Long-range Doppler lidar measurements of wind turbine wakes and their interaction with turbulent atmospheric boundary-layer flow at Perdigão 2017

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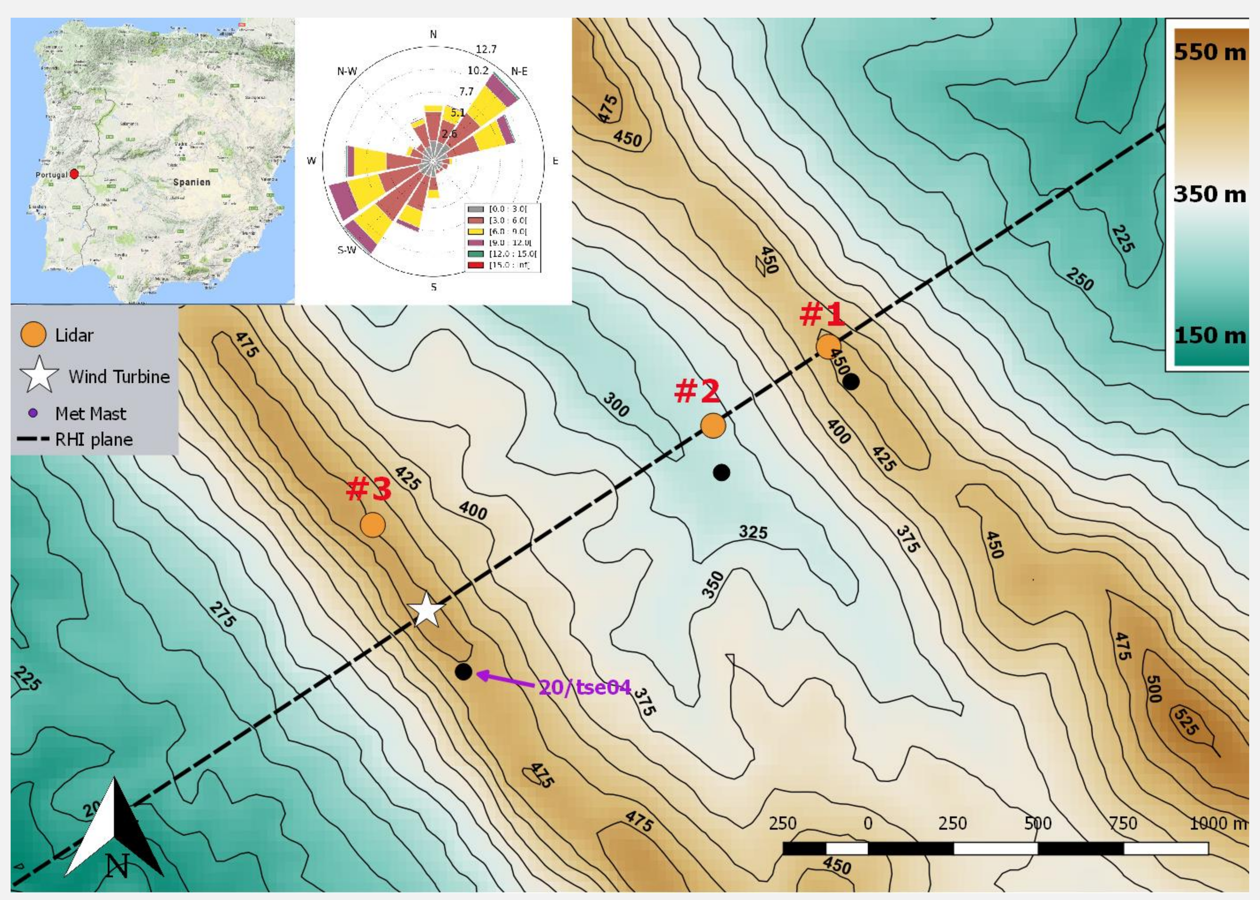
Abstract

As part of the Perdigão 2017 campaign, vertical RHI (range-height indicator) scans with long-range pulsed Doppler wind lidars were performed aligned with the main wind direction and a wind turbine (WT) located on a mountain ridge. The data are used to retrieve flow velocities, their variances and TKE (turbulence kinetic energy) dissipation rate. Turbulence in the WT wake is dependent on the turbulence of the inflow, but also on atmospheric stability. In stable conditions, wakes could be analyzed up to five rotor diameters downstream (*D*) and showed the maximum turbulence in the wake at 2-3 *D*, whereas in unstable conditions, the maximum was found at 2 *D* and the wake could not be detected further than 3 *D*. Wake turbulence is enhanced by the inflow turbulence intensity, leveling out at inflow turbulence intensities of 30%.

