ForWind
Center for Wind Energy Research
Bremen Hannover Oldenburg

CARL VON OSSIETZKY universität OLDENBURG

Characterization of Wake Turbulence Using Staring Lidar Measurements

D. Bastine, M. Wächter, D. Trabucchi, M. Kühn and J. Peinke

ForWind – Center for Wind Energy Research, Institute of Physics, Carl-von-Ossietzky University of Oldenburg, 26111 Oldenburg, Germany

Motivation

Wind turbines often operate in the wake of other turbines. Wakes are highly turbulent flows with a decreased mean velocity and an increased turbulence intensity. The characteristics of turbulent flows have a strong impact on the power production and the loads acting on a turbine. Thus, to understand the impact of wakes in detail their turbulent features need to be investigated.

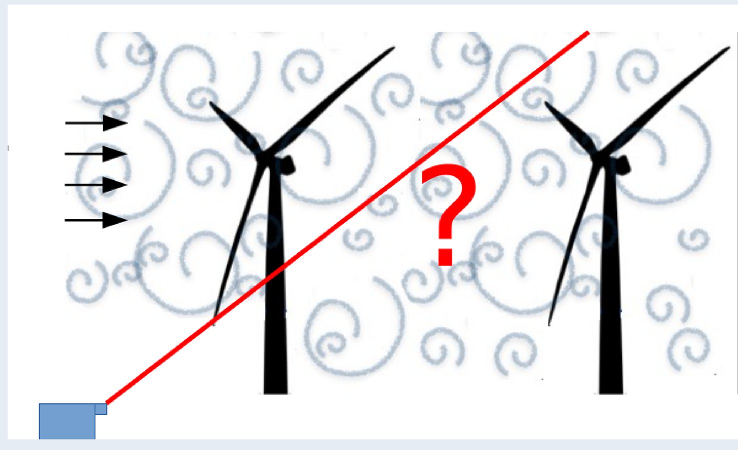

Figure 1: Turbulence of Turbulence?

For this purpose, we analyze "staring" lidar measurements performed in the offshore wind farm Alpha Ventus. Our results indicate that wind turbines modulate the turbulent structures on a wide range of scales. Spectral analysis and increment statistics reveal features of homogenous isotropic turbulence. This indicates the initiation of a new turbulent cascade starting on scales in the order of the rotor diameter.

