Determination of speed deficit and turbulence in wind turbine wakes

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DTU Mechanical Engineering
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Outline

1. Why make wake measurements?
2. Different kind of wake measurements;
3. Single point wake measurements;
4. Near wake measurements;
5. Far wake measurements;
6. Recommendations;
7. References.

Why make wake measurements

- Validation simple wind turbine prediction models (BEM, AD, AL, Vortex, LES, ..);

- Validation of wind farm prediction models for different terrain types:
  - Onshore;
  - Offshore;
  - Complex terrain.

- Validation of aero-elastic wind turbine models;

Different kind of measurements

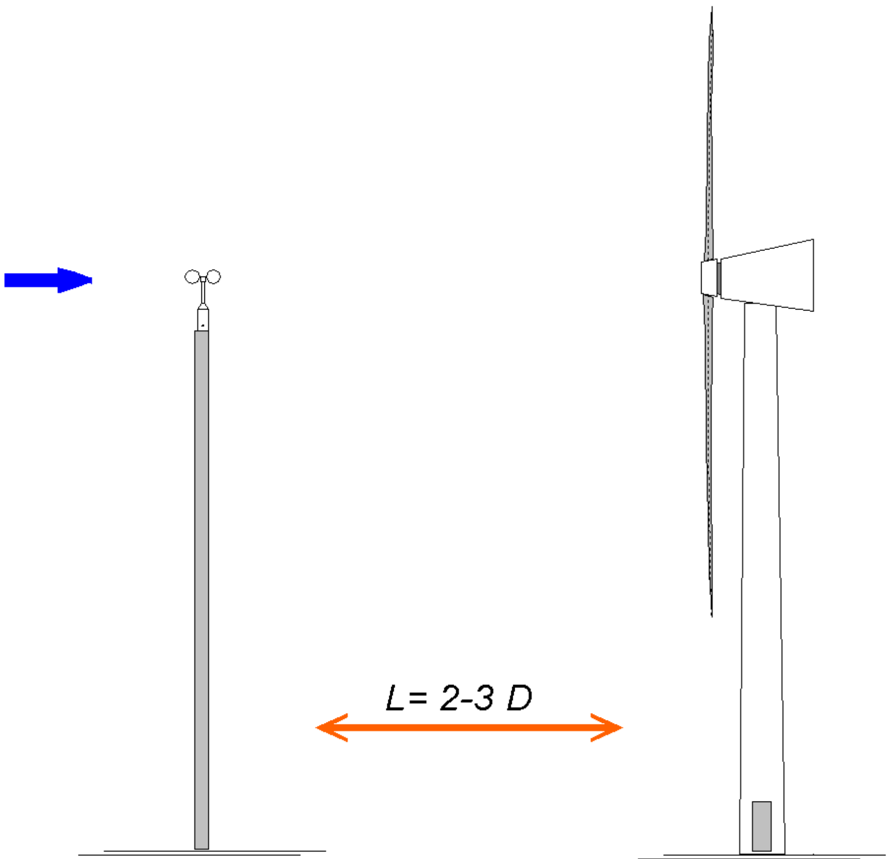
- Classic wind turbine measurements (power curve determination)

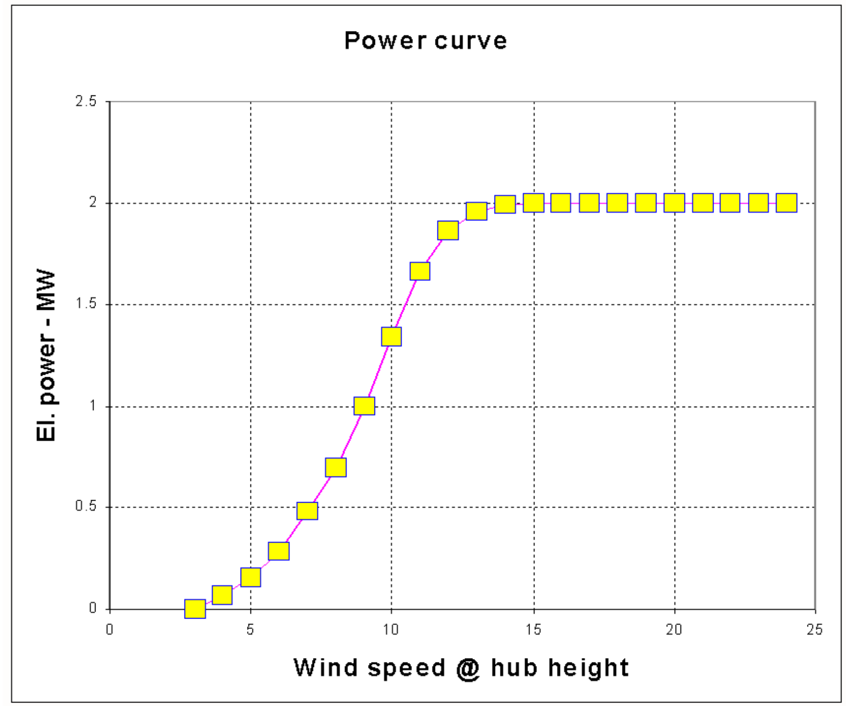
- Near wake measurements (1-5D)
  - [stationary] mast equipped with cups or 3D sonics
  - [stationary] ground based vertical LiDAR
  - [nacelle located] horizontal LiDAR

- Far wake measurements
  - [stationary] masts or LiDARs
  - [statinorary] wind turbines (power, nacelle wind speed..)

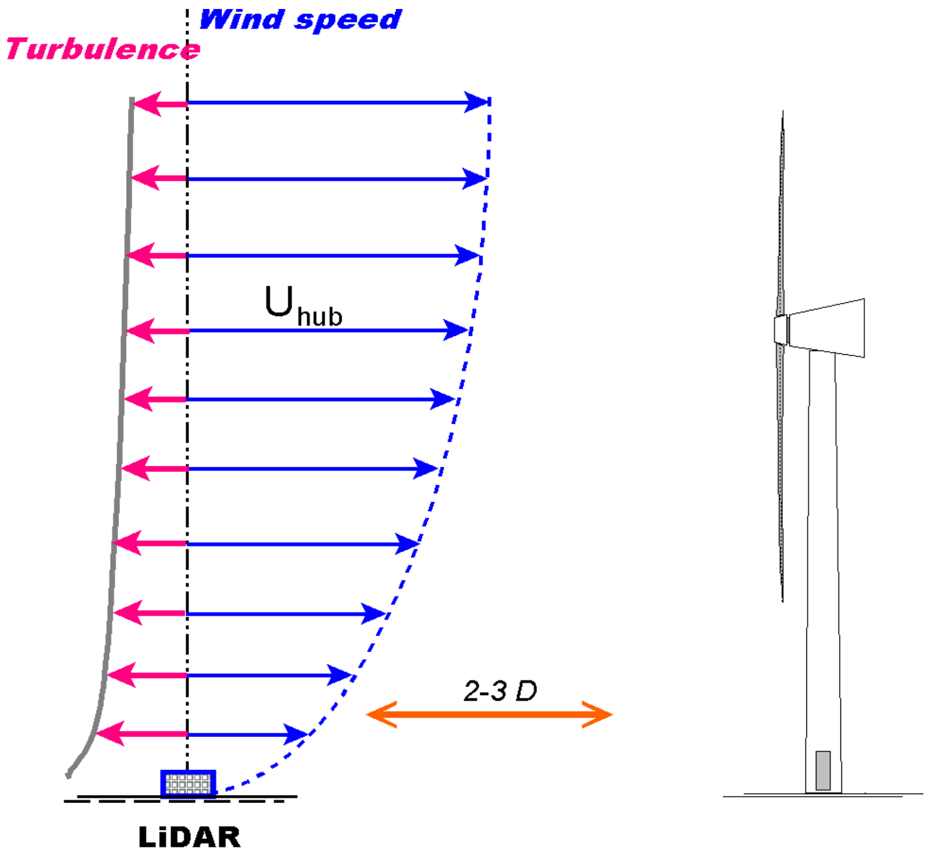
Power curve measurements;

based on single point measurement



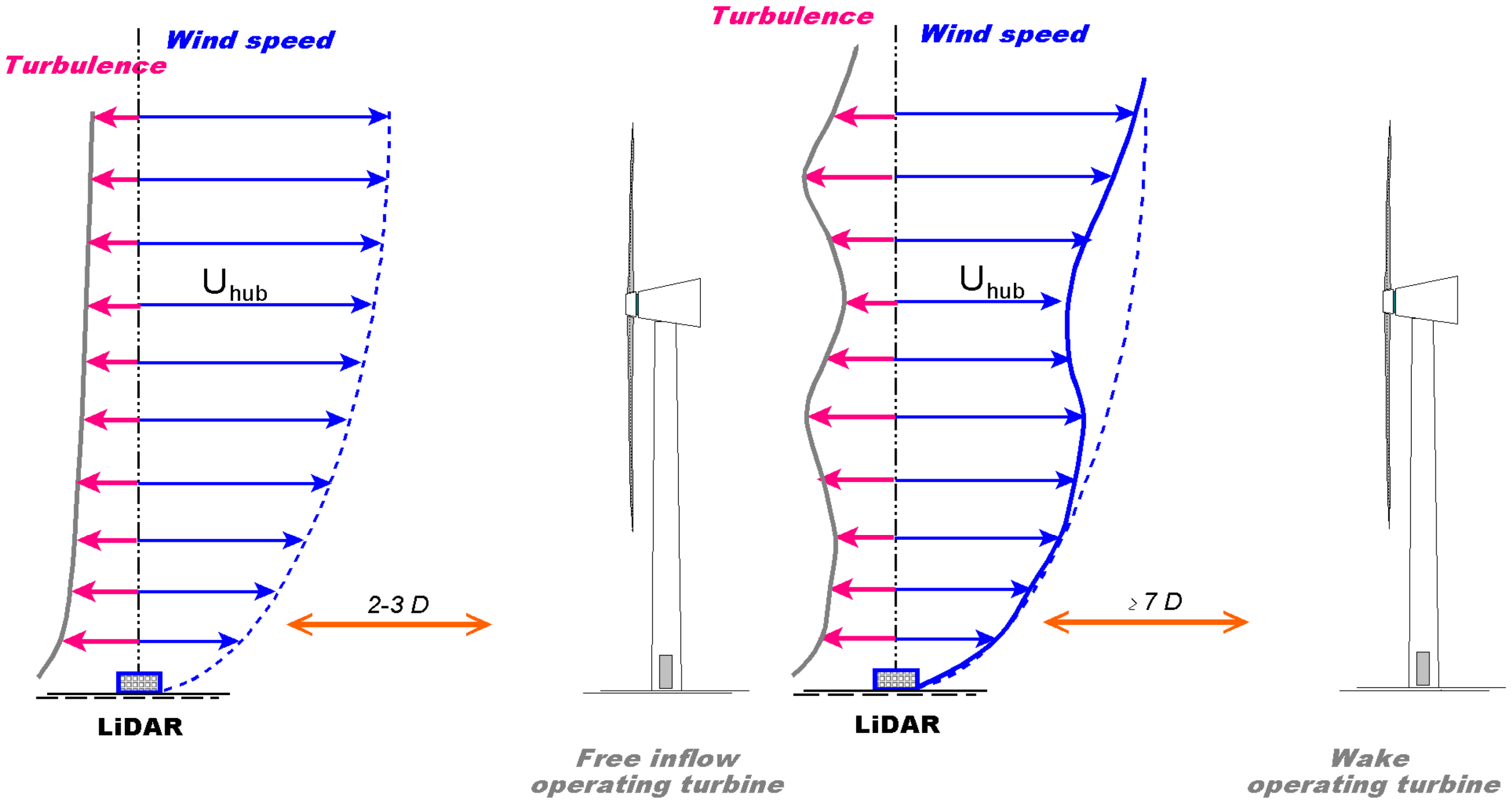


Power curve measurements;
based on a ground based LiDAR



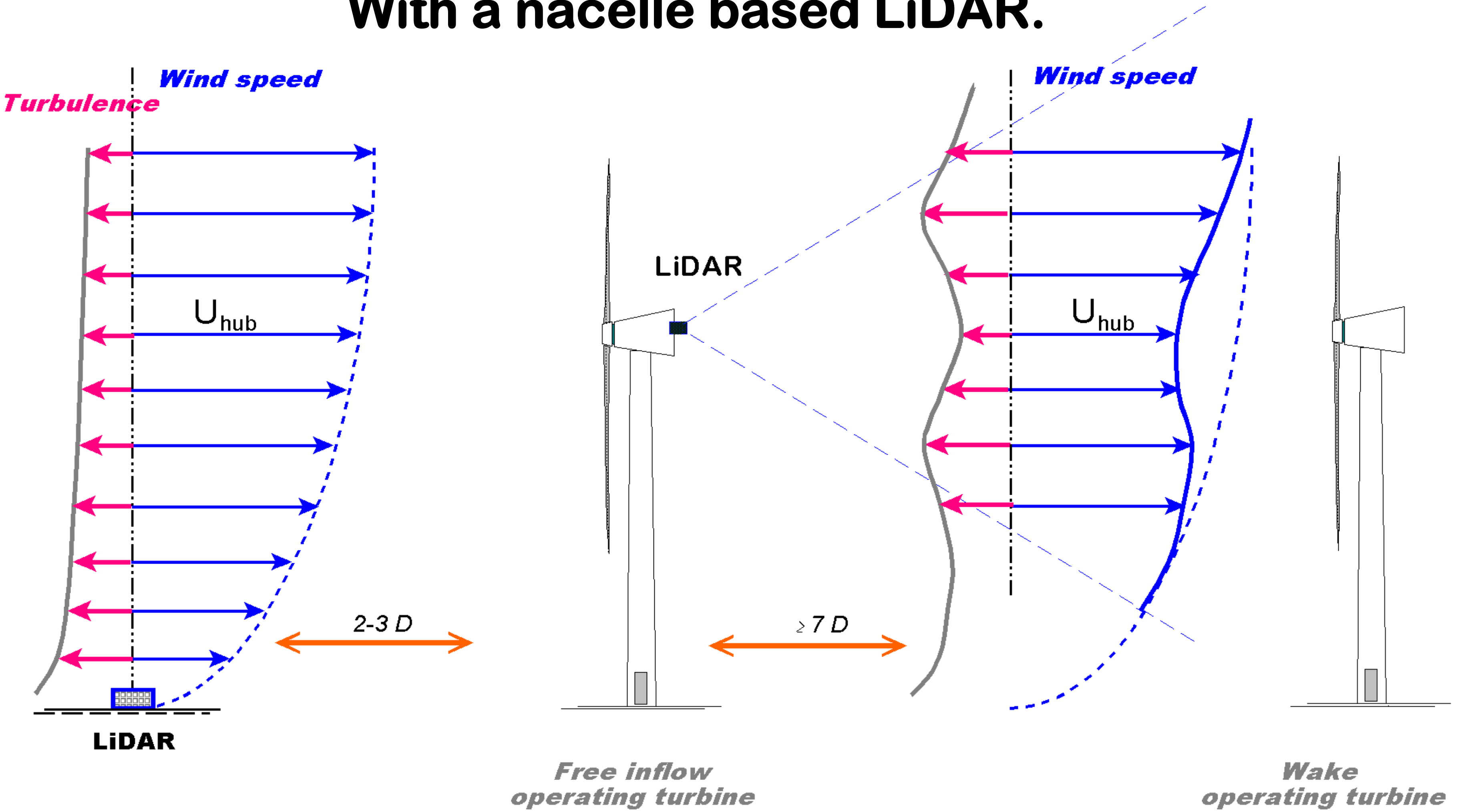
Wake measurements;

With a ground based LiDAR.

