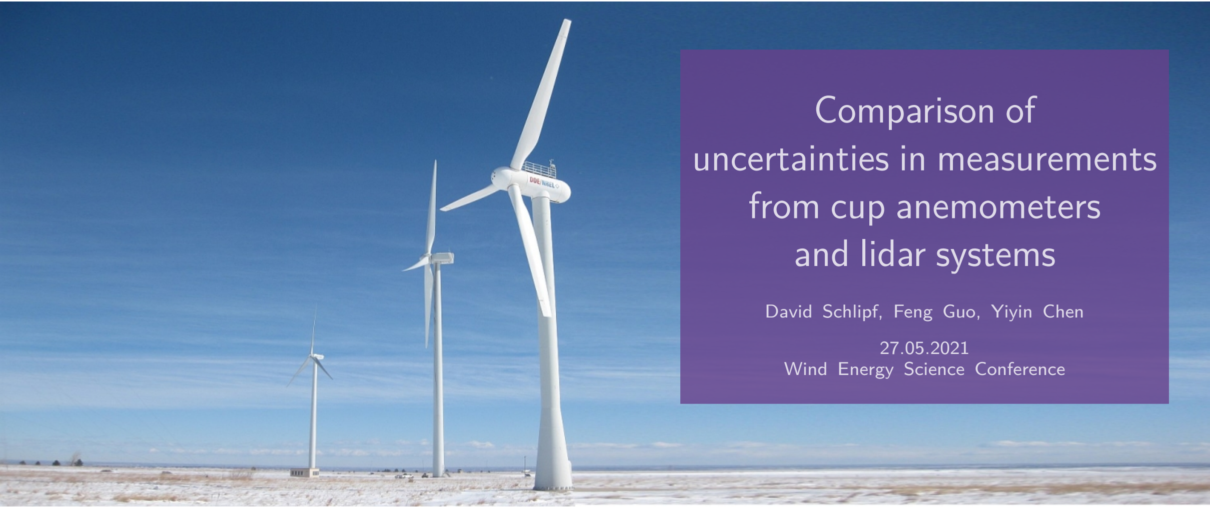

Comparison of uncertainties in measurements from cup anemometers and lidar systems

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SWE Stuttgart Wind Energy
@ Institute of Aircraft Design

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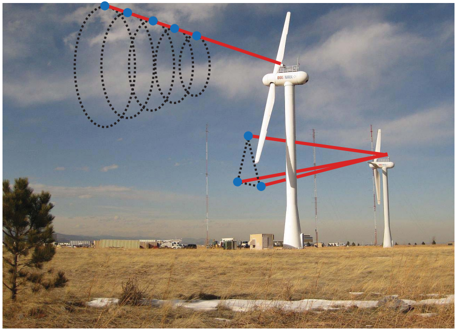
Motivation



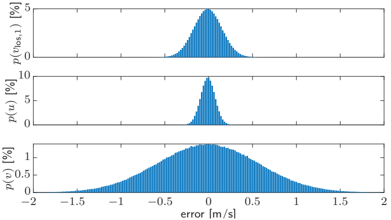
Lidar systems for power performance testing

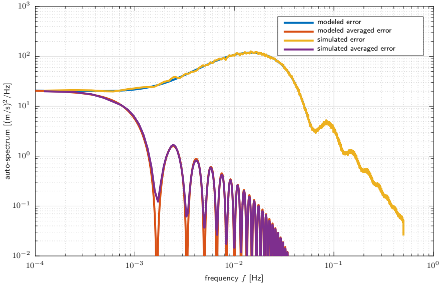
- cost-effective alternatives to cups on masts
- obtain only the line-of-sight wind speed
- need model-based wind field reconstruction
- common feeling: lidar uncertainty might be higher than cup uncertainty?
- caused by traditional comparison to cup?
- but less scatter in lidar-based power curves [1]

Main questions

- Does a cup really outperform a lidar system estimating the wind speed of another cup?
- Is a cup or a lidar system better to estimate the rotor-effective wind?

Modeling Uncertainties of Wind Field Reconstruction Using Lidar [2]





Measurement uncertainties

- due to calibration, installation issues, etc.
- error propagation from line-of-sight to reconstructed signals can be calculated
- depends mostly on practical issues

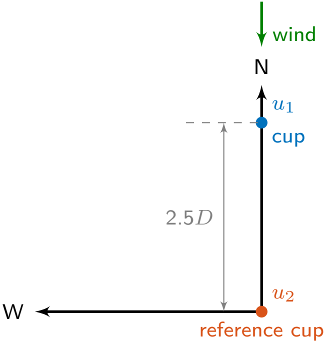
Model uncertainties

- due to homogeneous flow assumption
- can be modeled with wind spectral models
- can be larger than measurement uncertainties

Here, we focus on model uncertainty in 2.5 D only and compare it to a cup anemometer!