Measurements

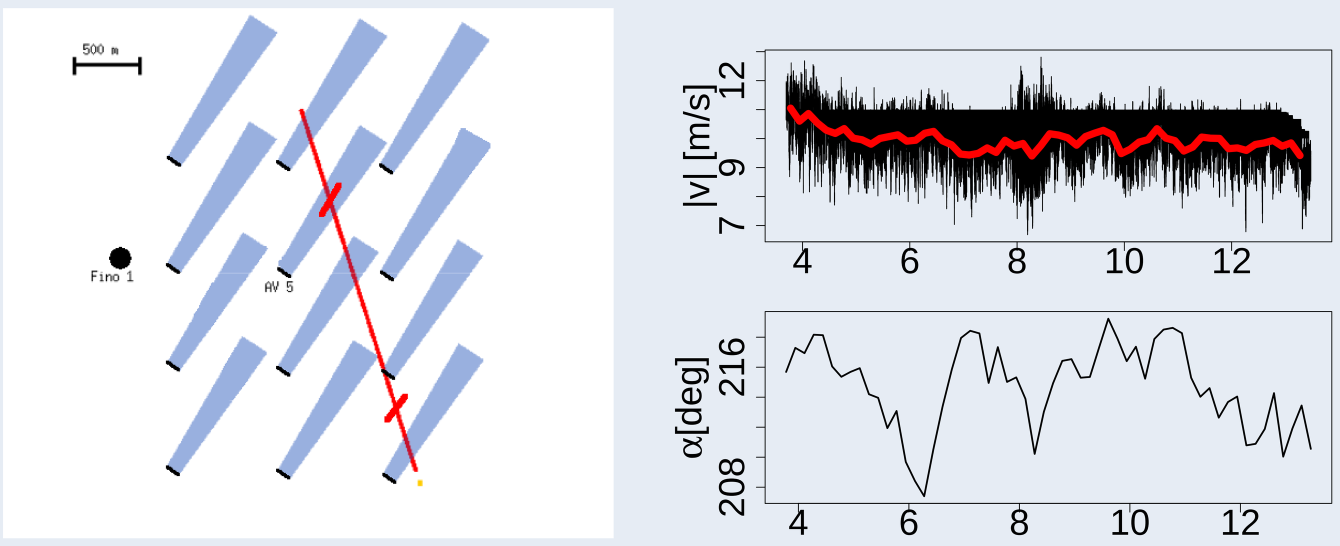

Figure 2: Left: Illustration of the measurement scenario. Right: Measurements from the platform Fino1. Time series of the magnitude and direction of the wind velocity. The mean velocity is given by approx. $10\frac{m}{s}$, denoted by U in the following.

- Measurements in the German offshore wind farm Alpha Ventus
- Staring Mode ⇒ instantaneous measurements along the line of sight (los) with approx. 1 Hz.

Setting	Value
Elevation angle	1.80 °
Pulse length	200 ns
Physical resolution	30 – 40 m
Range gate size	4 – 15 m

Tab. 1: Technical lidar settings

- Relatively Stationary Conditions for approx. 10 hours (Fig. 2 right)
- Comparing free flow region with inner region of the far wake (5D) of AV 5
- Following large scale changes of wind direction: Split time series into ten minute windows. Maximum velocity deficit of ten minute average as wake center. (Fig. 3 right) Statistics for every 10 minute window followed by an averaging procedure over all windows.

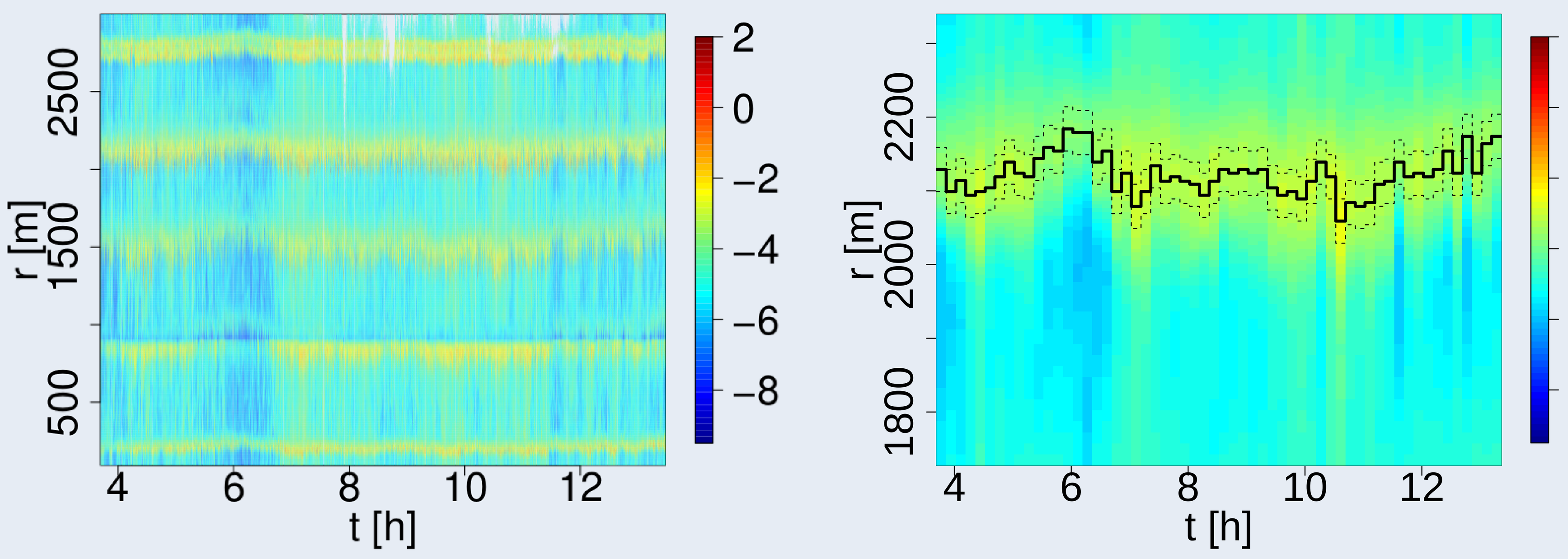

Figure 3: Left: Los velocity, denoted by the color, dependent on the distance along the laser beam r and the time t. Right: Ten minute average of the los velocity for the wake of AV5. Solid line: max. deficit. Dashed line: Boundaries of defined inner wake region.

