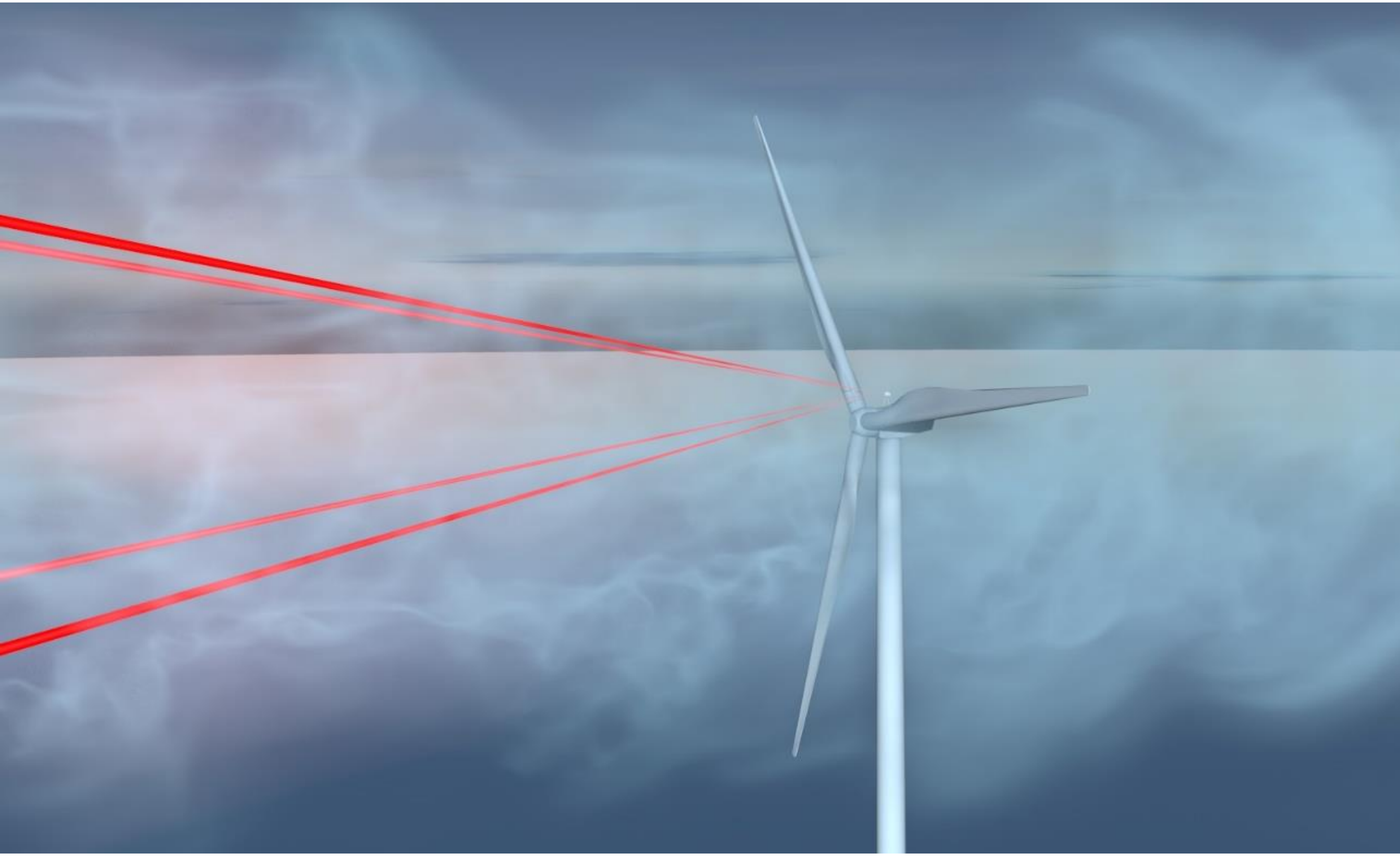
Improved modeling of lidar wind preview for wind turbine control

IEA Wind TCP Task 52



Presenter:

Feng Guo – ESR11

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Supervisors:

Prof. David Schlipf (FUAS)

Prof. Po Wen Cheng (Uni Stuttgart)

Secondment Supervisors:

Prof. Jakob Mann(DTU)

Dr. Steffen Raach (SOWENTO)

Hochschule Flensburg University of Applied Sciences

University of Stuttgart Germany

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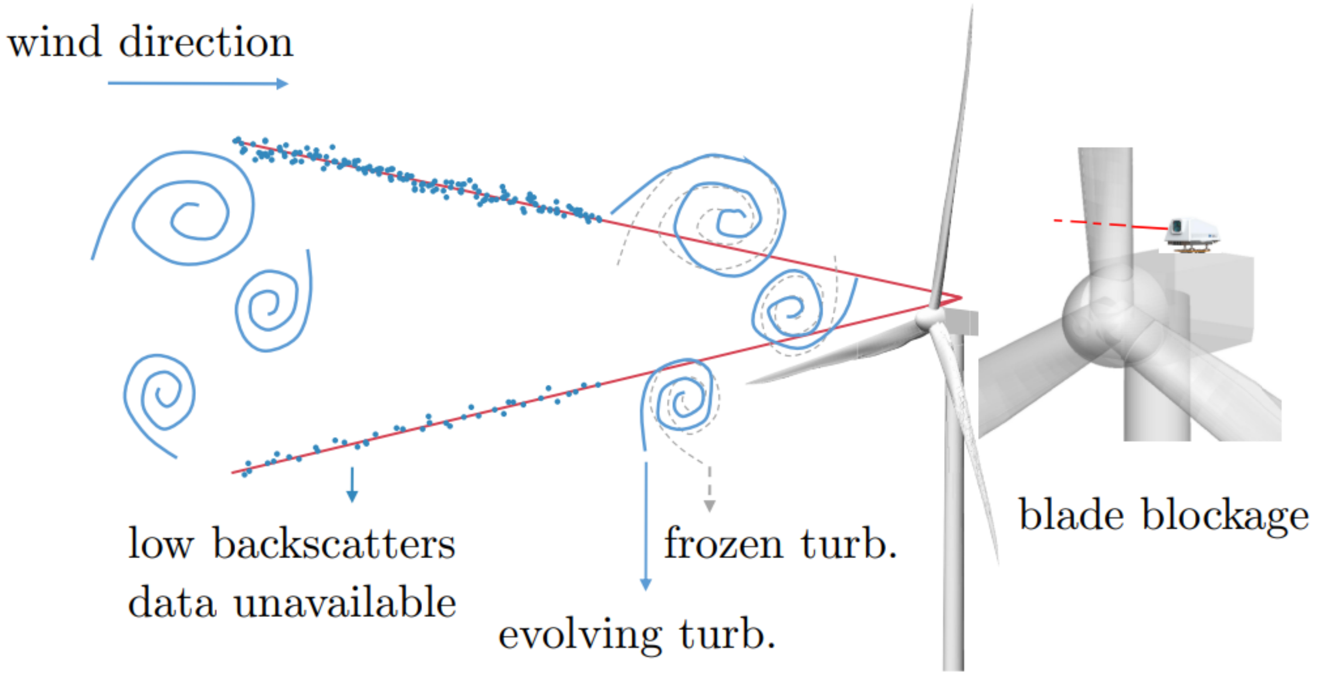
Motivations

When evaluating lidar-assisted control (LAC), unrealistic assumptions are present, e.g.

- Frozen turbulence,
- Full lidar measurement availability
- Invariant turbulence characteristic (always IEC spectra and coherence)



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Wind preview quality of lidar with improved modeling

- Wind preview quality: how lidar-estimated Rotor Effective Wind Speed (REWS) is correlated with the actual REWS.
- REWS: average longitudinal wind components over rotor swept area (more important for collective pitch control).
- Lidar-estimated REWS: average of estimated longitudinal wind components by different LOS measurements.

Wind preview quality indicators:
magnitude-squared coherence between lidar-and rotor-REWSs, the correlation in frequency domain

$$\gamma_{\mathrm{RL}}(f) = \frac{|S_{\mathrm{RL}}(f)|^2}{S_{\mathrm{RR}}(f) S_{\mathrm{LL}}(f)}$$

The transfer function for optimal low-pass filtering. A larger gain means more frequency components can be used for control.

$$|G_{\mathrm{RL}}(f)| = \frac{|S_{\mathrm{RL}}(f)|}{S_{\mathrm{LL}}(f)}$$

Contributions/Contents

1. **Improve simulation of turbulence evolution.**
2. Improve lidar measurement availability simulation.
3. Investigate the wind preview quality of lidar with improved modeling.
4. Evaluate LAC using various turbulence characteristics (spectra, coherence) related to atmospheric stability classes.

