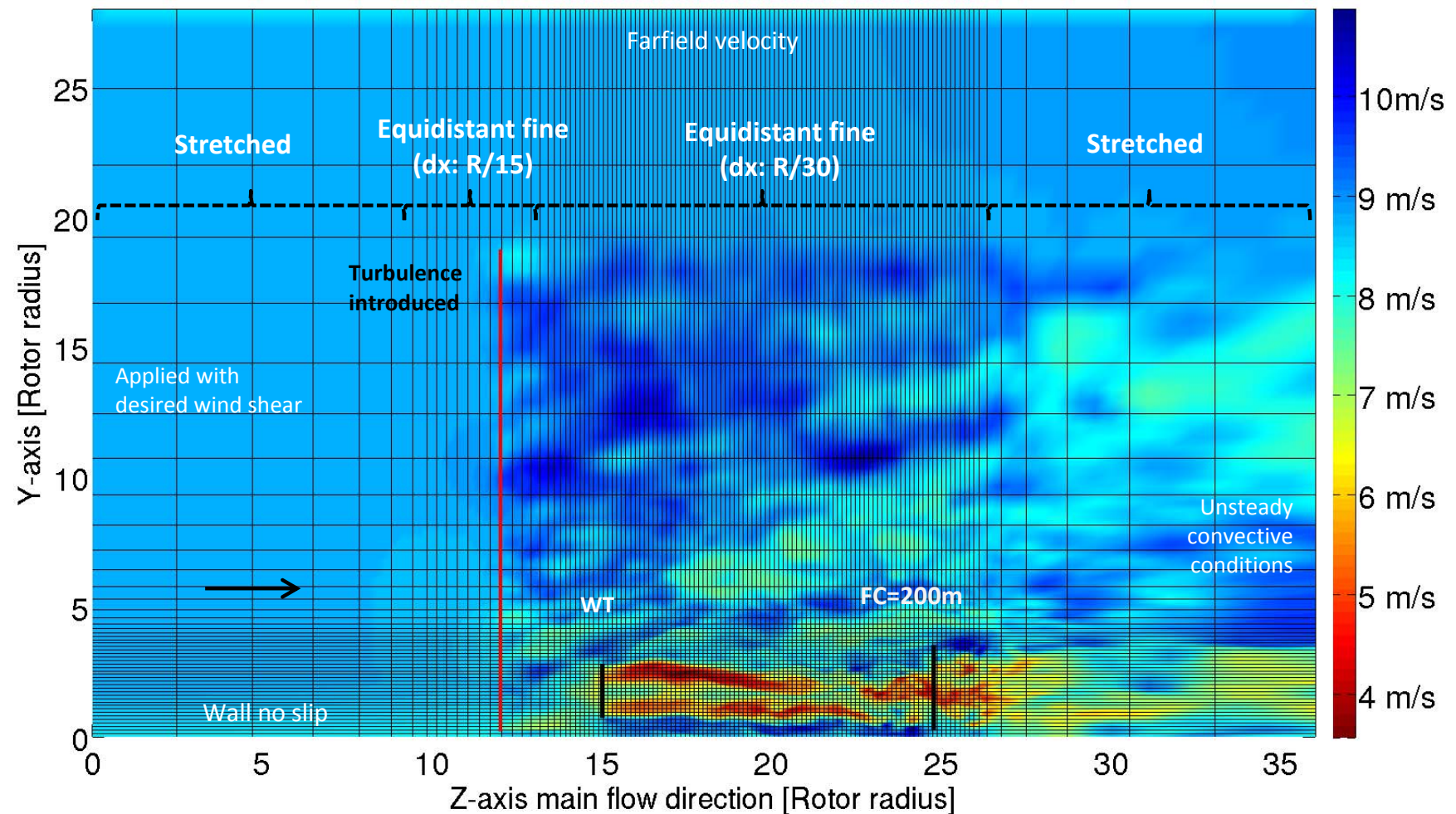


- Wake resolving similar to previous study using Continuous Wave Lidar at Tjaereborg