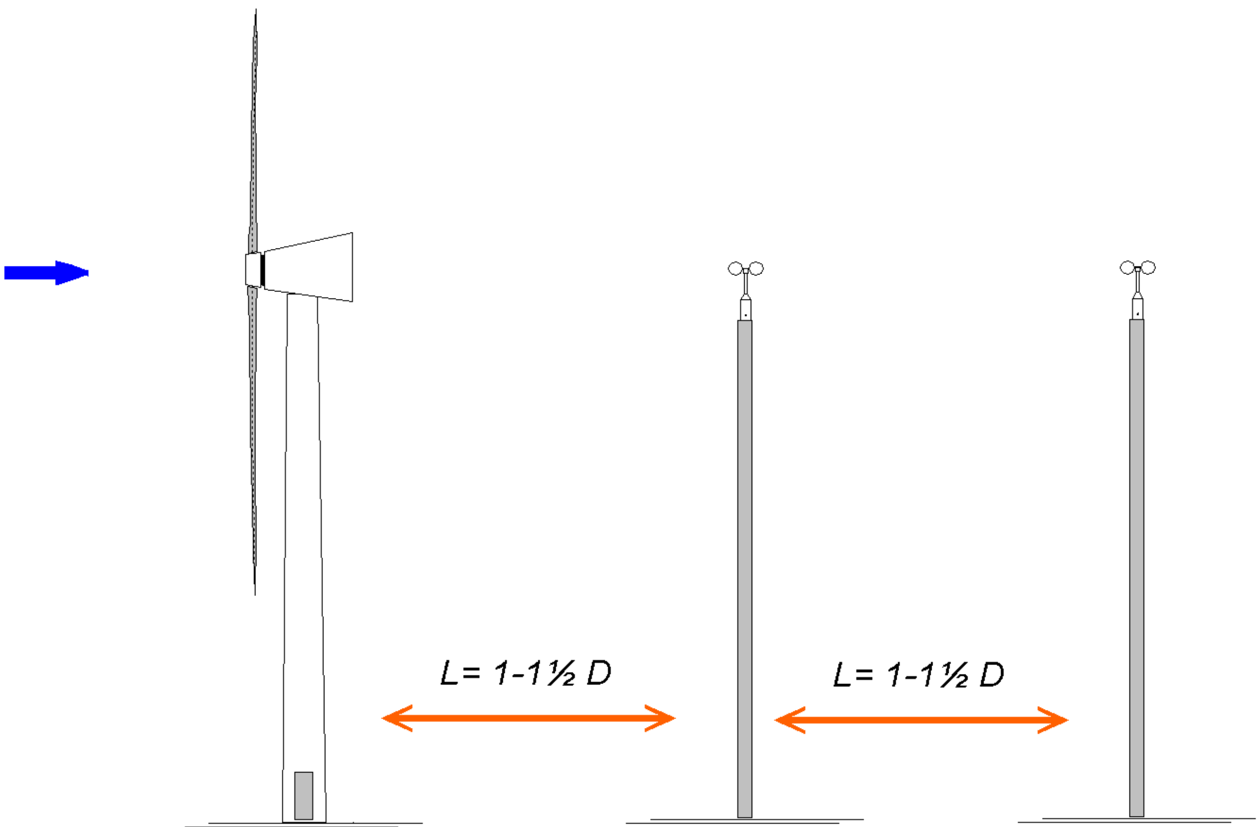


Wake measurements;

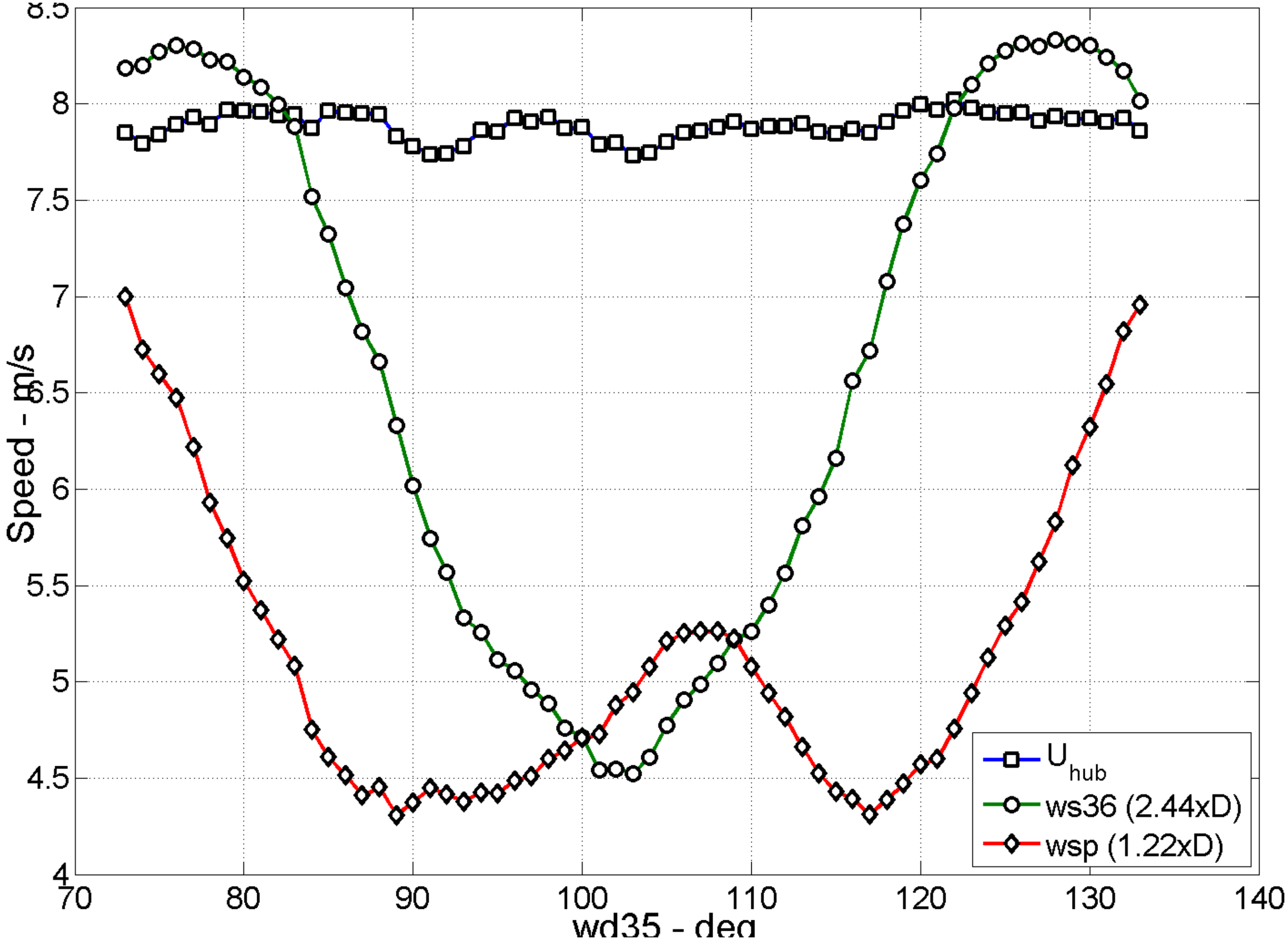
With a nacelle based LiDAR.



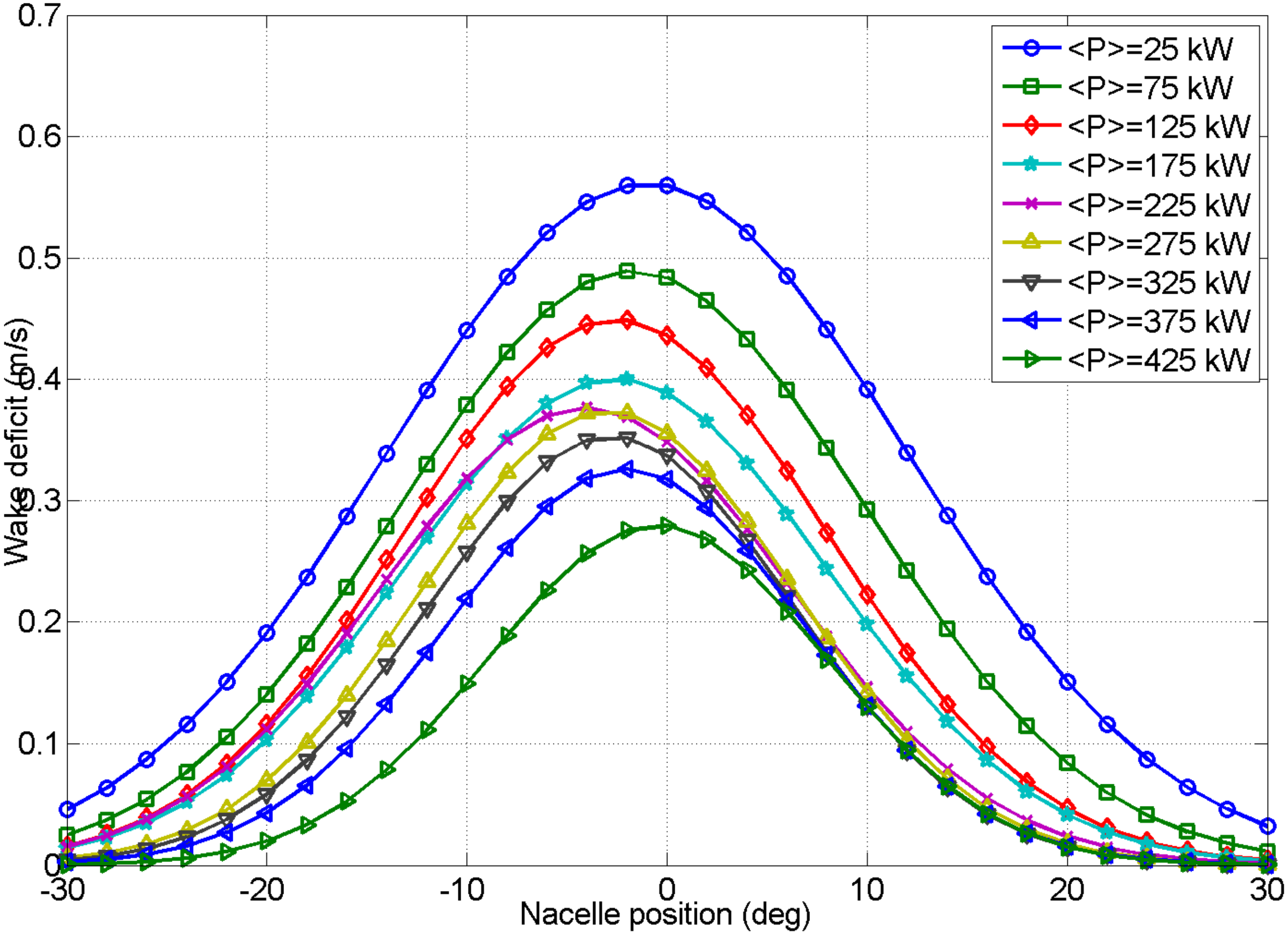
Near wake measurements
based on single point measurements



Wind speed behind a 500kW stall controlled wind turbine



Nordtank: Wake speed deficit, spacing=2.5xD (ambient wind speed has been removed)



Near wake analysis
based nacelle mounted LiDAR

- Perform full-scale wind speed measurements in the wake of an operating 80m / 2.5 MW wind turbine.
- Resolve the wake characteristics in the meandering frame of reference, i.e.
  - Wake deficit
  - Inhomogeneous wake turbulence intensity characteristics

Reference project is EU-TOPFARM.

Test turbine:

