Nacelle Based Lidar Measurements for the Characterisation of the Wake of an Offshore Wind Turbine under Different Atmospheric Conditions

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Wake losses and wake models

50% uncertainties
on prediction of **wake losses**
for offshore wind farm projects

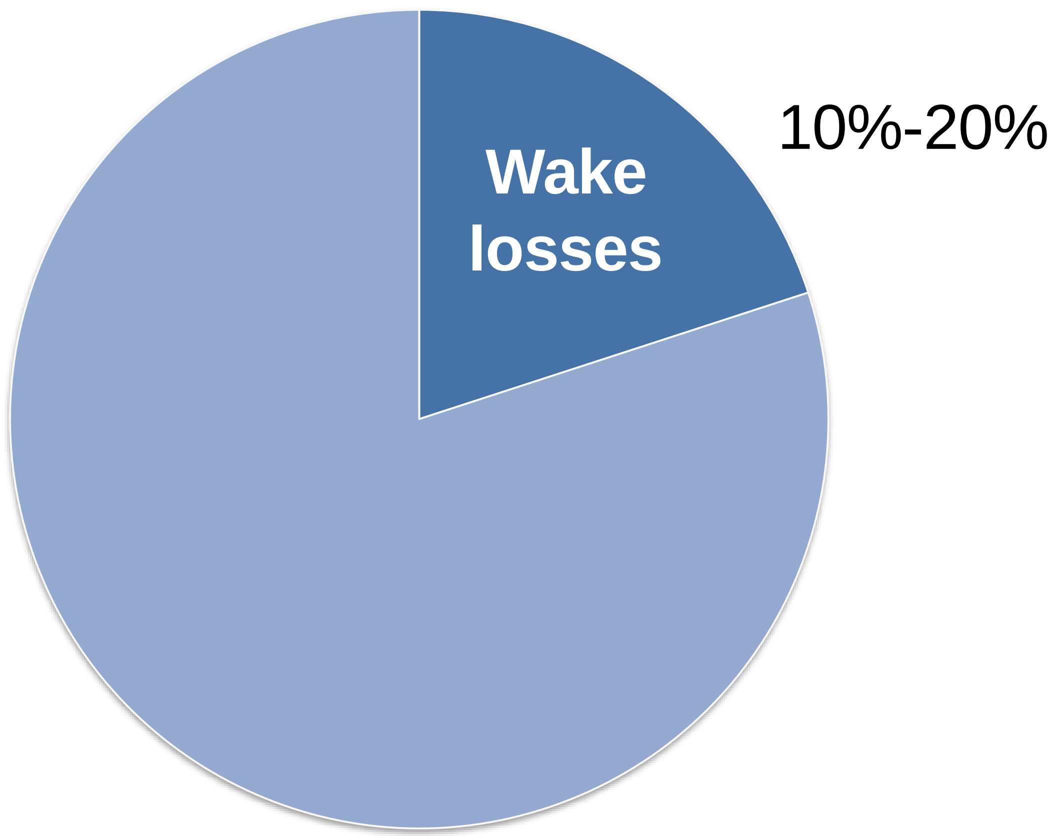
↓

Negative influence on external investors

↓

Wake models need to be improved

Power production



Objective

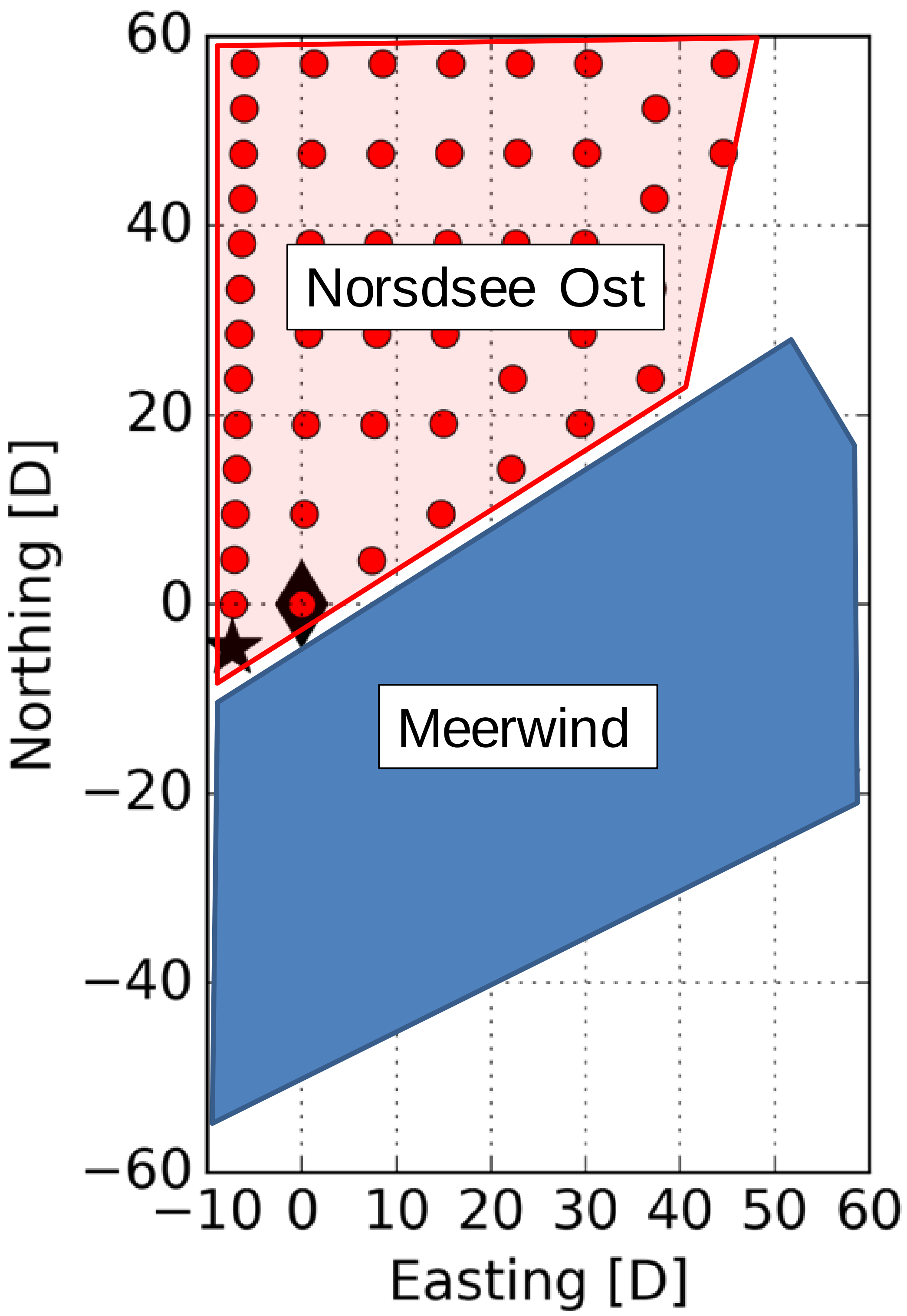
Show how full-field lidar data can be applied to the verification of wake models

Outline

1. Measurements
2. Wake model
3. Parameter fit
4. Results

Measurements
Experimental setup in Nordsee Ost

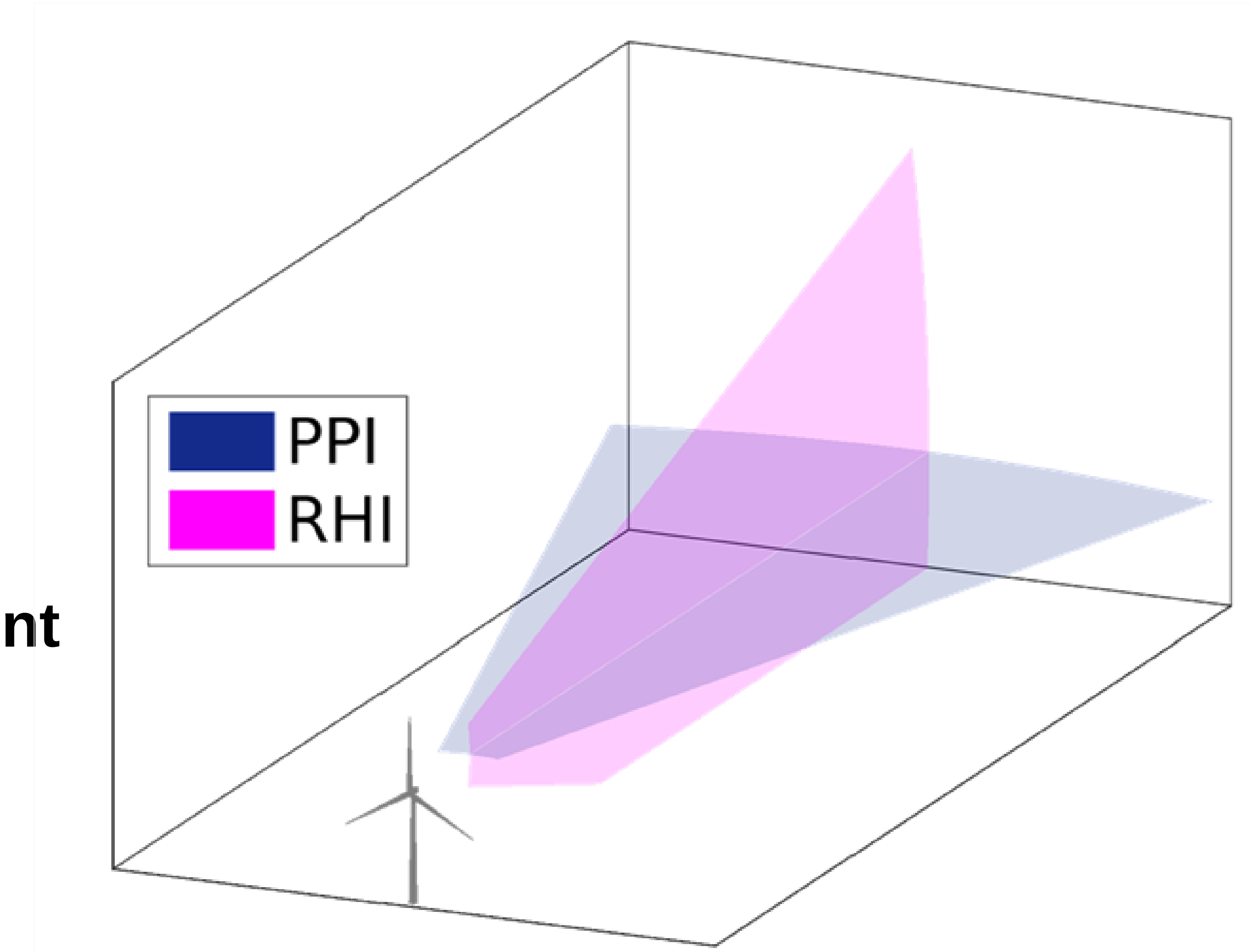
- 48x Senvion 6.2M126
- Mast with cup anemometers and vane at hub height
- Nacelle based long range scanning lidar on NO48
- Operational data of NO48