3 – Numerical approach: set up

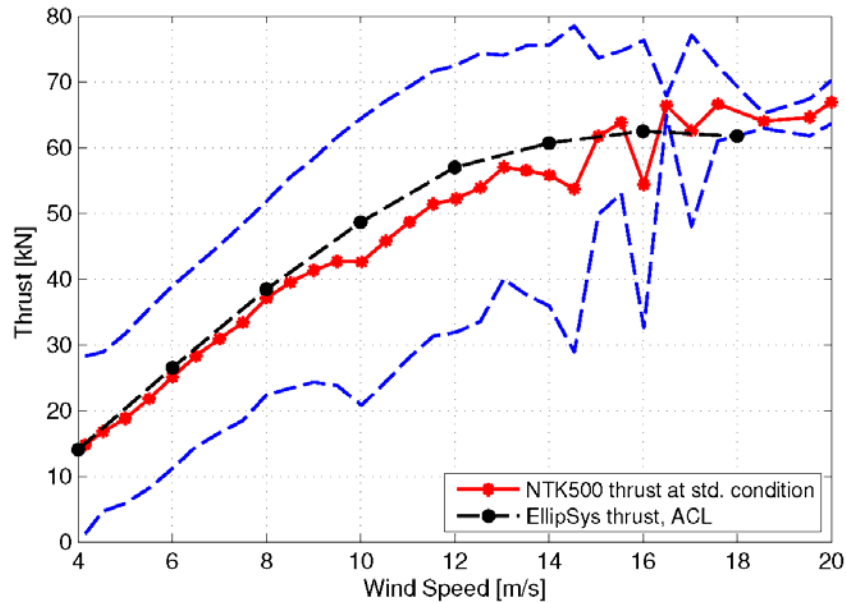
Key features:

- **EllipSys3D** flow solver ; **Actuator Line Technique** ; **Large Eddy Simulation** , Constant RPM, constant pitch, no yaw
- **ABL** modeled:
 - **shear**: applied at the inlet using a power law
 - **synthetic turbulent** fluctuations, **Mann model** applied in a single cross section close to the inlet
- Unsteady computations: 10 minutes flow field statistic

