Structural monitoring of a 5 MW offshore wind turbine

The case of Alpha Ventus wind park

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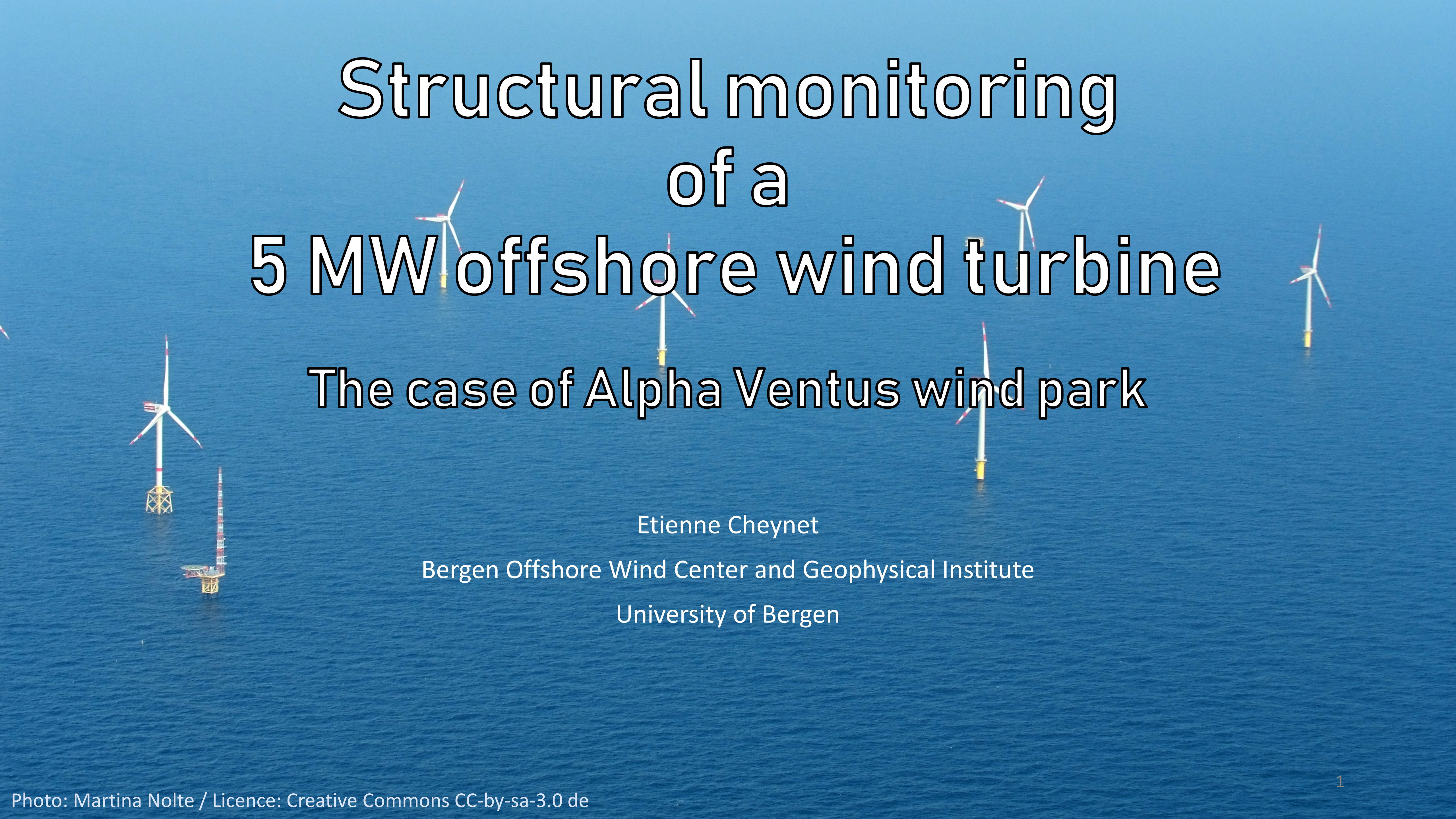


Motivation

To access the dependency of the acceleration response of an offshore wind turbine tower on the environment conditions

The tower is the most expensive part of a wind turbine [1]

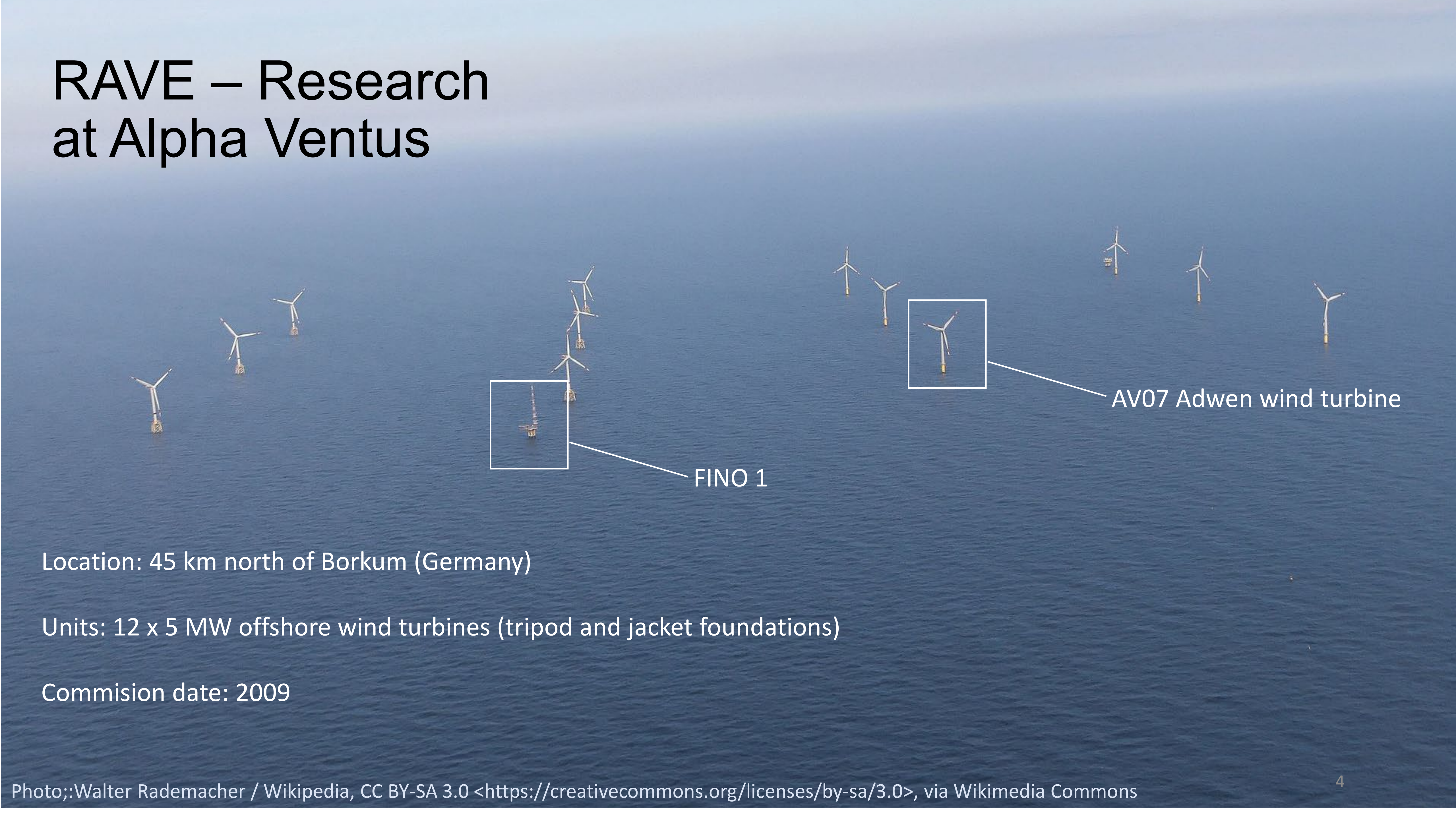
[1] Pérez, J. M. P., Márquez, F. P. G., Tobias, A., & Papaelias, M. (2013). Wind turbine reliability analysis. *Renewable and Sustainable Energy Reviews*, *23*, 463-472.

Method

1. Using the RAVE database, identify the along-wind and cross-wind motions of the tower

2. Studying the standard-deviation of the acceleration response of the upper part of the tower

RAVE – Research at Alpha Ventus



Location: 45 km north of Borkum (Germany)

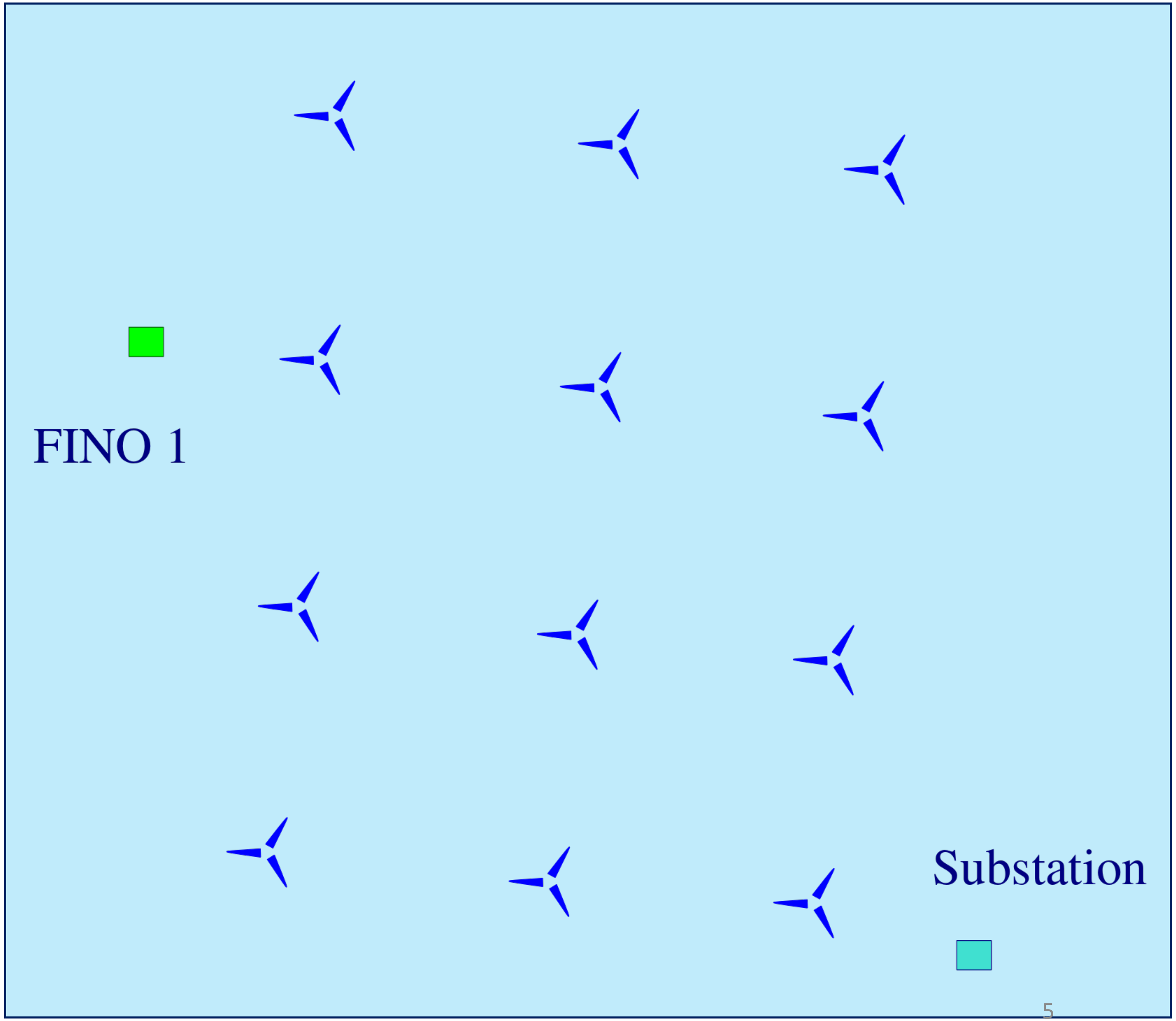
Units: 12 x 5 MW offshore wind turbines (tripod and jacket foundations)