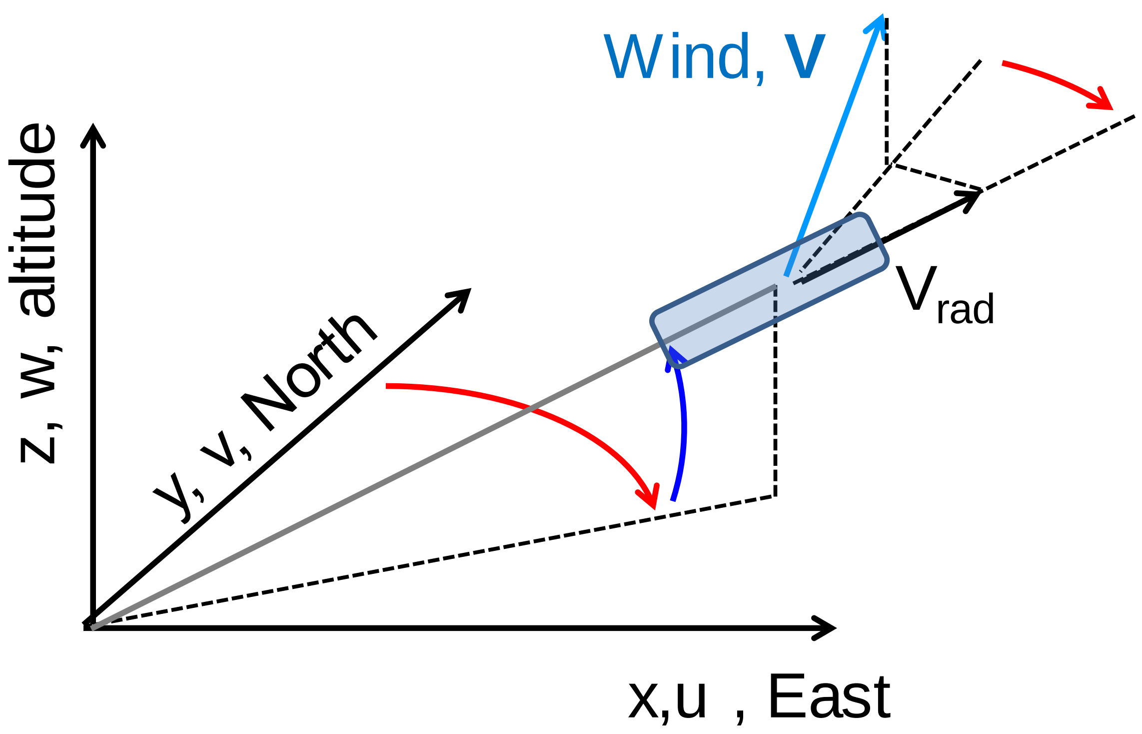


Measurements
Lidar principles & settings

- Light pulses illuminate a thin volume
- Doppler effect from aerosol backscatter

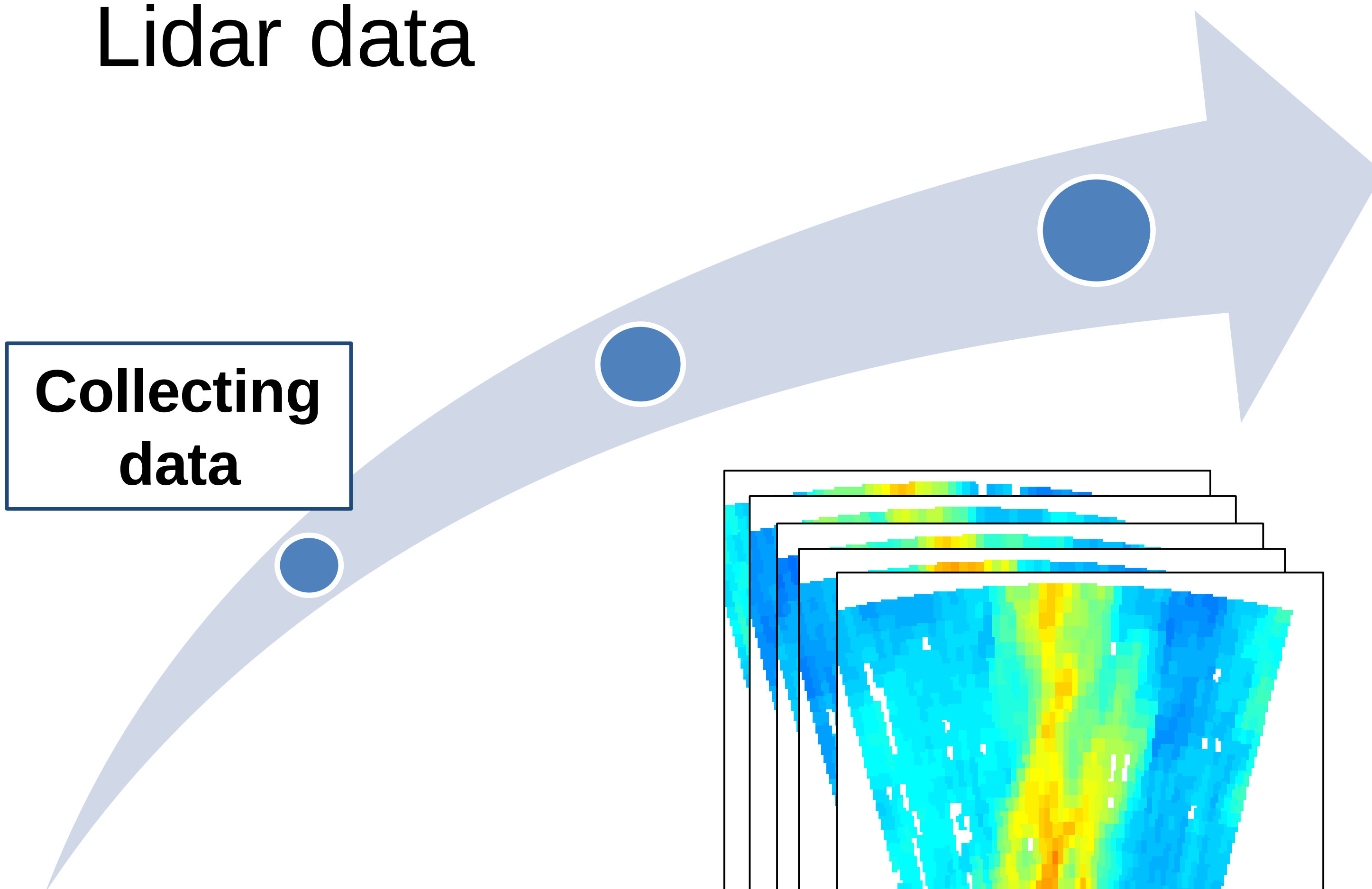
⇒ Measurement of **radial wind component** as **volume average**