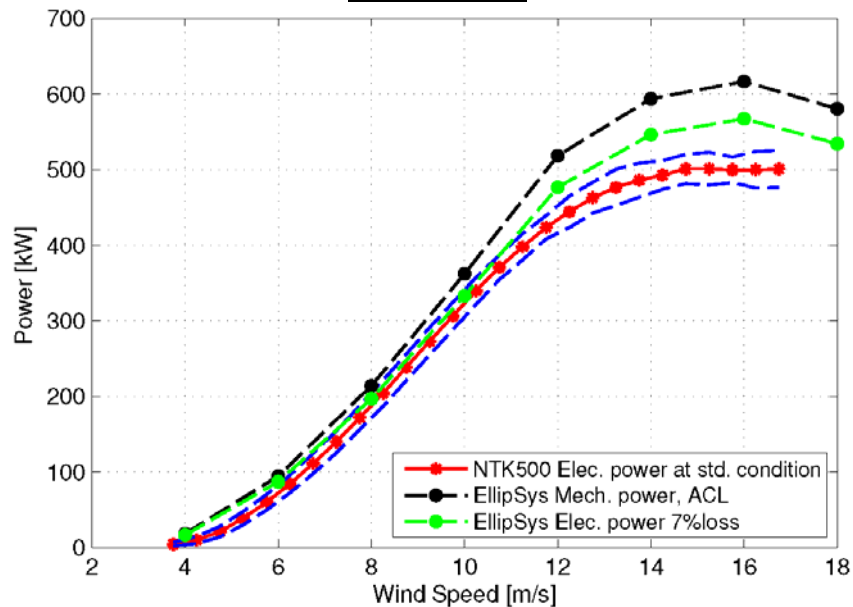


3 – Numerical approach: validation

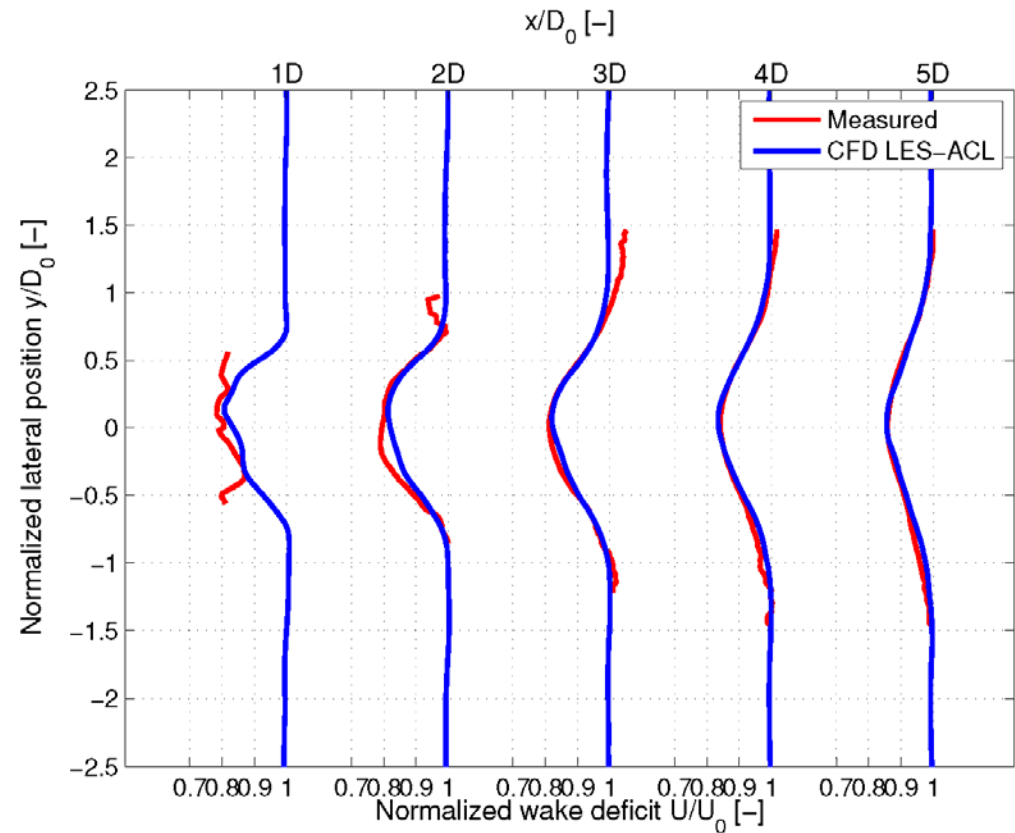
Thrust curve



Power curve



Normalized wake deficit in meandering frame of reference



4 – Measured wake meandering

- Mean shear contribution removed



- Tracking procedure for each lidar sweep

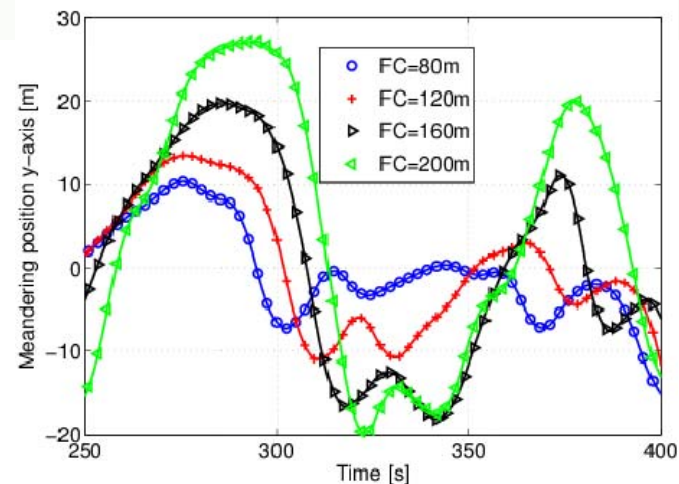