Commision date: 2009

RAVE – Research at Alpha Ventus

https://www.rave-offshore.de/en/data.html

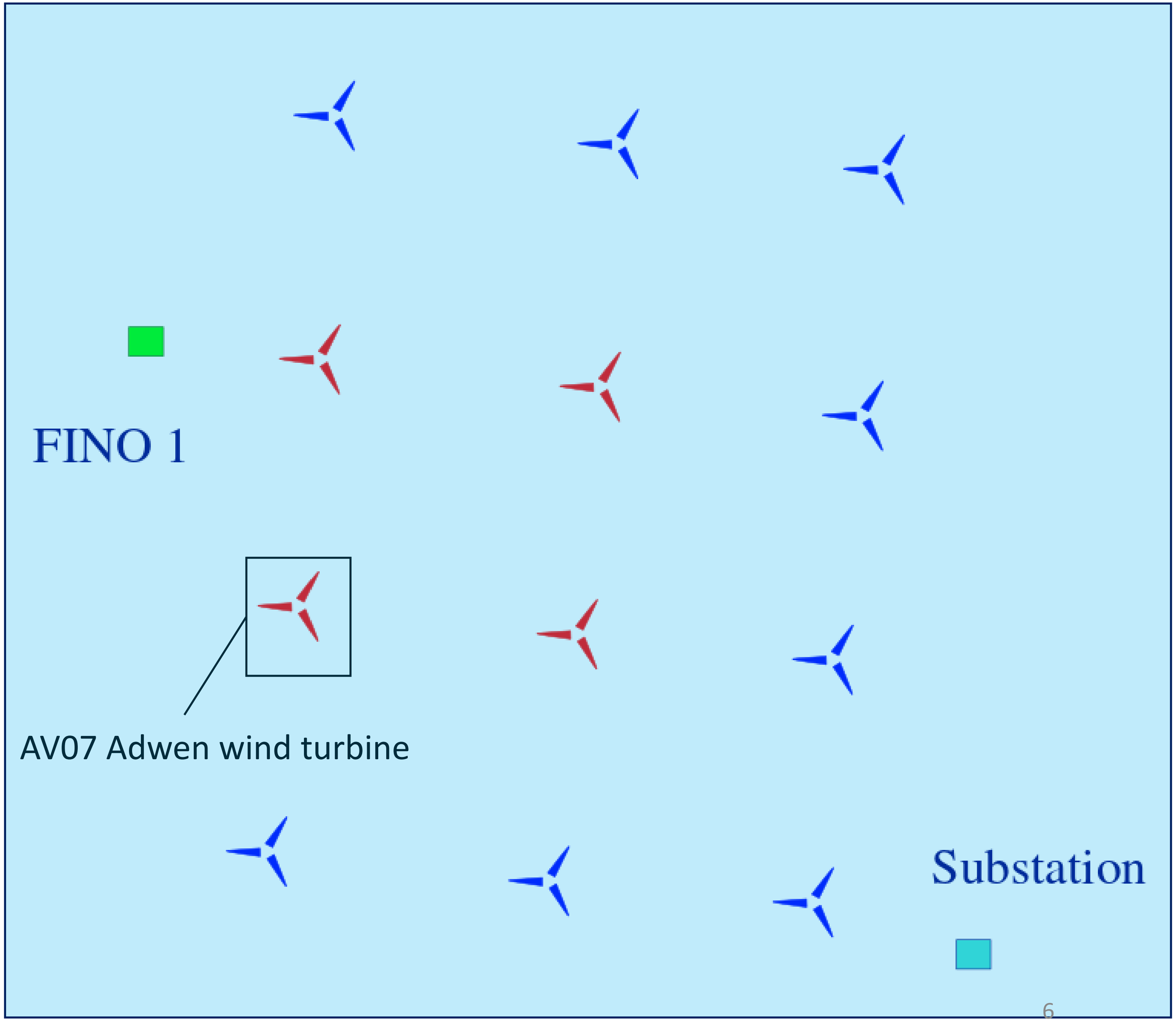
RAVE is the research initiative for the first offshore wind farm project in Germany



RAVE – Research at Alpha Ventus

https://www.rave-offshore.de/en/data.html

- Structural monitoring of four wind turbines since 2009
- Atmospheric measurements from FINO1 Platform
- Wave measurements from buoys (BSH) less than 1km from FINO1
- 10-min averaged SCADA data available

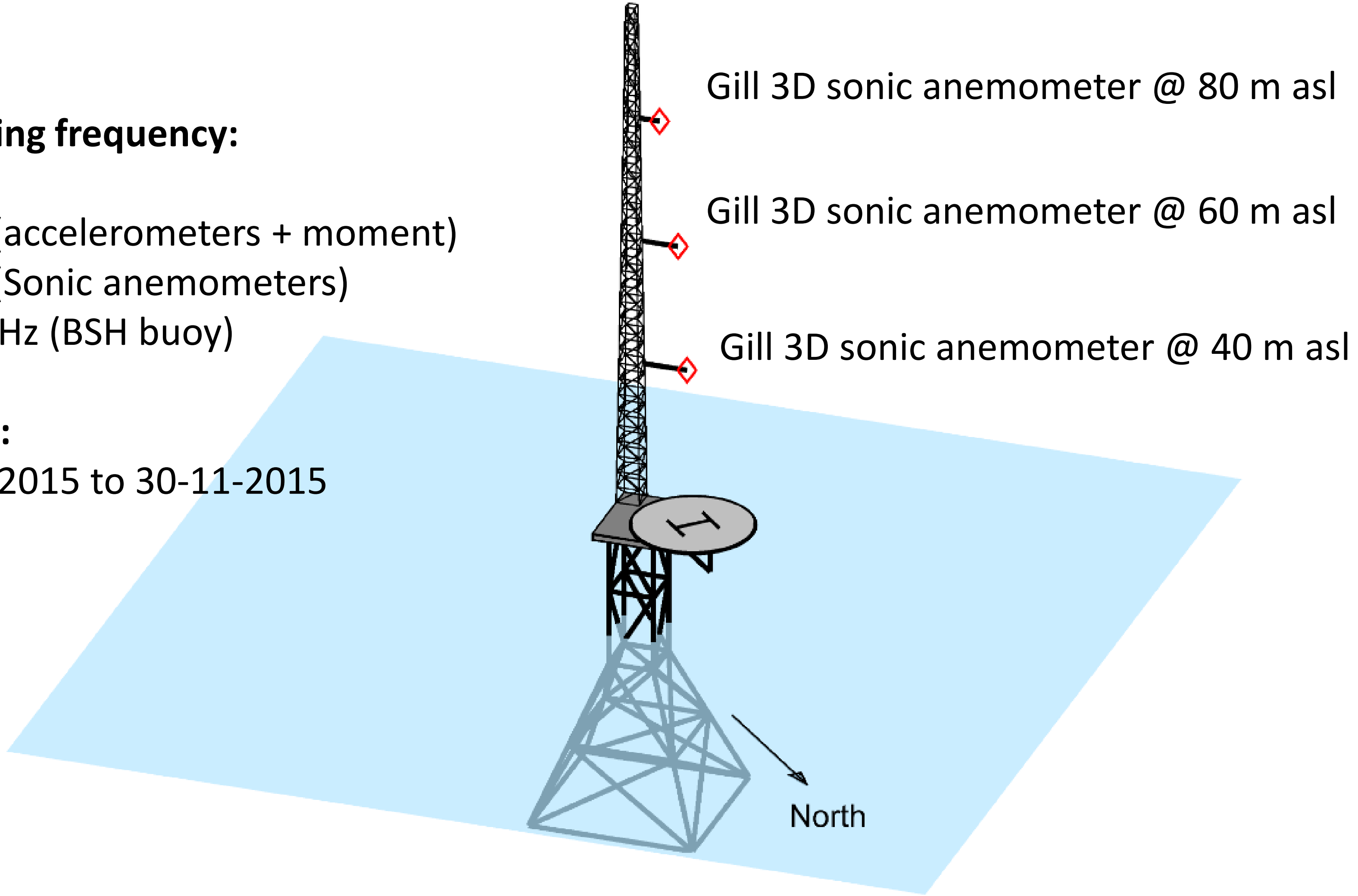


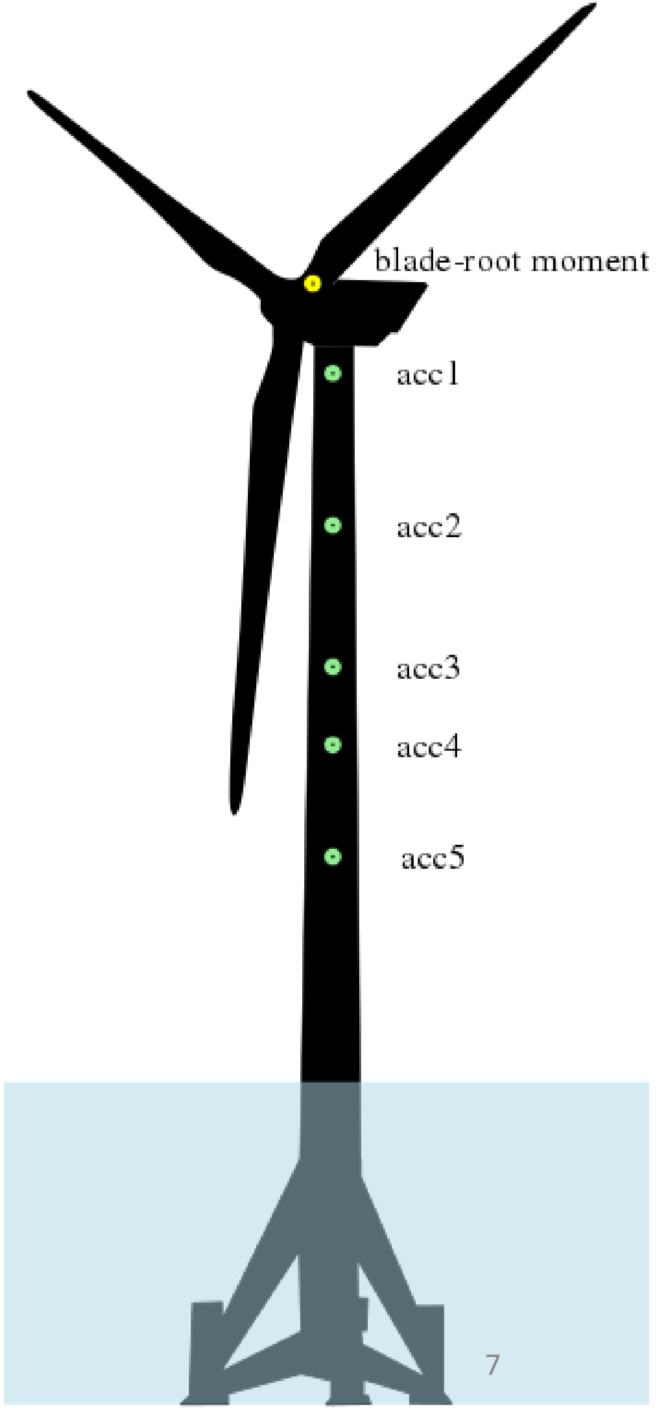
Dataset from the RAVE project + BSH database + DEWI sonic anemometers

Sampling frequency:

50 Hz (accelerometers + moment)
20 Hz (Sonic anemometers)
1/600 Hz (BSH buoy)

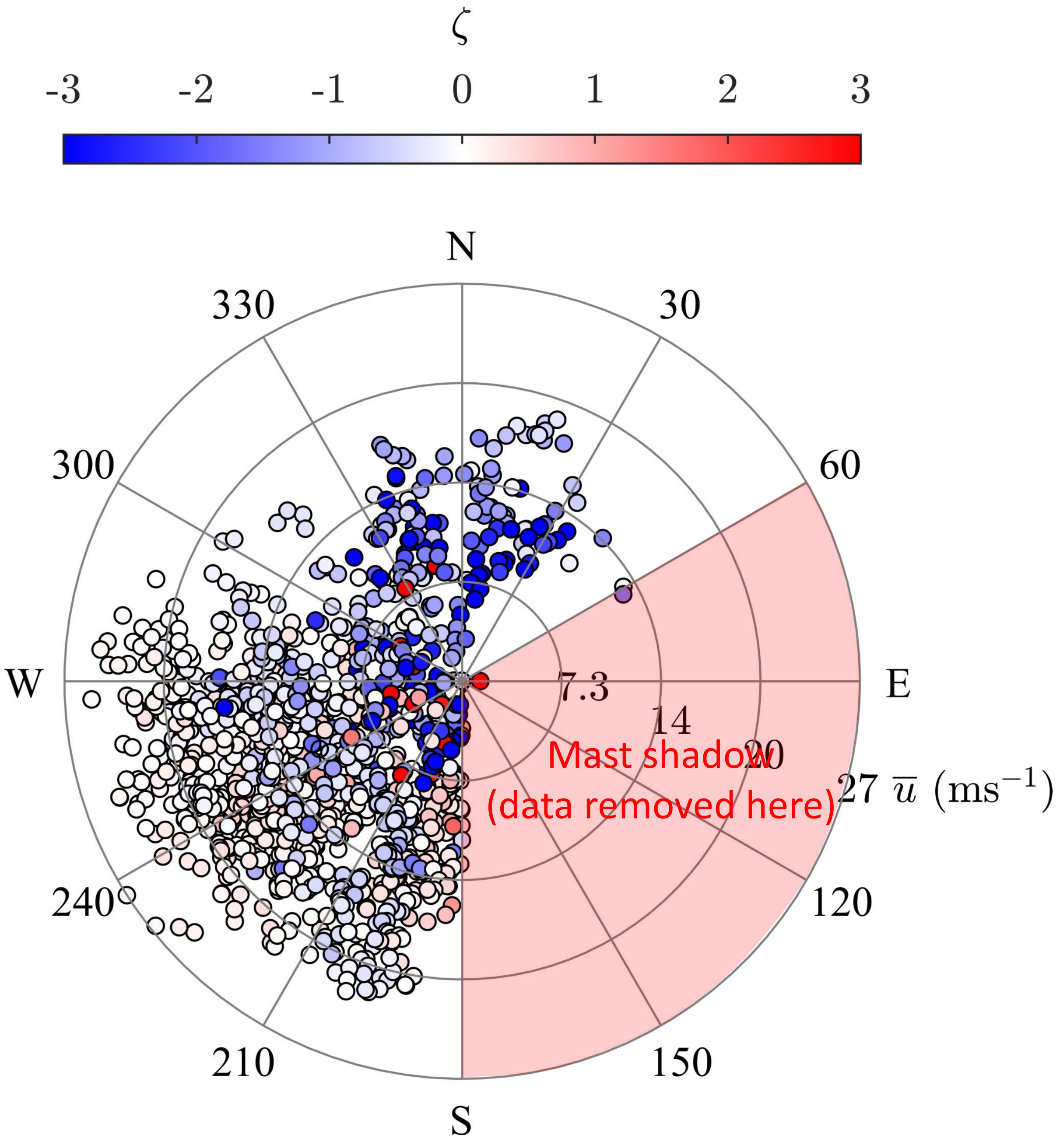
Period:
01-11-2015 to 30-11-2015



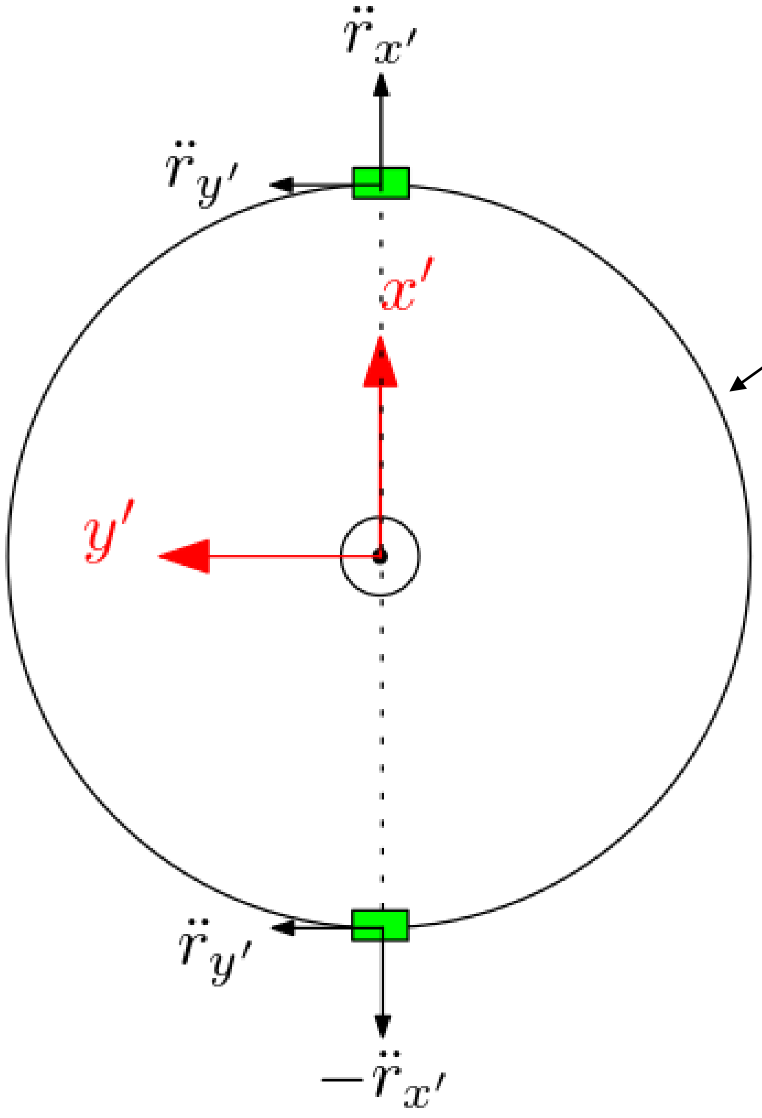


Why November 2015?

- 475 h of stationary wind records (high-quality data) from the sonic anemometer at FINO1, located 80 m asl.
- Both wind speeds below cut-in and above cut-out speed.
- Large variety of wind stability conditions ($\zeta = z/L$, non-dimensional Obukhov length).
- High data availability from the accelerometers.
- Good data availability for the wave conditions from the BSH buoy.

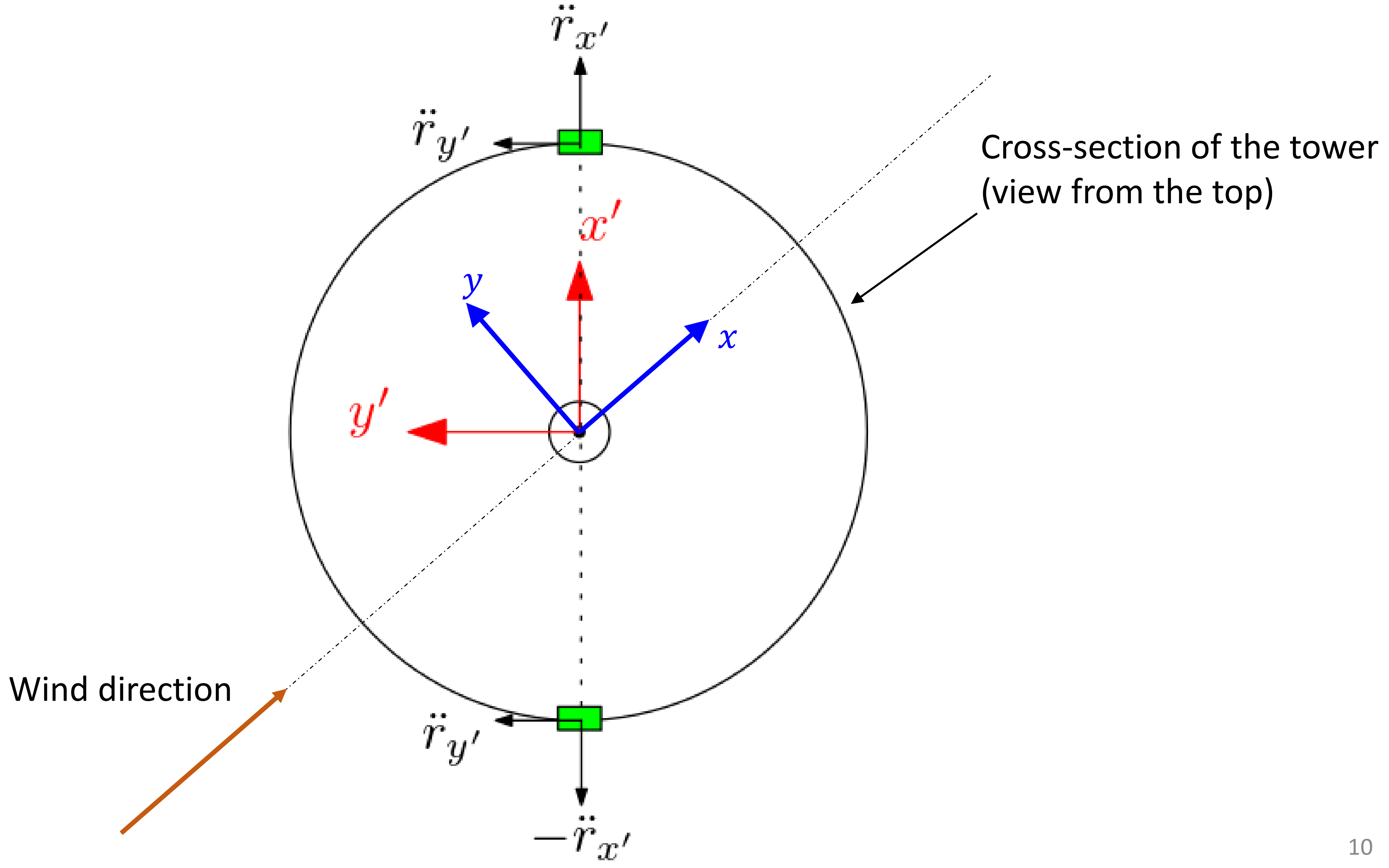


Retrieving the along-wind and cross-wind motions

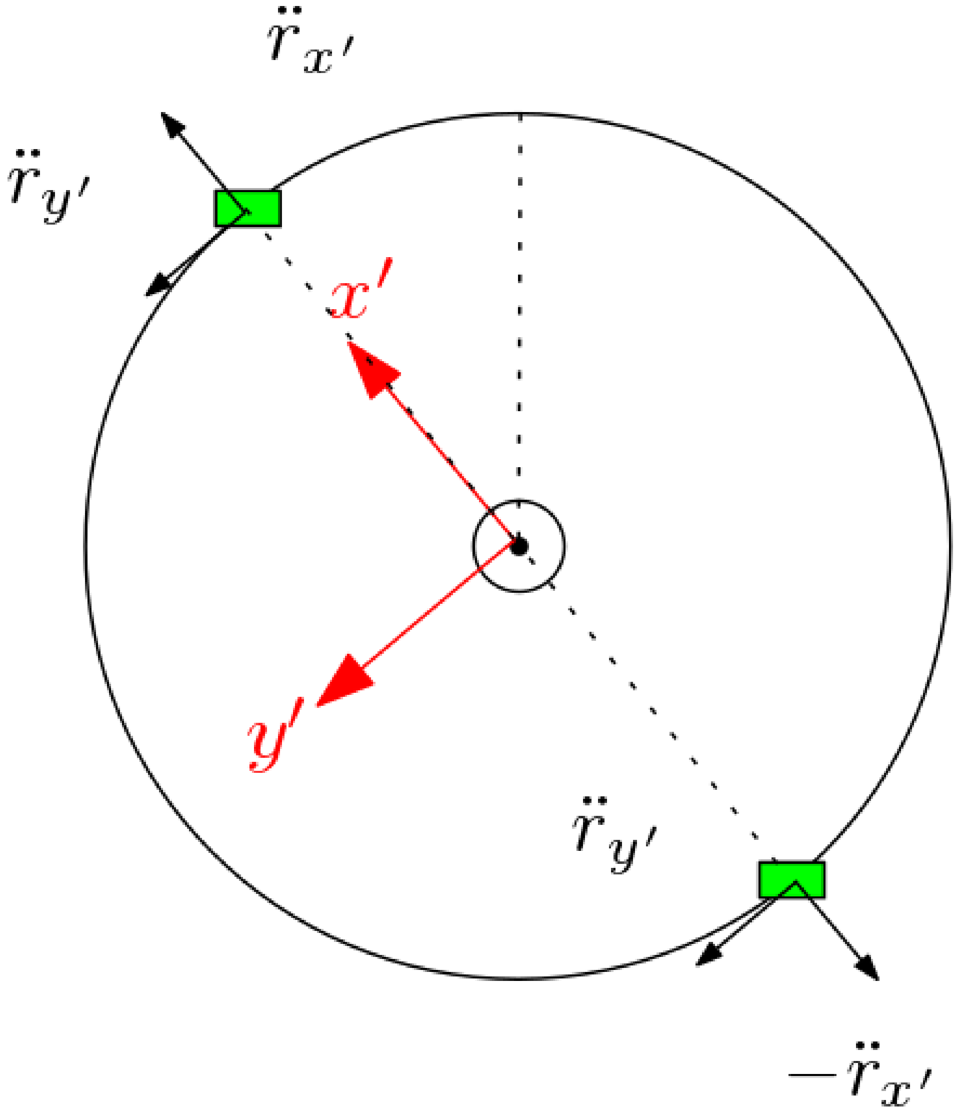


Cross-section of the tower
(view from the top)

Retrieving the along-wind and cross-wind motions



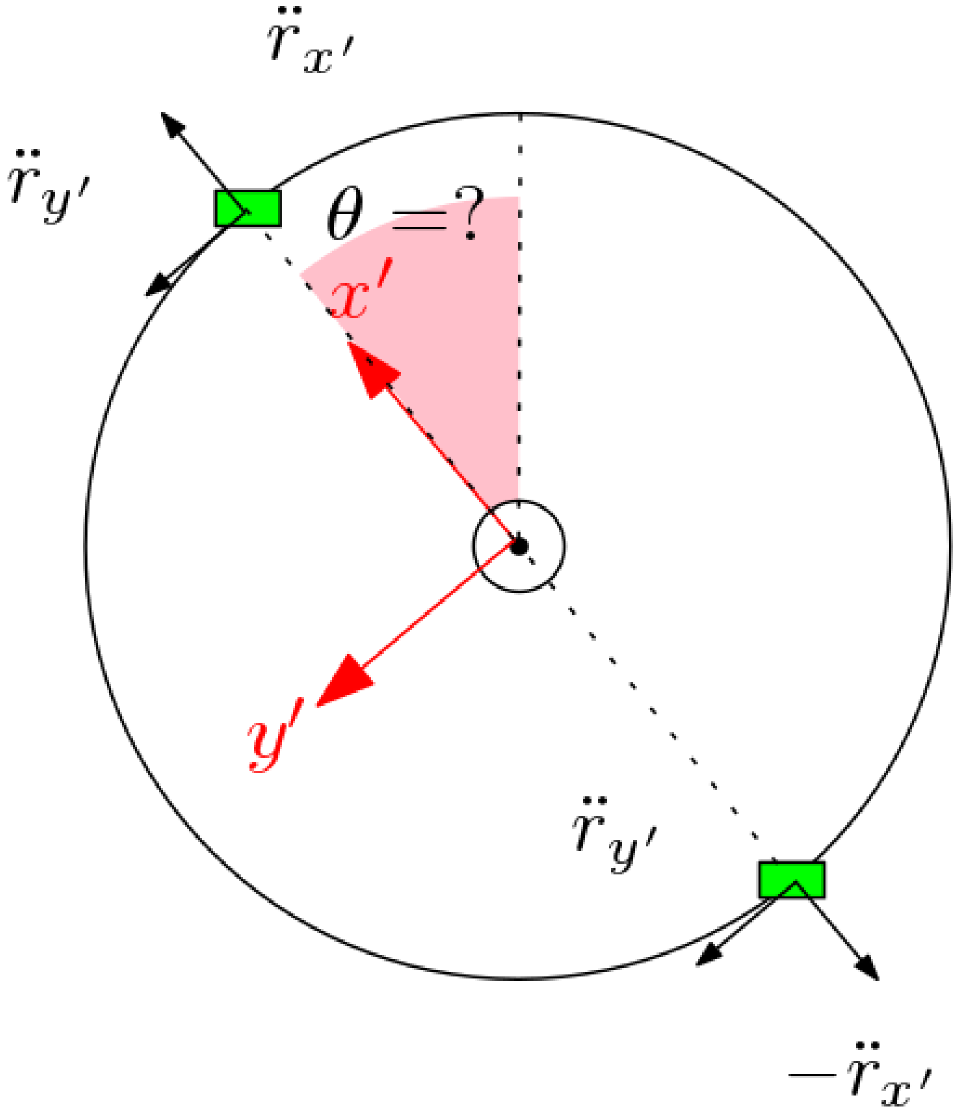
Retrieving the along-wind and cross-wind motions