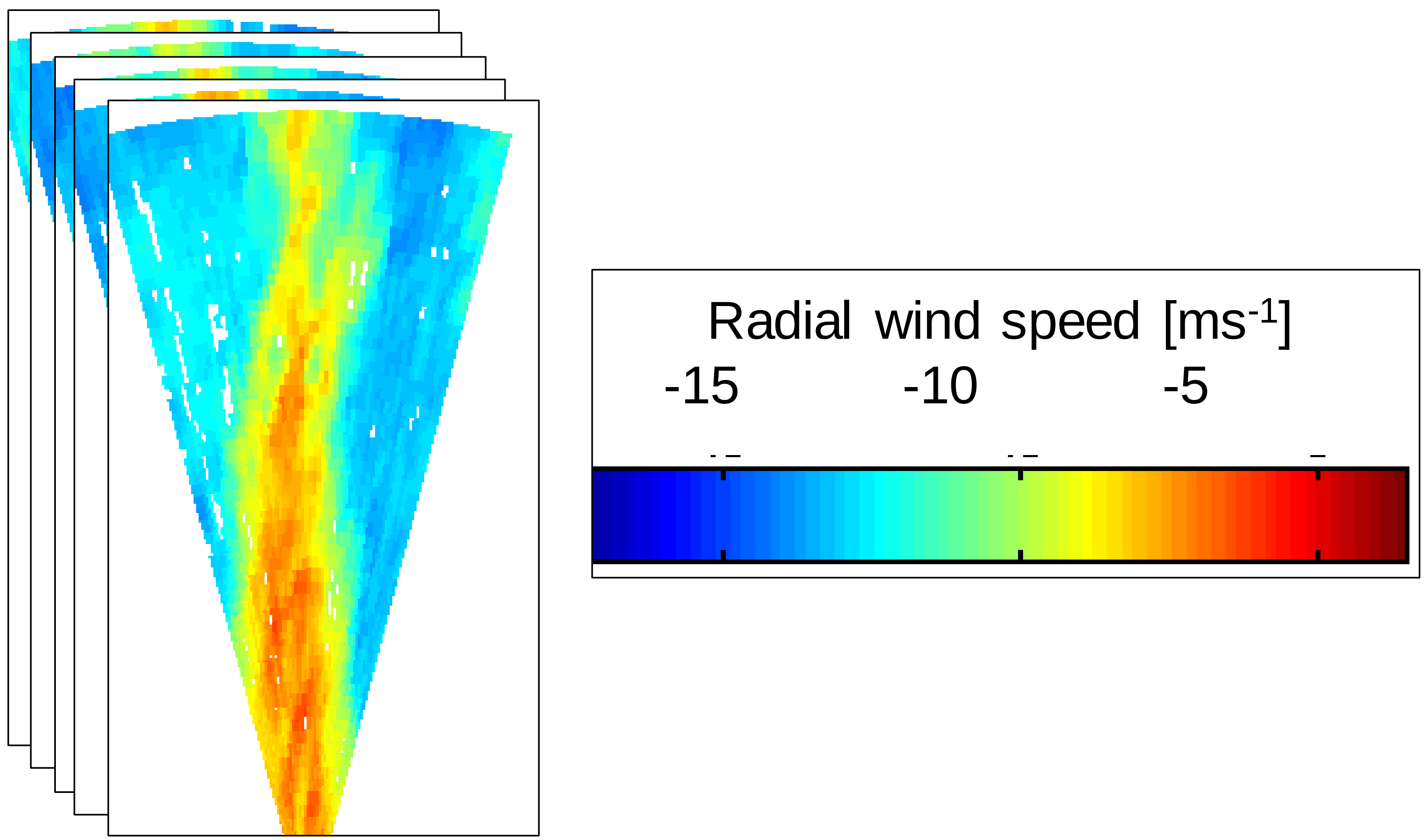




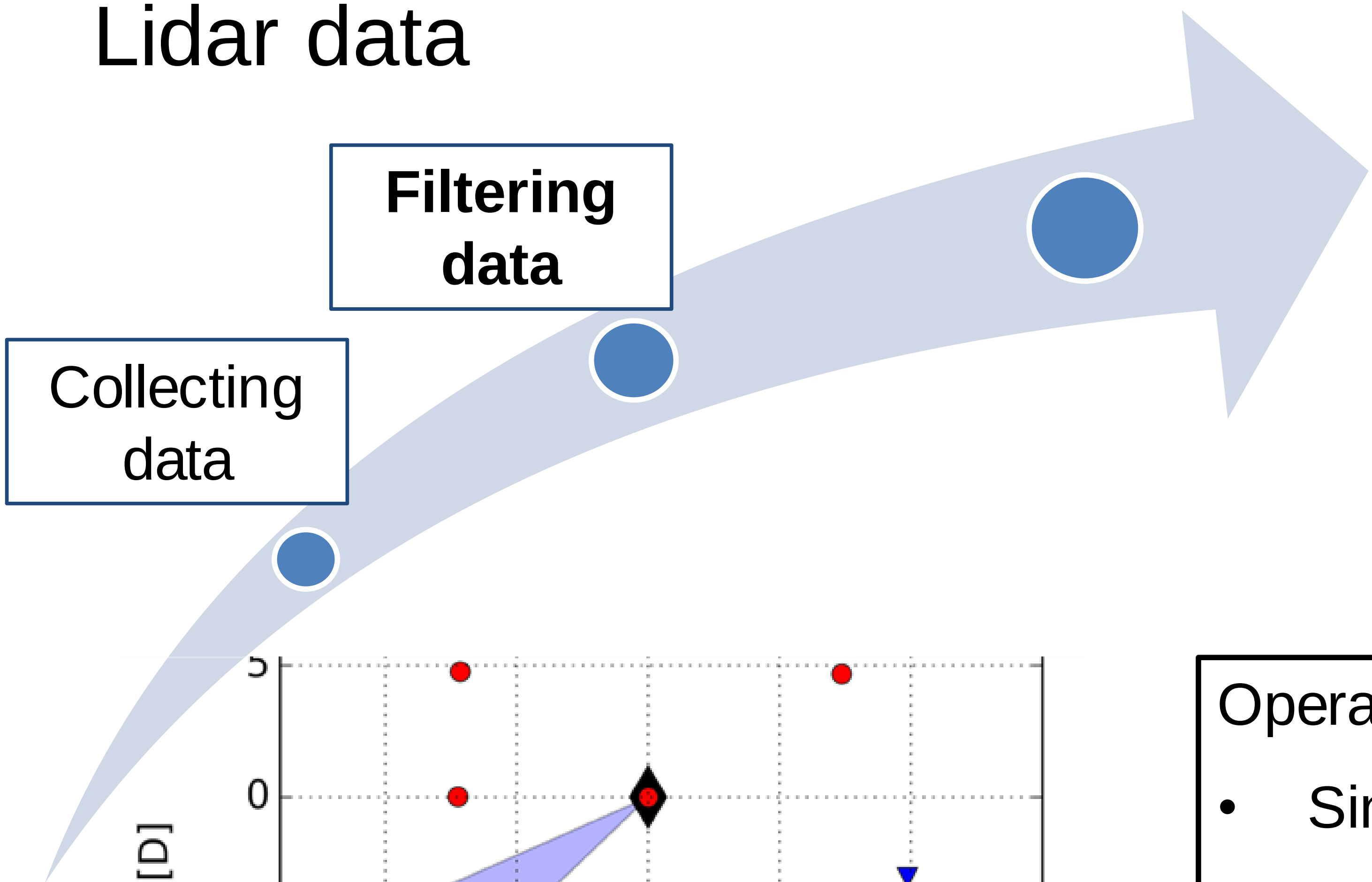
Scanning parameters	
Cycle (≈200s)	5PPI+1RHI
Sector	-15° → +15° (0.5° res.)
Speed	1°/s
Accumulation time	0.5s
Range	100 m → 1000m (100 m → 2500m)
Range spacing	15m (25m)