Turbulence background

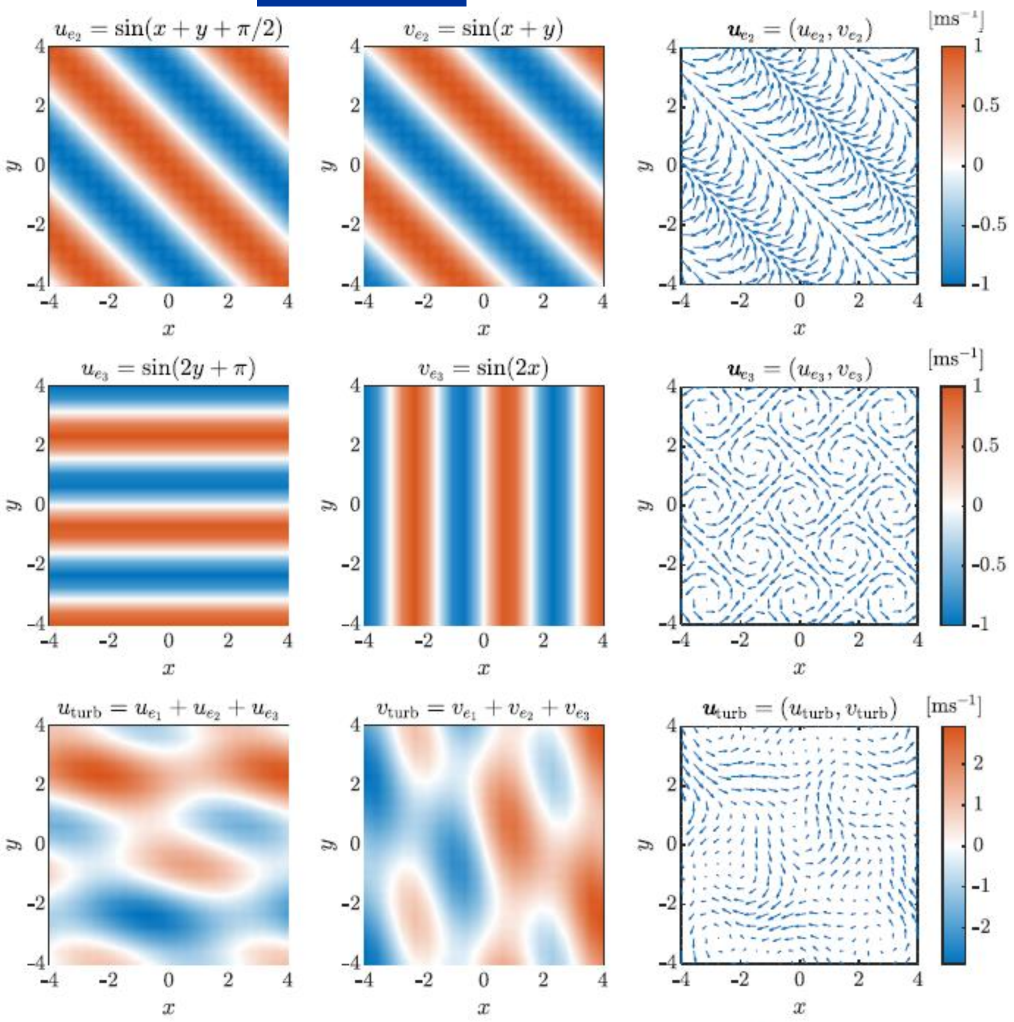

Figure 2.6: Example of eddy superimposition for the turbulent flow $\boldsymbol{u}_{turb}$. The field is superimposed by eddies with different wavelengths.

In atmospheric turbulence studies, "eddy" does not refer to any specific local distribution of velocity but to an arbitrary local flow pattern that is characterized only by its length scale [7].

The energy of eddies of different sizes is described by a spectrum. The turbulent motion can be superimposed by sinusoidal waves of different wavelengths [7].

Turbulence evolution in IEC Kaimal model

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Assumption: the combined coherence with 3D separation is the product of longitudinal and lateral-vertical coherence. [1]

$$\gamma_{u,xyz}(f) = \gamma_{u,yz}(f)\gamma_{u,x}(f).$$

Advantage: 4D turbulence can be composited from statistically independent 3D turbulence. The pre-calculate 3D turbulence can be used to efficiently generate evolving turbulence.

Disadvantage: combined coherence is underestimated, the coherence of v w components are not included.

An Opensource tool *evoTurb* is developed:https://github.com/SWE-UniStuttgart/evoTurb/releases

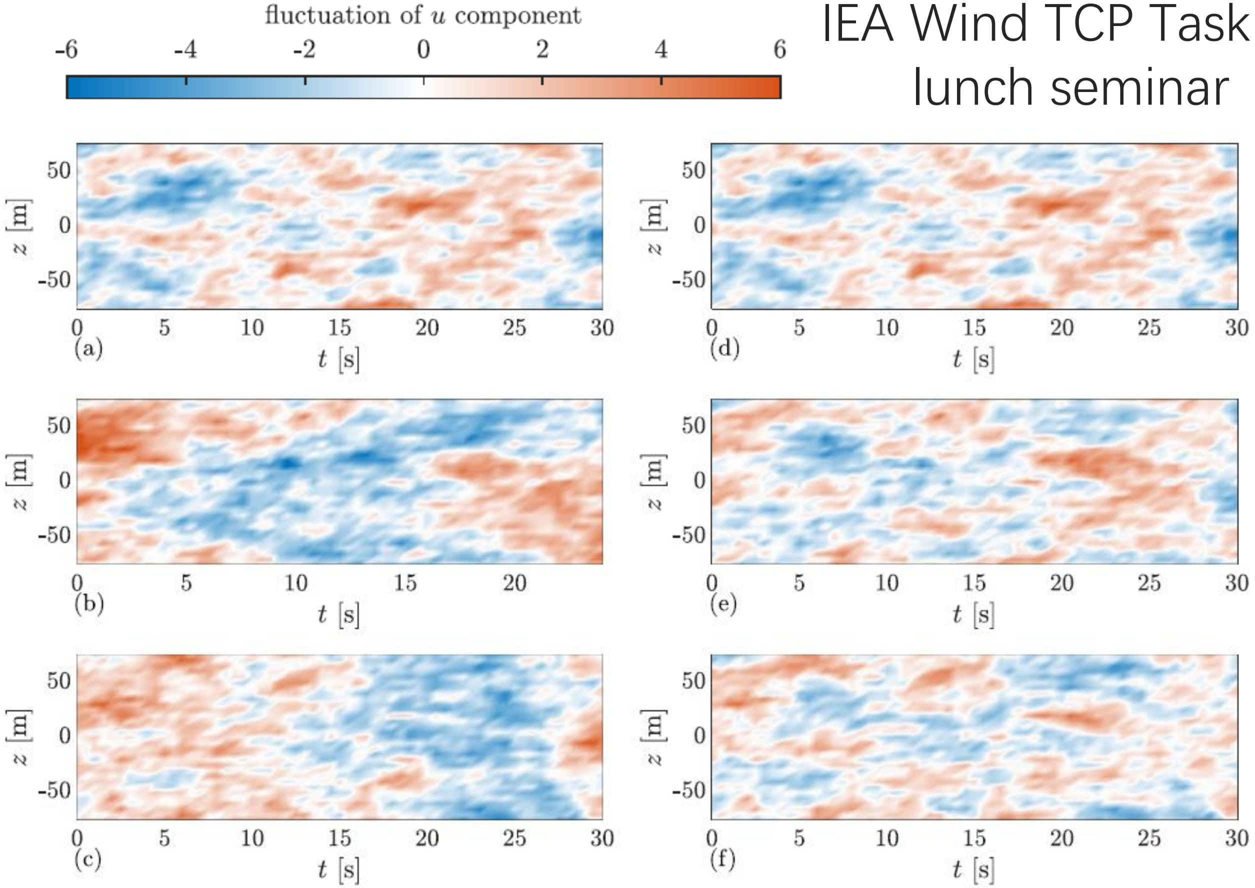

Figure 4.1: Demonstration of a 4-D turbulence field composited by three independent 3-D turbulence fields. (a–c): three independent realizations of 3-D turbulent wind fields generated using TurbSim. (d–f): 4-D turbulence field at three longitudinal positions $x = 0\,\text{m}$, $x = 60\,\text{m}$, and $x = 120\,\text{m}$, that are composited using Equation 4.73. The 4-D turbulence is generated assuming the exponential longitudinal coherence (Equation 4.64) with $U_{\text{ref}} = 16\,\text{ms}^{-1}$, $a_x = 2$ and $b_x = 0$. Note that the temporal shifts owing to the turbulence transport by the mean wind speed is not shown.