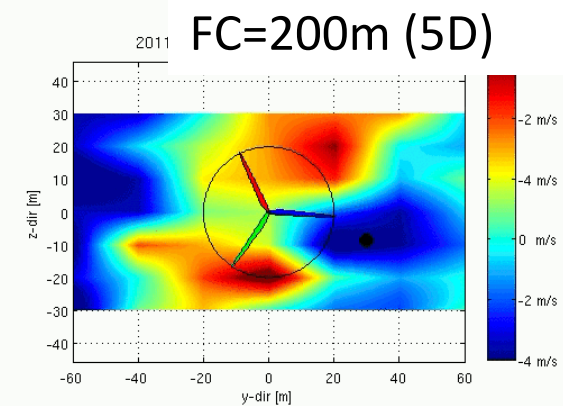
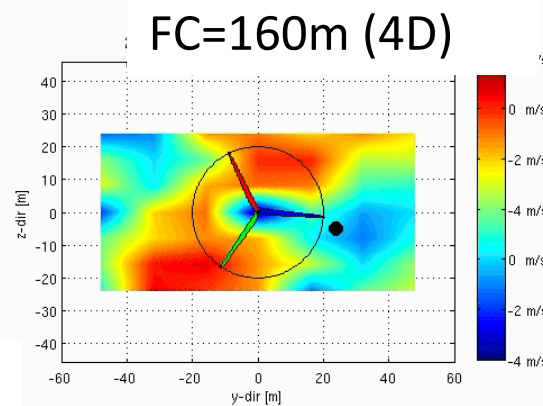
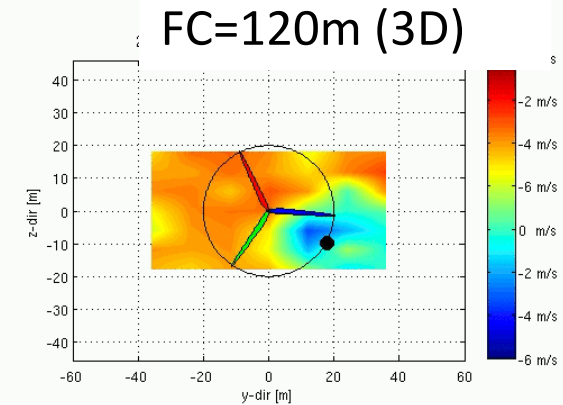
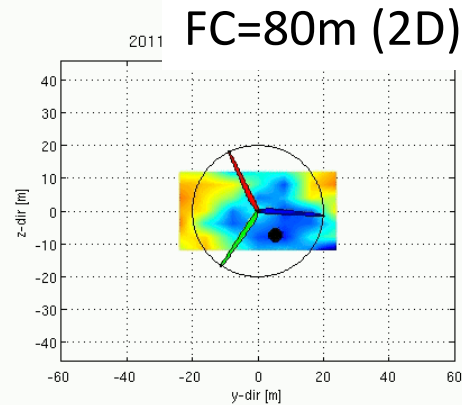


→ Optimization: bivariate Gaussian shape fitting through least-squares approach

$$f = \frac{A}{2\pi\sigma_y\sigma_z} \exp\left[-\frac{1}{2}\left(\frac{(y_i - \mu_y)^2}{\sigma_y^2} + \frac{(z_i - \mu_z)^2}{\sigma_z^2}\right)\right]$$