The position of the accelerometers on the towers is currently not openly available (ongoing documentation)

Retrieving the along-wind and cross-wind motions

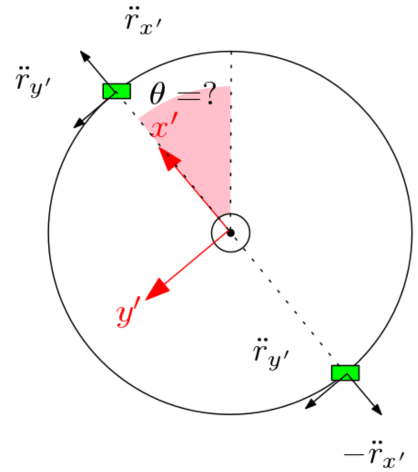
The angle θ is unknown

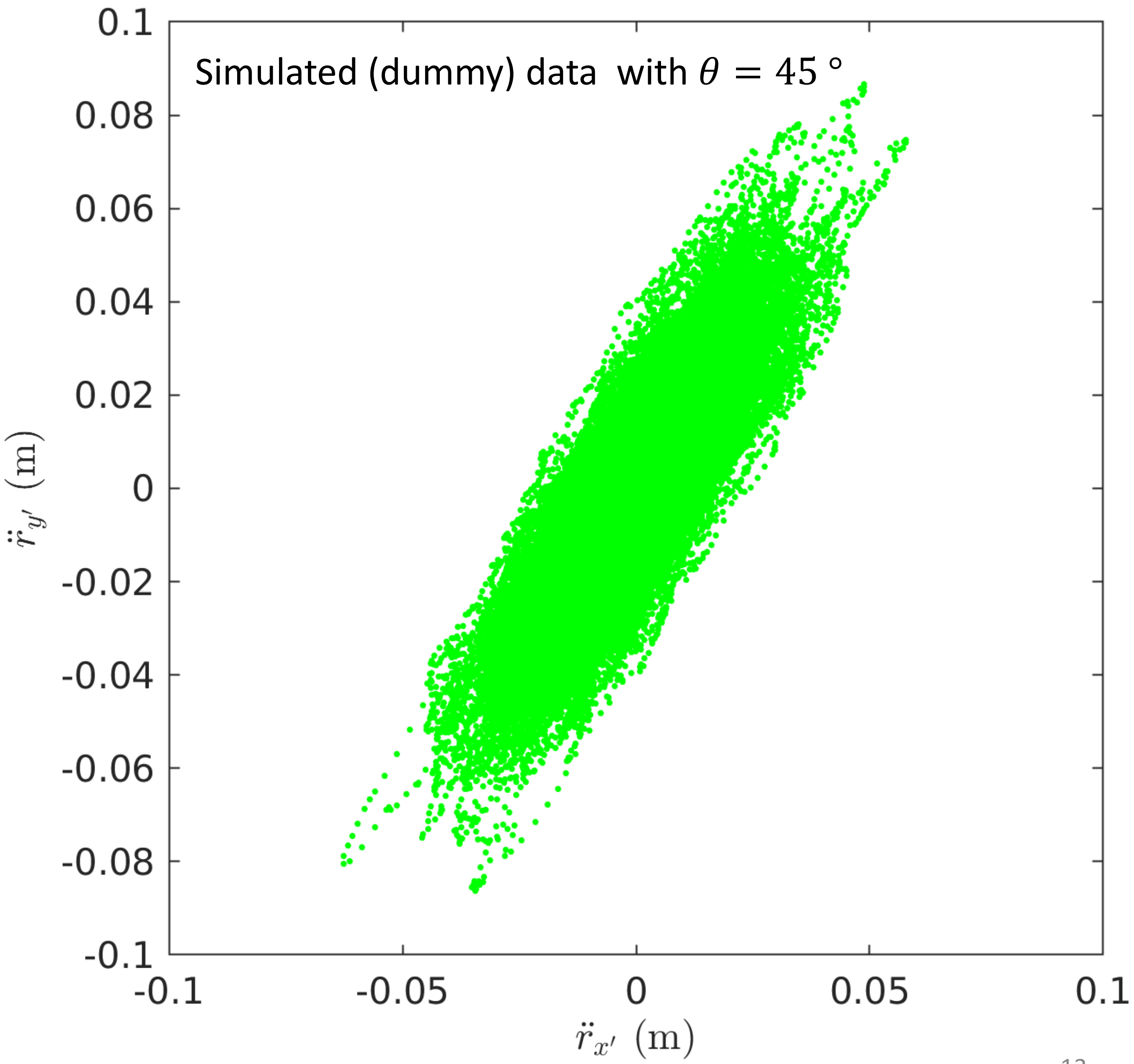


Principal component analysis

Correlated variables → PCA → Linearly uncorrelated variables

Here: Two channels with orthogonal components
-> We need to identify a rotation matrix





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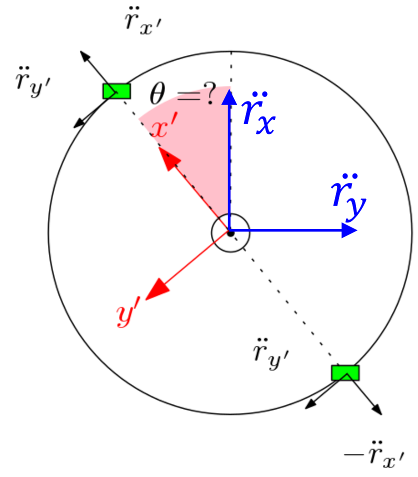