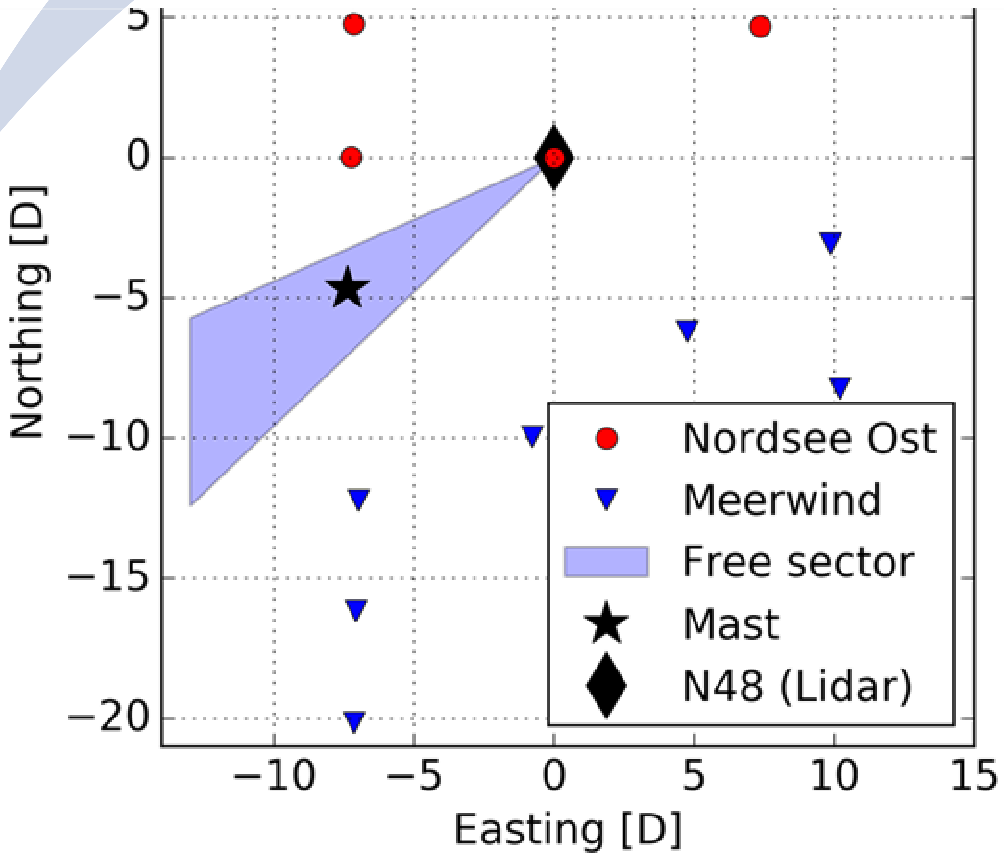
Measurements
Lidar data





Measurements
Lidar data





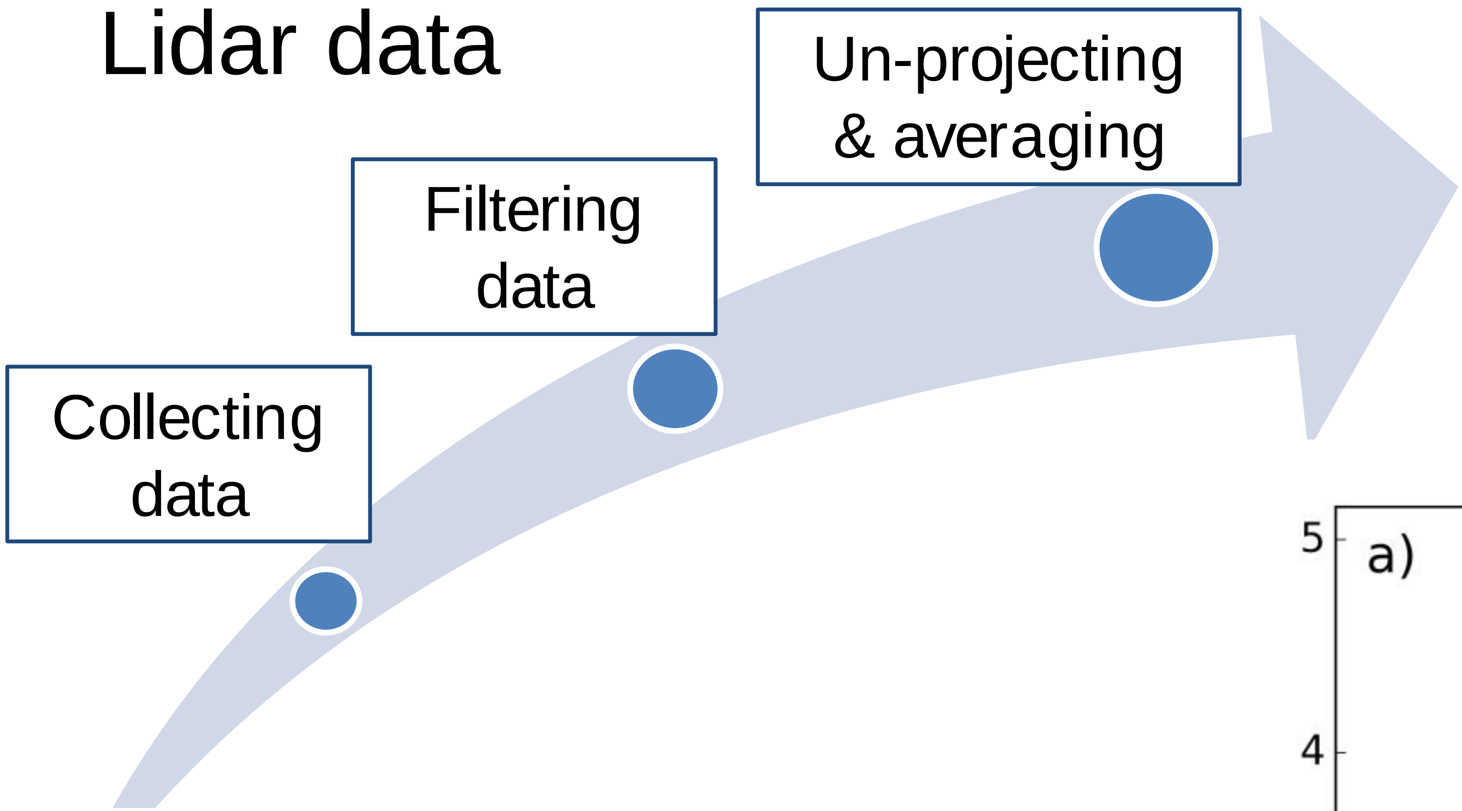
Operation

- Single wake sector
- No nacelle yaw
- Yaw misalignment < 3°
- No near wake
- No influence of downstream turbine