Temporal Correlations

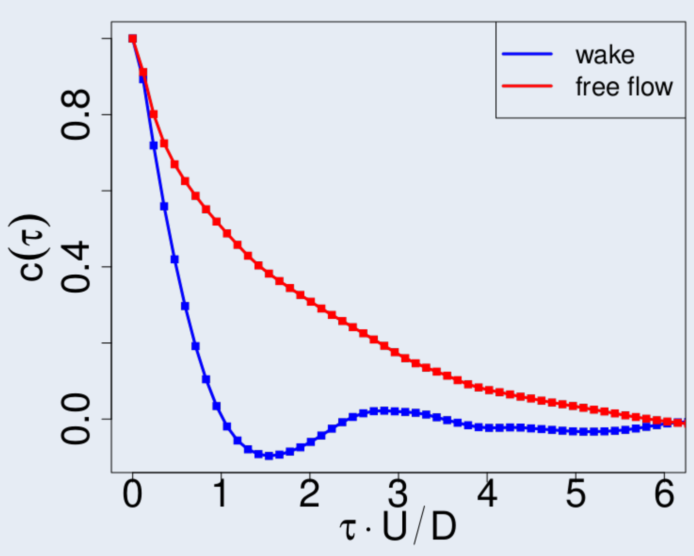

Figure 4: Auto-correlation function $c(\tau)$. Time scale is normalized with $\frac{D}{U} \approx 12s$.

- Integral time scale smaller in the wake (approx. $\frac{D}{U}$).
- Larger Structures have less impact on the dynamics of the wake.