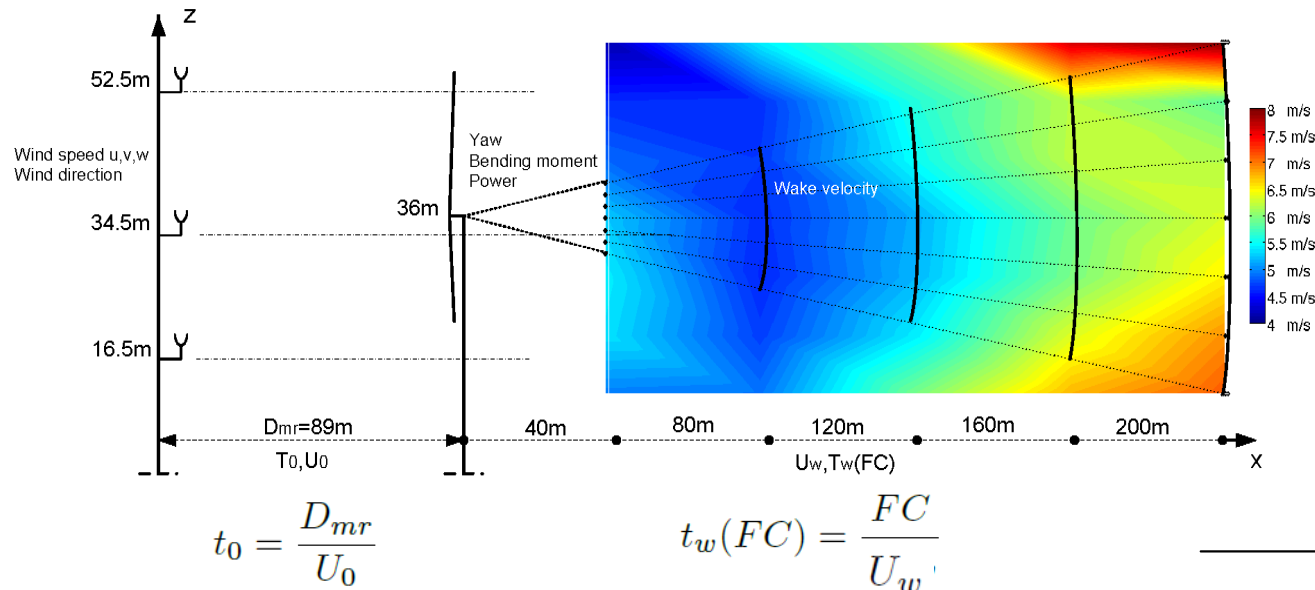


- Discrete to continuous meandering paths for wake center



4 – Modeled wake meandering (DWM model)

- 1- Main flow direction: constant Taylor advection velocity U_T



Guess: N.O. Jensen

$$U_w = \sqrt{1 - CT} \cdot U_0$$

↑
Tower bending moment

- 2- Lateral displacement: large scale lateral turbulent velocities at specific position and time instant

$$y(FC, \tilde{t}) = v_c(\tilde{t}) \cdot \tilde{t}(FC) + h_{yaw}(FC, \tilde{t})$$

$$z(FC, \tilde{t}) = w_c(\tilde{t}) \cdot \tilde{t}(FC) + h_{tilt}(FC, \tilde{t})$$