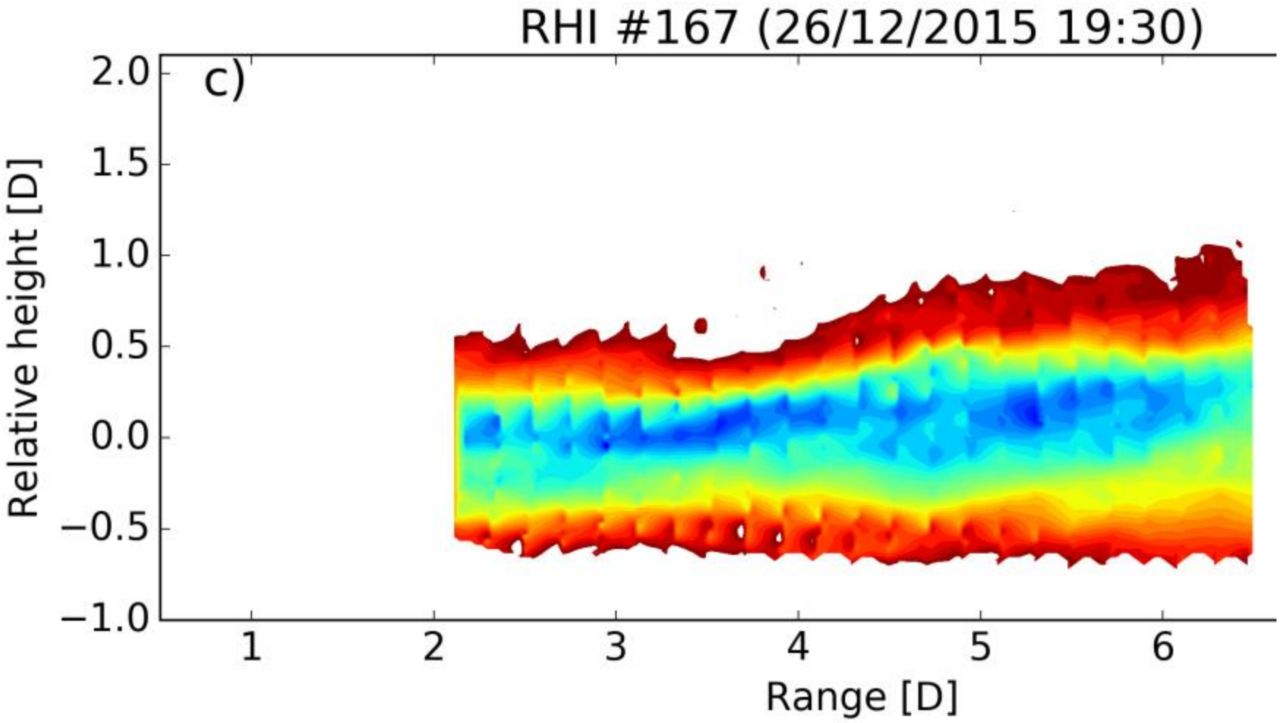
Lidar data

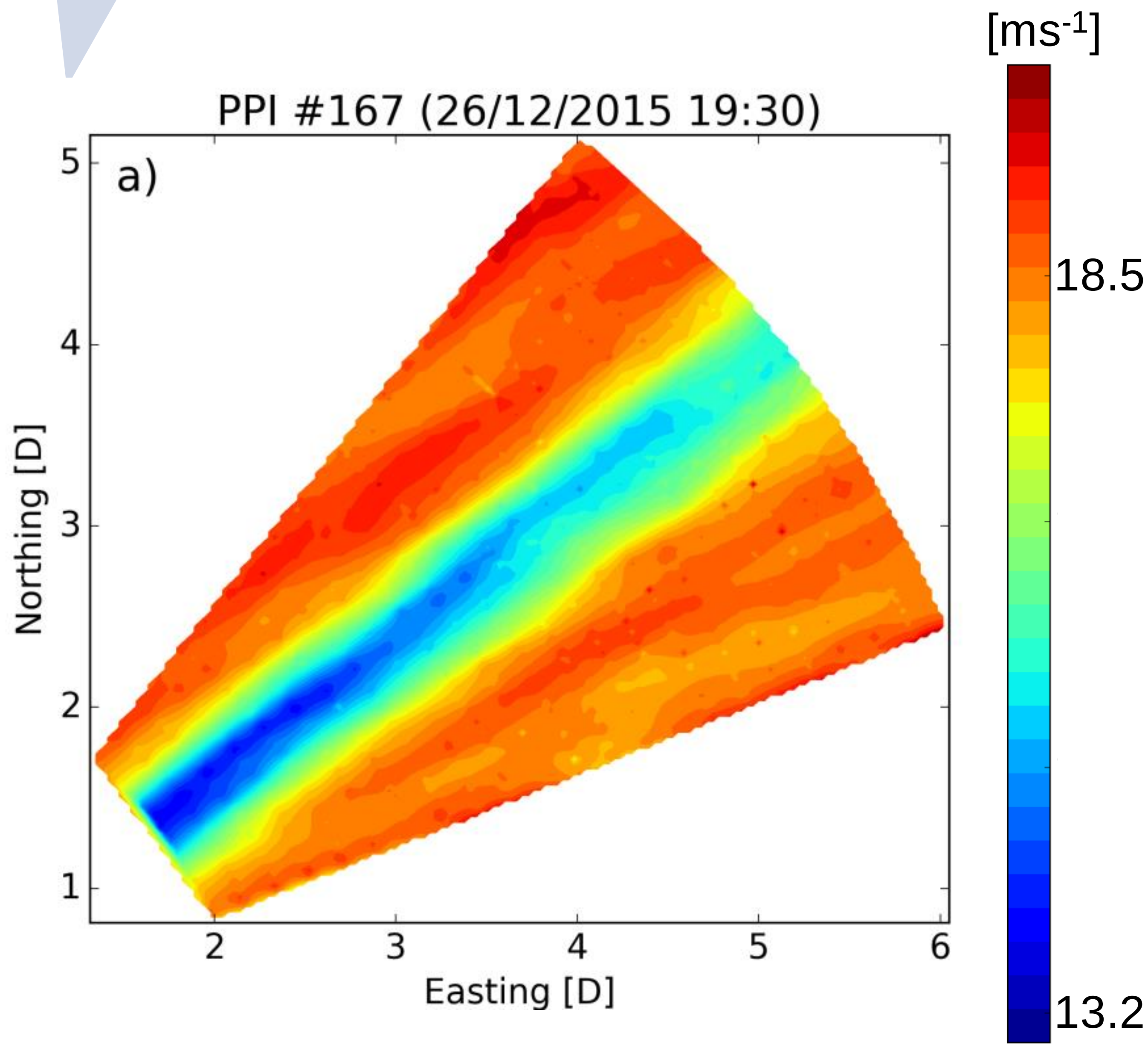
- Hard target
- High noise
- Outliers

Measurements
Lidar data



10 min average horizontal wind speed





Analytical wake model

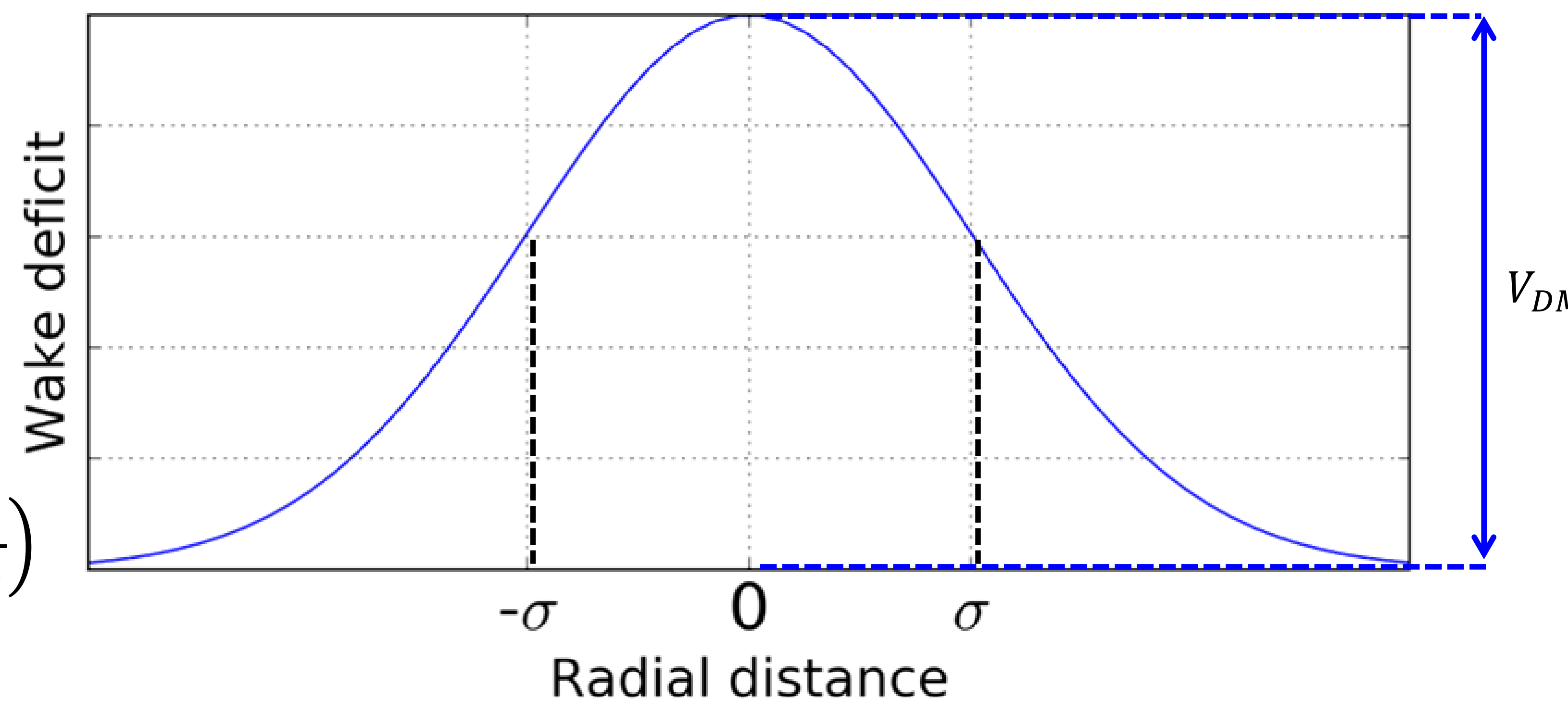
Profile

Wake deficit

$$V_D = 1 - \frac{V_{hor}}{V_{hub}}$$

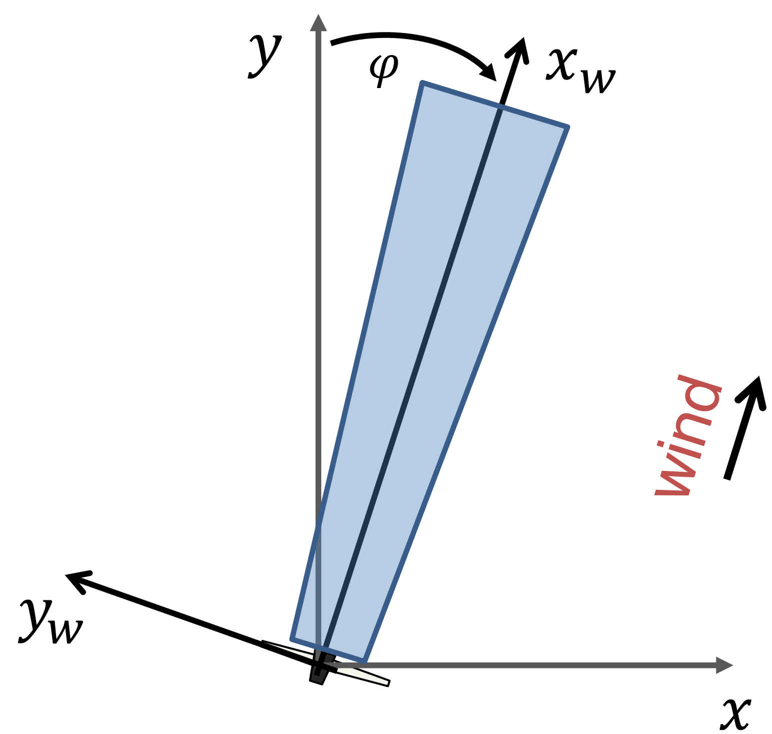
Wake deficit model

$$V_{DM} = \mathrm{A}(x_w, C_T)\ \exp\left(-\frac{y_w^2 + z_w^2}{2\sigma(x_w)^2}\right)$$



Rotation according to wind direction φ

$$x_w = x \sin(90 - \gamma) + y \cos(90 - \varphi)$$
$$y_w = y \cos(90 - \gamma) - x \cos(90 - \varphi)$$



Analytical wake model

Downstream development [1]

$$V_{DM} = A(x_w, C_T)\exp\left(-\frac{y_w^2 + z_w^2}{2\sigma(x_w)^2}\right)$$

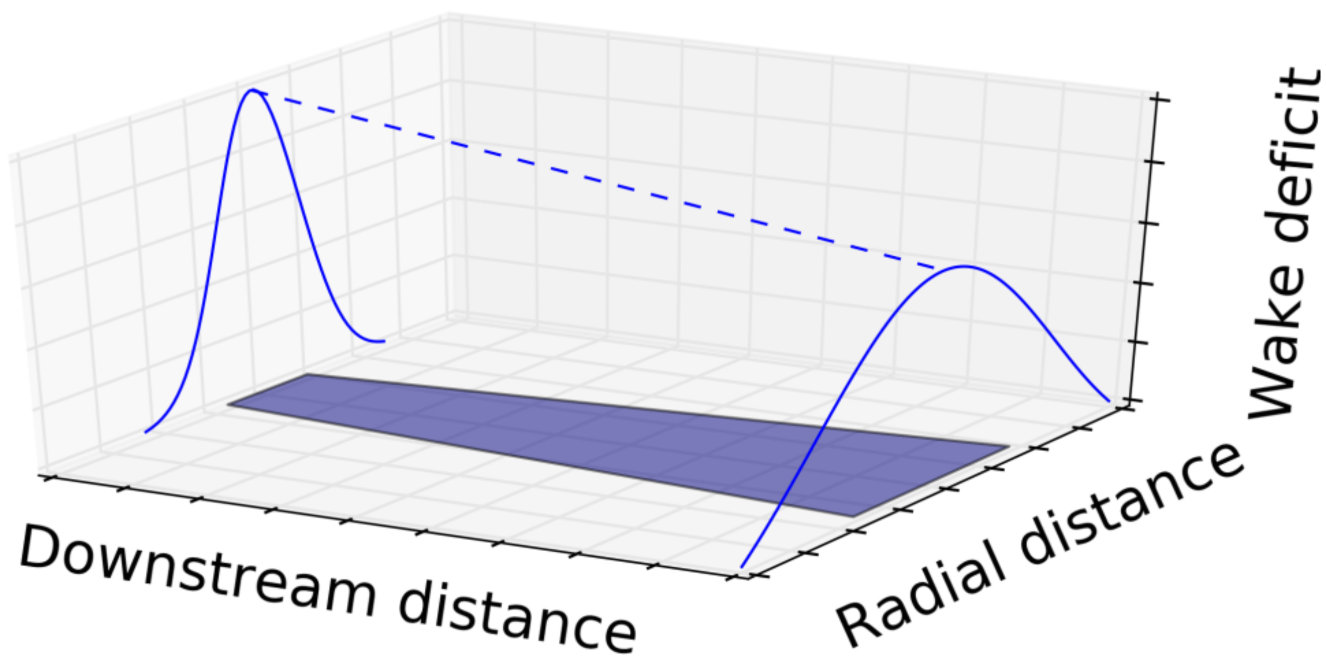
- Linear wake expansion
  $\sigma = \varepsilon + k^* x_w$
- From
  1. Thrust coefficient C_T
  2. Mass conservation
  3. Momentum balance