Tjæreborg Enge

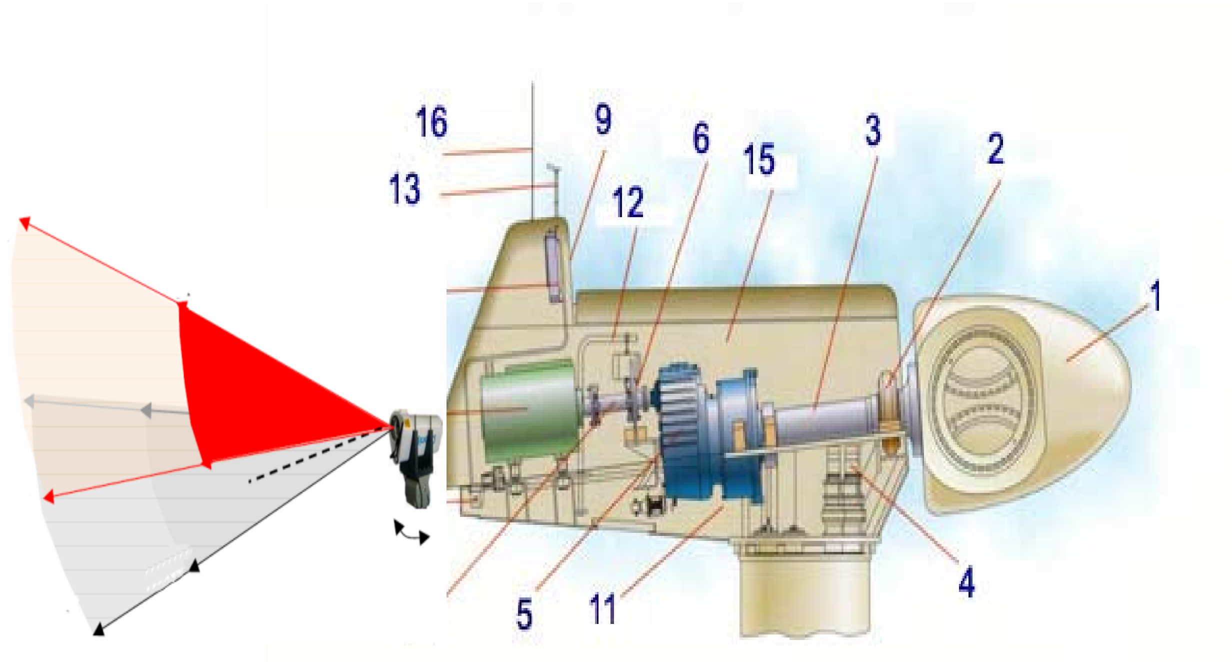
NM80

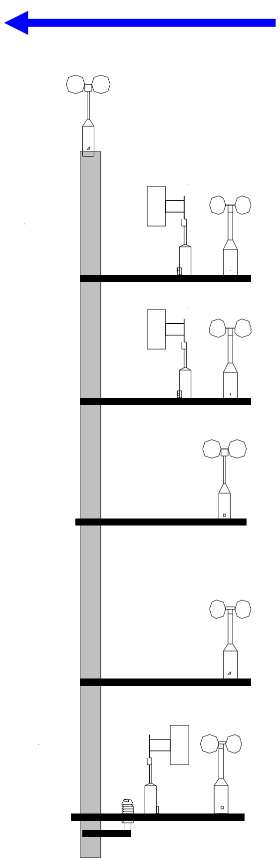
2.5MW

80m

Horizontal LiDAR

Wake measurements
with a horizontally mounted LiDAR

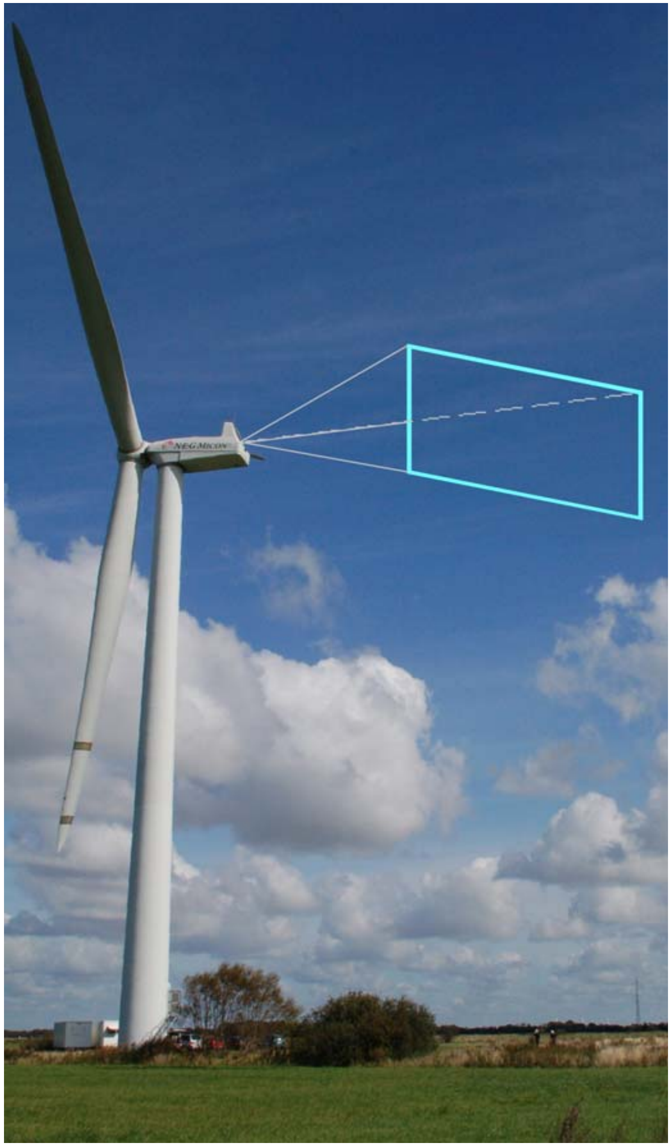




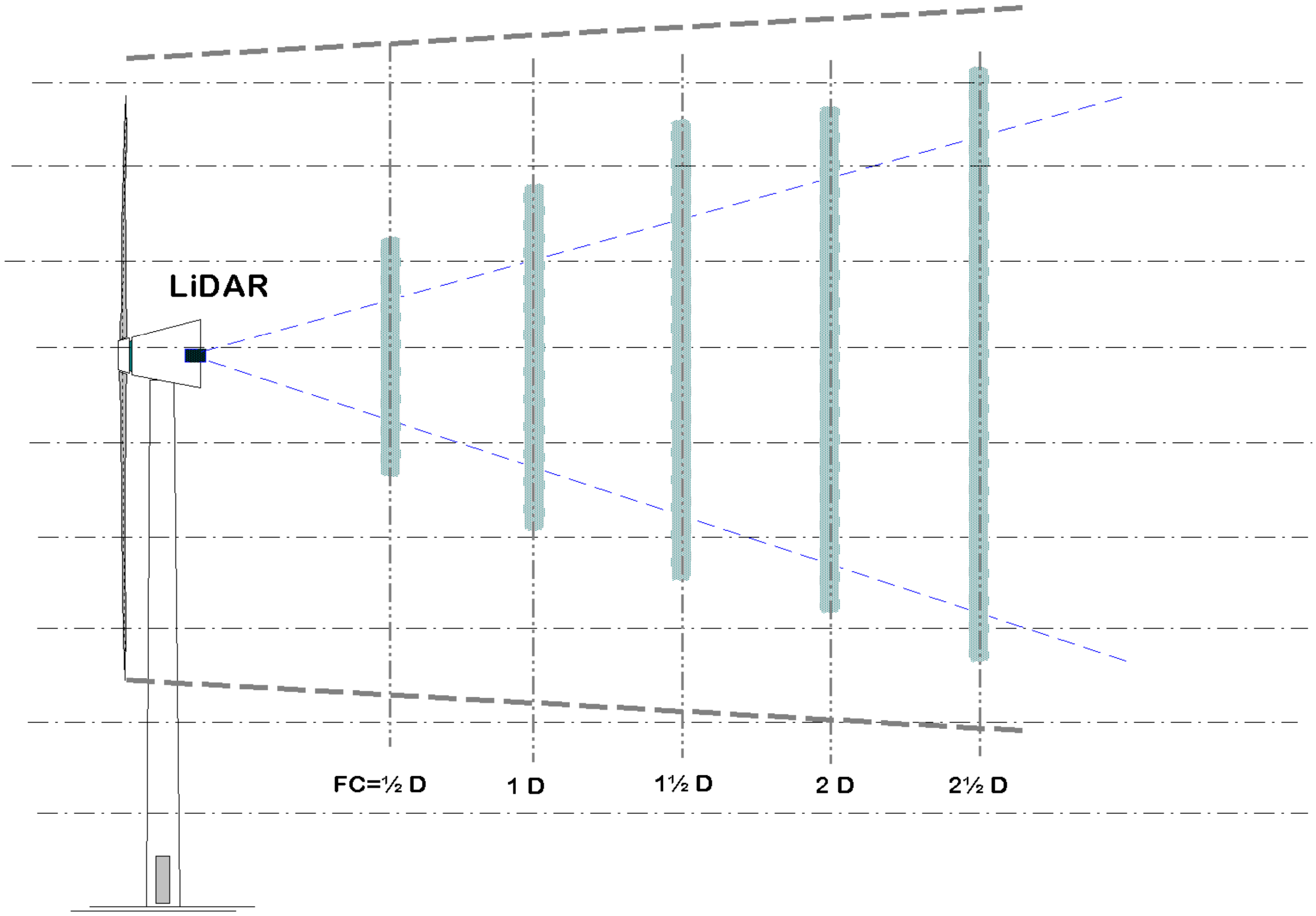
NM80; 80m / 2.5MW; VP & VS

Wake scanning

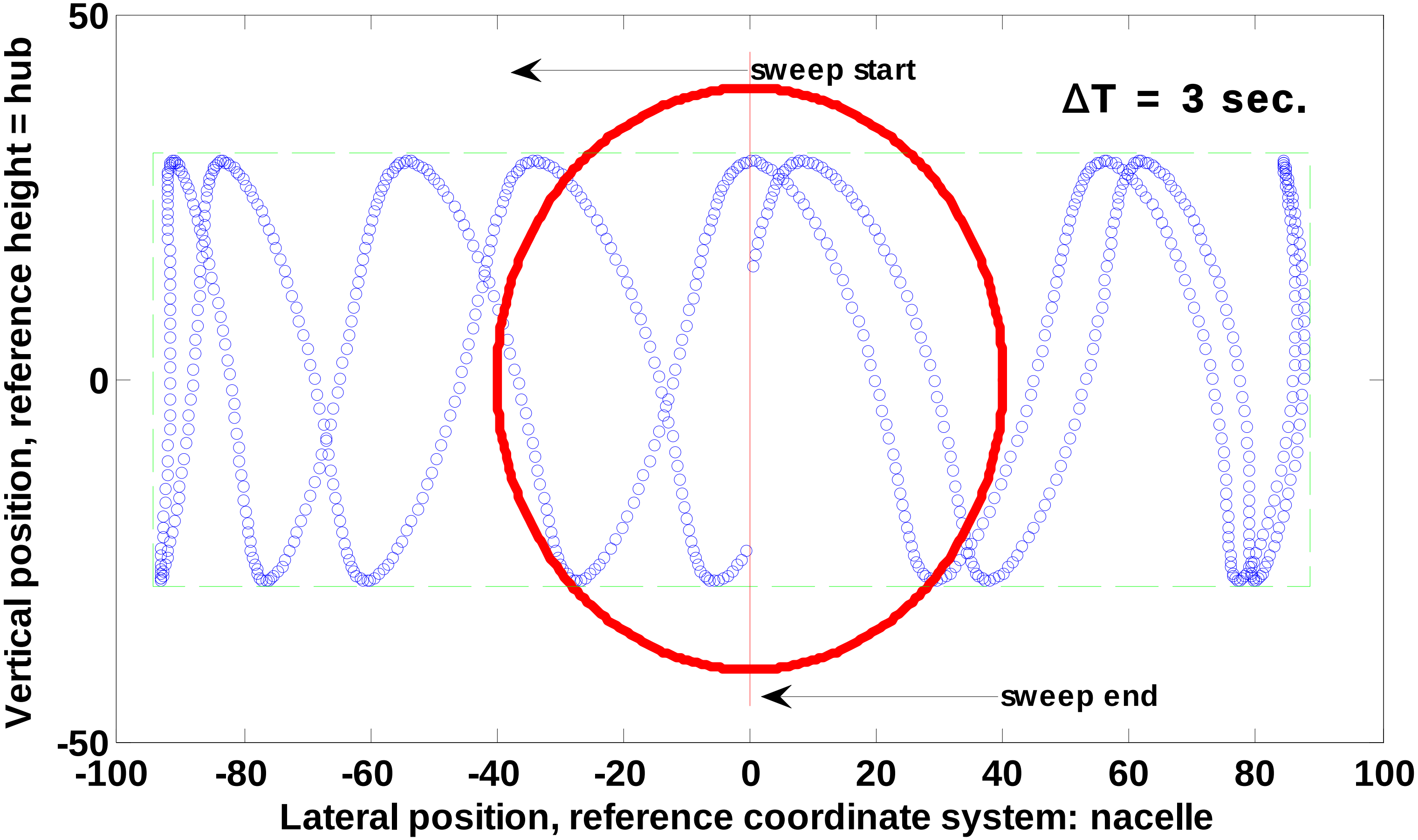
- LiDAR: Experimental QinetiQ ZephIR.
- PAN (lateral) angle: ± 26.5º
- TILT (vertical) angle: ± 8.5º
- Resolution: 349 Hz
- 1047 positions/plane
- Focus distances= 40, 80, 120, 160 or 200m



Full scal wake measurements



Wake measurement pattern, FC=200 (=2½D)



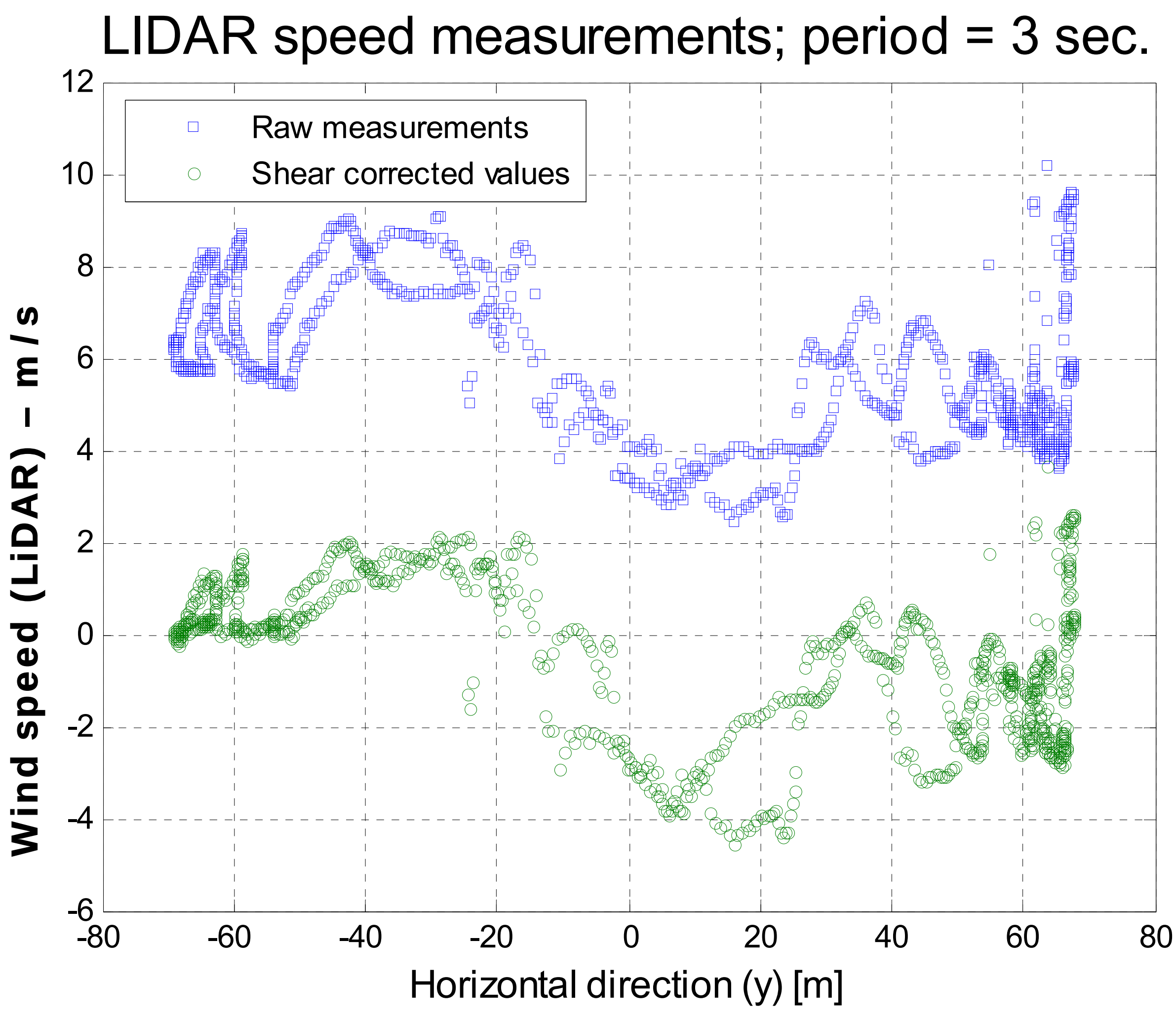
Coordinate transformation to Meandering Frame of Reference - MFR

1 sweep 2-3 seconds
equal of ~1050 observation

Remove wind shear
(10 min. speeds from mast)

Determine wake center
coordinates (y_c,z_c)

Align coordinates to MFR (y',z')



LIDAR speed measurements; period = 3 sec.
Raw measurements
Shear corrected values
Wind speed (LiDAR) – m/s
Horizontal direction (y) [m]
12
10
8
6
4
2
0
-2
-4
-6
-80
-60
-40
-20
0
20
40
60
80