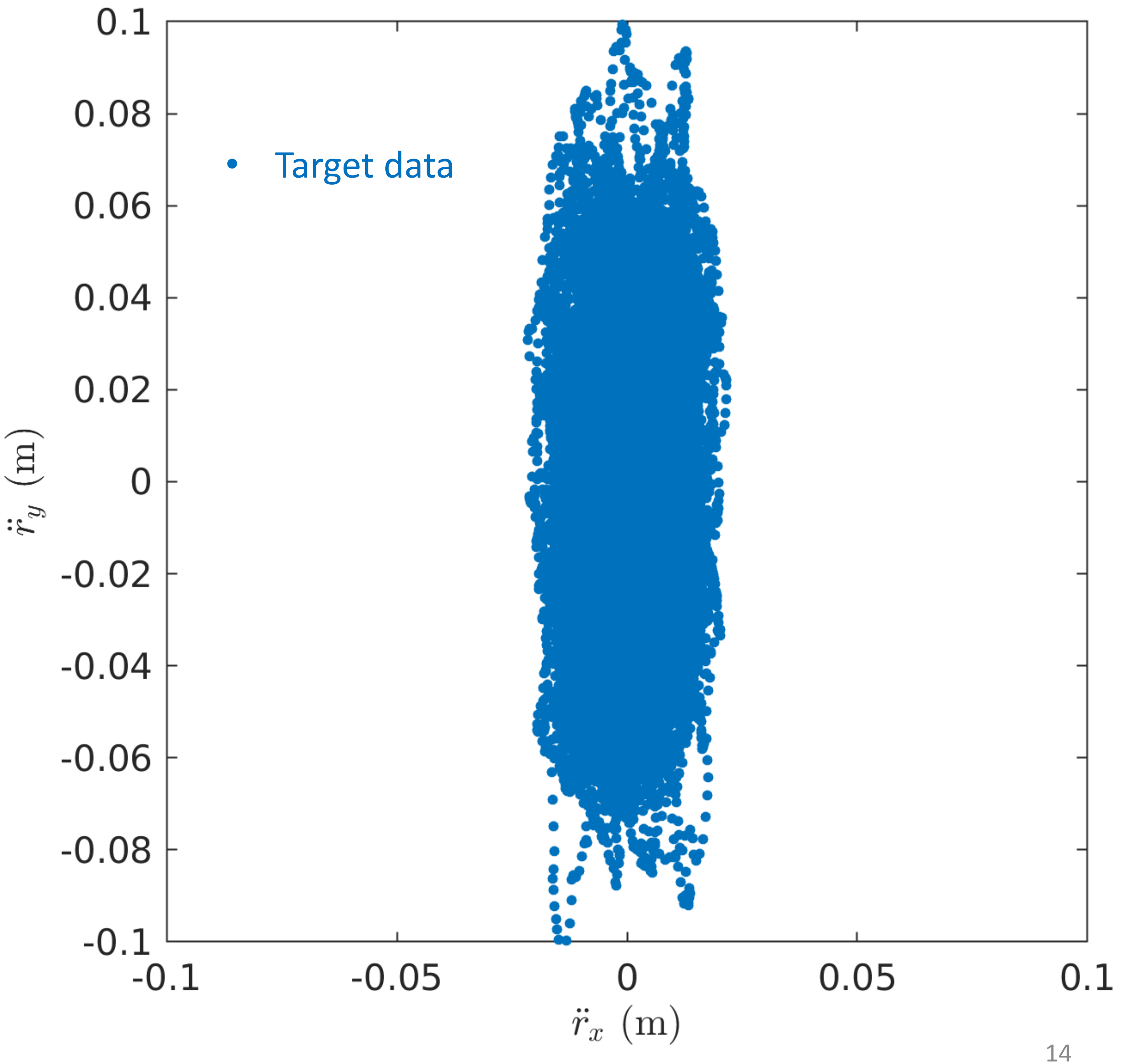

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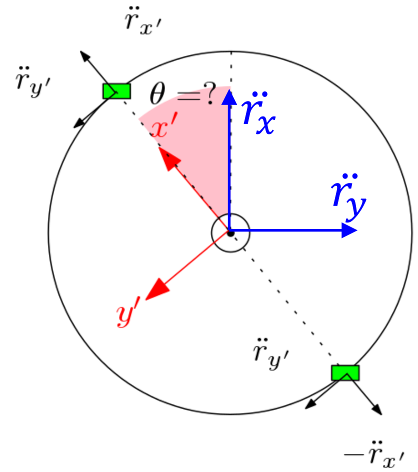
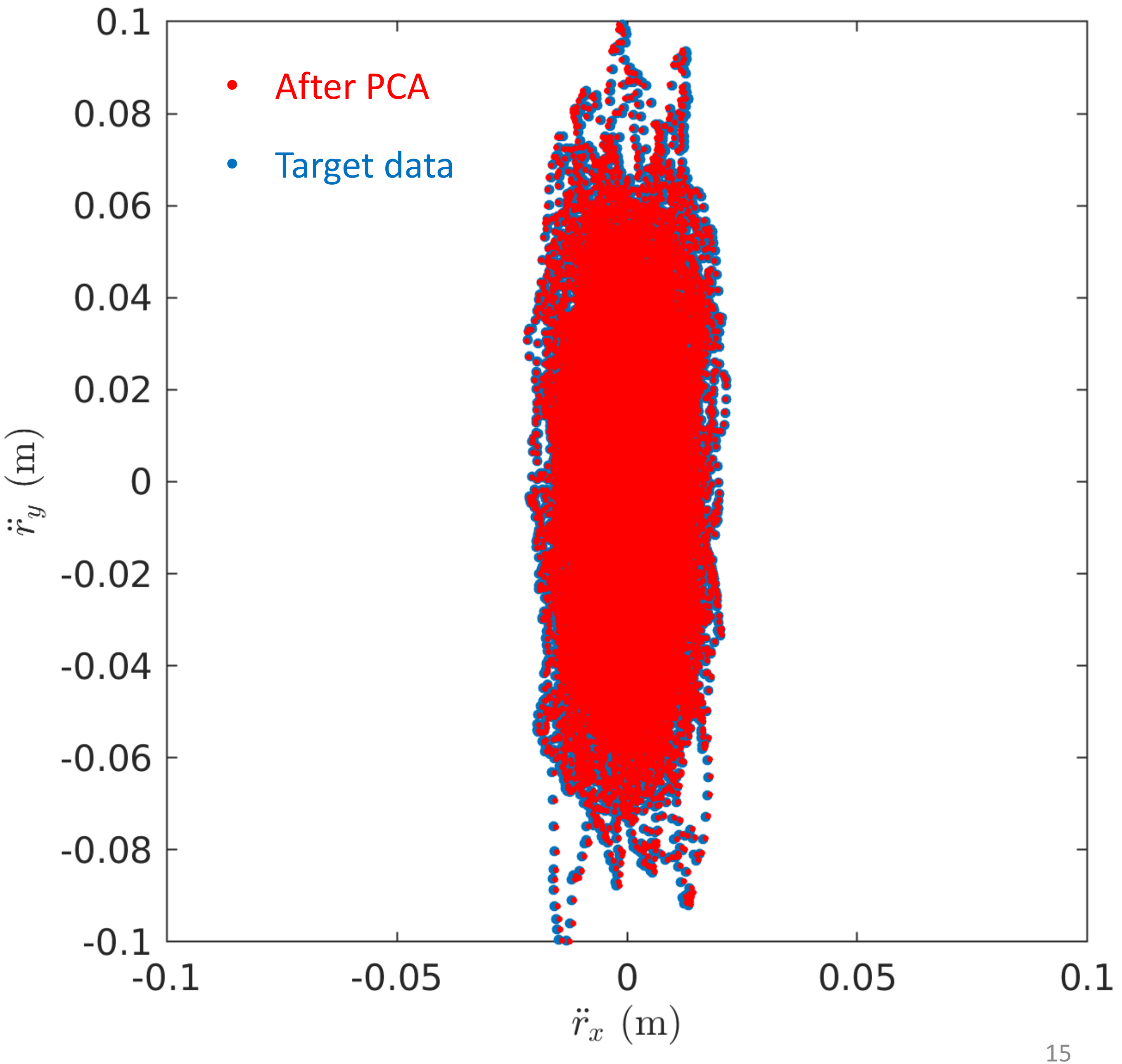
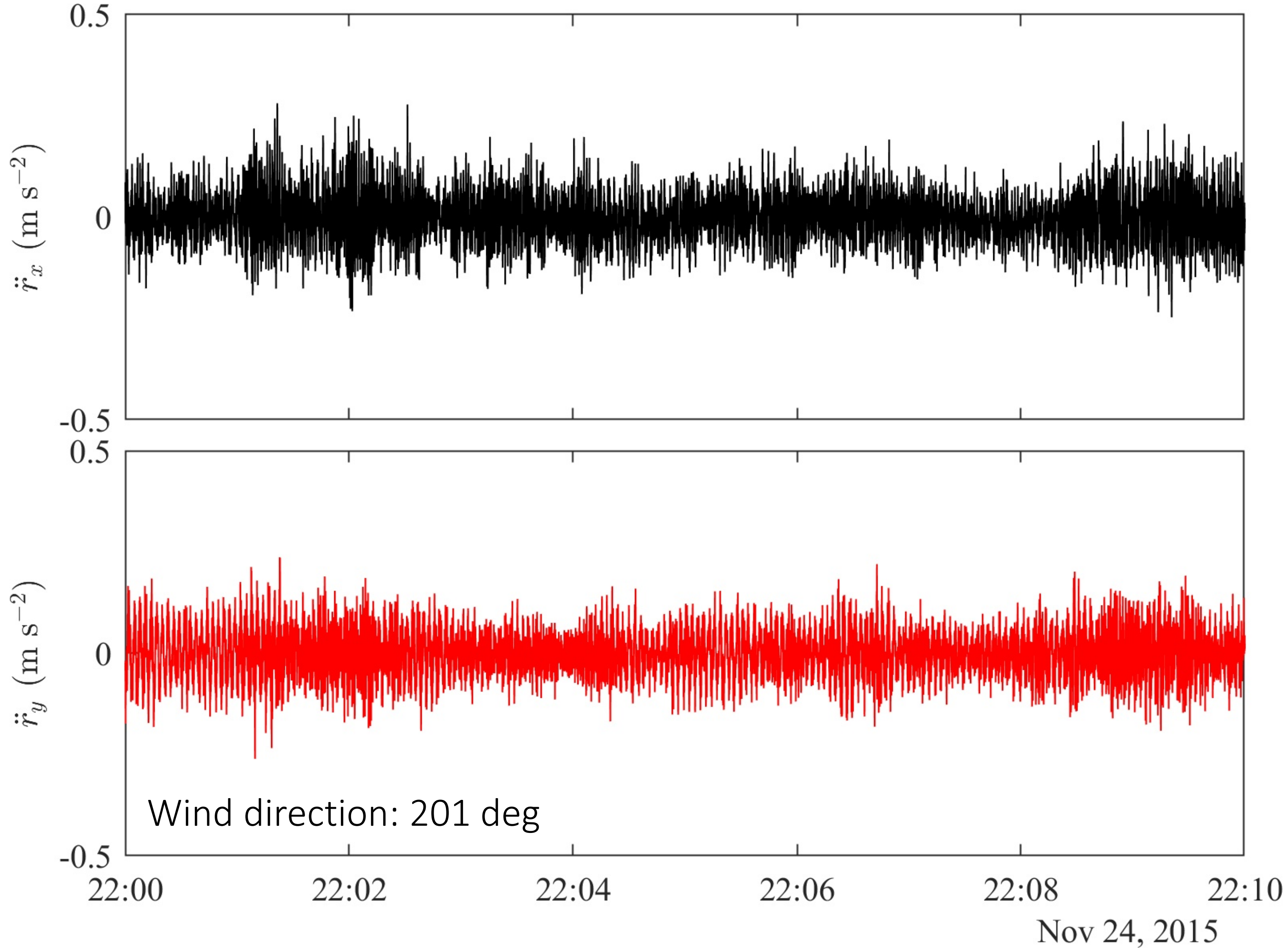




Example 1

Acceleration data from the top of the tower (acc1)

Mean wind speed below rated wind speed (10.5 m/s)

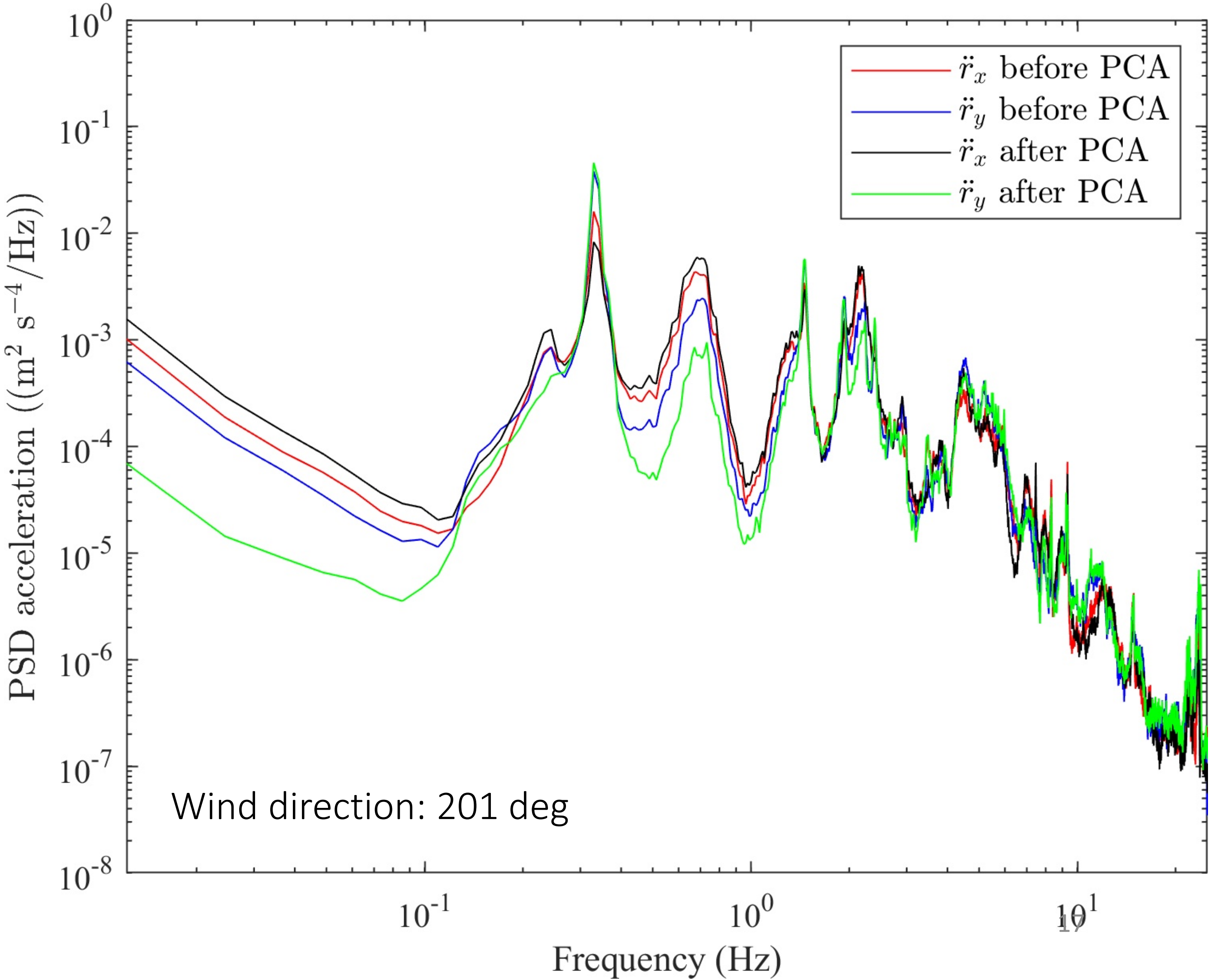


Example 1

The average of signals from each accelerometer pair is selected to remove the torsional component.

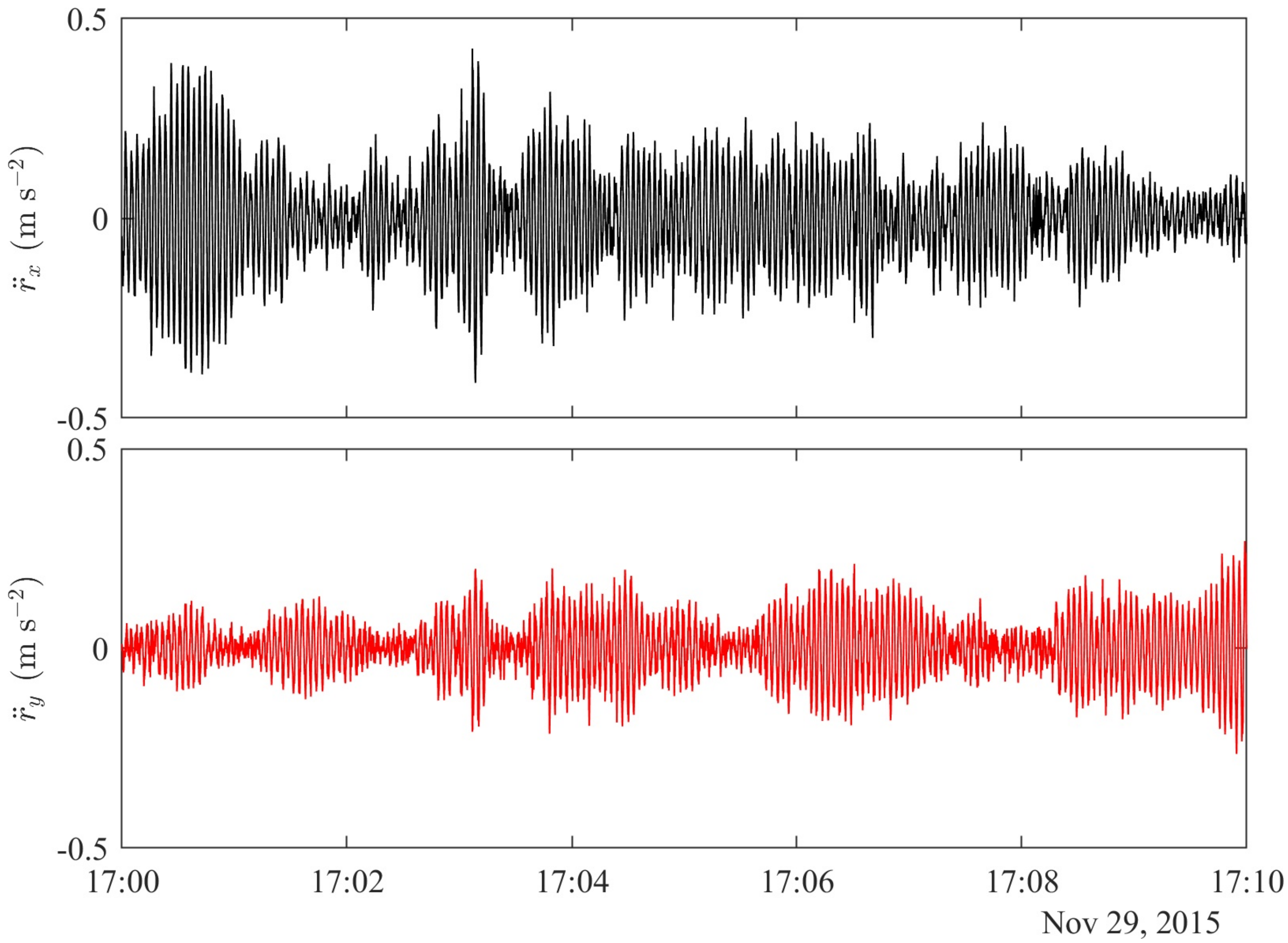
Then the PCA is applied to retrieve the along-wind and cross-wind component.

$\theta \approx 330 - 345°$ (?)