$$\Rightarrow \varepsilon \approx 0.2\sqrt{\beta} \quad \text{with} \quad \beta = \frac{1}{2}\frac{1+\sqrt{1-C_T}}{\sqrt{1-C_T}}$$

$$\Rightarrow A = \left(1 - \sqrt{1 - \frac{C_T}{8\sigma^2}}\right)$$

- From scaled experiment LES[2]

$$\Rightarrow k^* = 0.3837\,TI + 0.003678$$

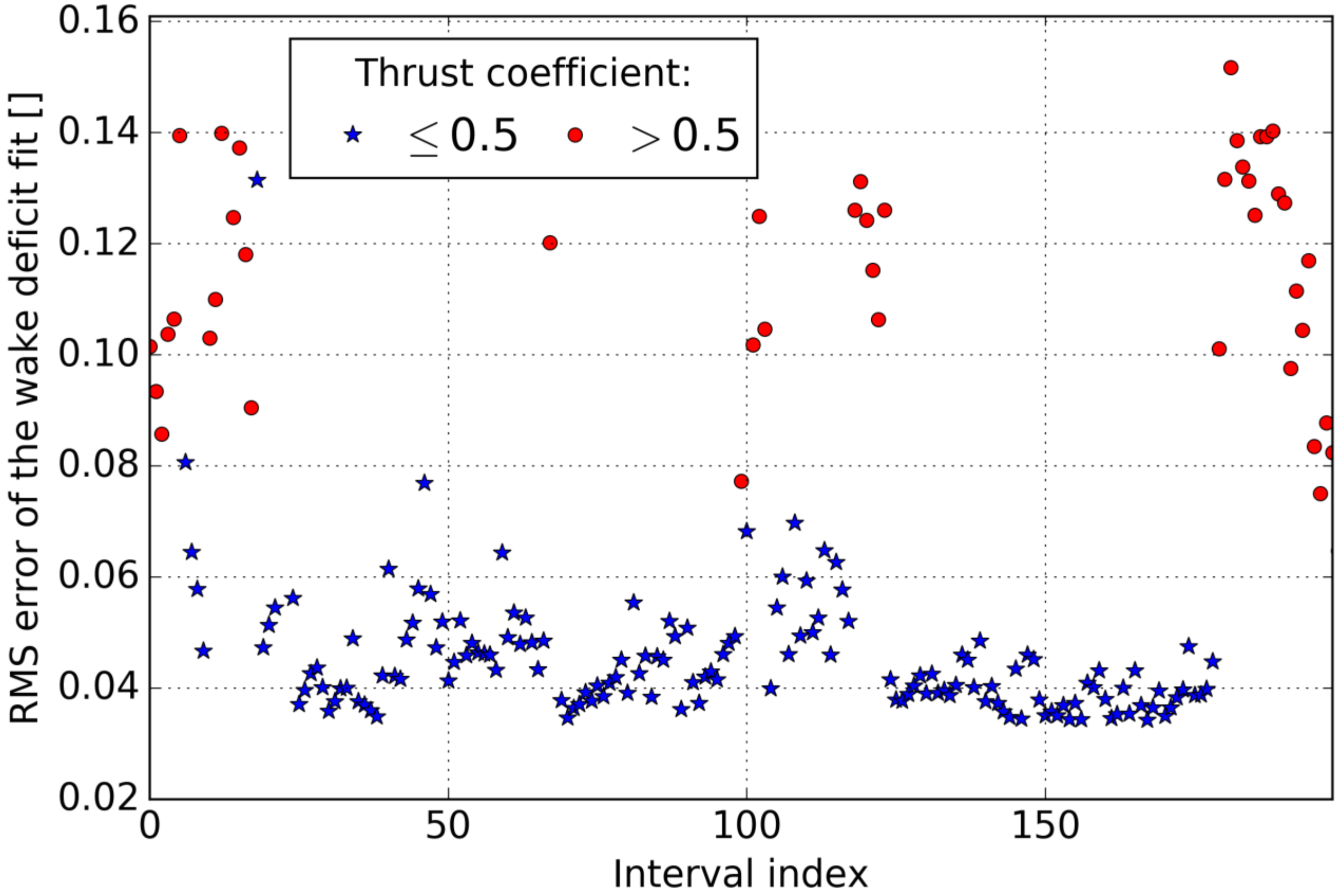


1:Batankhah 2014
2:Niayifar 2016

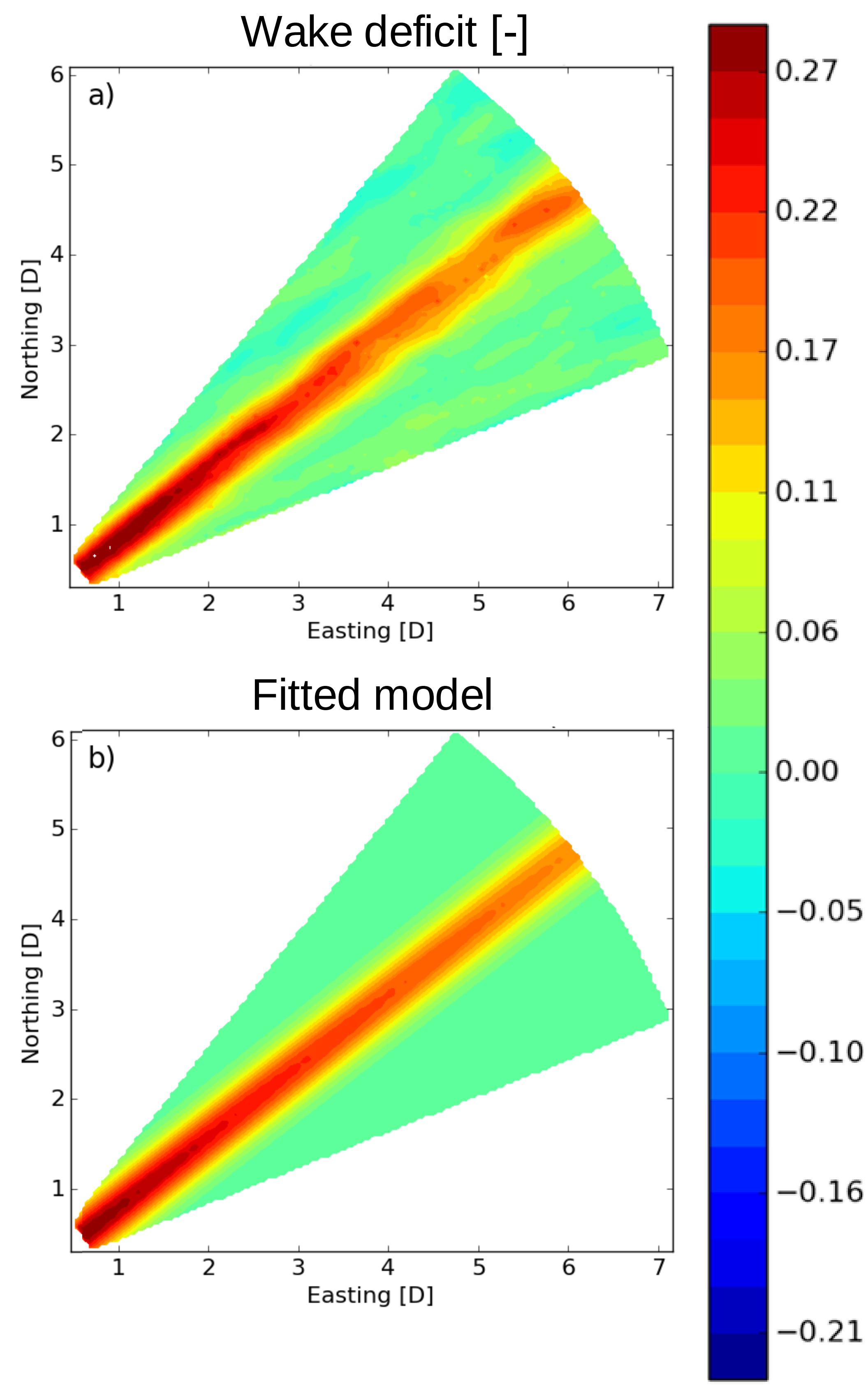
Results

Fit to the data

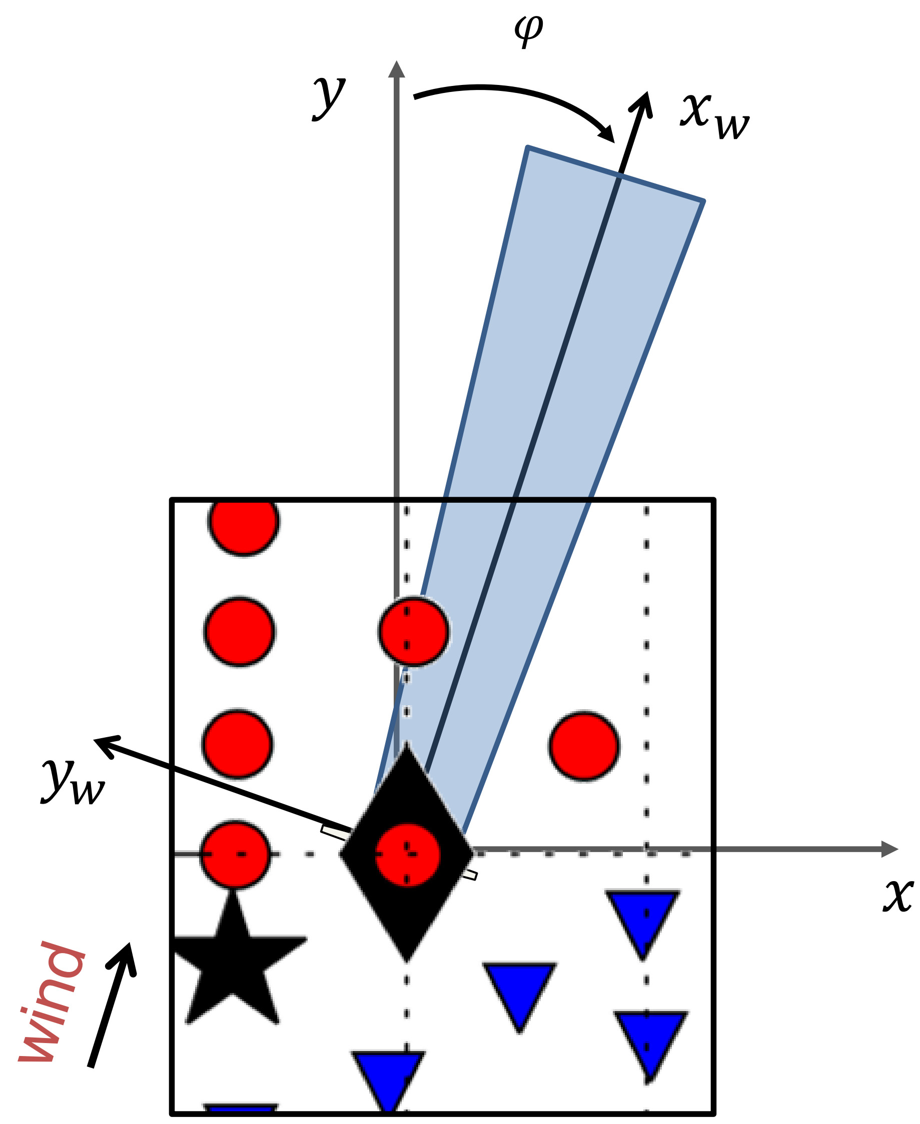