Contents

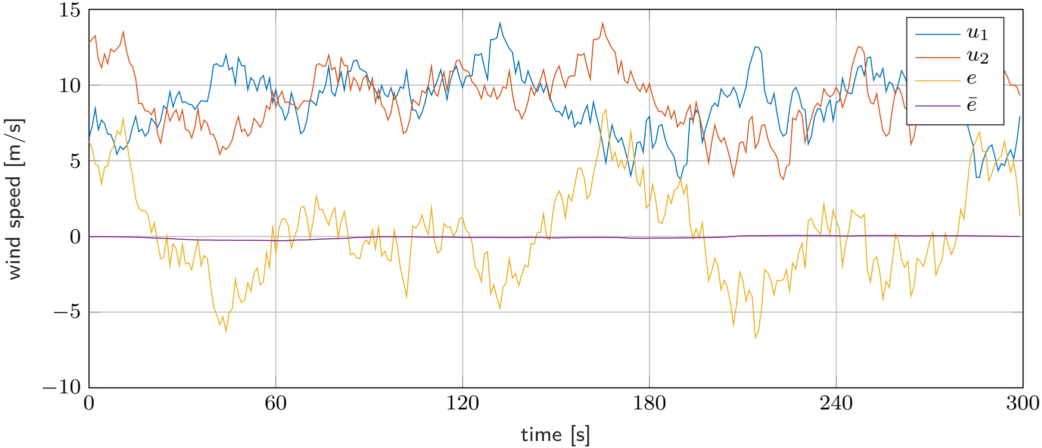
How can we model the cup-cup uncertainty?



Assumptions

- IEC Kaimal turbulence spectrum [3] at $\bar{u} = 10\,\mathrm{m/s}$
- turbulence class A
- $2.5D$ distance with $D = 130\,\mathrm{m}$
- exponential decay wind evolution model [4]
- uncertainty defined as 2σ of measurement error e between u_1 and u_2 averaged over $T = 10\,\mathrm{min}$

Cup-Cup Uncertainty - Time Example



Even without wind evolution and perfect alignment, the uncertainty is in average 0.24 m/s.

Cup-Cup Uncertainty - Frequency Model

Time domain equation

$$e = u_1 - u_2$$
$$\bar{e}(t) = e(t) * \mathrm{rect}\left(\frac{t - T/2}{T}\right)$$

Error spectrum

$$S_{ee} = S_{u1u1} + S_{u2u2} - 2\Re(S_{u1u2})$$
$$S_{ee} = 2S_u - 2S_u\Re(\gamma_{u1u2})$$
$$S_{\bar{e}\bar{e}} = S_{ee}\,\mathrm{sinc}^2(fT)$$

Coherence

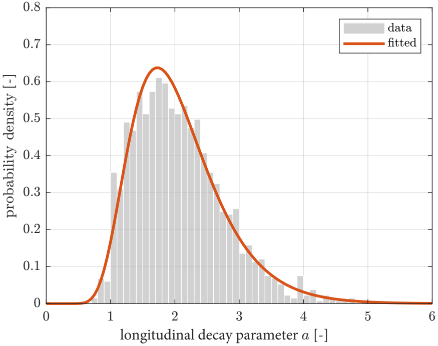
$$\gamma_{u1u2} = \underbrace{\exp\left(-i2\pi f\frac{\Delta x}{\bar{u}}\right)}_{\text{time shift}}\underbrace{\exp\left(-\frac{a}{2}f\frac{\Delta x}{\bar{u}}\right)}_{\text{wind evolution}}$$

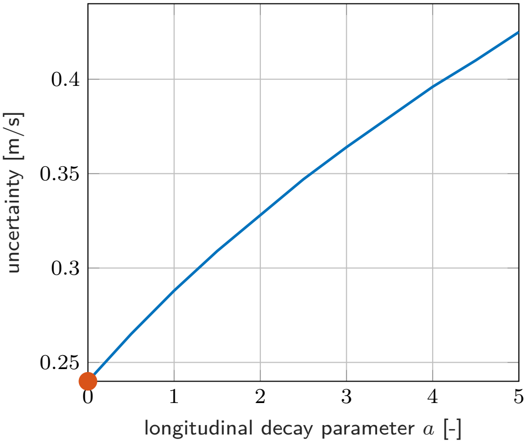
Uncertainty by integration

$$U_{\mathrm{cc}} = 2\sqrt{\int_0^\infty S_{\bar{e}\bar{e}}\,\mathrm{d}f}$$

- We can calculate the error spectrum considering effects such as time shift and wind evolution!
- We multiply the error spectrum with $\mathrm{sinc}^2(fT)$ to get the 10-minute-averaged error!
- We calculate the uncertainty via the variance, which is the integral of a spectrum!