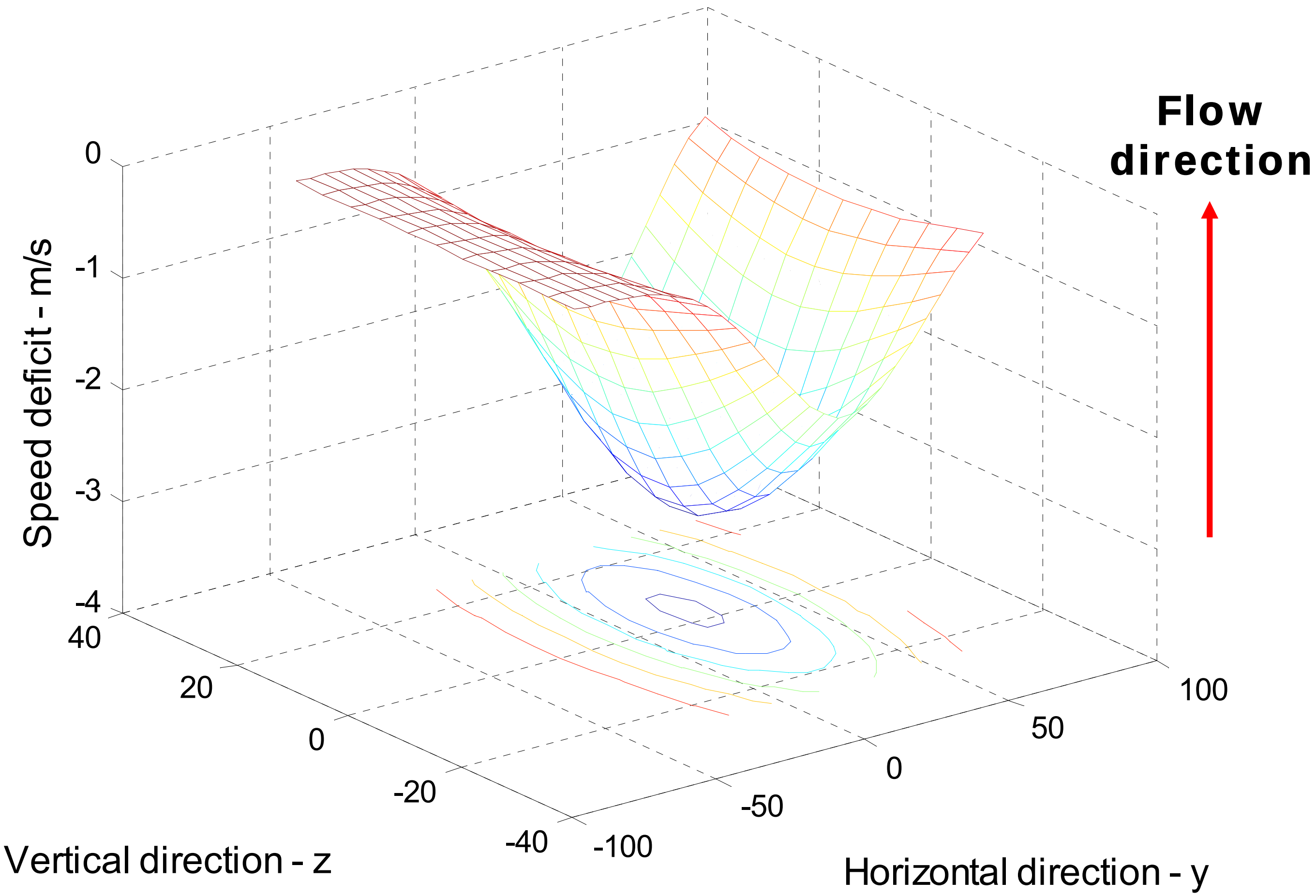
Wake position identification based on a bivariate Gaussian least square fit method

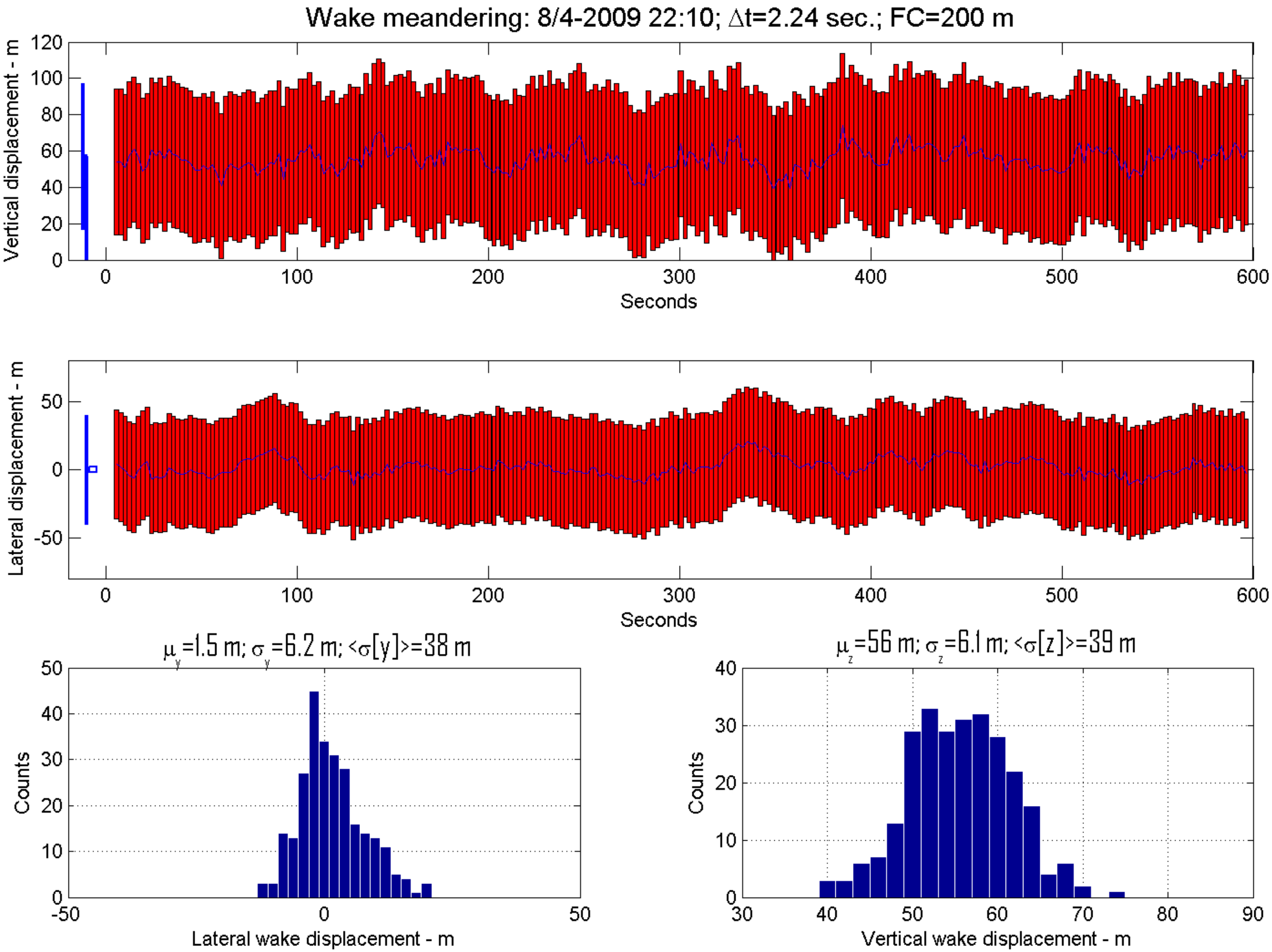
$$f(A,\mu_y,\mu_z,\sigma_y,\sigma_z)=\frac{A}{2\pi\sigma_y\sigma_z}\exp\left[-\frac{1}{2}\times\left(\left(\frac{(y_i-\mu_y)^2}{\sigma_y{}^2}\right)+\left(\frac{(z_i-\mu_z)^2}{\sigma_z{}^2}\right)\right)\right]$$

ΔT = 3 sec.

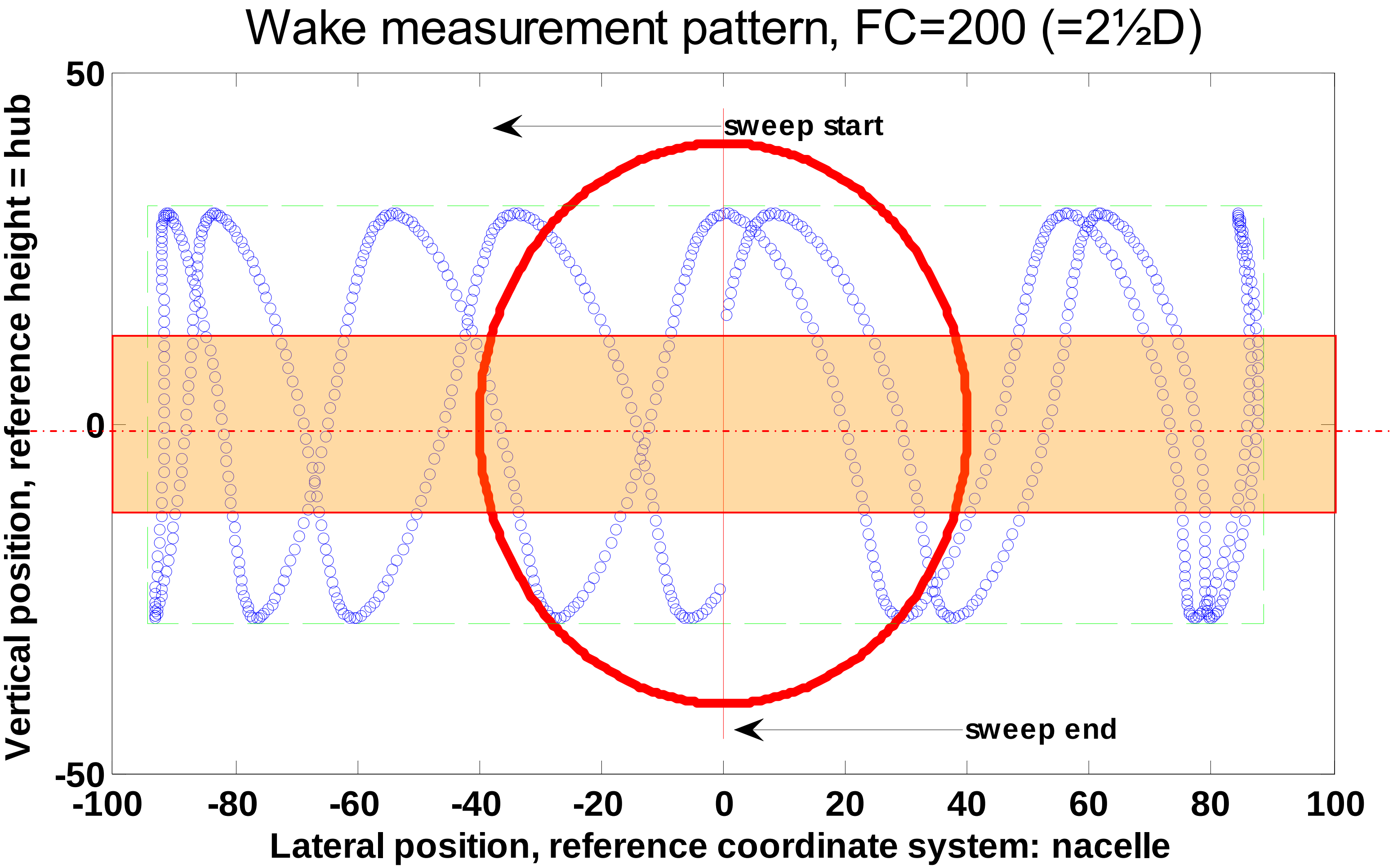
μ_y, μ_z	**Lateral and vertical deficit centers**
σ_y, σ_z	**Lateral and vertical width of distribution**
A	**Scaling parameter**

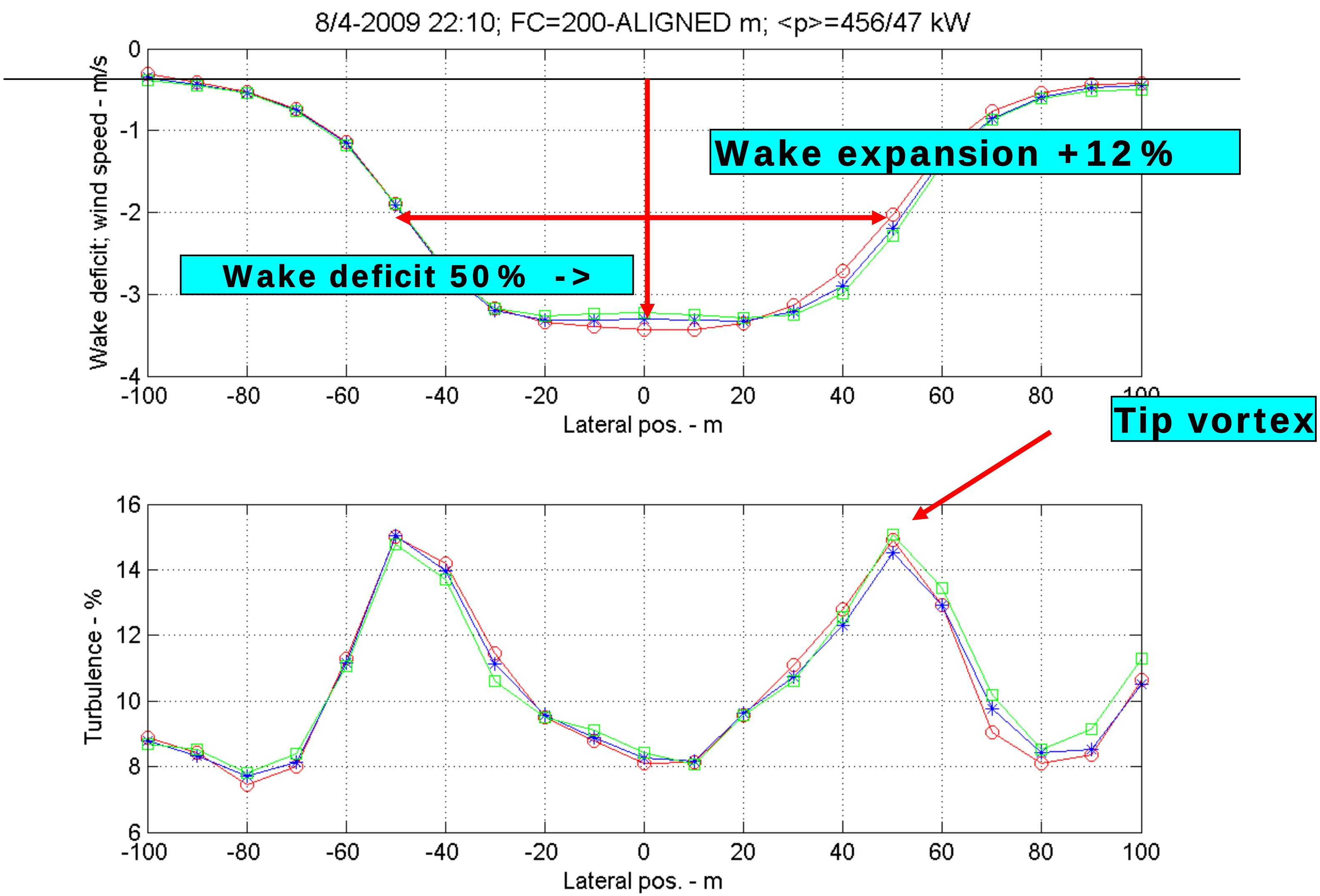
Fitted speed deficit; ts=3 sec.