Contact

david.bastine@uni-oldenburg.de

Spectral Analysis

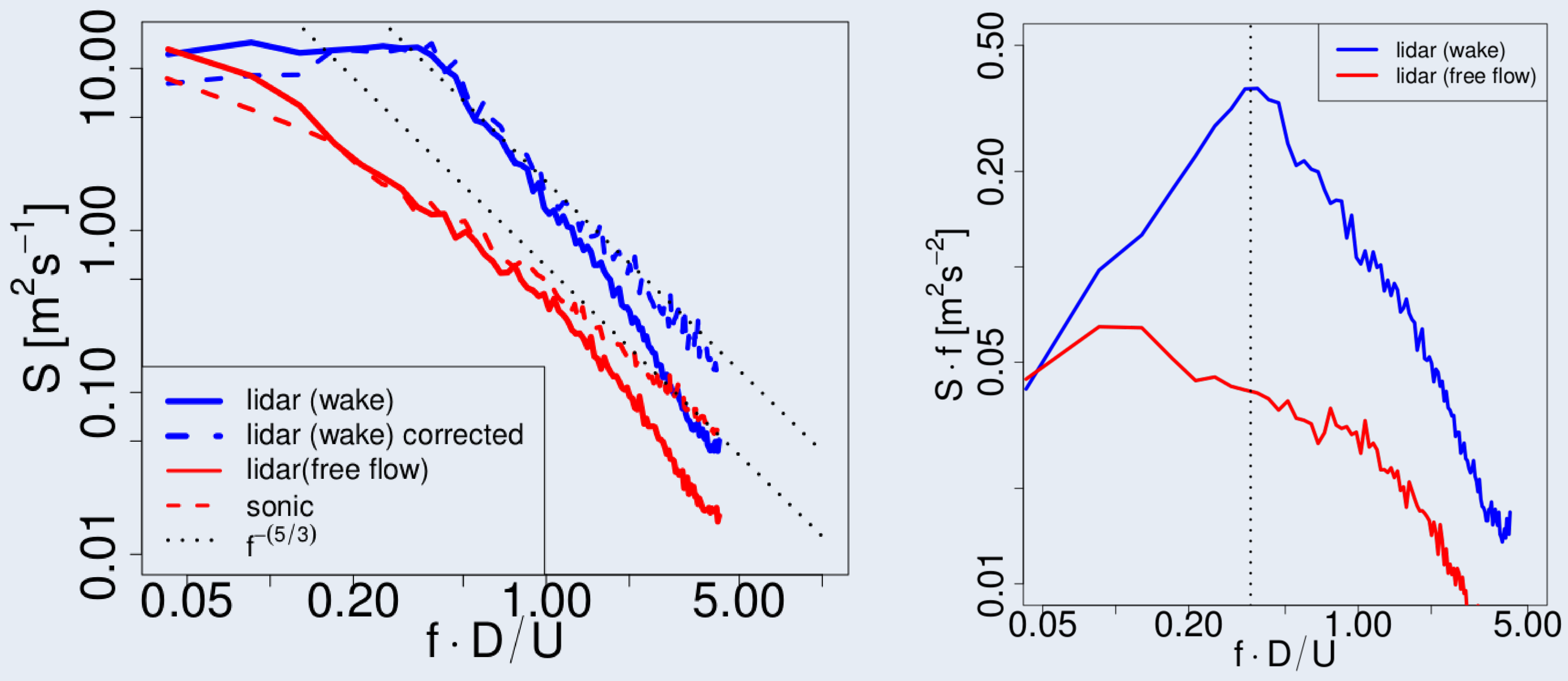

Figure 5: Left: Power spectra of wake and free flow for lidar and sonic measurements (Fino 1). Additionally, a roughly corrected wake spectrum is plotted. The frequency is normalized with $\frac{U}{D} \approx 0.08\ Hz$. Right: Power spectra multiplied with the frequency.

- Modulation on a wide range of scales agreeing with lab results (Fig. 6).
- Approx. power law behavior in the wake ($S \propto f^{-\alpha}$)
- Rough correction for volume averaging effect ⇒ $\alpha \approx \frac{5}{3}$ for scales smaller than the rotor diameter.
- Initiation of a new turbulent cascade starting on scales of the the rotor diameter.

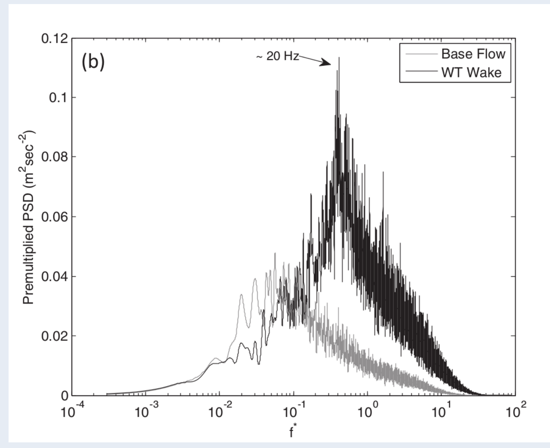

Figure 6: Corresponding lab results with $f^* = f \cdot \frac{D}{U}$. Taken from [2].