Cup-Cup Uncertainty - Results

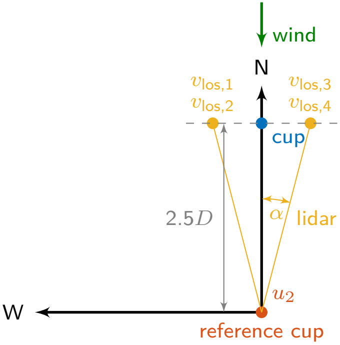




- a can vary significantly
- based on real measurements [5]

- significant impact on uncertainty
- fits well to time domain example

How can we model the lidar-cup uncertainty?

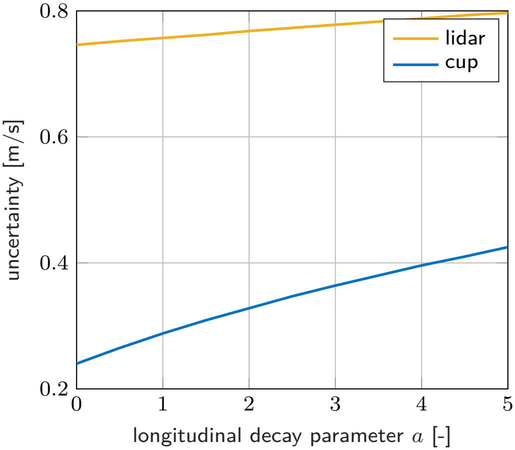


Assumptions

- commercial pulsed lidar system with 4 beams
- horizontal half opening angle $\alpha = 15\,\text{deg}$
- vertical half opening angle $\beta = 5\,\text{deg}$
- probe volume (Full Width at Half Maximum): 60 m
- cross contamination: in every point i all 3 wind components impact line-of-sight wind speed $v_{\text{los},i}$
- standard wind field reconstruction:

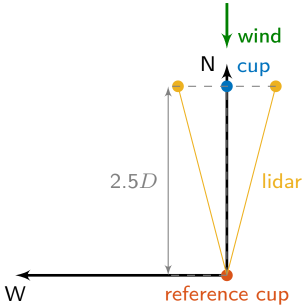
$$u_{\text{L}} = \sum_{i=1}^{4} \frac{v_{\text{los},i}}{4\cos(\alpha)\cos(\beta)}$$

Lidar-Cup Uncertainty - Results



- higher uncertainty compared to cup ☹
- less impact of wind evolution compared to cup ☺
- But this is only valid for the north wind direction! 😉
- Let's check the other wind directions! 😎

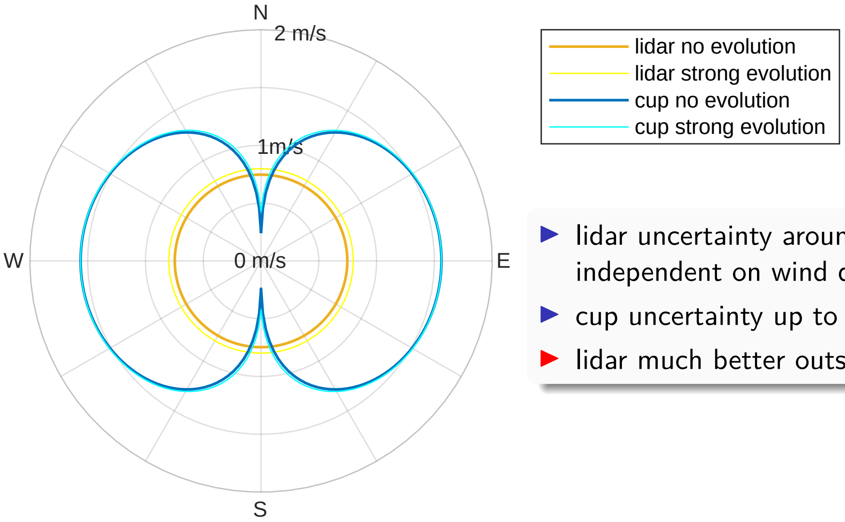
Lidar-Cup and Cup-Cup Uncertainty - Setup



Assumptions

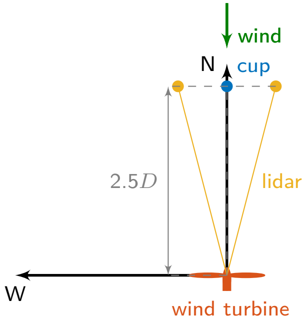
- wind direction is the same at both cups and the lidar system
- lidar system is always perfectly aligned with the wind