Scanning head aligned horizontally with ground

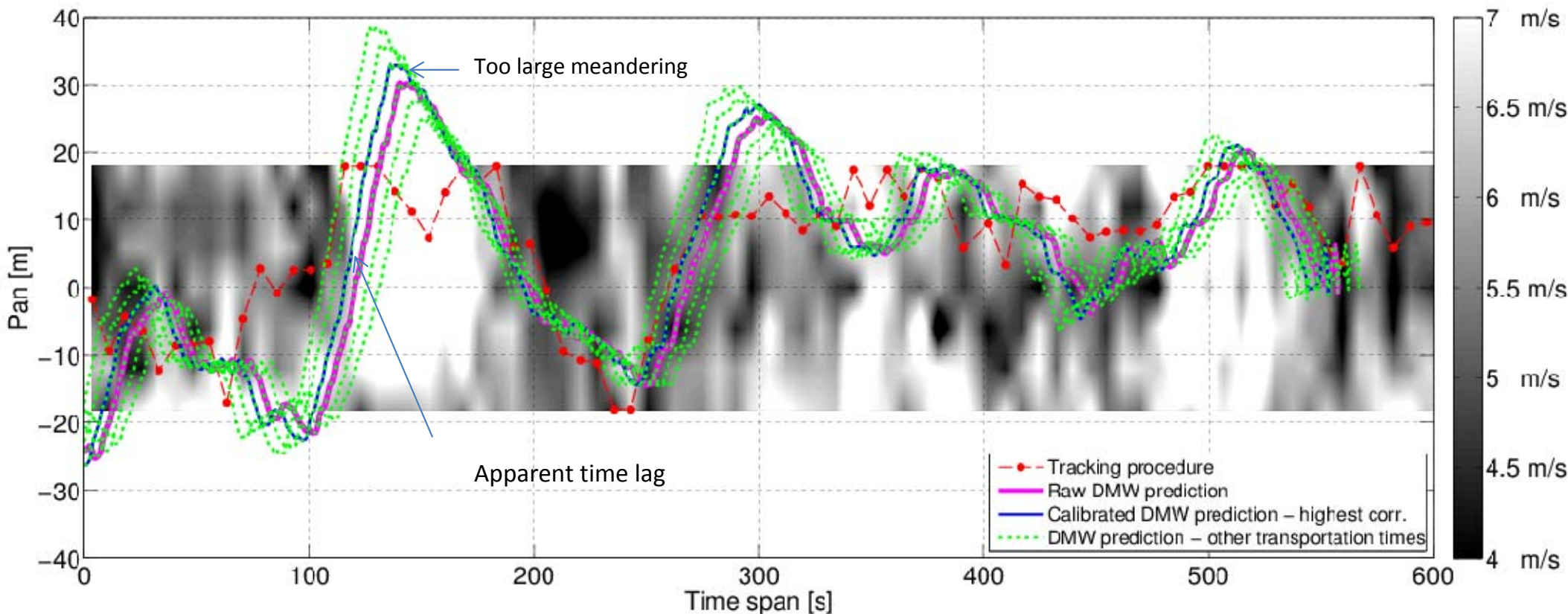
$v_c(\tilde{t})$: large scale lateral velocities

$h_{yaw}(FC, \tilde{t})$: yaw displacement contribution

\tilde{t} : elapsed time for wake release to reach FC

4 – Analysis - Dynamic Wake Meandering

Prediction from model against measured meandering at FC=120m (3D)