The Perdigão 2017



Instrumentation *for this study:*

- Leosphere **Windcube 200S** (#2, see map above)
  - **RHI** cross-valley scans
  - In-line with main wind direction and WT
- Tower 20/tse04 80 m **sonic anemometer** as in-situ reference

Conditions *for dataset:*

- Wind direction between **225° and 245°**
- Wind speed between **5 m s^{-1} and 9 m s^{-1}**.
- Wind **turbine** was **operating**.
- A wake **signature** could be **detected**.
- Good data quality (**CNR >-25dB**).

➢ **6 hours in stable conditions**

➢ **34 hours in neutral / unstable**

Retrieval for TKE dissipation rate ε from RHI scans

The variance in the investigated areas is calculated as the **sum of line-of-sight variances and turbulent broadening** of the Doppler spectra:

$$\sigma_v^2 = \hat{\sigma}_v^2 + \sigma_t^2$$

Zero wind speed and **sheer-related broadening** are removed from spectral width to obtain the turbulent broadening:

$$\sigma_t^2 = \hat{\sigma}_{sw}^2 - \sigma_0^2 - \hat{\sigma}_s^2$$

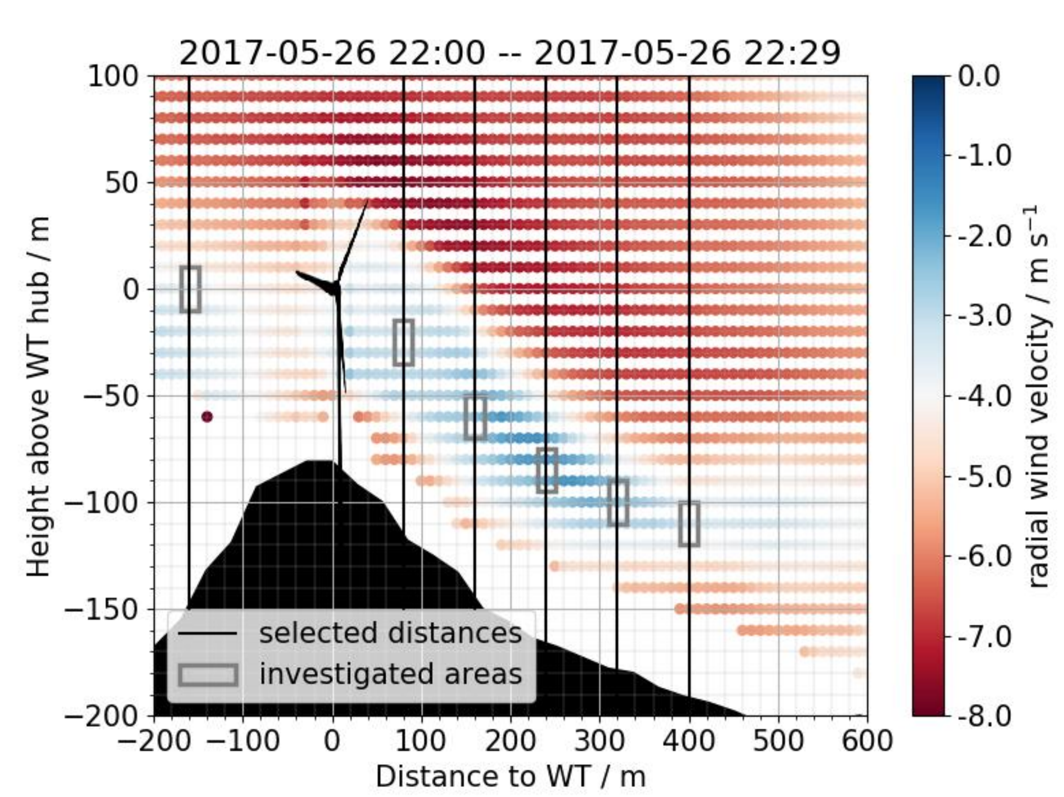
Integral length scale L_v and **dissipation rate ε** are calculated from the variances:

$$L_v = c_1 \left(\frac{\sigma_t^2}{\sigma_v^2}\right)^{c_2} + c_3$$

$$\varepsilon = \frac{1.972}{C_k^{3/2}} \frac{\sigma_v^3}{L_v}$$

More details in *Wildmann et al. (2019).*

RHI scan with indicated detection areas

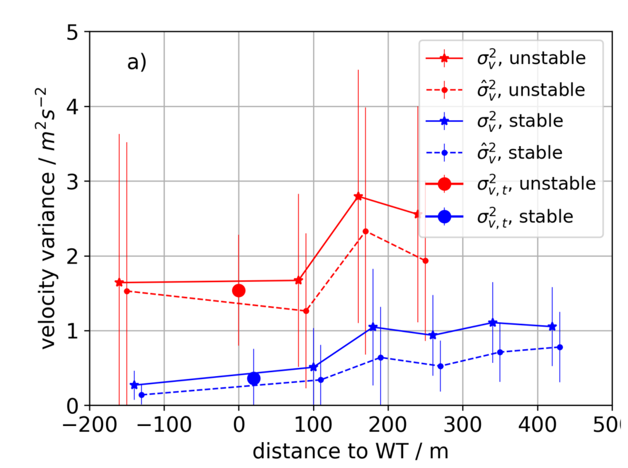


- **Wake center detection** through Gaussian fits.
- **20x20m boxes** around wake center for turbulence detection in **30-minute averages**.
- Criteria for wake detection limits, see *Wildmann et al. (2018).*

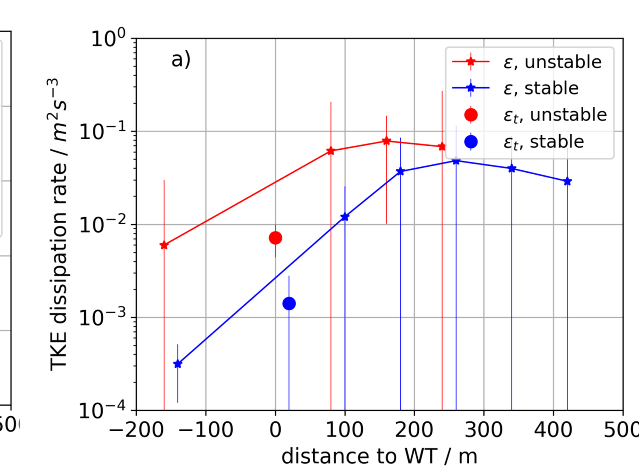
Wake turbulence vs. distance to WT

- Discrimination of **stable vs. unstable** cases
- **LOS variance $\hat{\sigma}_v^2$** (dashed) vs. **combined variance σ_v^2** (solid)
- Longer **wake detection lengths** in stable conditions (5 D, vs. 2 D, with D = 80 m)
- **Increase of turbulence** in the wake is evident