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Turbulence evolution in Mann model

Assumption: the eddies decay with a lifetime function:

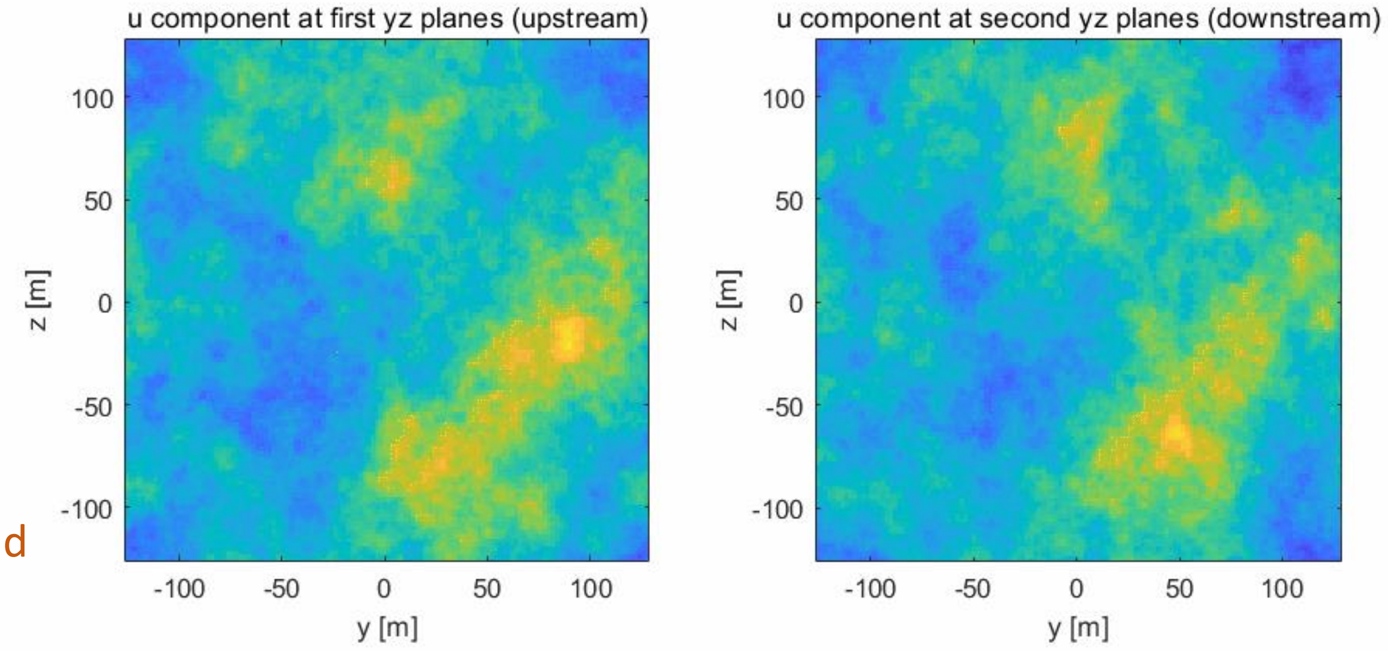
$$\tau_e(\boldsymbol{k}) = \gamma \left[a \left(|\boldsymbol{k}| L \right)^{b_1} \left((|\boldsymbol{k}| L)^{10} + 1 \right)^{\frac{b_2 - b_1}{10}} \right]$$

Then a space-time tensor is obtained [2]:

$$\Theta_{ij}(\boldsymbol{k}, \Delta t) = \exp\left(-\frac{\Delta t}{\tau_e(\boldsymbol{k})} \right) \Phi_{ij}(\boldsymbol{k}),$$

Advantage: Overall better representation of spectra and coherence based on measurement data.

Disadvantages: More complex mathematical expressions.



An example of Mann model-based 4D stochastic turbulence fields

The 4D Mann turbulence generator available from
https://github.com/MSCA-LIKE/4D-Mann-Turbulence-Generator

Validation of 4D turbulence models

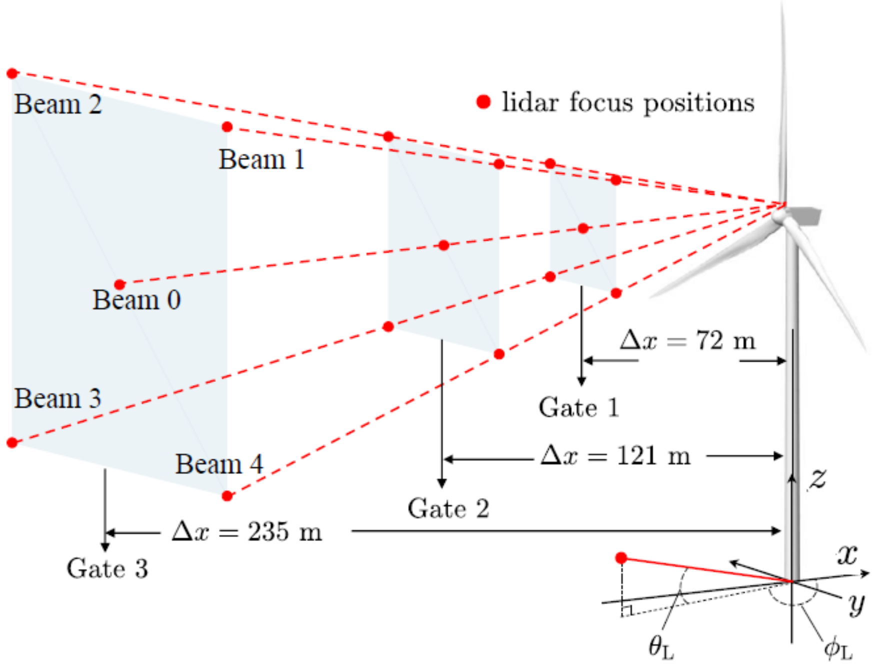
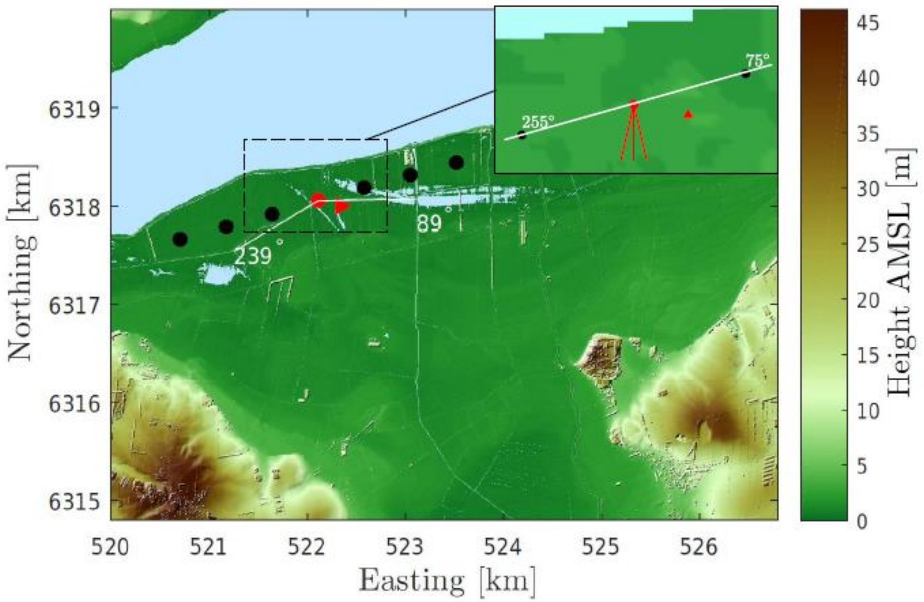


Figure 4.8: Sketch of the five beam Avent lidar measurement characteristics. Only three measurement gates are shown as examples.