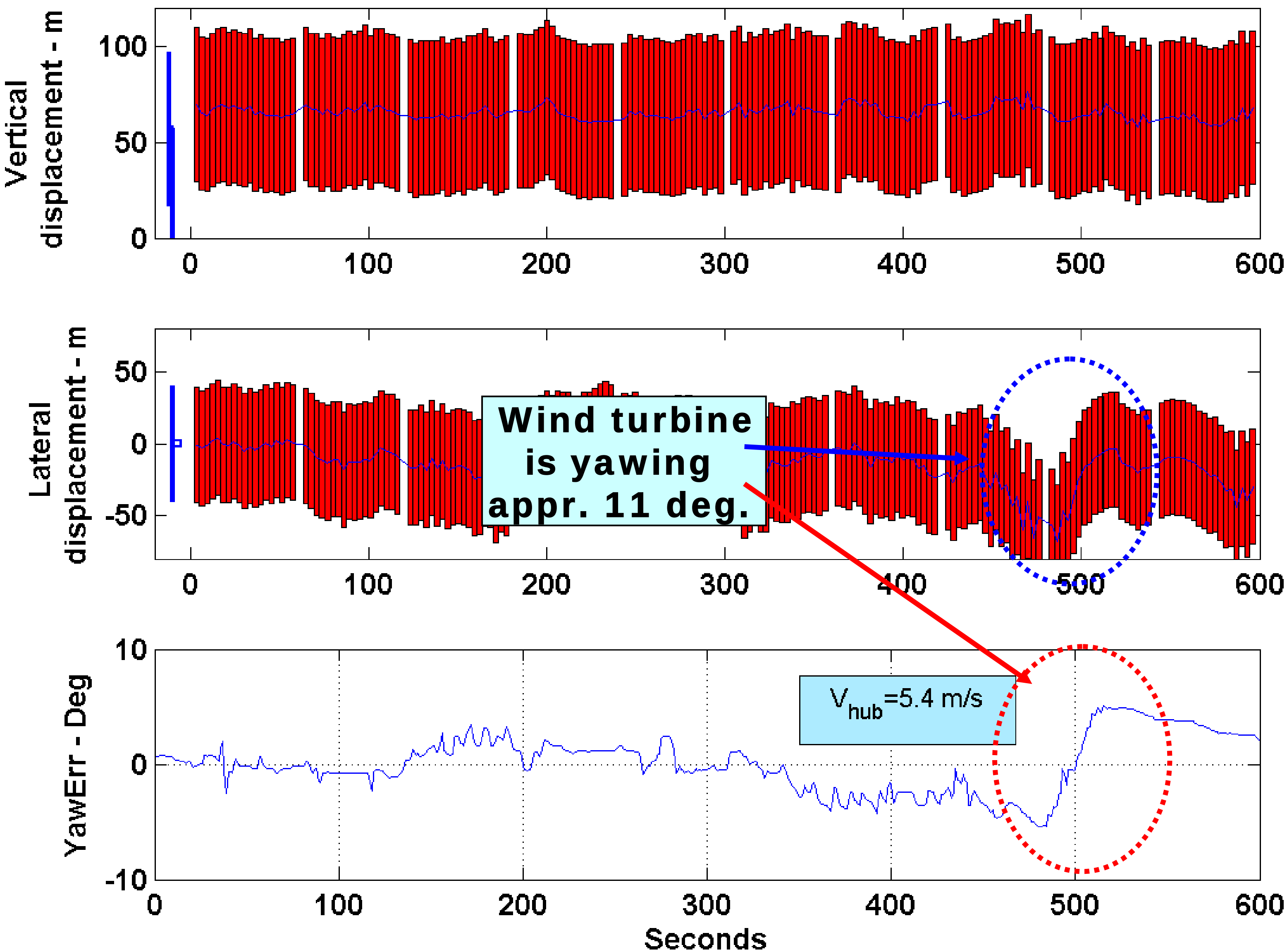

Wake meandering: 8/4-2009 22:10; Δt=2.24 sec.; FC=200 m
Vertical displacement - m
Seconds
Lateral displacement - m
Seconds
μ_y=1.5 m; σ_y=6.2 m; <σ[y]>=38 m
Counts
Lateral wake displacement - m
μ_z=56 m; σ_z=6.1 m; <σ[z]>=39 m
Counts
Vertical wake displacement - m

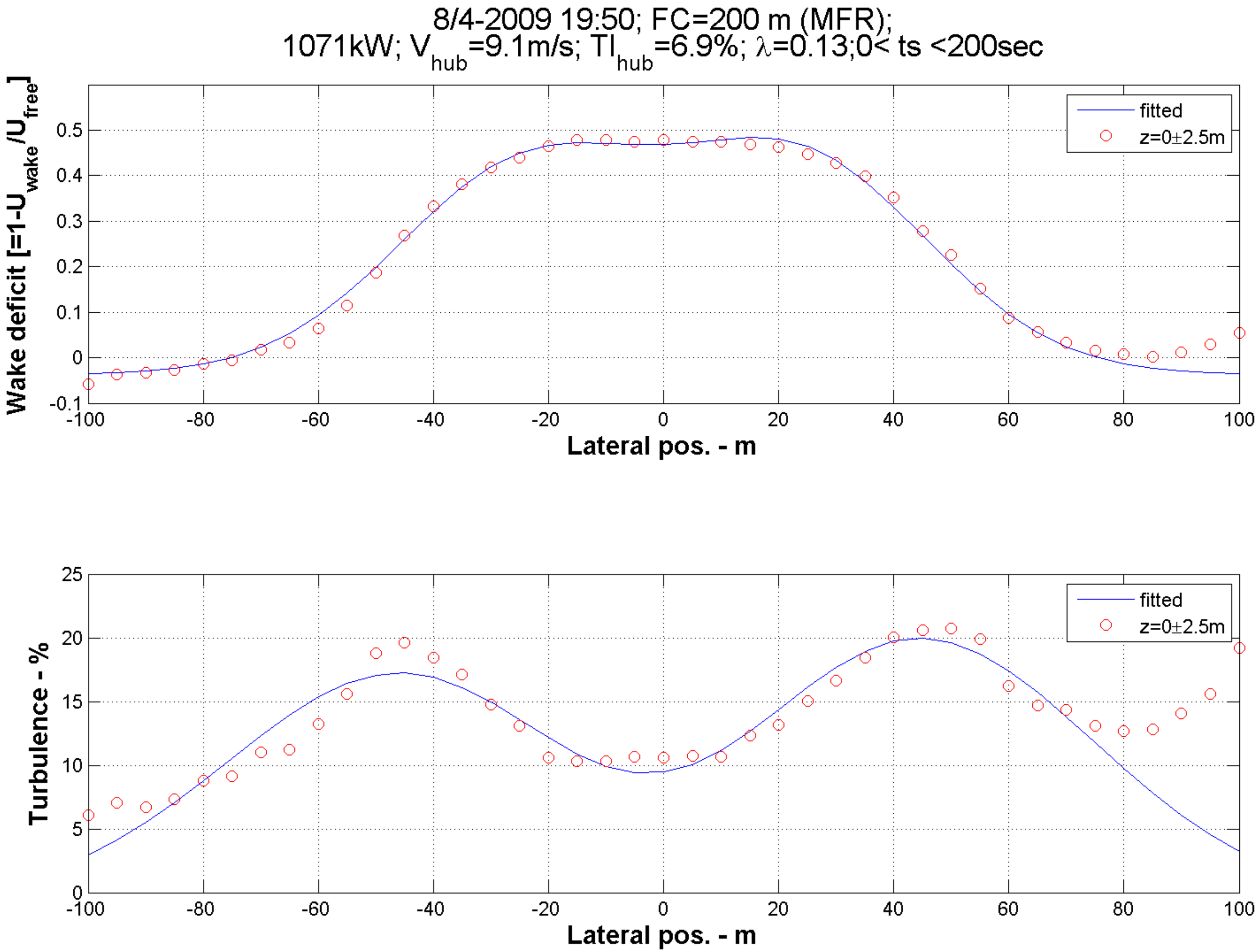
Lateral wake deficit profiles




8/4-2009 22:10; FC=200-ALIGNED m; <p>=456/47 kW
Wake deficit; wind speed - m/s
Lateral pos. - m
Wake expansion +12%
Wake deficit 50% ->
Tip vortex
Turbulence - %
Lateral pos. - m

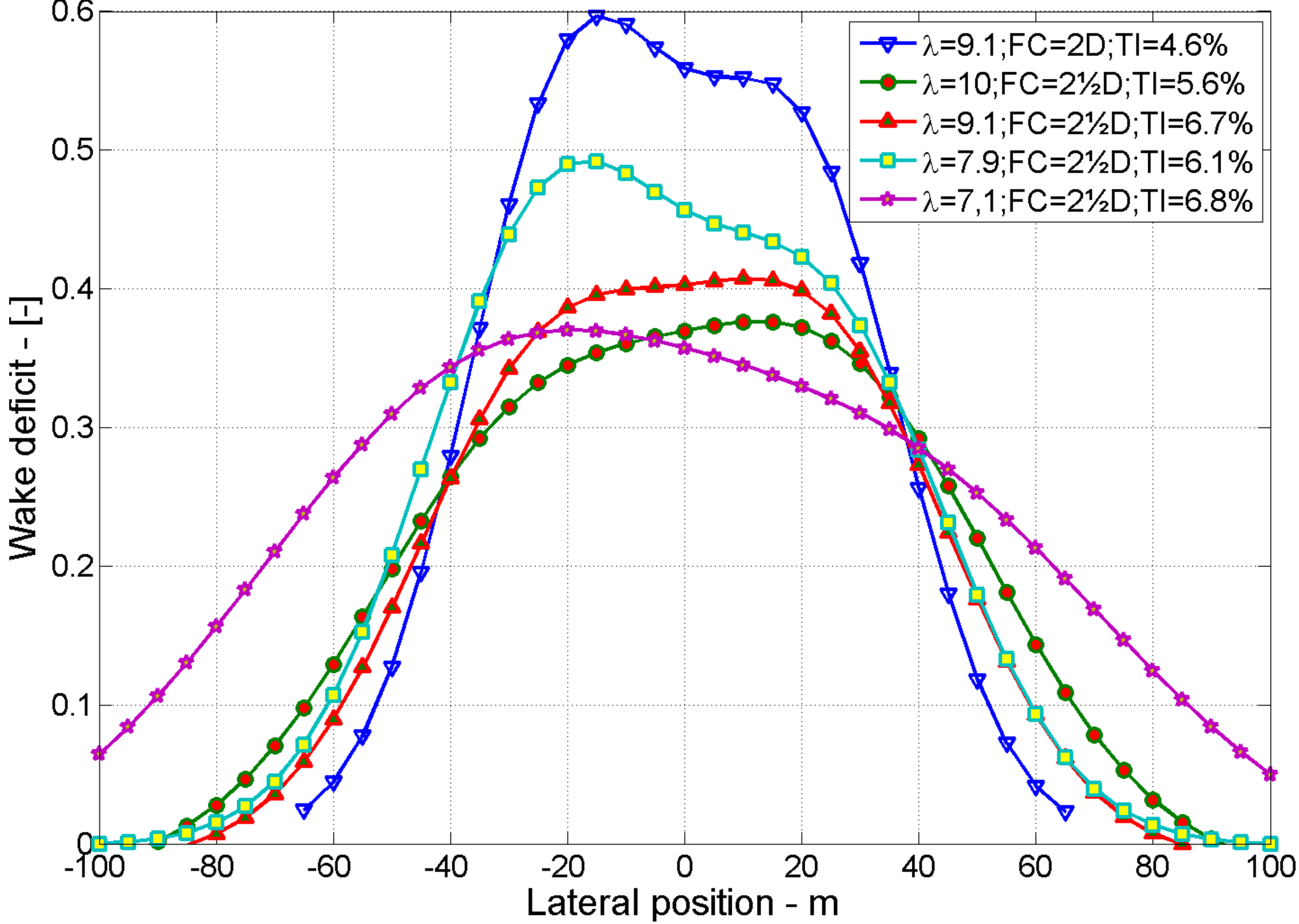
Wake meandering: 8/2-2009 10:0; Δt=3 sec.; FC=160 m





8/4-2009 19:50; FC=200 m (MFR);
1071kW; V hub =9.1m/s; TI hub =6.9%; λ=0.13;0< ts <200sec
Wake deficit [=1-U wake /U free]
Lateral pos. - m
fitted
z=0±2.5m
Turbulence - %
Lateral pos. - m
fitted
z=0±2.5m

Lateral deficit 2-2½ D behind a 80m wind turbine



Conclusion on near wake measurements

- The wake deficit has been resolved in the meandering frame of reference.

- The transformation to MFR is only possible for low turbulence intensities (<10%) and a distinct wake deficit.

- The deficit distribution highly depend on the ambient turbulence intensity and the wind turbine loading.

Far wake analysis
based on power measurements

Purpose:

Determination of wake deficit inside the wind farm as function of wind speed & flow direction, turbulence and atmospheric stability.

Wind farm wake analysis

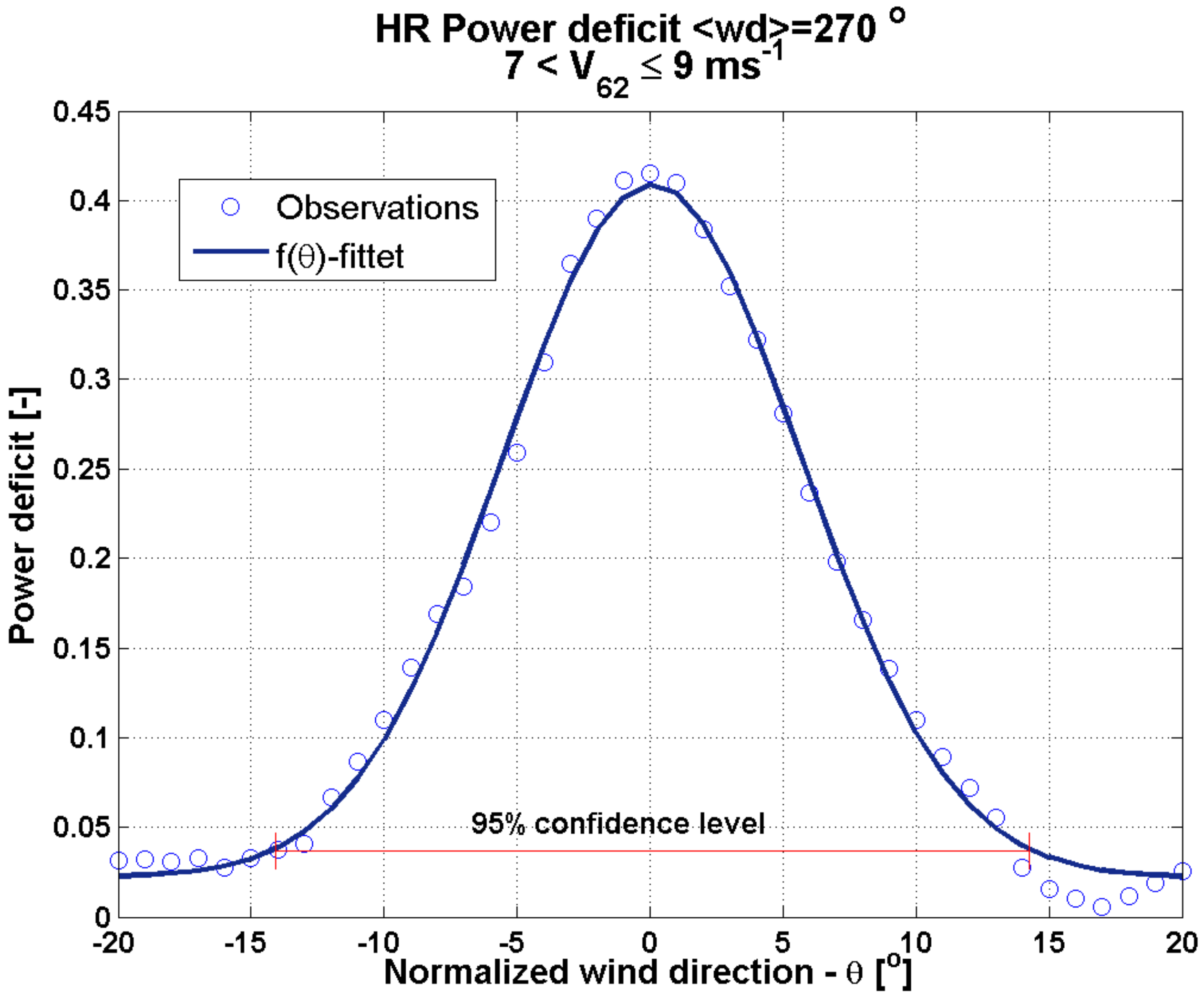
- Identification of wind farm
- Identifical of possible measurements
  - SCADA data
- Data preparation
  - Signals, organization & synchronization
  - Wind farm layout
  - Data qualification
  - Derived parameters
  - Identification of descriptors
  - Data filtering
- Data queries & wake analysis
- Reporting & conclusion
- Acknowledgements & references