$$V_{DM} = \left(1 - \sqrt{1 - \frac{C_T}{8(\varepsilon + k^* x_w)^2}}\right) \exp\left(-\frac{y_w^2 + z_w^2}{2(\varepsilon + k^* x_w)^2}\right)$$



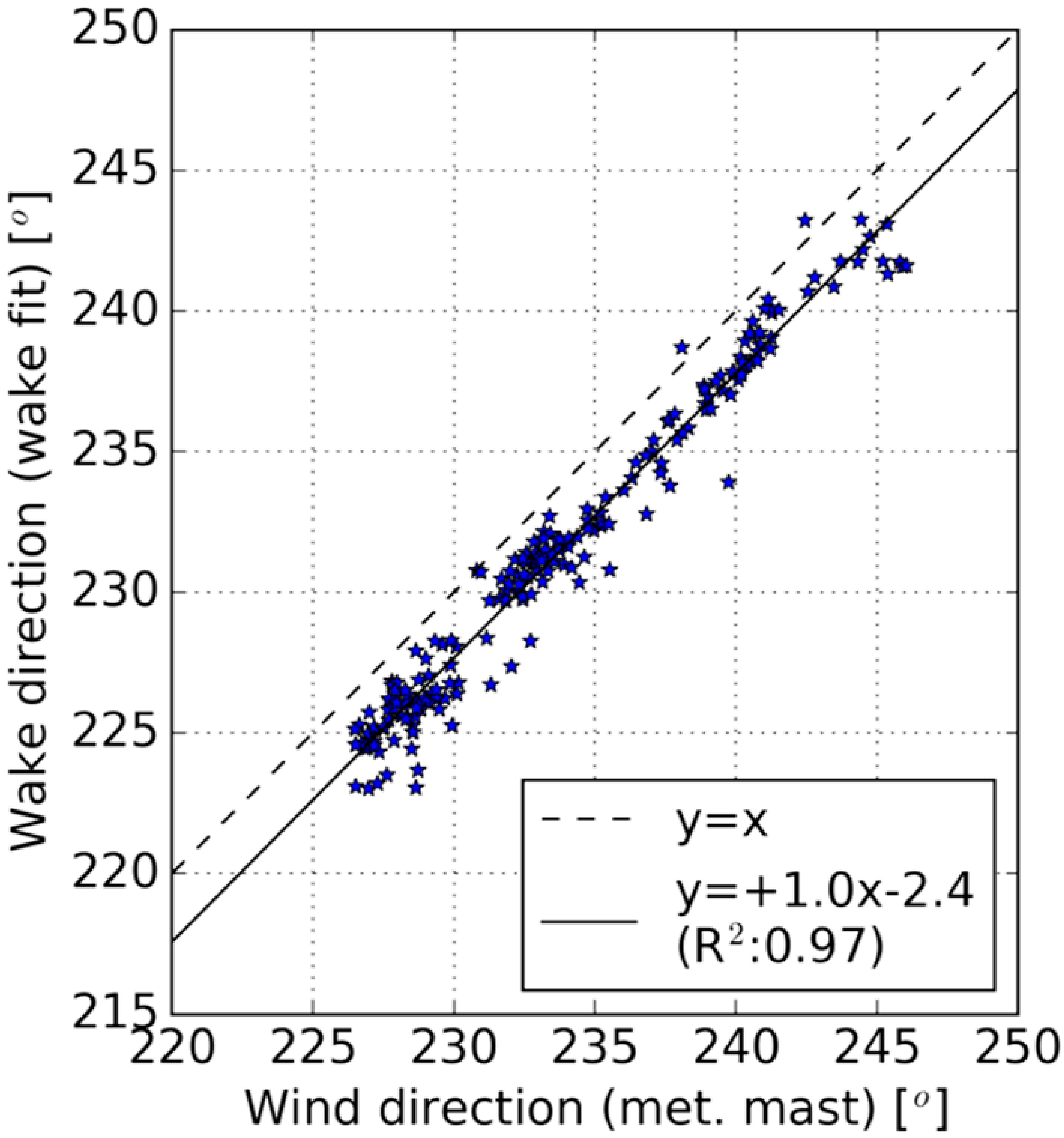
- Better fit for lower thrust coefficient
- Only few time intervals excluded after visual inspection



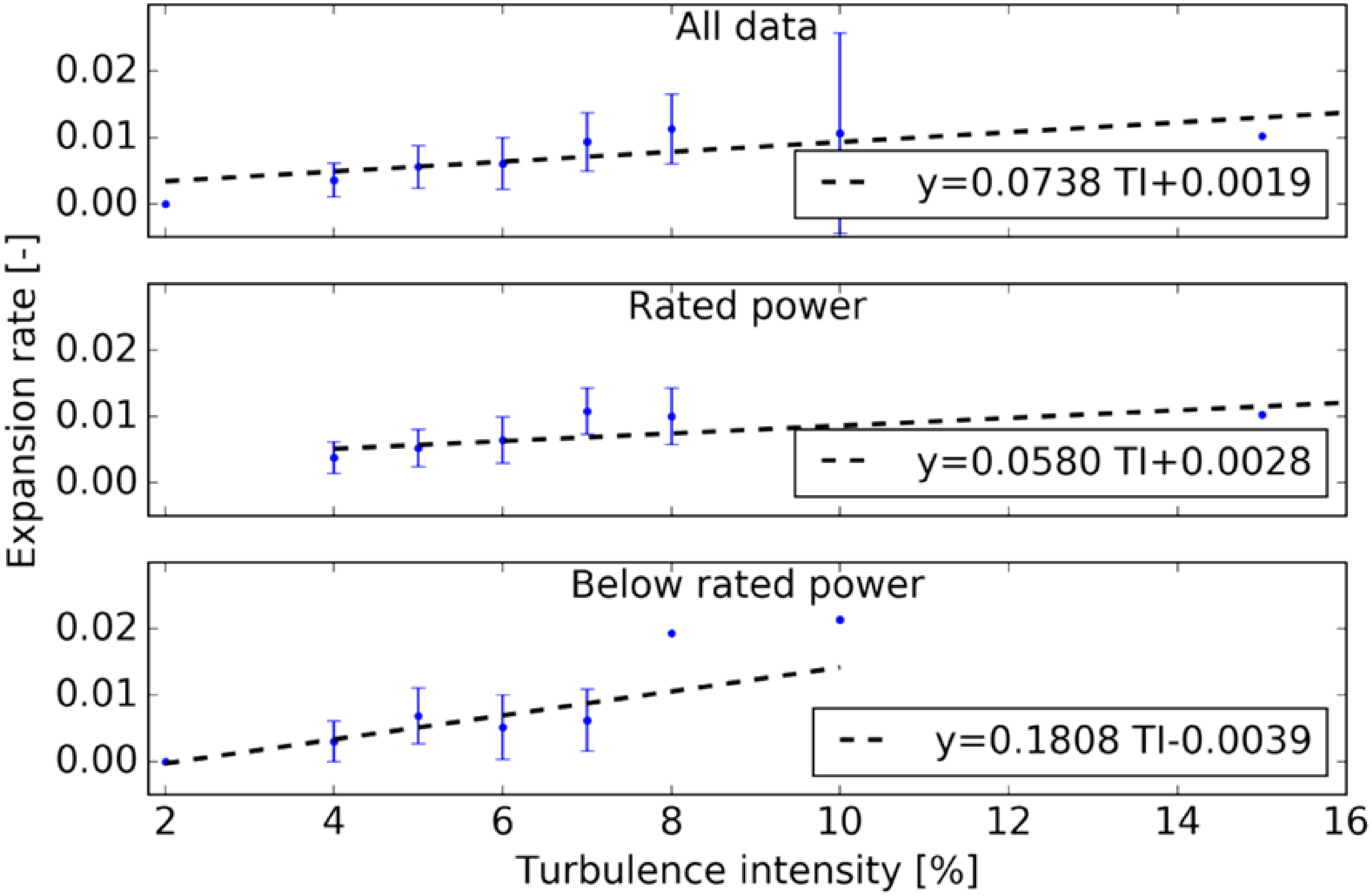
Results
Wake and wind direction



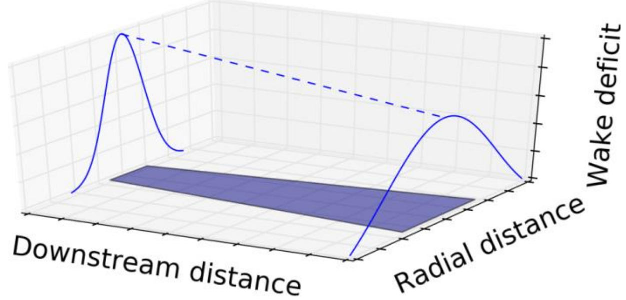
- Good agreement
- Small offset



Results
Expansion rate



- Very small offset similar as Niayfar et al. 2016
- Smaller slope than Niayfar et al. 2016
- Improved agreement for cases below rated power