Lidar and Sonic measurements (triangle in the right figure) were collected from Nørrekær Enge wind farm (northern Jutland, Denmark). Provided by Technical University of Denmark [2]

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Improve simulation of turbulence evolution

Validation of 4D turbulence models

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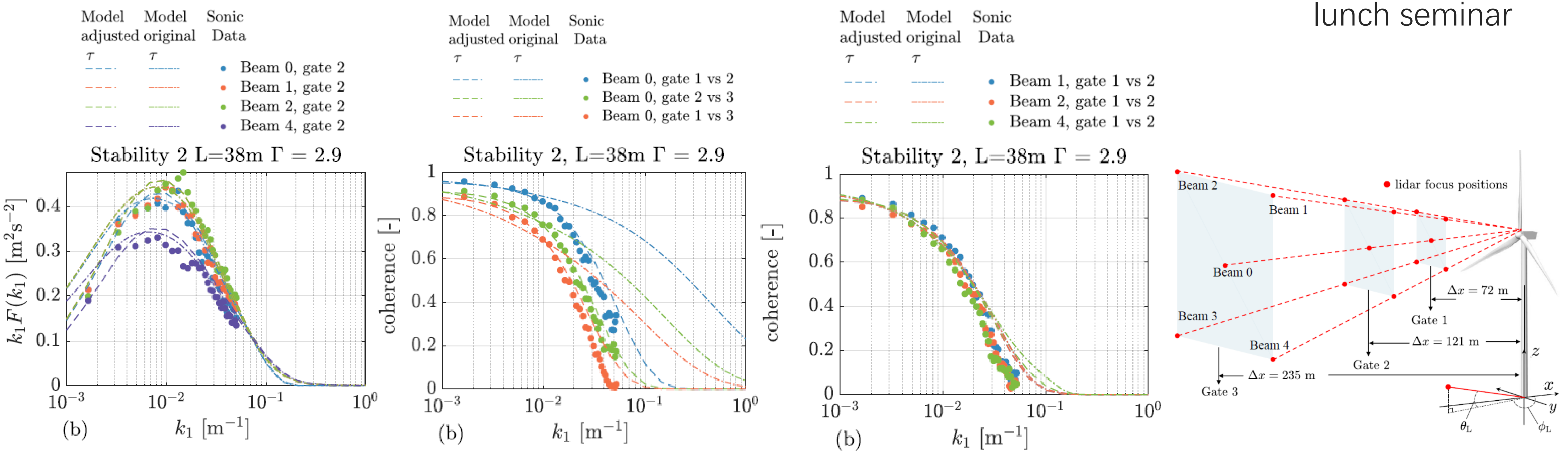

Comparison of lidar LOS velocity spectra (left), longitudinal coherence (middle), and 3D spatial coherence (right) of the Mann model-derived ones and those calculated from Avent measurements.

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Improve lidar measurement availability simulation

Lidar CNR analysis and modeling

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Figure 6.4: Overview of the lidar measurement site for CNR data analysis.

Campus of Flensburg University of Applied Sciences in northern Germany, using the four-beam pulsed lidar (Molas NL200)

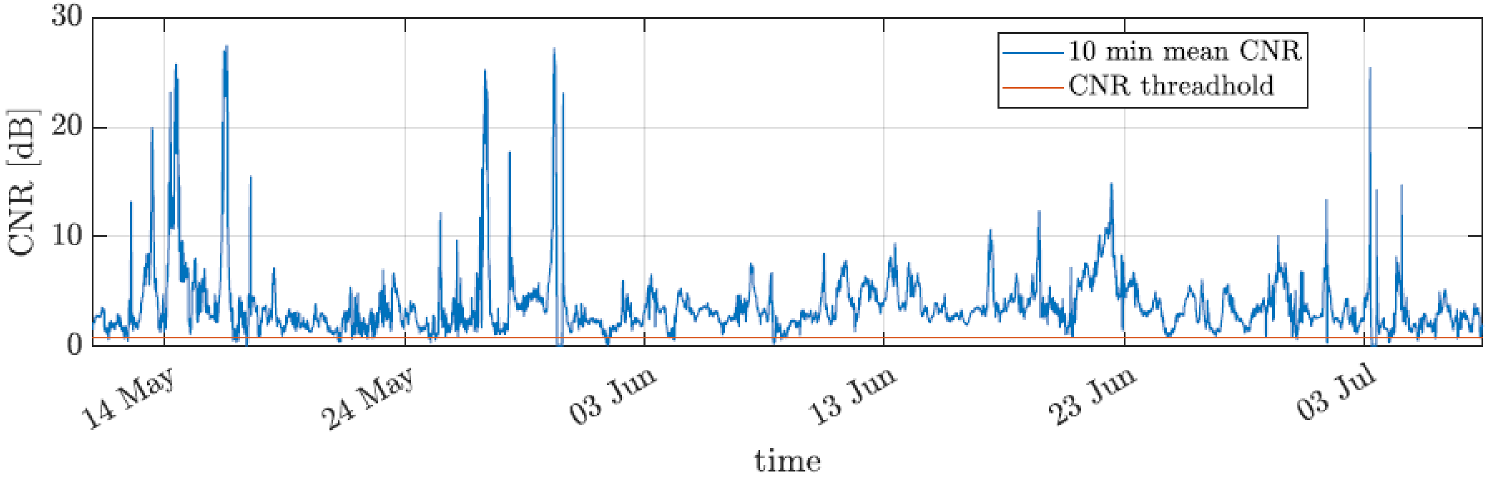

Figure 6.5: 10min mean CNR of beam 1 from the Molas NL200 lidar.

The CNR durations with mean CNR below the threshold looks statistically stationary. [3]

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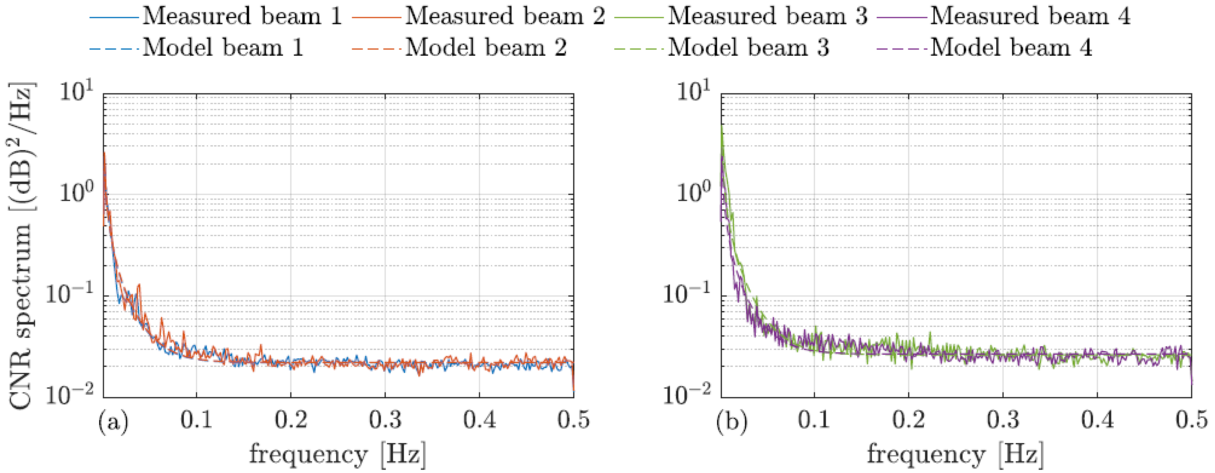
Lidar CNR model