σ_v^2

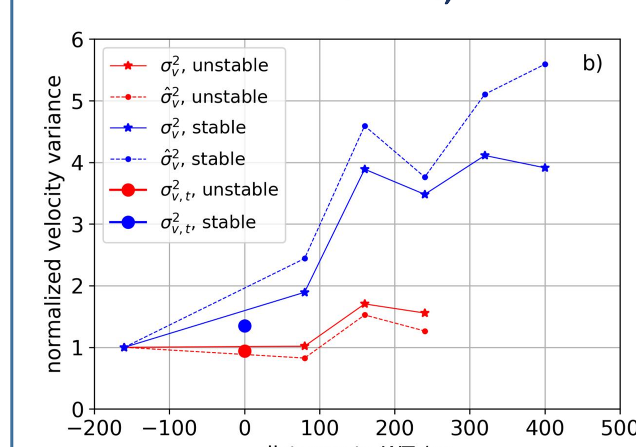


ε

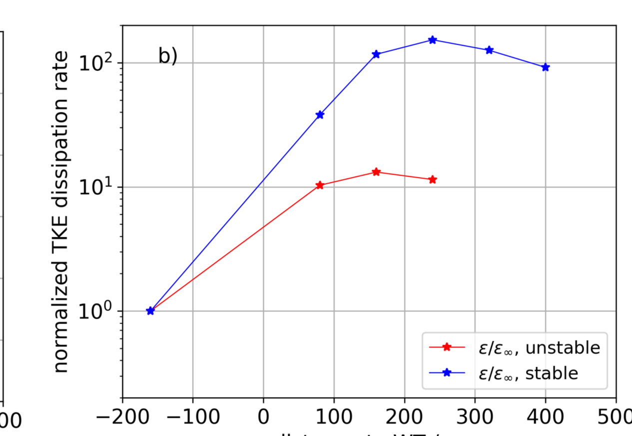


- **Normalization** to inflow parameters (∞)
- Higher **relative increase** in stable conditions

$\sigma_v^2/\sigma_{v,\infty}^2$



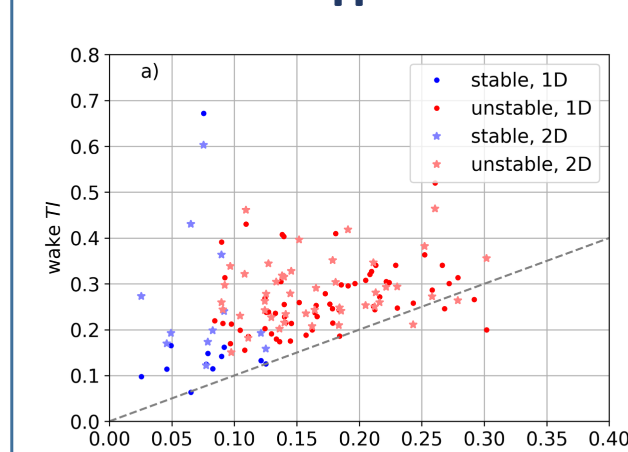
$\varepsilon / \varepsilon_\infty$



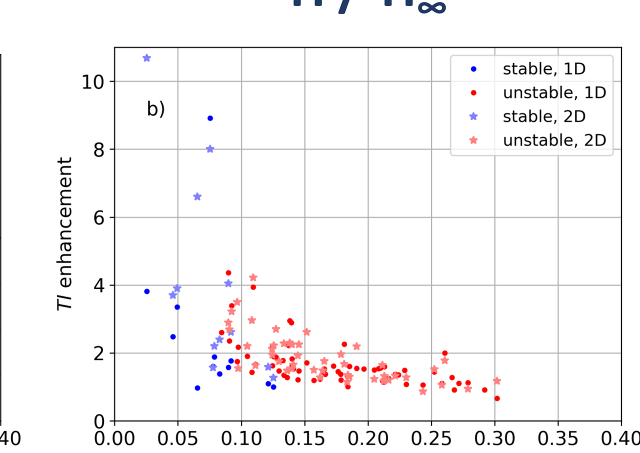
Wake TI vs. background TI

- The turbulence in the wake depends on **inflow/background** turbulence intensity (TI).
- **Normalization with TI_∞** shows the TI enhancement

TI



TI / TI_∞



Conclusion & Outlook

- A new method to retrieve **TKE dissipation rate** from **long-range Doppler wind lidar** systems has been applied to WT wake measurements.
- Higher **absolute** variances for **unstable**, but higher **relative** increase in **stable** conditions.
- TKE **dissipation rate** ranges up to **10^{-1} m^2 s^{-3}** in all cases, with the maximum appearing further downstream in stable conditions
- **Enhancement of TI** by the WT wake can be detected with background TI up to 20%.
- Specific **challenges** with the Perdigão dataset:
  - Uncertainty of **upstream wind**
  - Interaction with the **terrain**
  - Limited range of **wind directions**
- **Extending the dataset** to flat terrain will help in future to investigate wake turbulence more extensively.

References

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- Wildmann, N., Bodini, N., Lundquist, J. K., Bariteau, L., and Wagner, J.: Estimation of turbulence dissipation rate from Doppler wind lidars and in situ instrumentation for the Perdigão 2017 campaign, Atmos. Meas. Tech., 12, 6401–6423, https://doi.org/10.5194/amt-12-6401-2019, 2019

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