Example 2

Mean wind speed above cut-out speed (26 m/s)



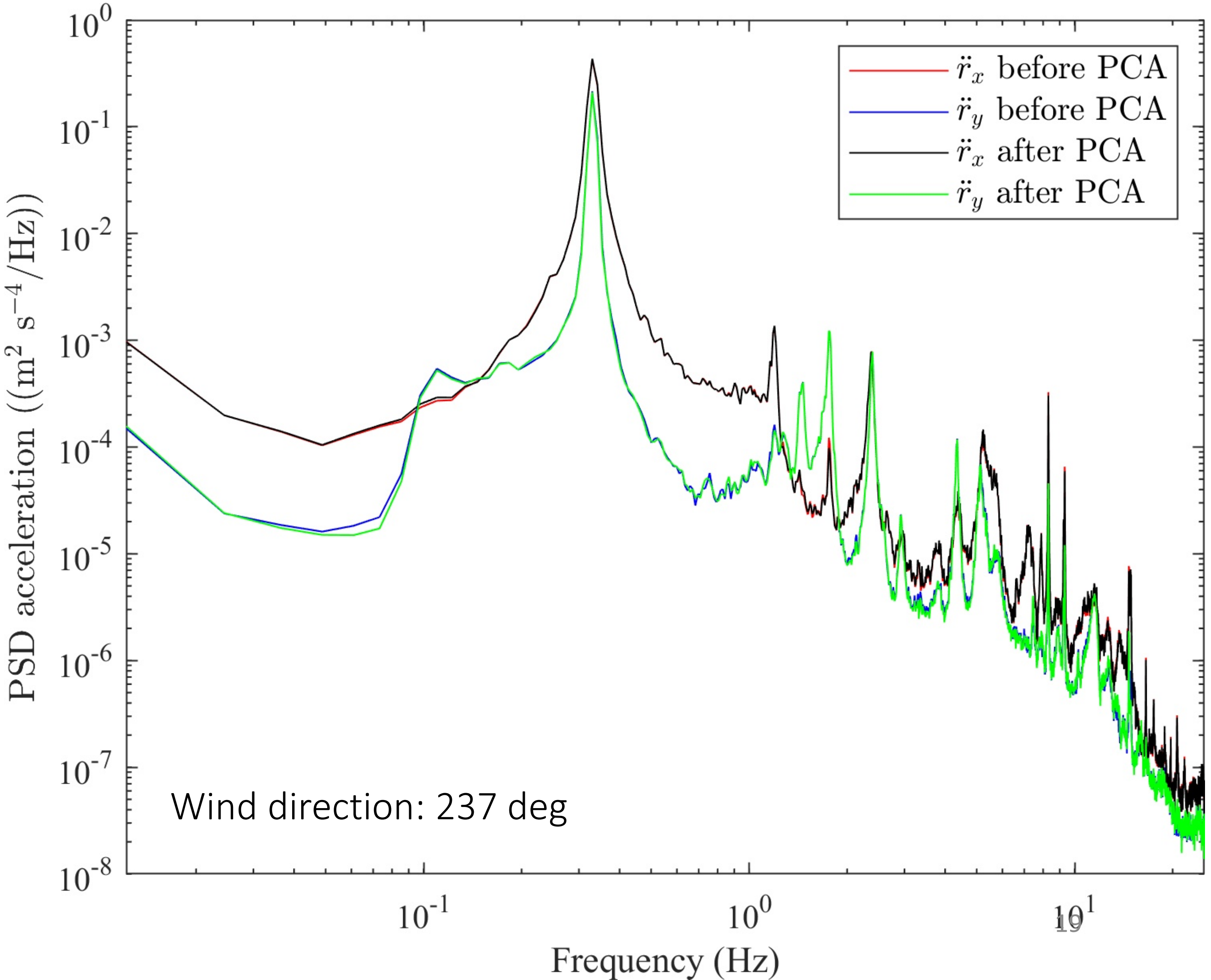
Example 2

The average between each accelerometer is selected to remove the tortional component.

The principal component analysis is applied to retrieve the along-wind and cross-wind component.

For the case at hand: almost no rotation required between the (x',y') and (x,y) coordinate systems.

The wind direction is almost perpendicular to the line crossing the two accelerometers

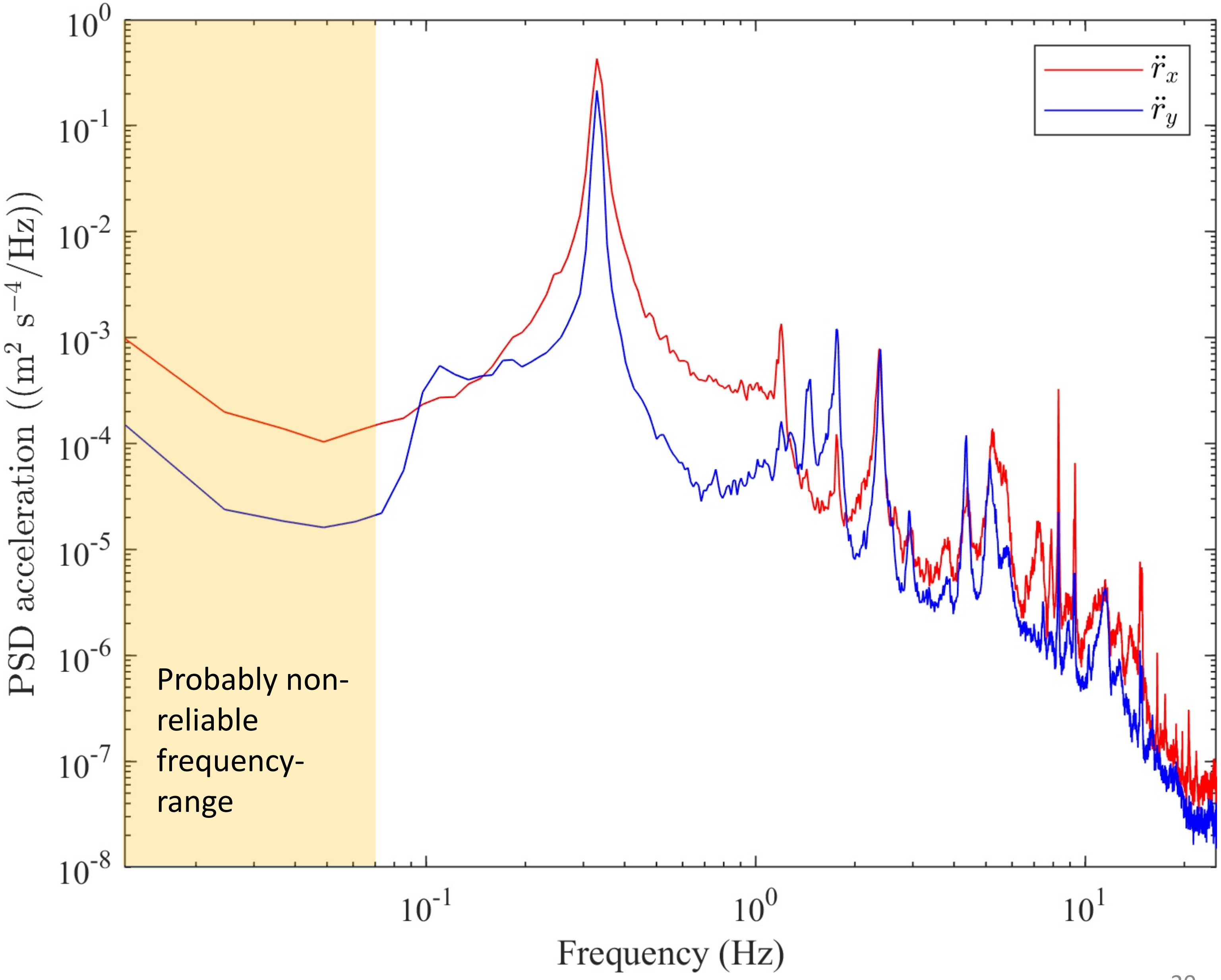


Along-wind and cross-wind responses

Mean wind speed above cut-out speed (26 m/s)

Cross-wind response has less damping than the along-wind response

Along-wind response has a larger quasi-static component, which is known from tower measurements



Operational modal analysis

case of the first bending mode

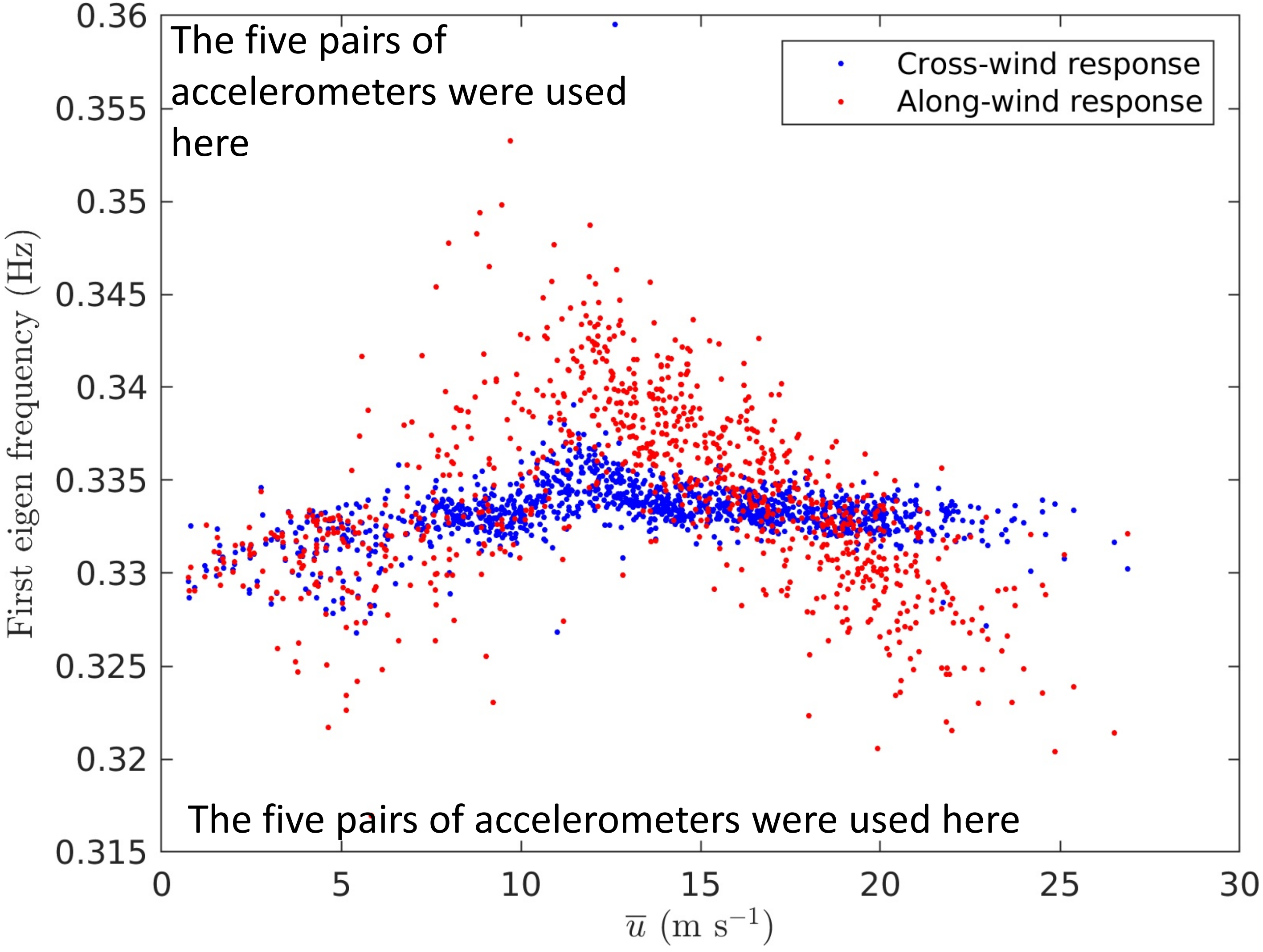
Automated Subspace stochastic identification covariance-based algorithm (SSI-COV)

This algorithm was originally tested on the Lysefjord Bridge (Norway)

Open-access:

https://se.mathworks.com/matlabcentral/fileexchange/69030-operational-modal-analysis-with-automated-ssi-cov-algorithm