Basic definitions

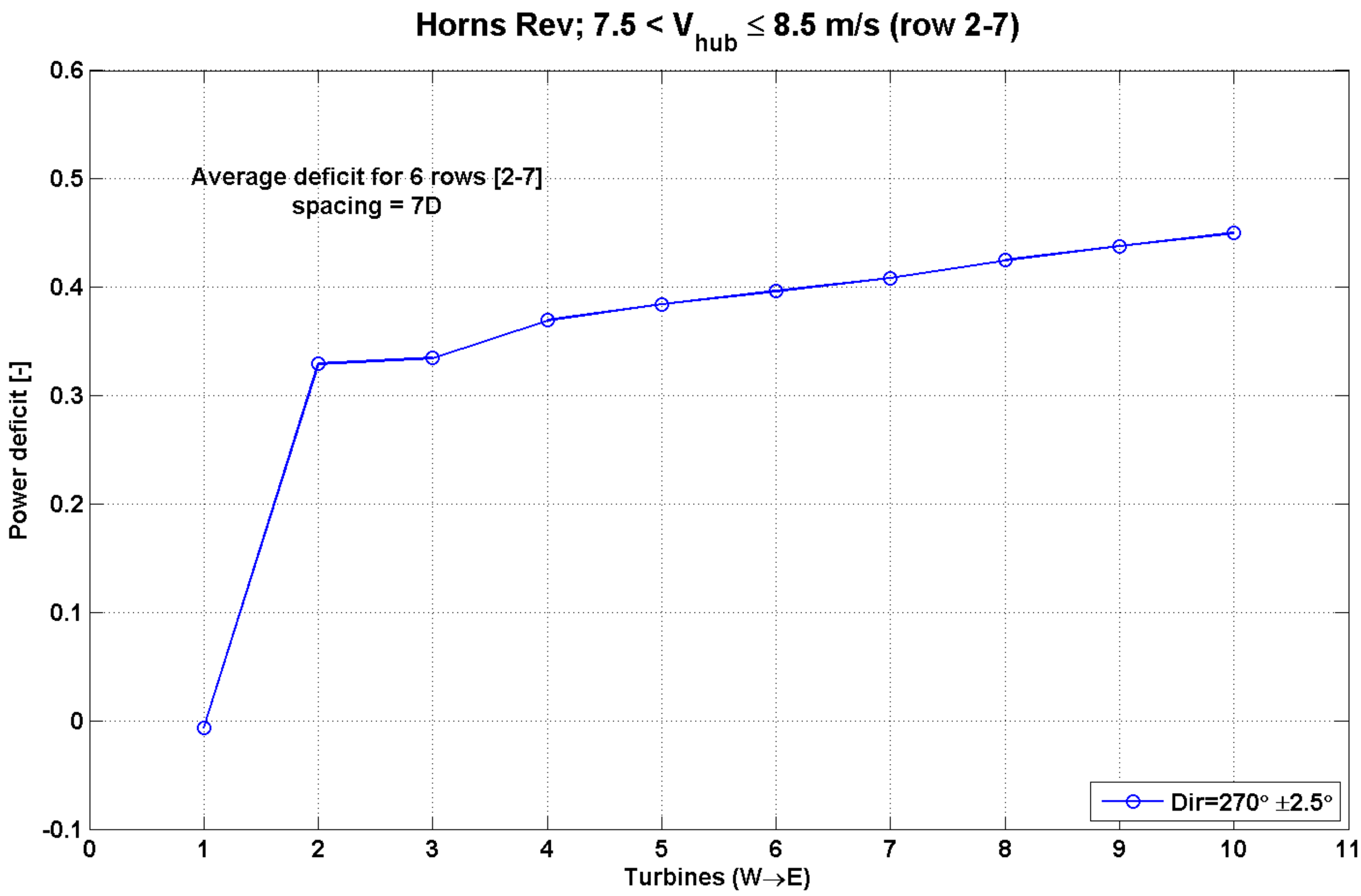
Speed deficit; $\mu_{speed} = 1 - U_{wake} / U_{free}$

Power deficit; $\mu_{power} = 1 - P_{wake} / P_{free}$

Definition of power deficit vs wind direction



Power deficit along a row of turbines

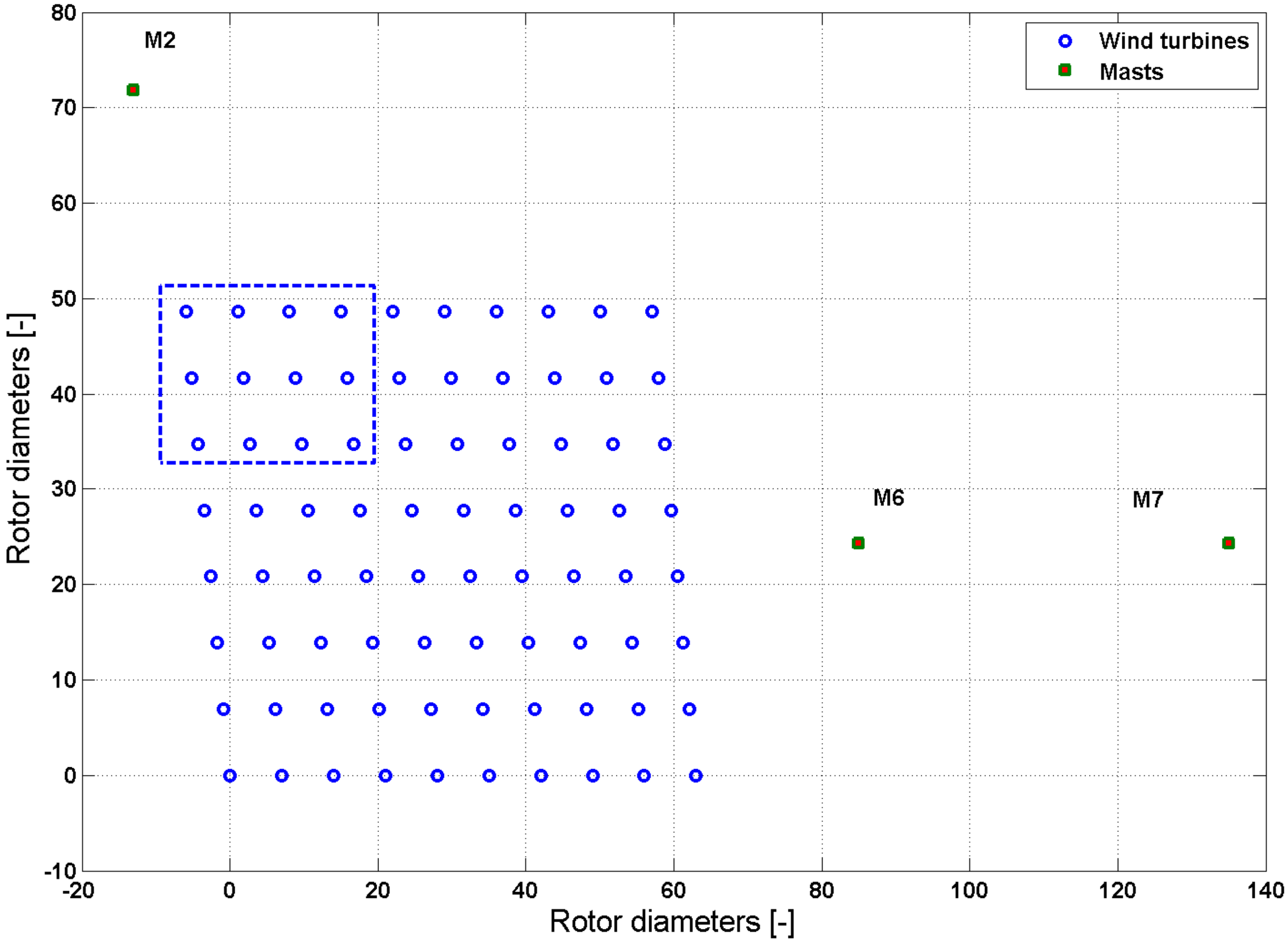


Necessary signals as 10 minute mean values

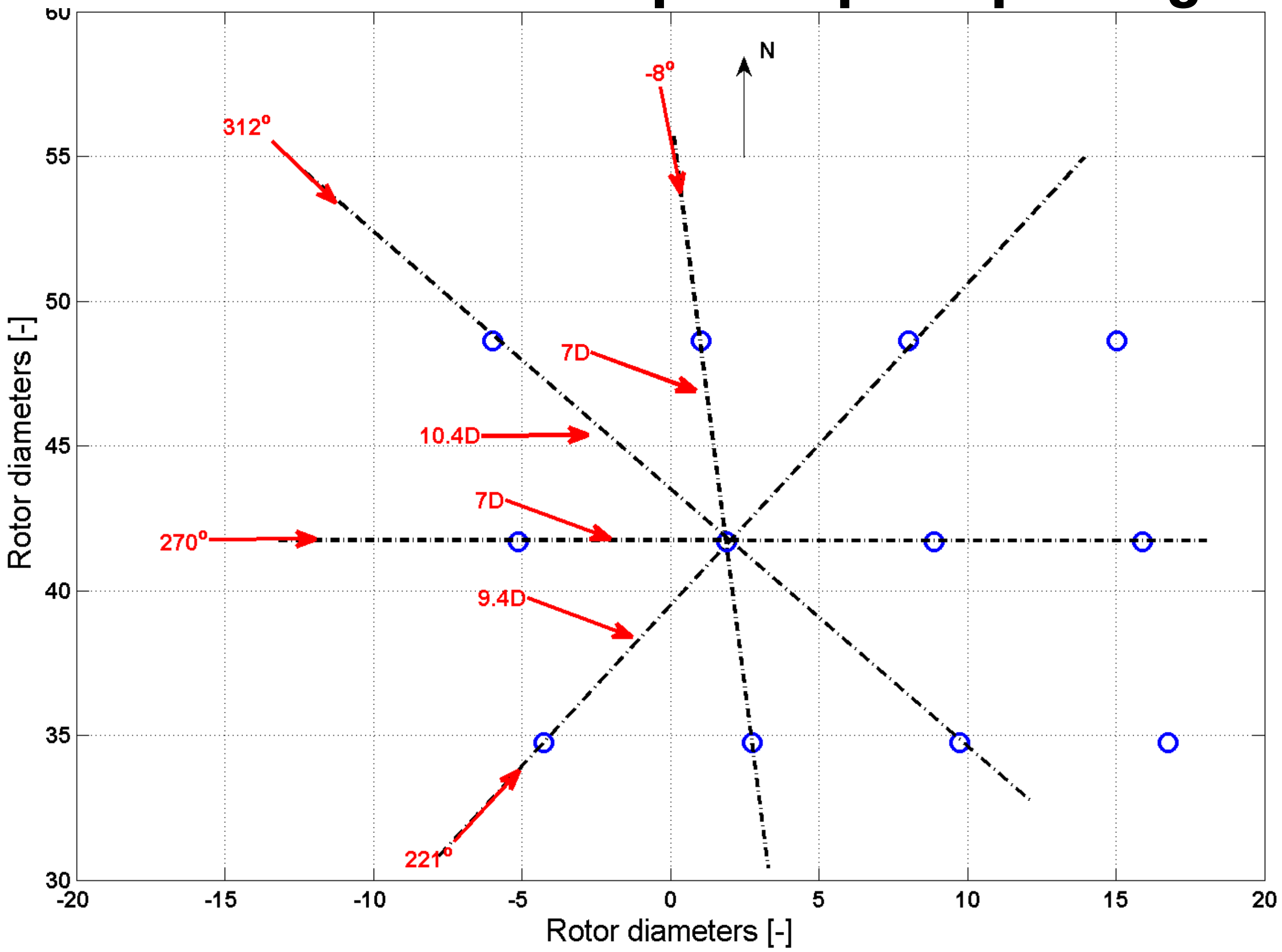
Number	Signal	Importance
1	Electric Power from all wind turbines	High
2	Wind speed from undisturbed mast(s) [1]	High
3	Wind direction at hub height	High
4	Yaw position from all individual turbines[2]	High
5	Nacelle wind speed from all wind turbines	Medium
6	Rotor speed from all turbines[3]	Medium
7	Pitch angle from all turbines	Medium
8	Temperatures (air & water)	Medium

[1] This will require several masts, but in case such signal is not available, it is necessary to use the power values to determine the inflow conditions.
[2] This signal is equal to nacelle position, and can be a substitute to the wind direction signal.
[3] The rotor speed is important for validating the operational behavior of dual or variable speed turbines.