A spectral model for the CNR signal

$$S_{\mathrm{CNR}}(f) = a_c(1 - 10^{-d_c f})^{-1} + e_c$$



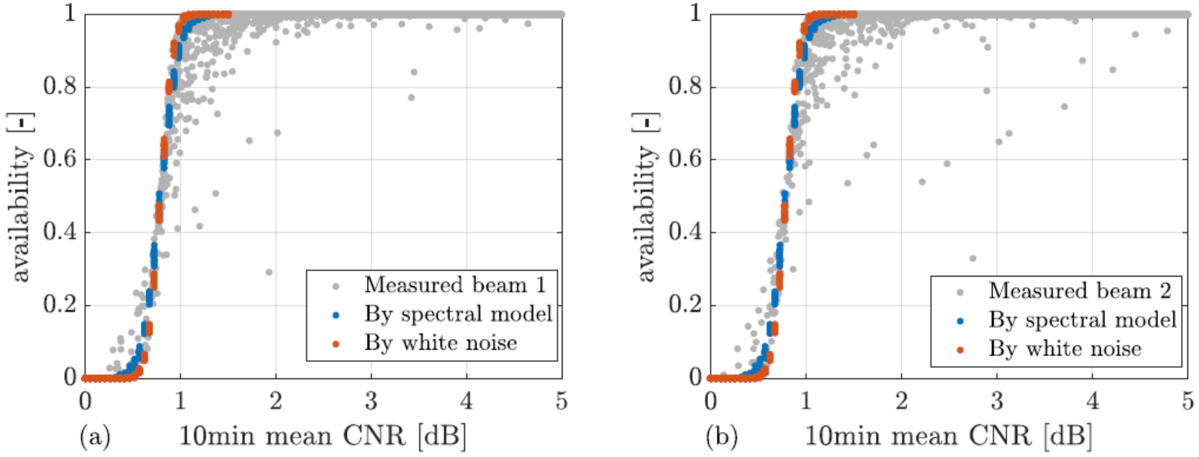
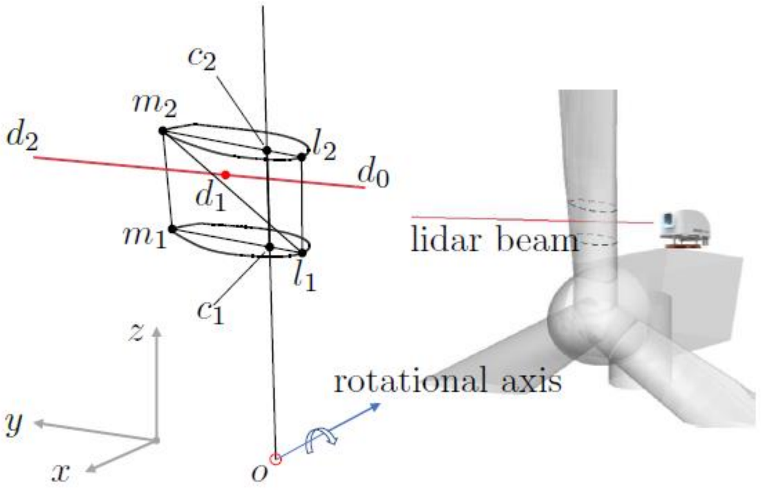


Figure 6.8: Comparisons of the availability using spectral model and measurement. The data from the range gate at $x = 190$ m are plotted.

While noise is sufficient to represent the availability caused by low CNR durations in a statistical manner.

Lidar measurement availability model: blade blockage



Geometrical sketch of the blade blockage detection algorithm. The lidar figure courtesy of Movelaser.

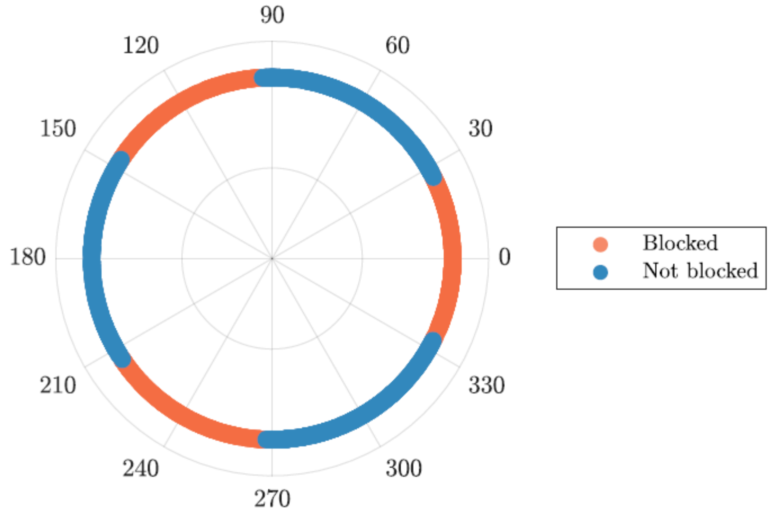


Figure 6.3: Polar scatter plot of the blade blockage status of the lidar beam based on OpenFAST simulation. The polar coordinates indicate the azimuth angle of the first blade in the rotational frame. Only the blockage status of beam 1 is plotted. The lidar measurement trajectory is provided in Table 5.3.

Validation of the algorithm in OpenFAST.

Improve lidar measurement availability simulation

Updated lidar simulation module in OpenFAST 3.0

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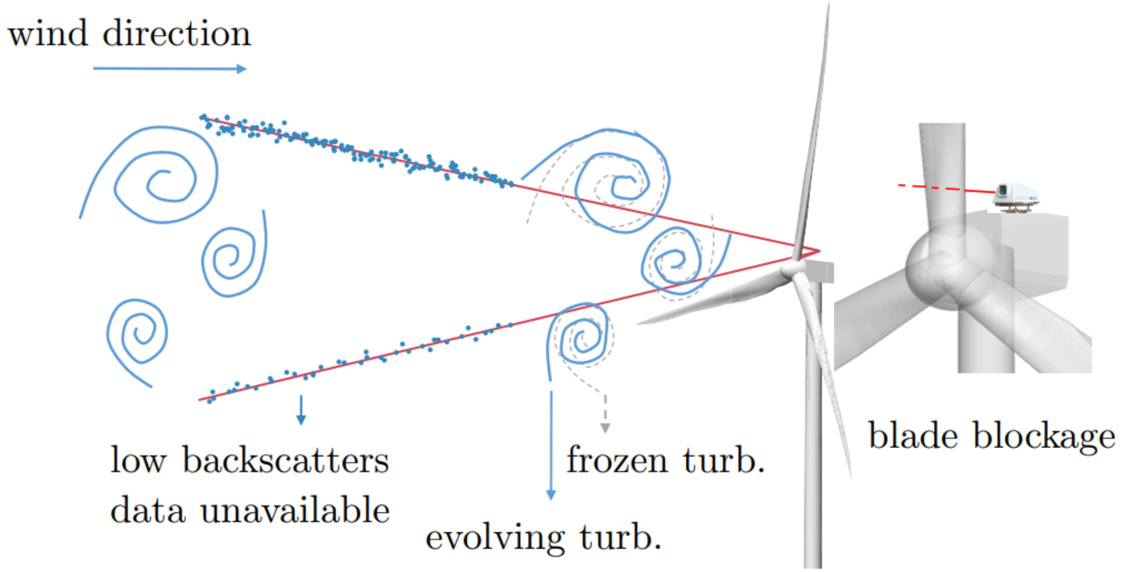
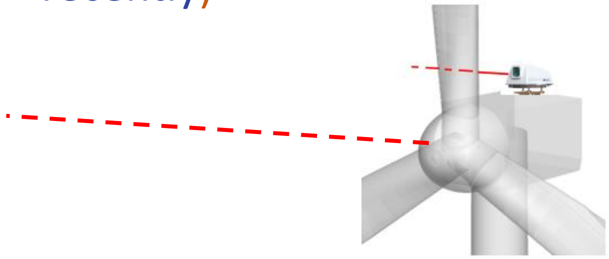


A more realistic and updated lidar simulation module in the aeroelastic simulation tool OpenFAST. [3]

a. Possibility to include evolving turbulence wind fields
b. Blade blockage effect simulated
c. Adjustable lidar measurement availability (due to low backscatters)
d. Possible to simulate a spinner-mounted lidar (added recently)

Available here: https://github.com/MSCA-LIKE/OpenFAST3.0_Lidarsim



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Wind preview quality of lidar with improved modeling