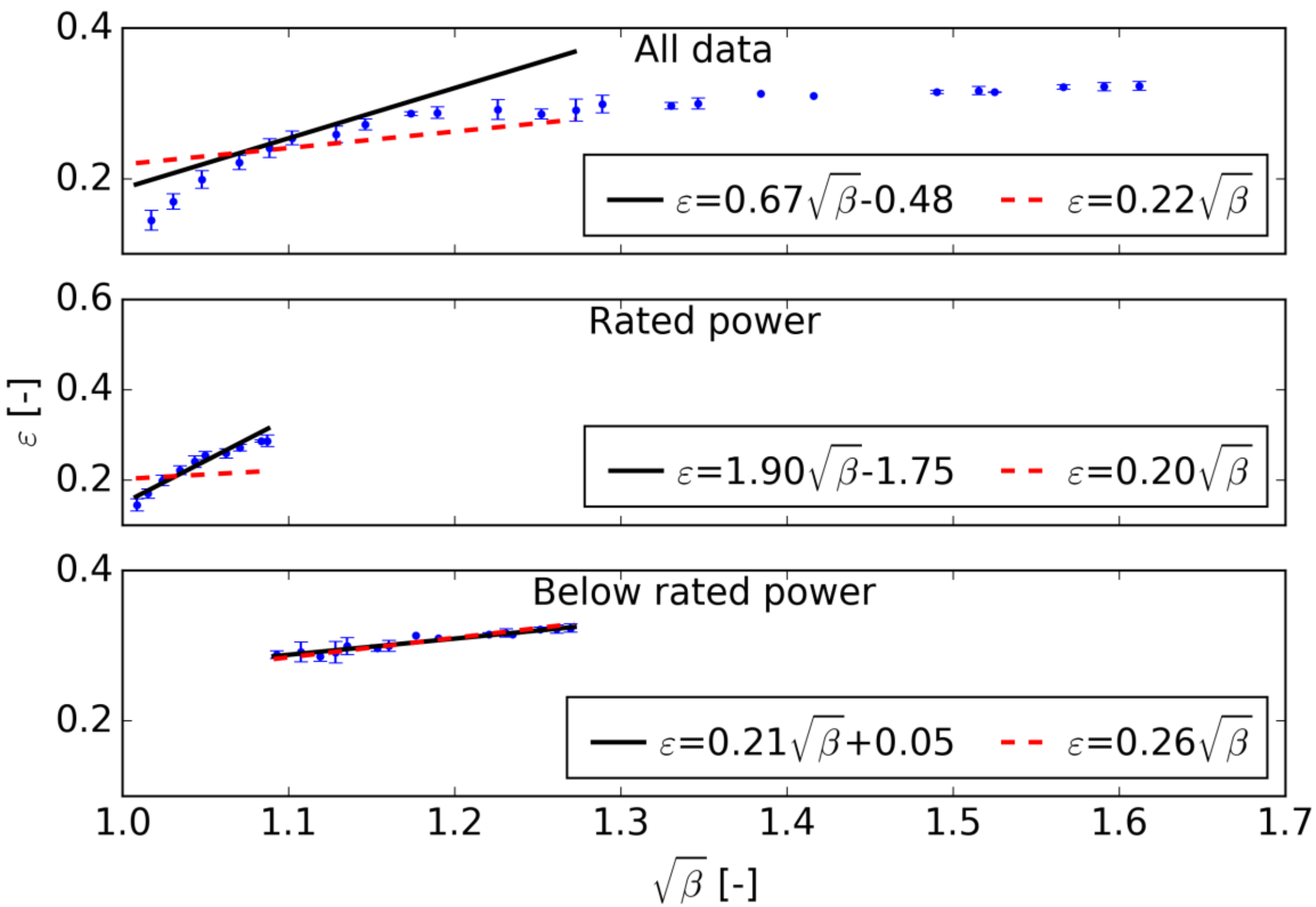


- Linear wake expansion: $\sigma = \varepsilon + k^* x_w$
- From scaled experiment and LES[2] : $k^* = 0.3837\, TI\, +\, 0.003678$

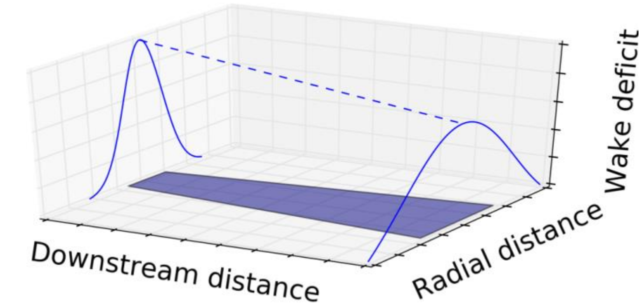
[2:Niayifar 2016]

Results

Initial width



- Agreement with expectations when the offset is forced to 0
- Improved agreement for cases below rated power



- Linear wake expansion: $\sigma = \varepsilon + k^* x_w$
- From theoretical study[1,2] : $\varepsilon \approx 0.2\sqrt{\beta}$ with $\beta = \frac{1}{2}\frac{1+\sqrt{1-C_T}}{\sqrt{1-C_T}}$

[1:Batankhah 2014
2:Niayifar 2016]

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Conclusions

- **Nacelle based measurements** of wind turbine wakes are a **suitable source** of data **for verification of wake models**
- **Full-field experiments** may provide **different calibration** of analytical wake models from test cases **from wind tunnel or high fidelity simulation**
- **Full-field results** are in **good agreement with theoretical expectations** from the conservation of mass and momentum when the turbine is operating below rated power

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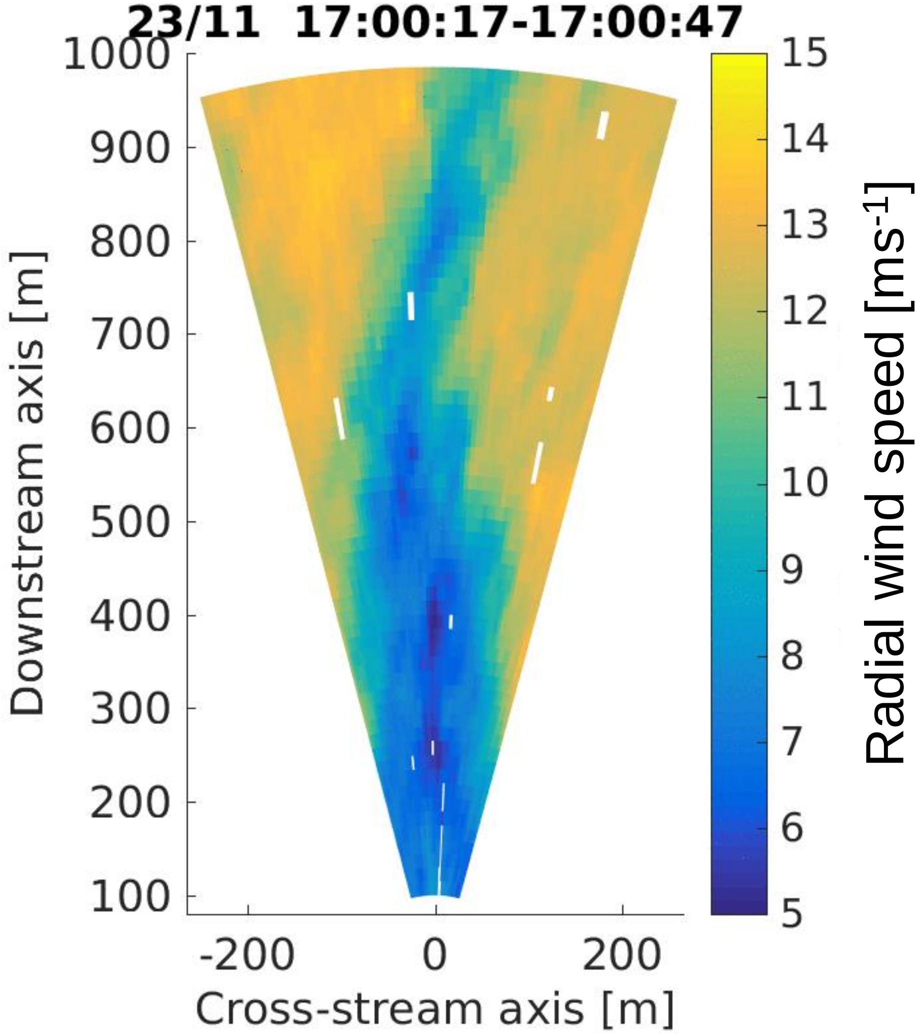

Thanks for the attention!

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References

[1] Bastankhah, M. & Porté-Agel, F. A new analytical model for wind-turbine wakes Renewable Energy , 2014, 70, 116 – 123

[2] Niayifar, A. & Porté-Agel, F. Analytical Modeling of Wind Farms: A New Approach for Power Prediction Energies, 2016, 9, 741