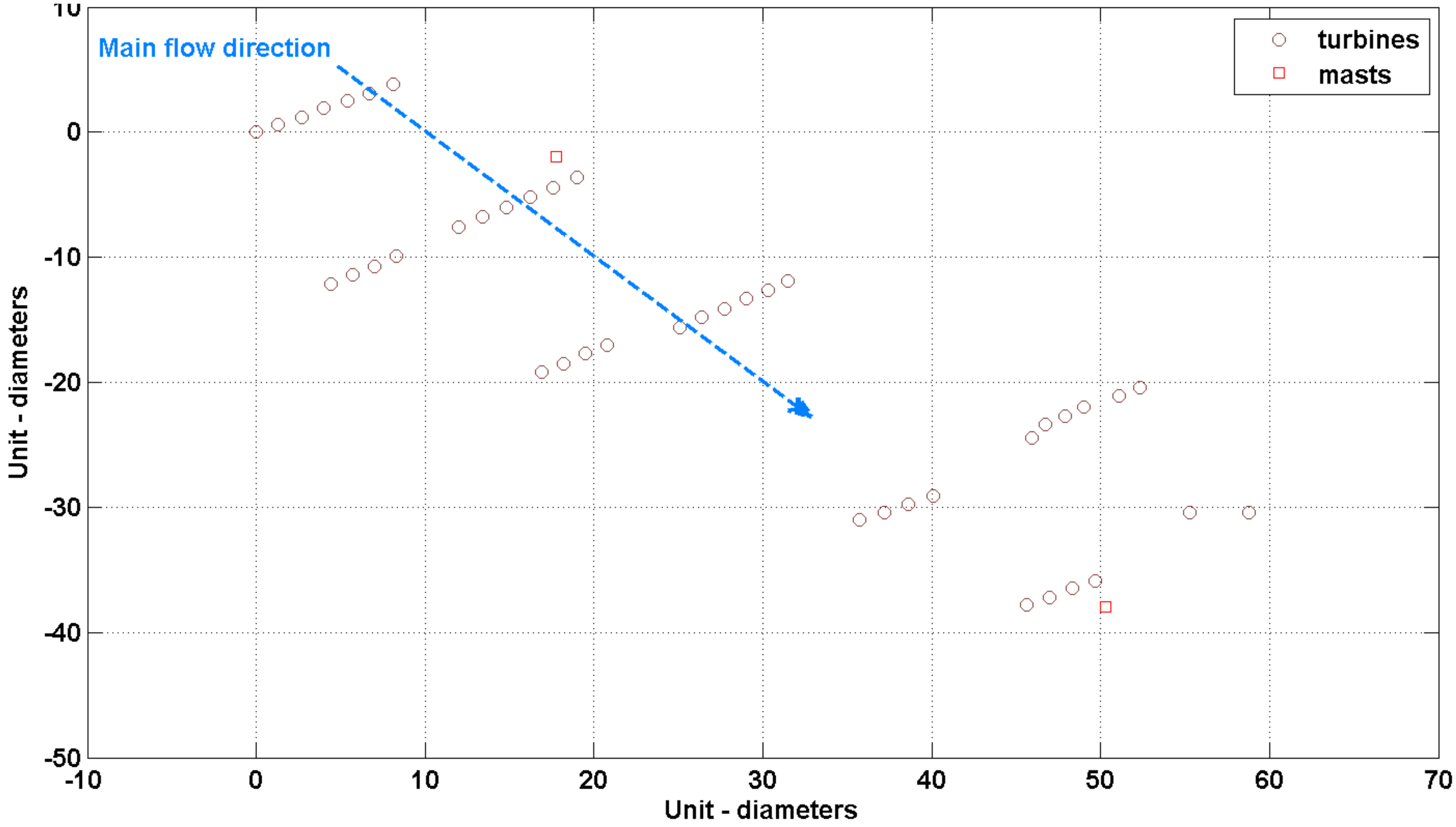
Wind farm layout; Unit = rotor diameter



Wind farm – upper left corner
Identifiction of principal spacings



Main flow direction in complex terrain



Data qualification

Wind speed:

- Exclude spikes, drop-outs or stationary periods
- Check correlation with other heights

Wind direction:

- Determine yaw position offsett

Wind turbine power:

- Exclude outliers, which can influence the analysis;
- Exclude periods where the turbine has been in transition mode eg. Start, stop or emergency stop sequence;
- Exclude periods where wind turbine power has been de-regulated.

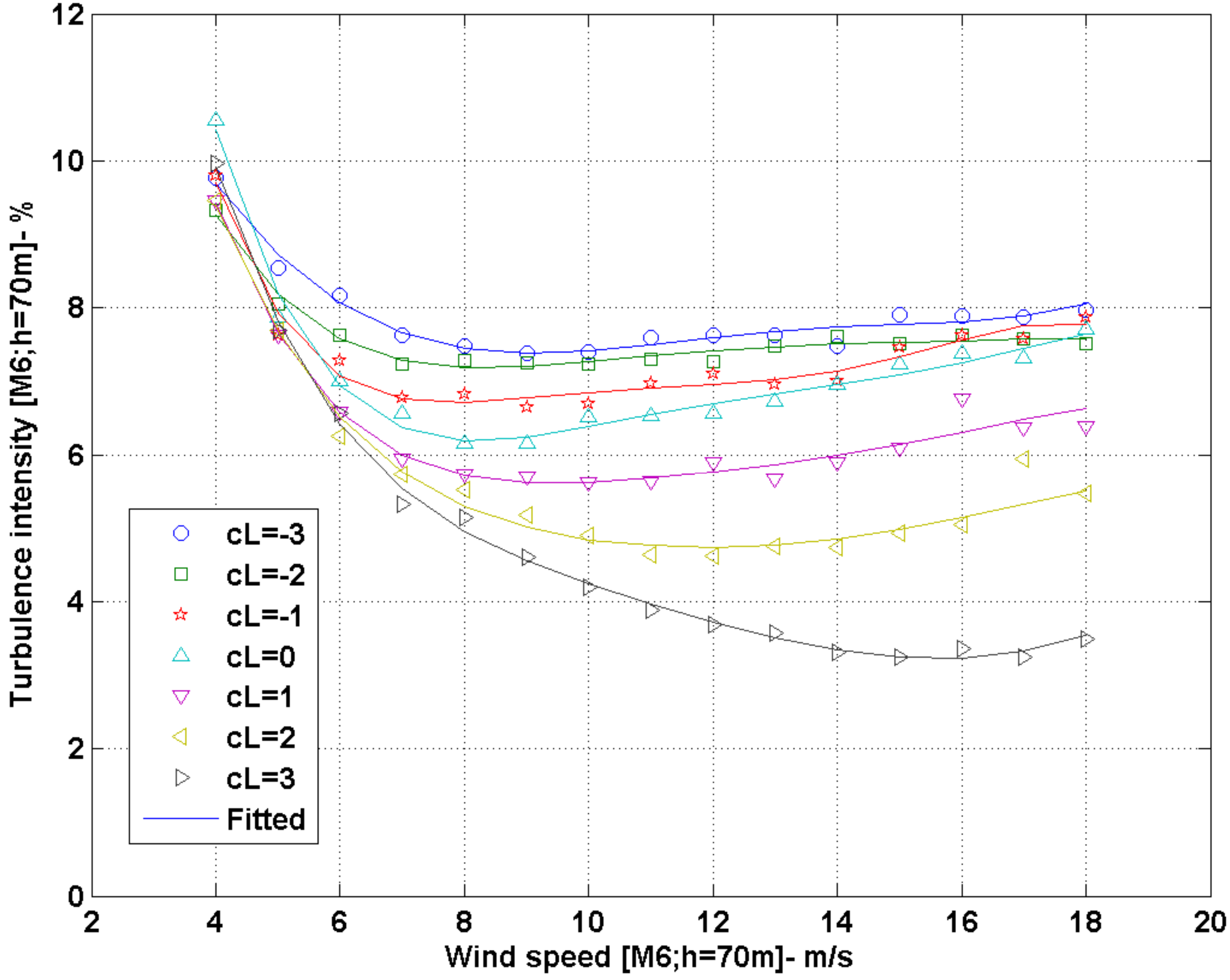
Derived parameters

- Free wind speed;
- Free wind direction;
- Monin-Obukhov length (L)→ Atmospheric stability classification.

Definition of stability classes based on Monin-Obukhov length, L (m).

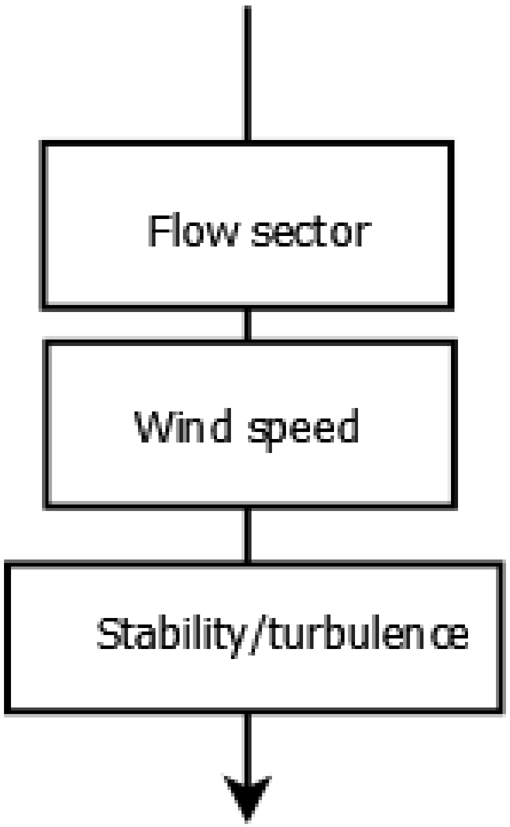
Class	Obukhov length [m]	Atmosperic stability class
cL=-3	$-100 \leq L \leq -50$	Very unstable (vu)
cL=-2	$-200 \leq L \leq -100$	Unstable (u)
cL=-1	$-500 \leq L \leq -200$	Near unstable (nu)
cL=0	$\|L\|>500$	Neutral (n)
cL=1	$200 \leq L \leq 500$	Near stable (ns)
cL=2	$50 \leq L \leq 200$	Stable (s)
cL=3	$10 \leq L \leq 50$	Very stable (vs)

Mean turbulence intensity for different stability classes.



Identification of descriptors and flow cases

Definition of flow cases

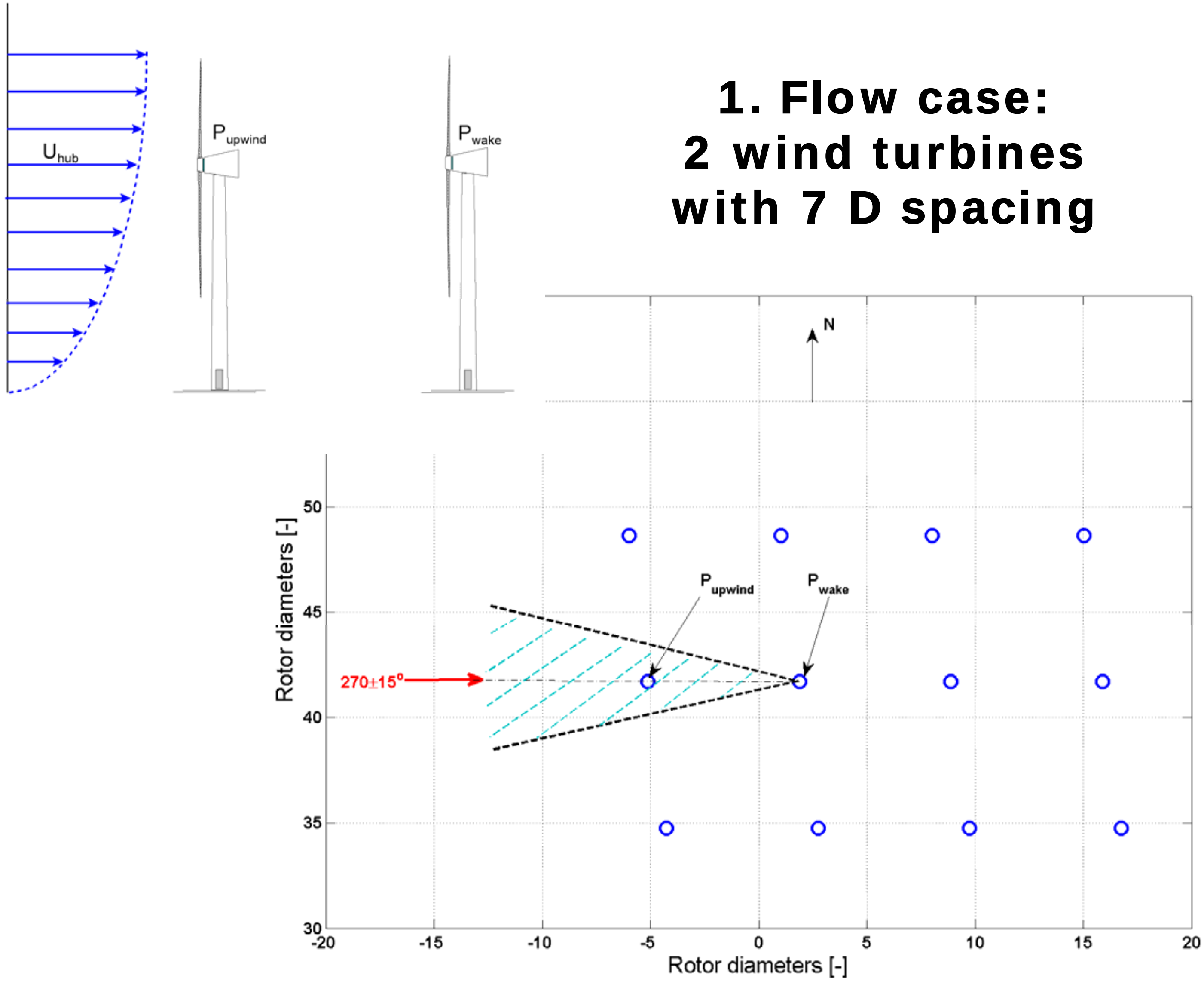


Definition of flow direction and sector size

Definition of wind speed interval

Definition of stability class or turbulence intensity interval

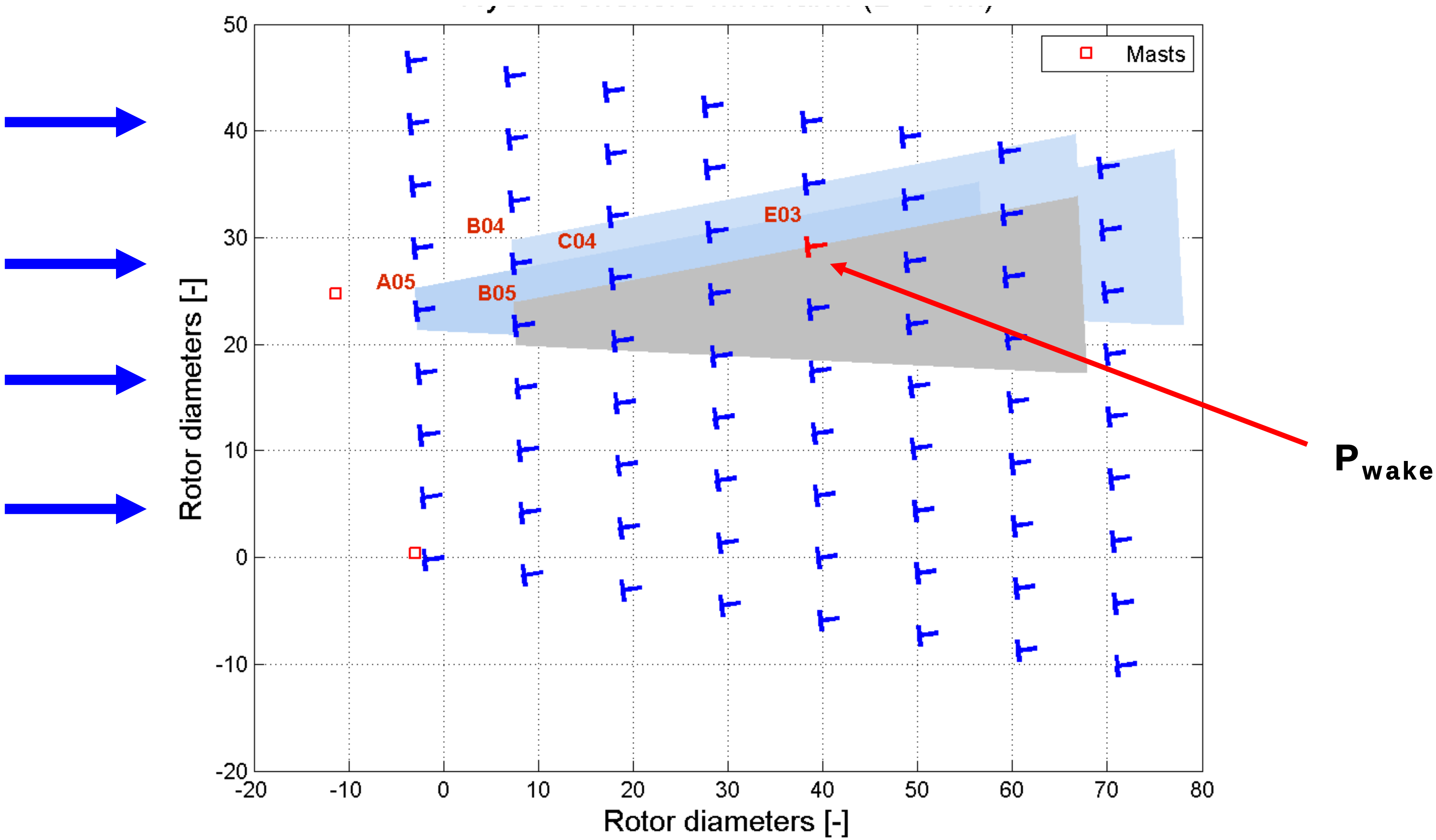
1. Flow case:
2 wind turbines
with 7 D spacing



Data filtering & conditions

- The free [upwind] wind turbine is grid connected 100% during each 10 minute period;
- The object [wake] wind turbine is grid connected 100% during each 10 minute period;
- All wake generating wind turbines should be grid connected 100% during each 10 minute period;
- Flow stationarity through the whole wind farm is required.