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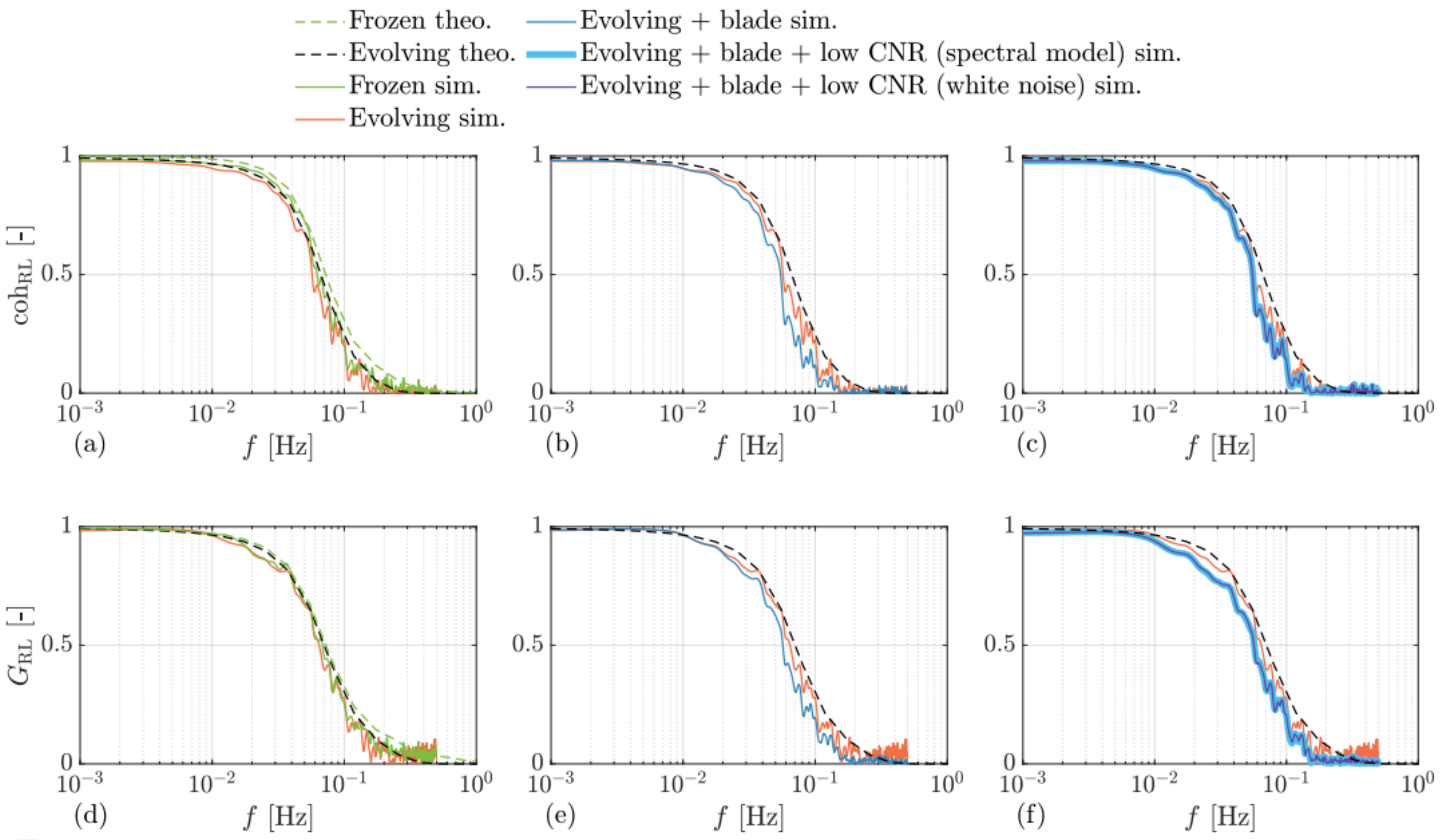
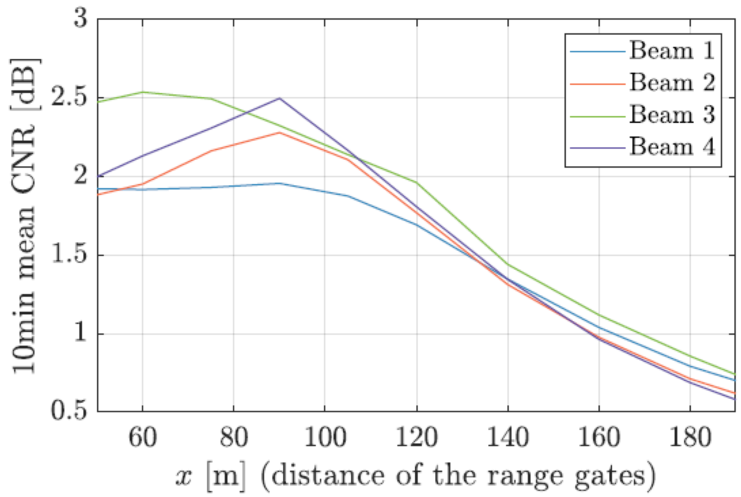
- ➢ Simulations using the updated OpenFAST LidarSim module and 4D Mann turbulence generator.
- ➢ Considering 4 beam 10 gates pulsed lidar and NREL 5MW rotor





CNRs from measurement are used for simulation

These phenomena show marginal impacts on the wind preview quality for the LAC of the NREL 5MW turbine using a four-beam pulsed lidar.

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Evaluate LAC using various turbulence characteristics classes.

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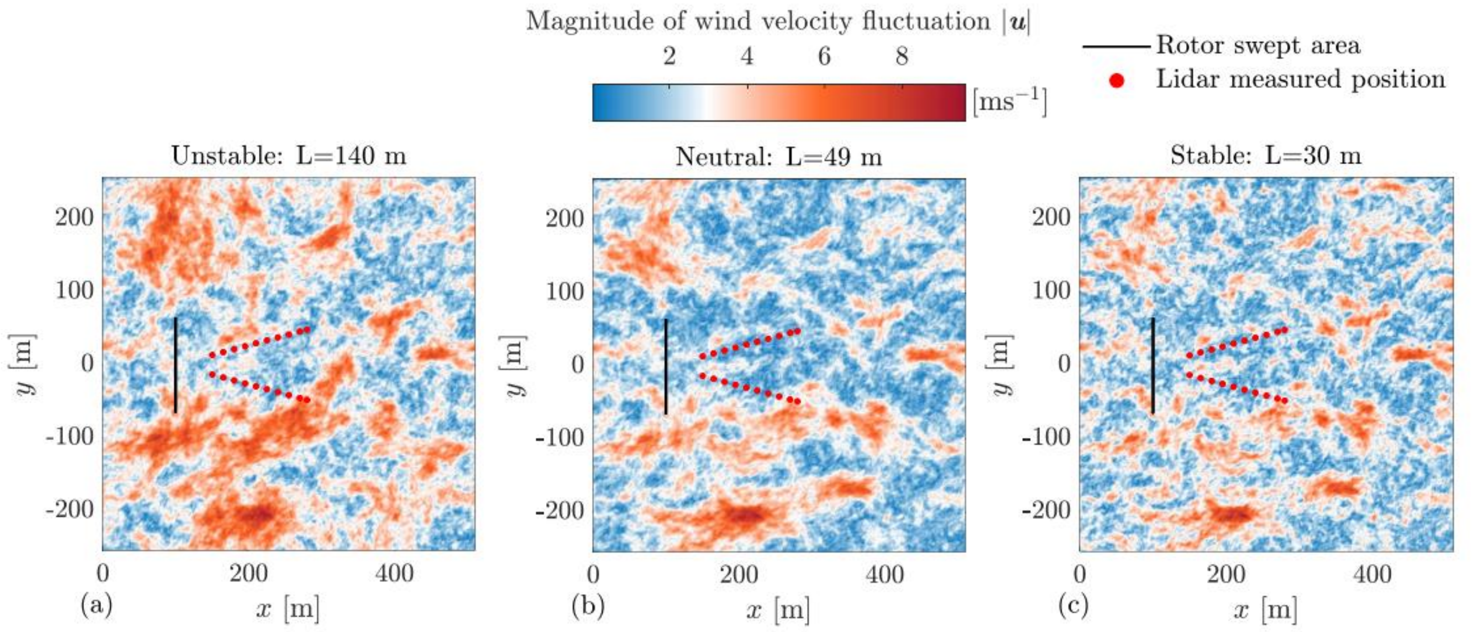

Figure 5.1: Top view of a turbulence field showing the eddy structures under different atmospheric stabilities, simulated using the *4-D Mann Turbulence Generator* with parameters listed in Table 5.1

Why this is important?

Its not clear if lidar-assisted control is robust in different atmospheric stability conditions [4]

A larger length scale (unstable atmosphere):

- More spatially coherent low-frequency components
- Turbulence decays more severely in the longitudinal direction
- Usually higher Turbulence intensity

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Evaluate LAC using various turbulence characteristics classes.