→ Mean advection time difference: cross correlation analysis → 5.5s

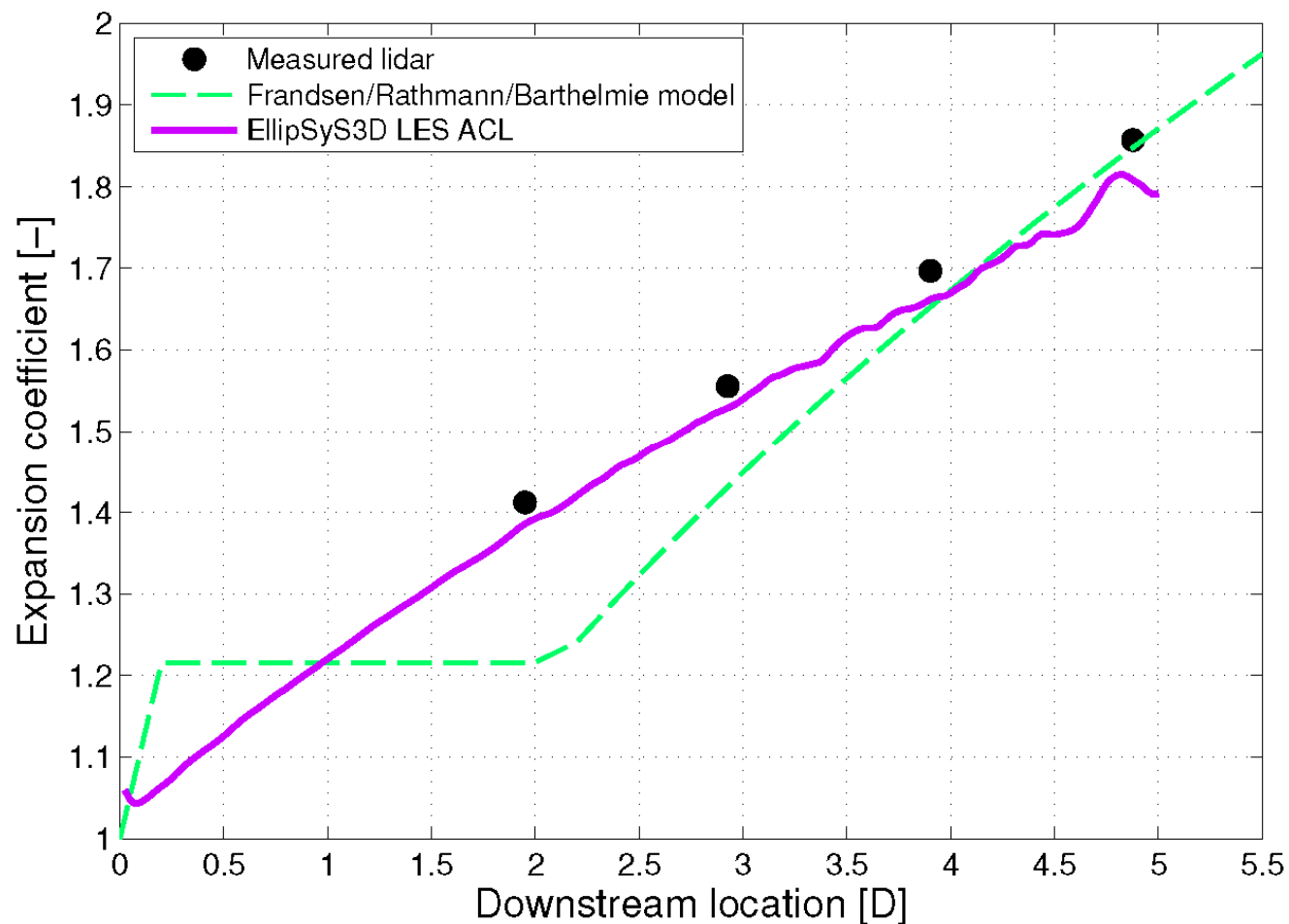
| ($U_0=8.1$ m/s) | U_w | t | t_{adv} |
|------------------|----------------------|-------|-----------|
| DMW Raw | 3.4m/s (N.O. Jensen) | 46s | 35s |
| DMW Calibrated | 4.06m/s | 40.5s | 29.5s |

→ N.O. Jensen model underestimate the wake advection velocity in this case

4 – Single wake expansion

10 min average expansion coefficient in fixed frame of reference

$E [-] = \text{Wake width [m]} / D_0 \text{ [m]}$



- Good agreement with EllipSyS3D
- Good agreement with engineering model in far wake

O. Rathmann, R. Barthelmie, and S. Frandsen.
Turbine Wake Model for Wind Resource Software. *EWEK 2006 Wind Energy Conference and Exhibition, Scientific Proceedings*, 2006.

5 – Conclusion and future work

Achievements:

- DWM prediction are robust
- Uncertainties in advection velocity using N.O. Jensen assumptions
- Good agreement between measured and simulated expansion in fixed frame of reference

Current / future work:

- Direct estimation of wake advection velocity from pulsed lidar measurements
- Empirical formulation of advection velocity as function of wake deficit
- New single wake expansion engineering model

Thank you for your attention

Questions ? Suggestions ?

Acknowledgment:

Flow Center

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