- All wake generating wind turbines should be grid connected 100% during each 10 minute period;

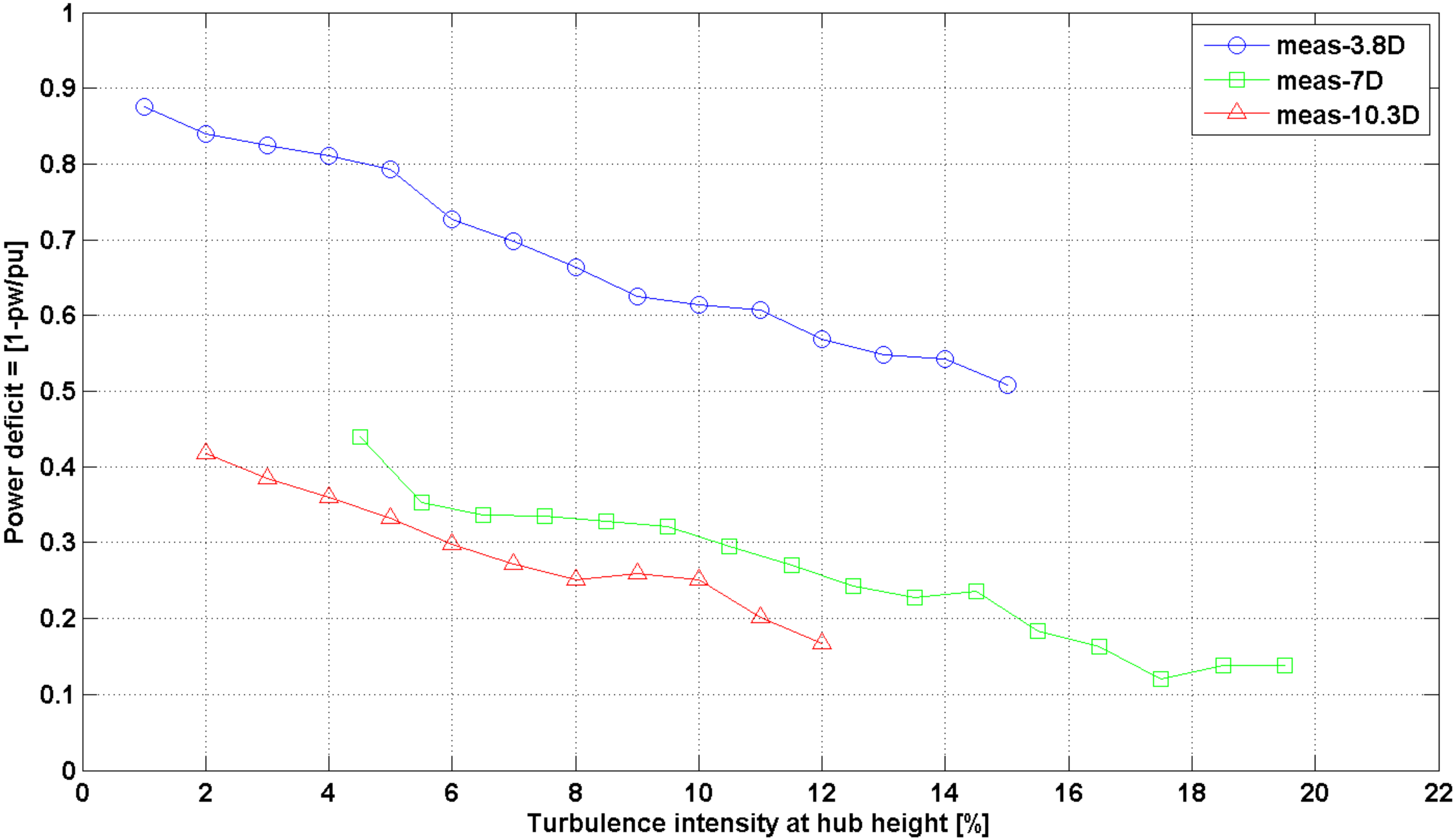


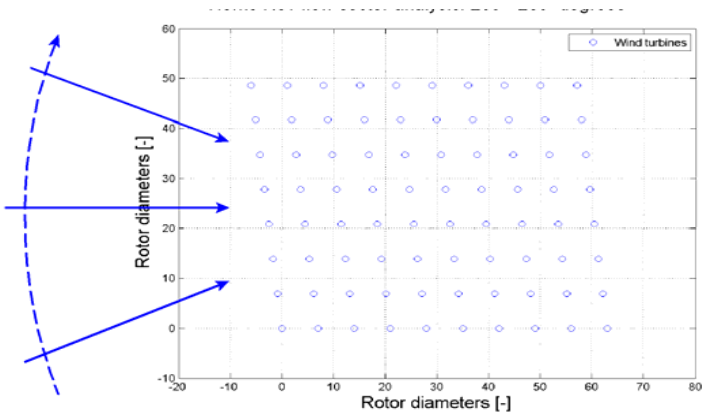
The wake analysis are formulated according to the complexity of the flow conditions and the purpose.

- Deficit for pairs of turbines as function of wind direction;
- Deficit for pairs of turbines with different spacing;
- Maximum deficit as function of turbulence intensity and spacing;
- Deficit along rows of turbines;
- Deficit for partly covered turbines as function of flow direction;
- Deficit variations at different atmospheric conditions;
- Park efficiency.

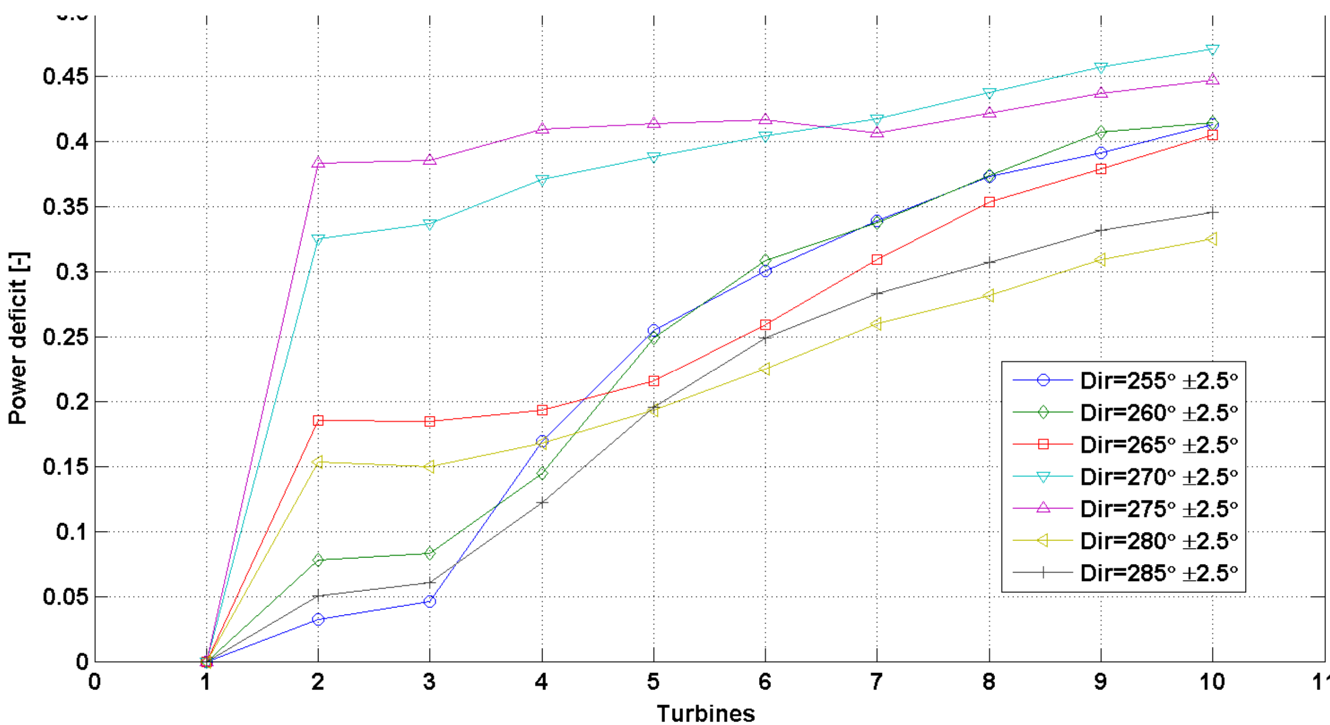
Increasing complexity

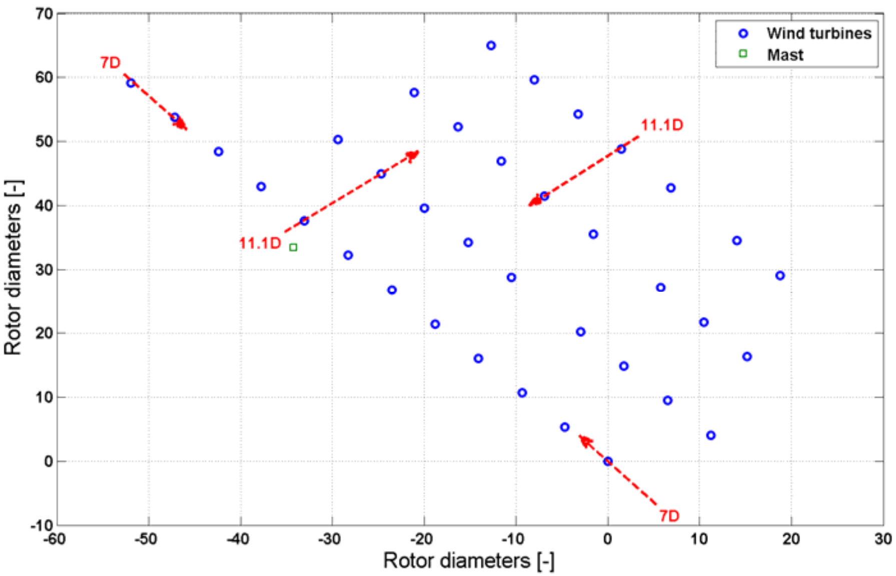
Maximum power deficit
for 3 spacings 3.8D, 7D & 10.3D



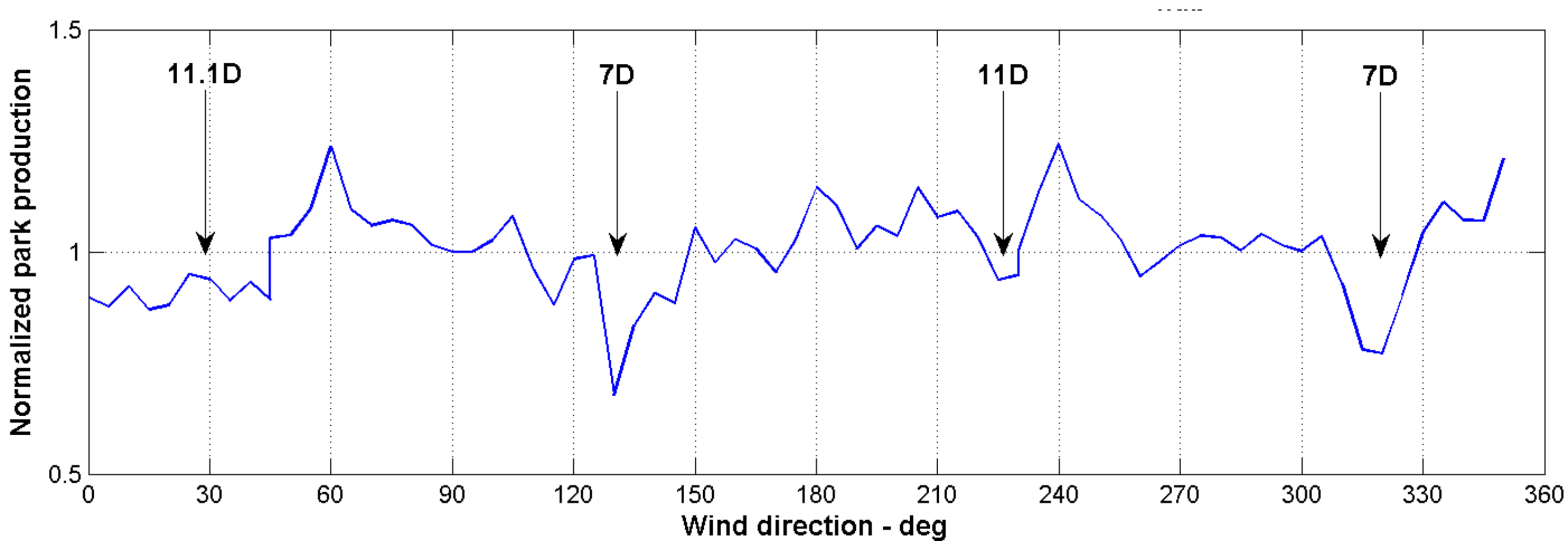


Mean power deficit: averaged along row 2-7





Wind farm efficiency
V_{hub}=8 m/s



Recommendations on wake analysis

- Identify validation parameters;
- Organize and qualify data carefully;
- Establish robust derived parameters;
- Establish datafiltering with respect to:
  - Wind speed;
  - Wind direction;
  - Spacing;
  - Atmospheric stability.

References

- UPWIND 1A2 Metrology. By Kurt S. Hansen et al. Final Report; ECN-E--11-013 FEBRUARI 2011
  - 8. Guideline to wind farm wake analysis
  - 10. Classification of atmospheric stability for offshore wind farms

- TOPFARM Final Activity Report, January 2011
- TOPFARM Publishable final activity report final 2011

- *The impact of turbulence intensity and atmospheric stability on power deficits due to wind turbine wakes at Horns Rev wind farm*, by Kurt S. Hansen et al.;we.512 Accepted for publication in Wind Energy (2011)