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- 16 ms^{-1}
- 22 ms^{-1}

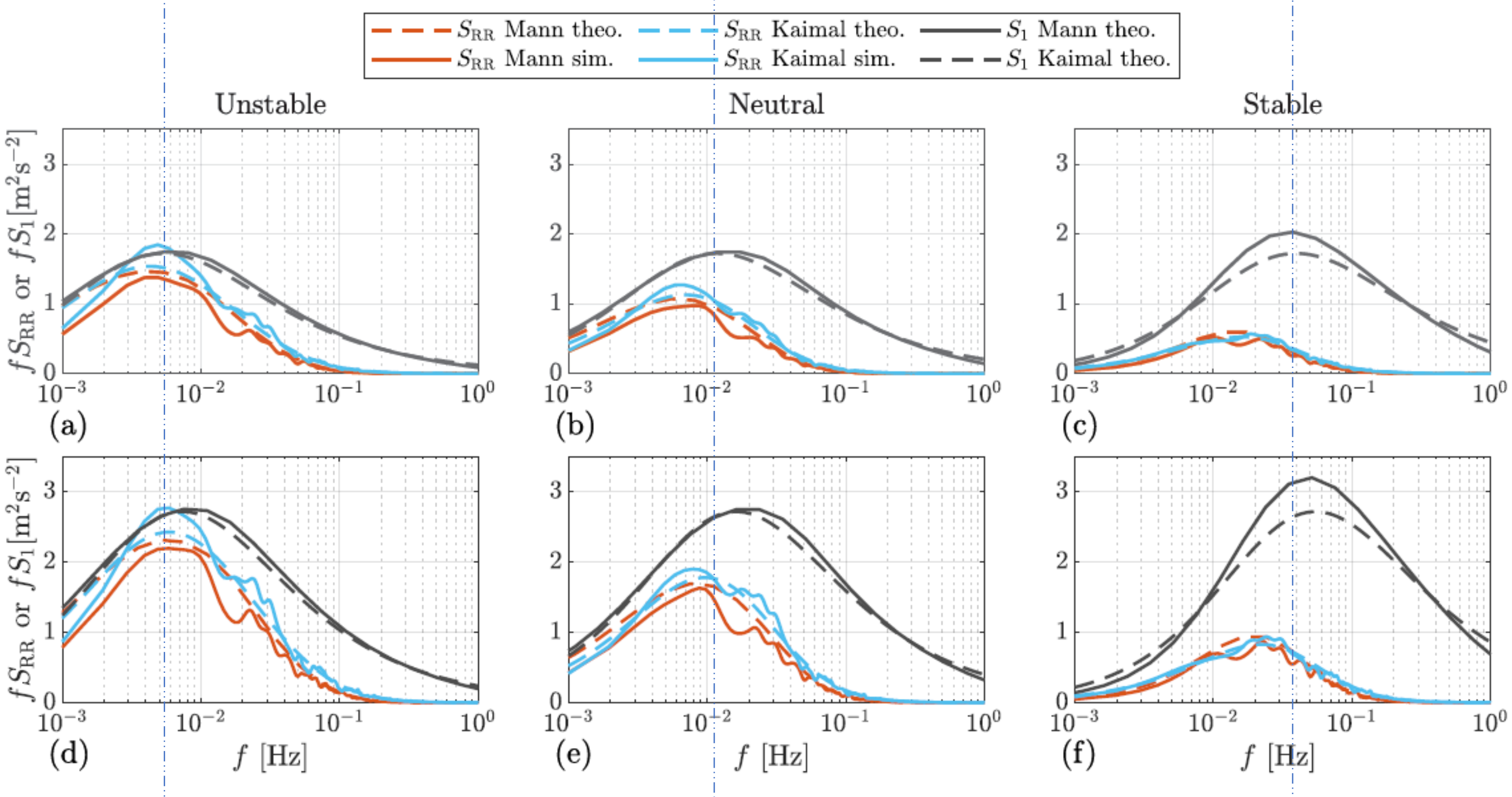

Figure 7.2: Auto-spectra of REWS. "theo.": theoretical spectra using the models discussed in Section 5.2.1, i.e., Equations (5.135) and (5.136). "sim.": spectra estimated from the time series of the turbulent wind fields in OpenFAST simulations using Welch's method [79]. (a) to (c): the results with a mean wind speed of 16 ms^{-1}. (d) to (f): the results with a mean wind speed of 22 ms^{-1}.

A larger length scale (unstable atmosphere):

Spectral peak frequency shift left

A higher mean wind speed

Spectral peak frequency shift right

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Evaluate LAC using various turbulence characteristics classes. NREL5MW

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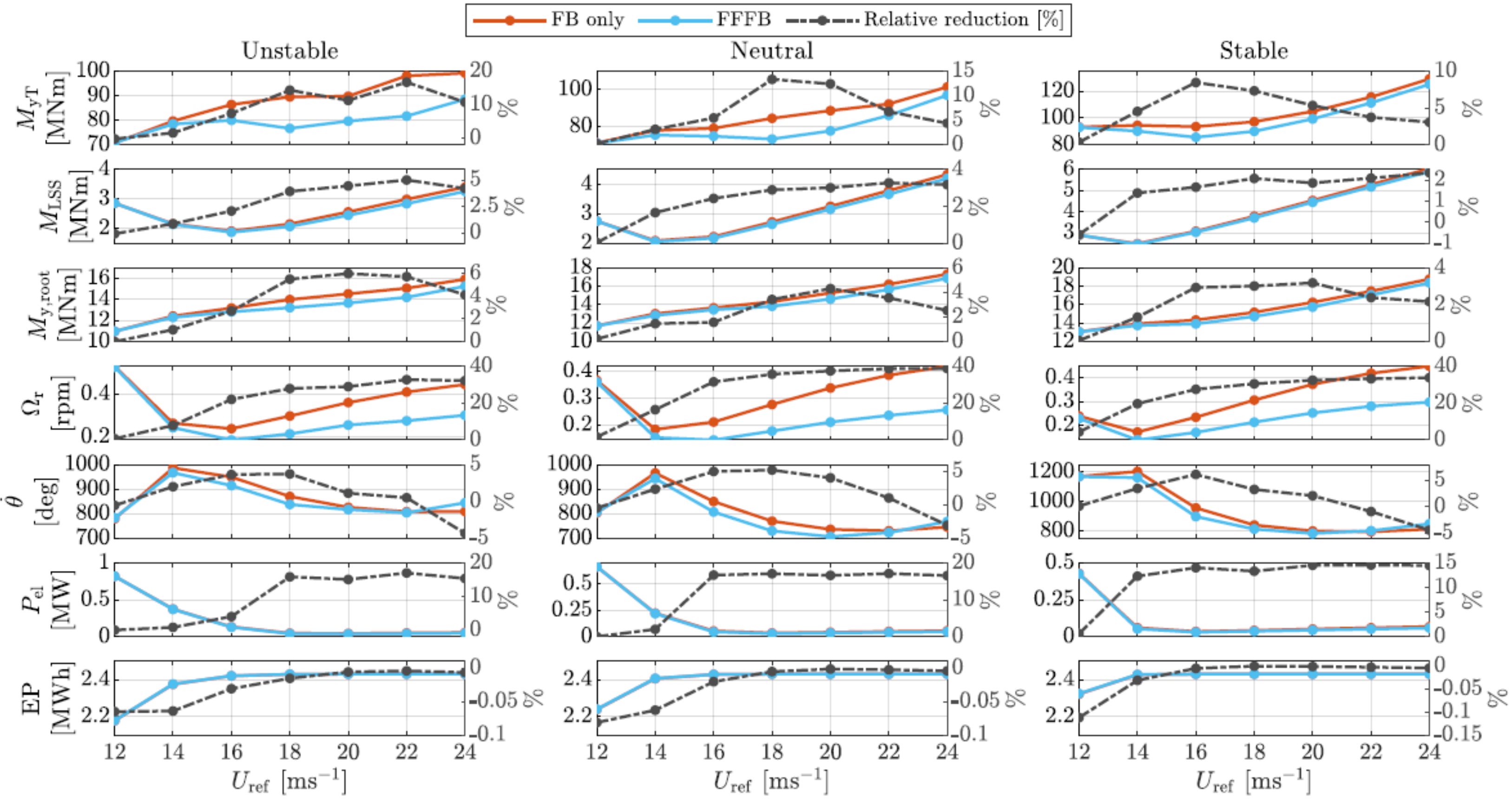

Figure 7.5: Comparison of DEL (M_{yT}, M_{LSS}, $M_{y,root}$), STD (Ω_r,$\dot{\theta}$,P_{el}), and EP, simulated using the Mann model. Note that the value of the relative reduction are reflected on the right right-hand side of the y axis. Relative reduction: the results using FB-only is extracted by the results using FFFB and then divided by the results of FB-only.