The «3D mode» can be decomposed into two modes with similar eigen-frequencies

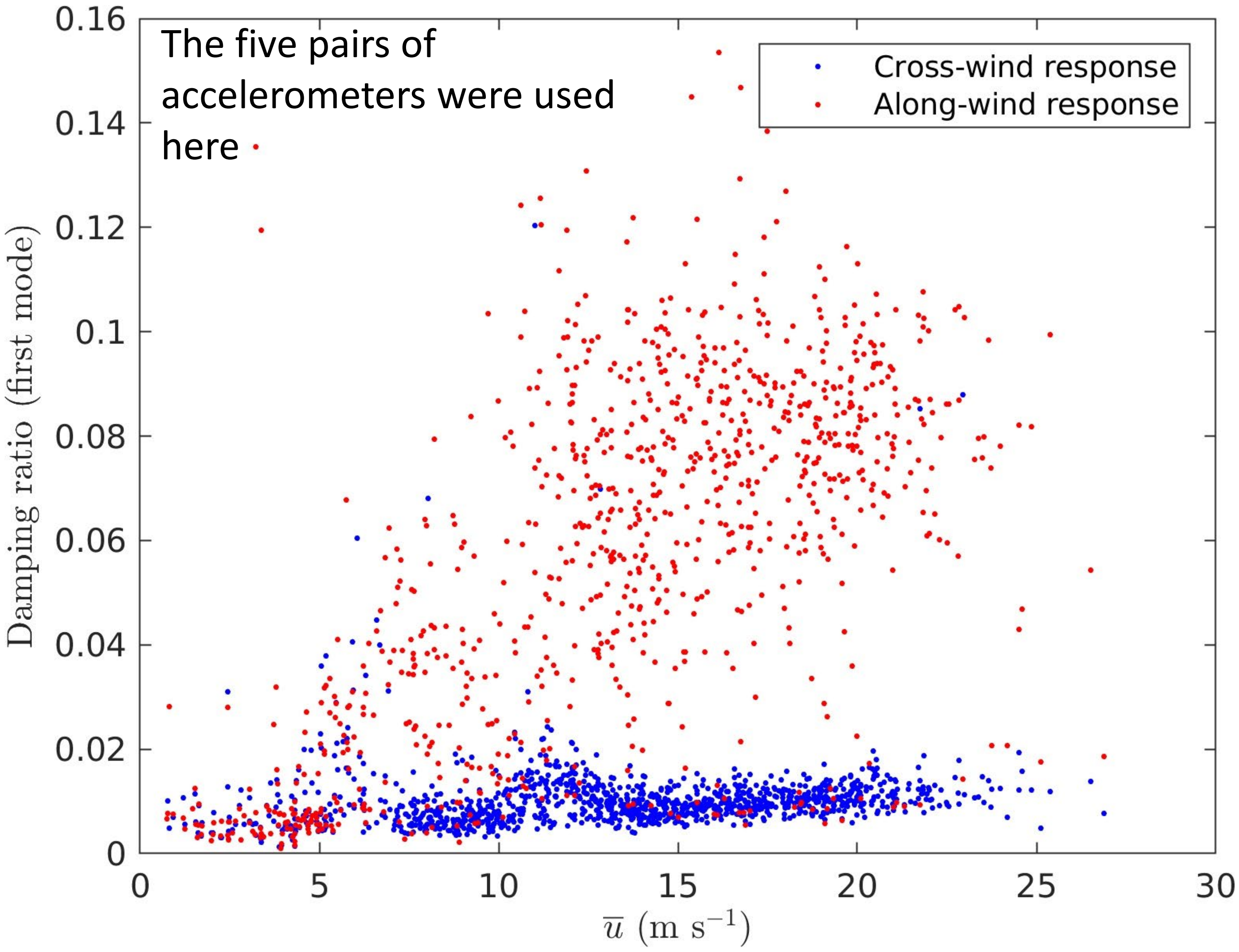


Operational modal analysis
case of the first bending mode

The damping-ratios are substantially different.

A large damping ratio is expected for the along-wind tower motion [2]

Note: Eigen frequencies up to 8 Hz were identified and are in good agreement with [3]



[2] Eliassen, L. (2015). Aerodynamic loads on a wind turbine rotor in axial motion.

[3] Häckell, M. W., & Rolfes, R. (2013). Monitoring a 5 MW offshore wind energy converter—Condition parameters and triangulation based extraction of modal parameters. *Mechanical Systems and Signal Processing*, *40*(1), 322-343.

Studying the standard-deviation of the acceleration response of the upper part of the tower

For different wind and wave conditions

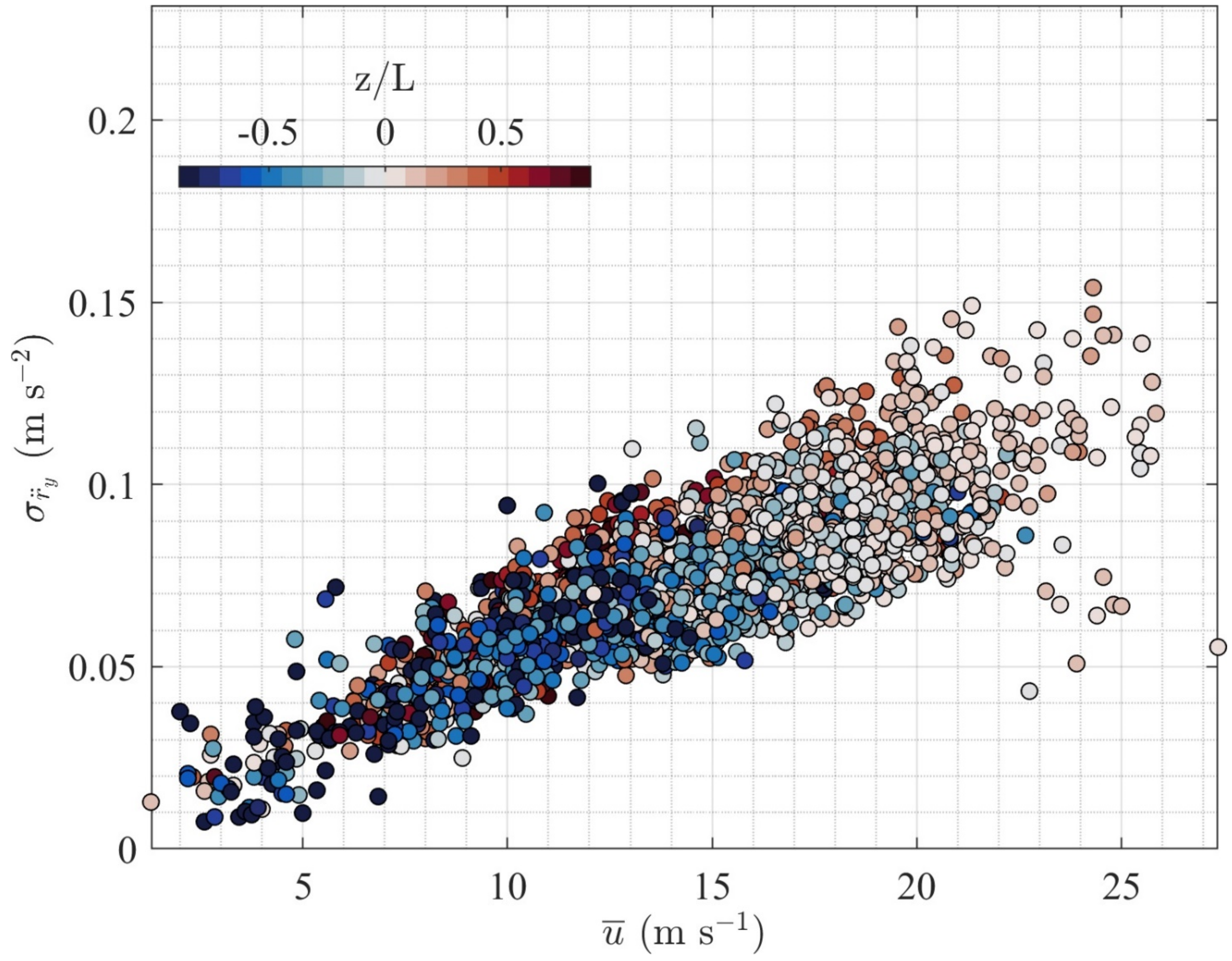
Crosswind response (acc1)

Averaging period: 10 min

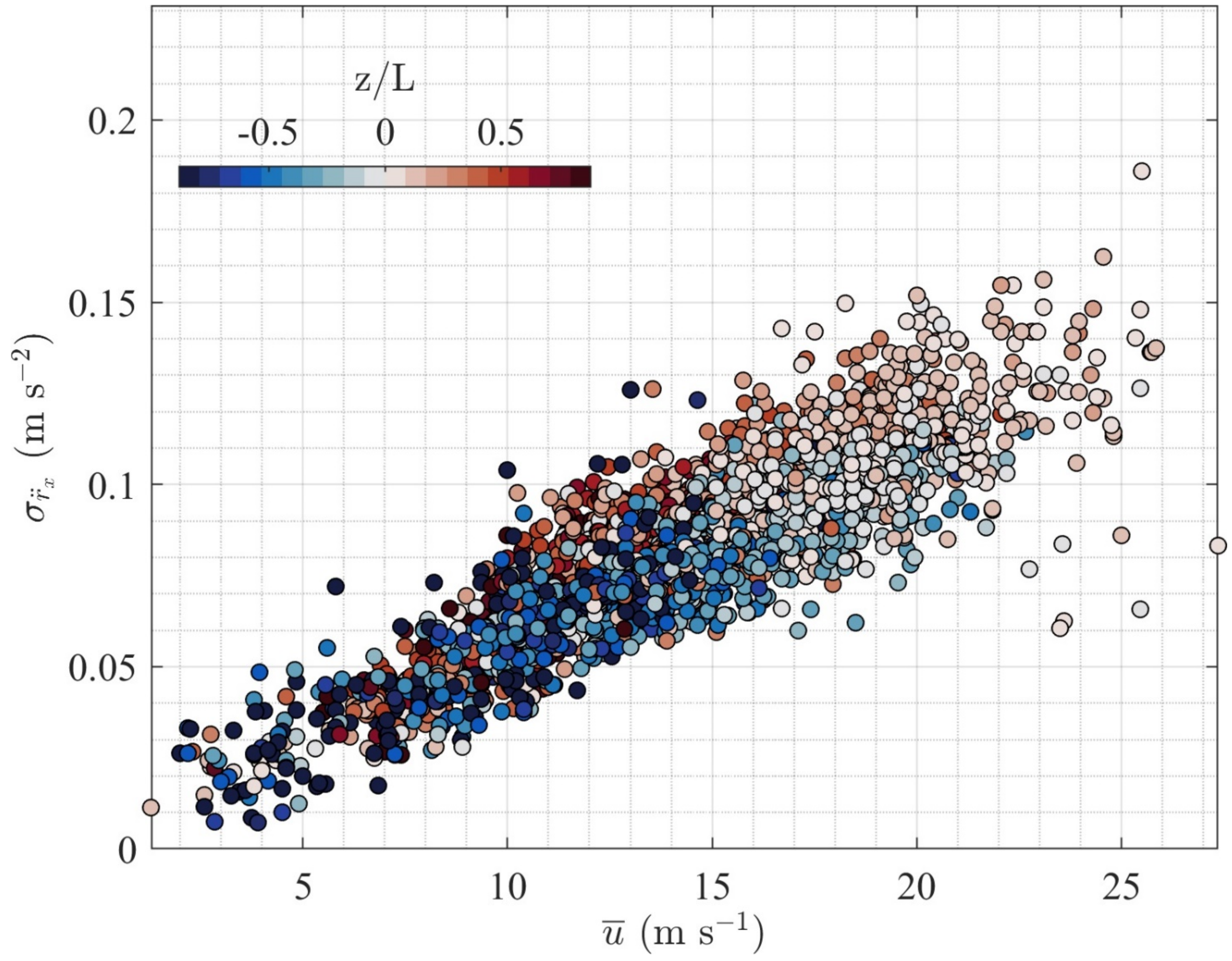
Only stationary data selected

z/L is calculated using 30-min records

Only wind directions from 180 deg to 360 deg are selected



Along-wind response (acc1)

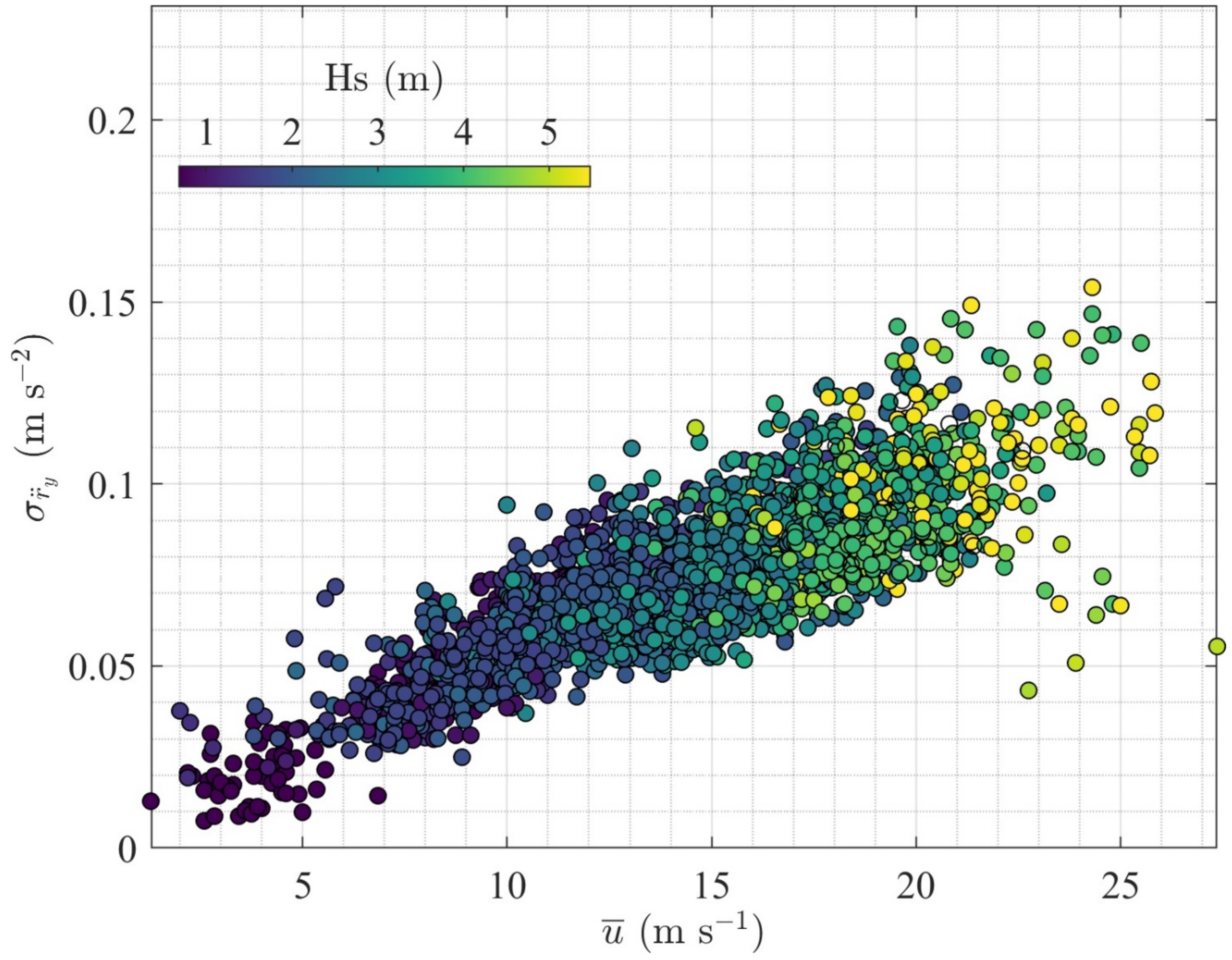


Crosswind response (acc1)