Increment Statistics

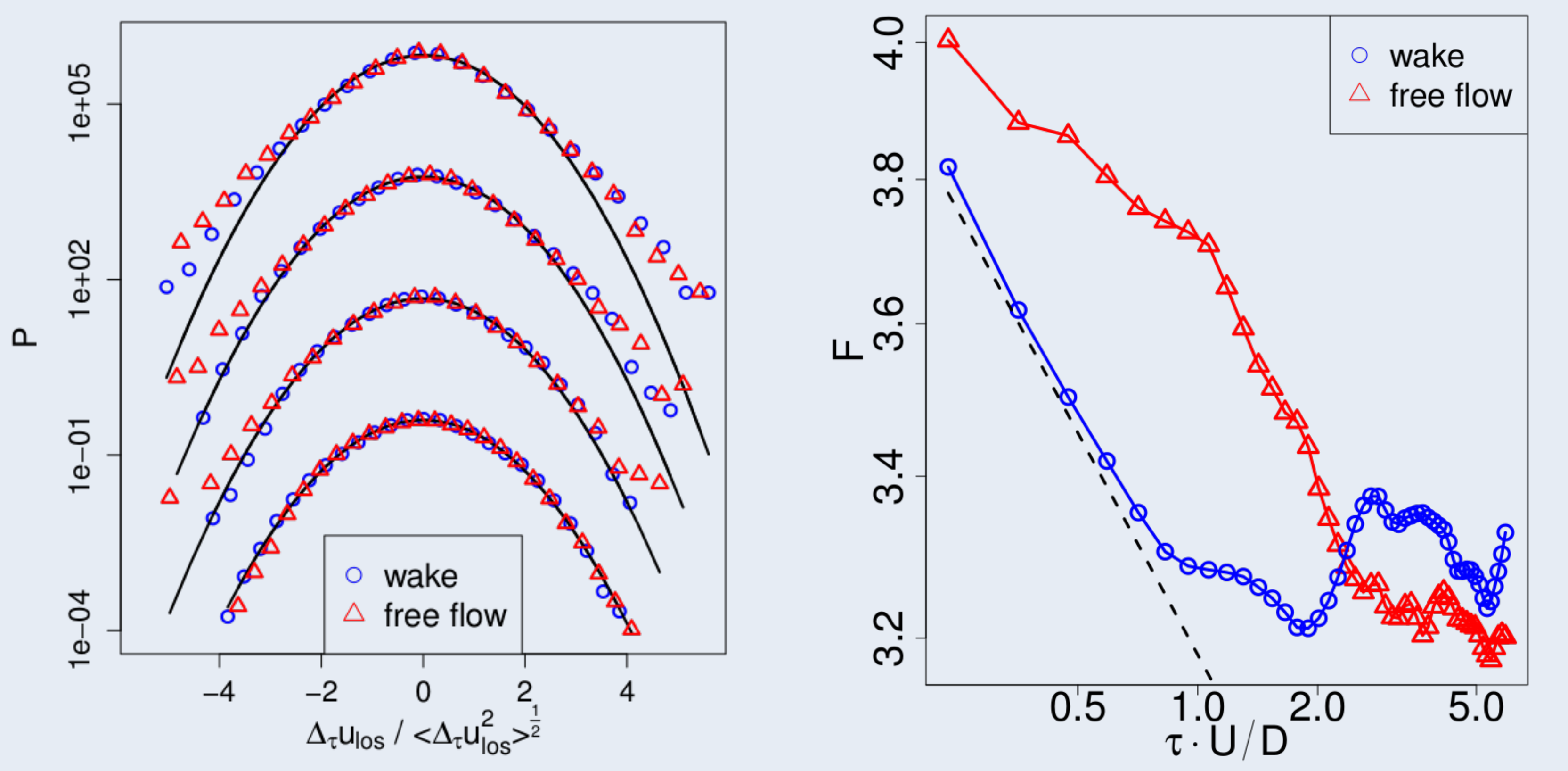

Figure 6: Increment Statistics with $\Delta_\tau u_{los} := u_{los}(t+\tau) - u_{los}(t)$. Left: Normalized probability density functions for different scales τ. Shifted for clarity with $\tau = 3\ s, 6\ s, 12\ s, 45\ s$ from top to bottom. Right: Corresponding flatness dependent on the scale τ.

- Multifractal Scaling behavior. (Gaussian for scales much larger than the rotor diameter).
- Less heavy tailed in the wake.
- Flatness ($F(\tau) := \frac{\langle \Delta_\tau u_{los}{}^4 \rangle}{\langle \Delta_\tau u_{los}{}^2 \rangle^2}$) in the wake follows power law for scales smaller than the rotor diameter.
- $F(\tau) \propto \tau^{-\frac{4}{9}\mu}$, $\mu \approx 0.27$ following K62-Theory [3]

Summary and Conclusions

- Lidar useful tool for qualitative investigation of wake turbulence.
- Qualitatively different turbulence for wake and free flow.
  ⇒ Increased turbulence intensity insufficient for modeling turbulent wake effects?
- Turbine modulates turbulent structures on a wide range of scales (even smaller than $0.2\frac{U}{D}$). Relevant for dynamic wake models relying on the passive tracer assumption for large scales.
- New turbulent cascade starting on scales of the rotor diameter.
- Properties of homogenous isotropic turbulence in the wake despite the anisotropic inflow (e.g. typical intermittency coefficient)
- Further Steps: Outer Wake Region, other velocity components, investigate consequences for turbines in the wake.

References

[1] D. Bastine et al. 2015, J. Phys.: Conf. Ser., 625, 00126
[2] A. Singh et al. 2014, Physics of Fluids, 26, ISSN 1070-6631
[3] A.N. Kolmogorov 1962, J. Fluid Mech., 13, 82-85

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