Using a four-beam 10 gates pulsed lidar

Opensource ROSCO is used for FB-only control [6]

LAC is beneficial in all stability, but more in unstable. The IEC turbulence length scale is closer to Stable... [4]

https://github.com/MSCA-LIKE/Baseline-Lidar-assisted-Controller/releases

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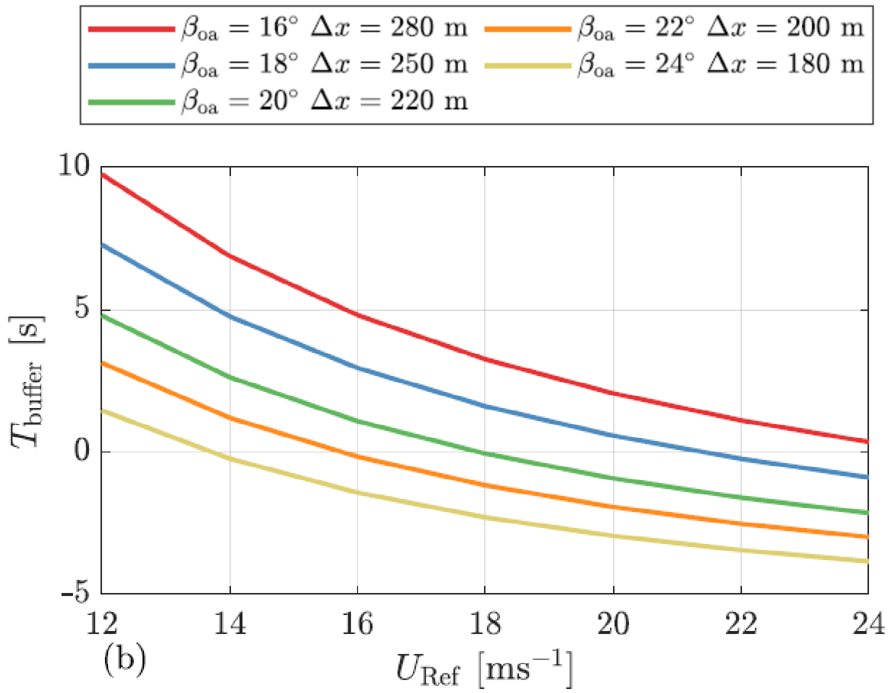
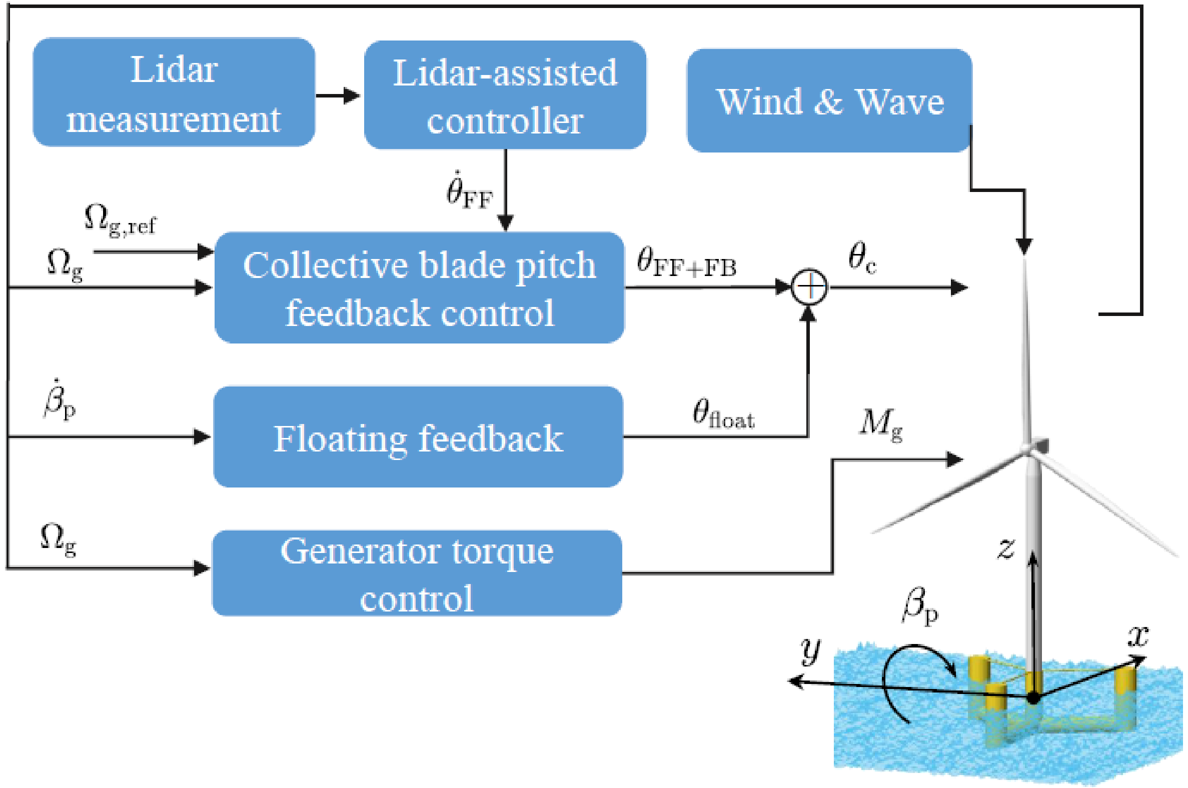
Evaluate LAC using various turbulence characteristics classes. IEA15MW

Using a four-beam
1 gate pulsed lidar, measuring 280m upstream.



(b)



An optimally tuned multivariable feedback, tuning variables: Kp Ti, floating feedback gain

Evaluate LAC using various turbulence characteristics classes. IEA15MW

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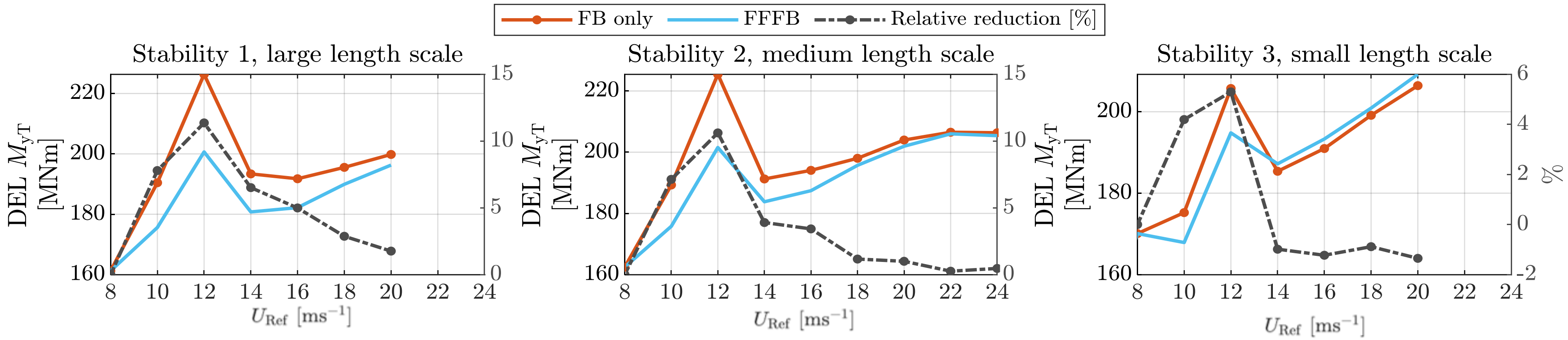
$\zeta \in$	Stability 1 [-0.3,-0.1)	Stability 2 [-0.1,0.1)	Stability3 [0.1,0.3)
L [m]	139	73	26
Γ [-]	2.3	2.6	2.8



Fitted based on FINO1 measurement by the Mann model. The length scale in stability 2 (close to neutral) is twice the IEC suggested value. Stability 2 has the highest probability among all mean wind speeds [5].

Check the Submission

WES-2023-9 | Research article

Received: 31 Jan 2023

Lidar-assisted feedforward and multivariable feedback controls for large floating wind turbines

Feng Guo and David Schlipf

Status: Initial associate editor decision (WES Discussions) | **Iteration:** Initial submission

- Clear reductions except for stability 3 with high mean wind speeds.
- The filter of LAC is derived from Stability 2.
- The length scale is close to the IEC value (34m) in Stability 3.

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Main Conclusions

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1. Spectra and spatial coherence of lidar LOS measurements show good agreement with current turbulence models.
2. For the 5MW turbine and 4-beam multi-range lidar, turbulence evolution, blade blockage, and typical low CNR durations have a marginal impact on the preview quality.
3. For the 15MW turbine, it is important to use a lidar measuring farther away.
4. For both turbines, LAC is more beneficial in atmospheric stability conditions that have a larger turbulence length scale.
5. Potentially underestimate LAC benefits if the IEC length scale used.

Suggestions and Outlooks

1. Site turbulence characterization can be carried on by nacelle lidar.
2. For fatigue analysis of large offshore turbines, especially floating ones, the uncertainty of using a rare small-length scale suggested by the IEC standard needs to be considered.
3. Lidar wind preview modeling under extreme operating conditions, e.g. extreme gust, extreme coherent direction change, and extreme turbulence, can be further studied.

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Thanks for your attention!

Lets talk more…

Feng Guo
feng.guo@sowento.com

There will be more interesting topics about lidar by LIKE people!

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Photo by Simon Rubin, during DeepWind Conference 2023

The project LIKE Lidar Knowledge Europe H2020-MSCA-ITN-2019, Grant no. 858358 is funded by the European Union.

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