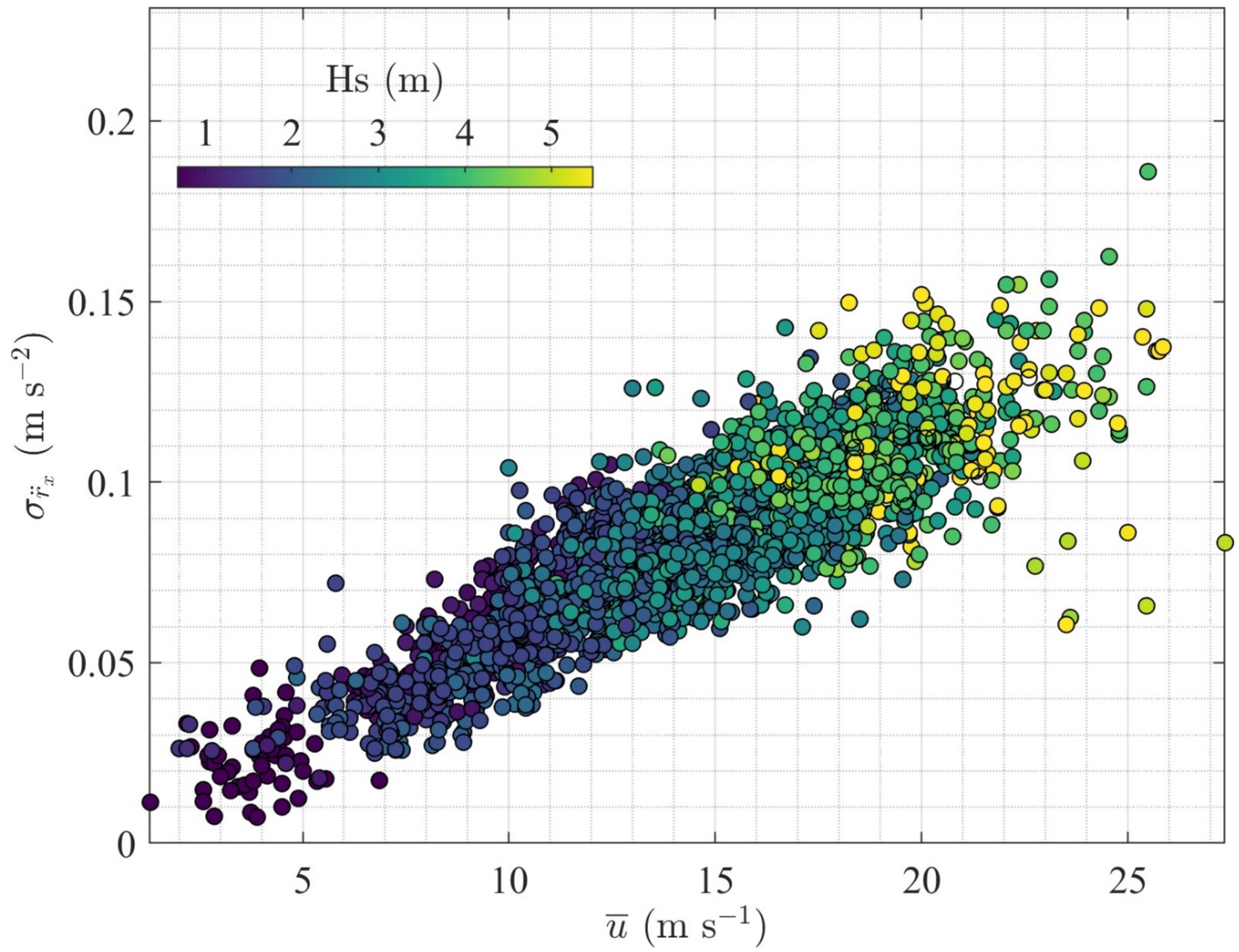
Averaging period: 10 min

Only stationary data selected

HS is calculated using 10-min records



Along-wind response (acc1)

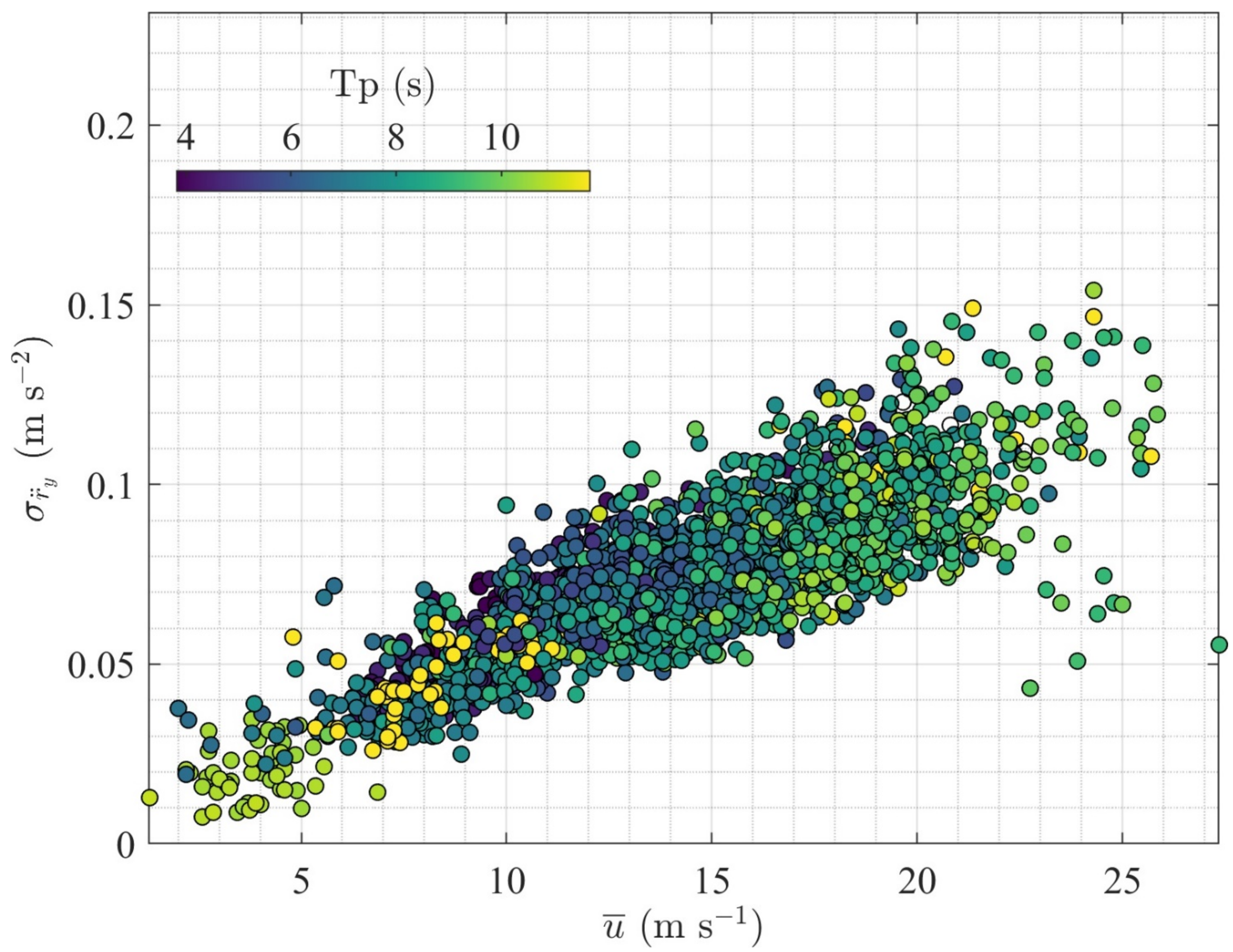


Crosswind response (acc1)

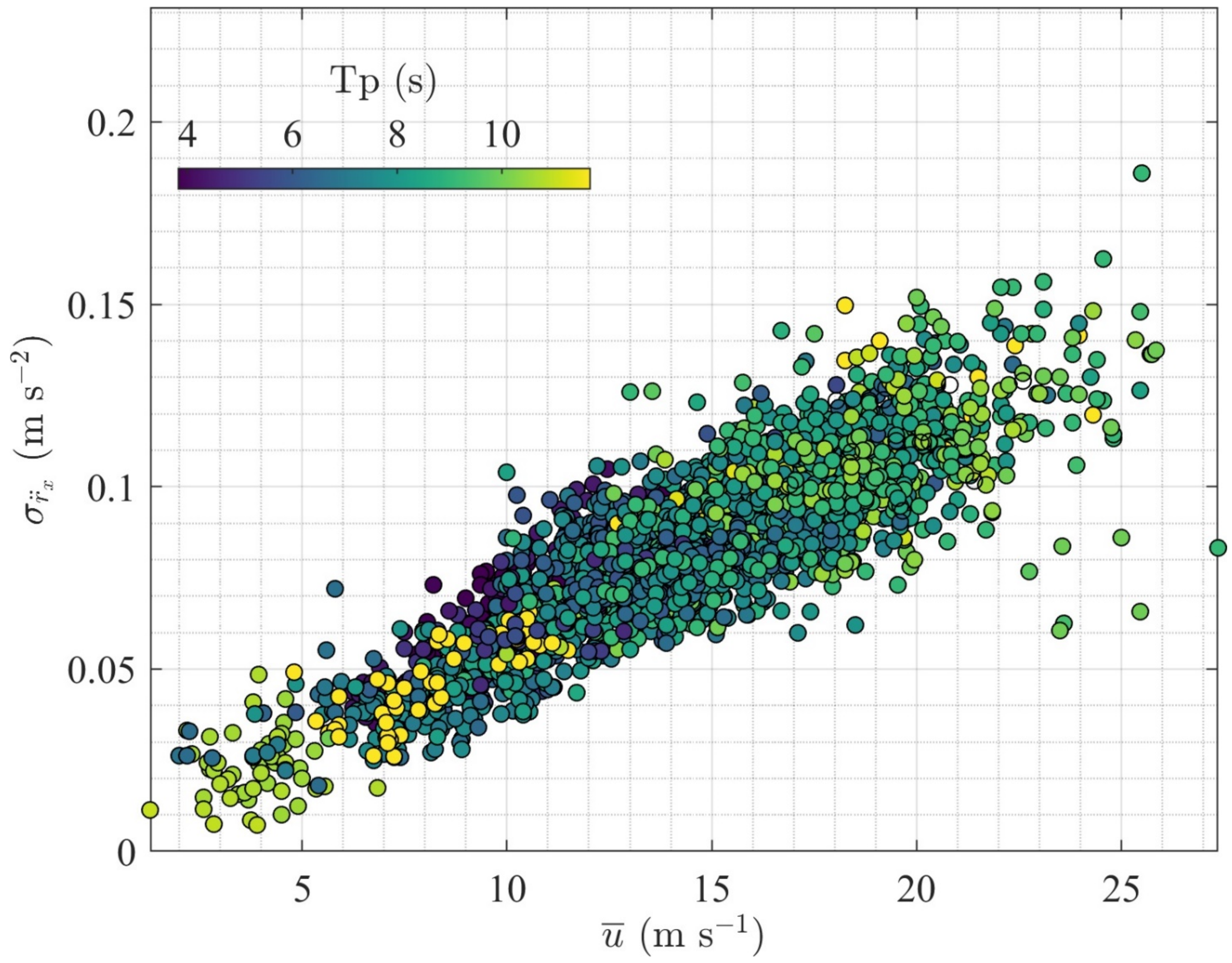
Averaging period: 10 min

Only stationary data selected

Tp is calculated using 10-min records



Along-wind response (acc1)



Conclusions

- The dynamic motion of the wind turbine tower was studied in terms of crosswind and along-wind vibration response, which are associated with different levels of damping.
- The principal component analysis may allow the study of the tower motion without precisely knowing the location of the accelerometers.
- The standard deviation of the acceleration response shows a large statistical uncertainty (random error?). Do we need more advanced load models if the random error is so large?

Thank you

Data was made available by the RAVE (research at alpha ventus) initiative, which was funded by the German Federal Ministry of Economic Affairs and Energy on the basis of a decision by the German Bundestag and coordinated by Fraunhofer IWES(see: www.rave-offshore.de)

Astrid Nybø is acknowledged for her help regarding the quality check of the sonic anemometer data. I am grateful to Nicolo Daniotti's help regarding the wind-induced motion of towers. I am grateful to Prof Jasna B. Jakobsen for her feedback on the presentation.