Lidar-Cup and Cup-Cup Uncertainty - Results



- lidar uncertainty around 0.8 m/s, independent on wind direction
- cup uncertainty up to 1.6 m/s
- lidar much better outside ±7 deg 😄

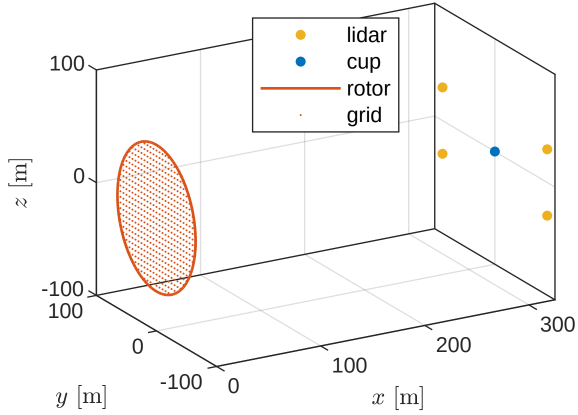
Lidar-Rotor and Cup-Rotor Uncertainty - Setup



Assumptions

- wind direction is the same at rotor, cup, and lidar system
- rotor with lidar system is always perfectly aligned with the wind
- no wake impact considered
- rotor-effective wind speed is the mean of all u wind speed components hitting the rotor

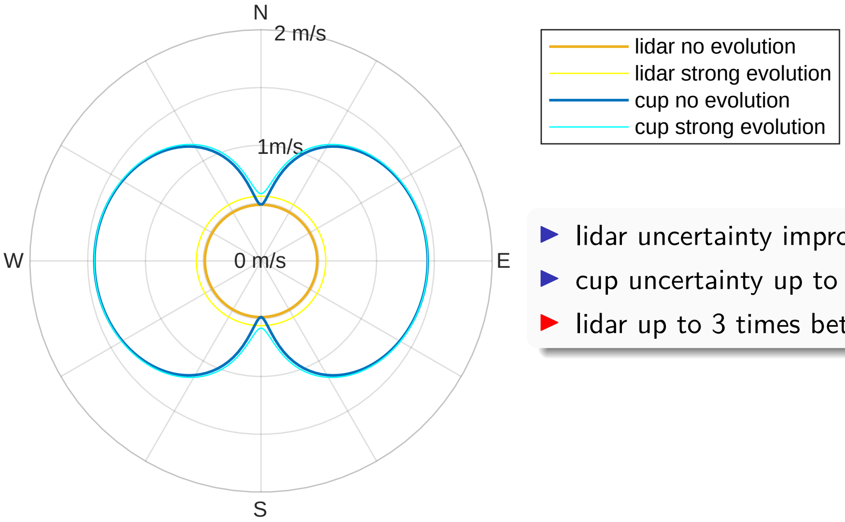
Lidar-Rotor and Cup-Rotor Uncertainty - Frequency Model



Main idea

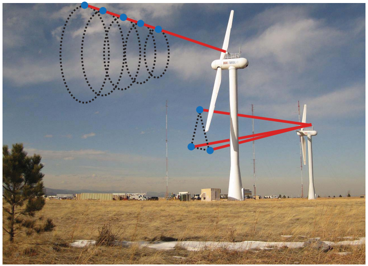
- common in lidar-assisted control
- calculate the error spectrum and then multiply it with the sinc^2
- more complex: every grid point of rotor needs to be considered

Lidar-Rotor and Cup-Rotor Uncertainty - Results



- lidar uncertainty improved to 0.5 m/s 🙂
- cup uncertainty up to 1.5 m/s 😜
- lidar up to 3 times better than cup 😄

Conclusions



Does a cup really outperform a lidar system estimating the wind speed of another cup?

- Presumable not! Here, cup is only better in a small section (± 7 deg)!
- Main reason: lateral de-correlation is usually stronger than longitudinal.

Is a cup or a lidar system better to estimate the rotor-effective wind?

- Lidar! Here, lidar uncertainty is up to 3 times smaller than cup uncertainty!
- Main reason: lidar is collecting more relevant information.

Outlook

More detailed analysis and publish it in a Journal paper

- using more realistic Mann spectral model and horizontal wind speed
- addressing perfect alignment of turbine, precision versus accuracy

"Smart Lidar" collaboration with sowento and MOVELASER

Evaluate the "Moving Horizon Lidar Data Processing" on our smart lidar system.
Smaller uncertainty expected using several distances, optimal filtering, and time shifting!

Collaboration within MSCA LIKE

- checking the results with real data
- combining it with measurement uncertainty

Opportunities for Collaboration within the IEA Wind Task 32

task 32
lidar

Work together to make lidar the best and preferred wind measurement tool!

- We should stop trying to be as good as a cup, since most likely lidar is much better!
- Make lidar more adjustable and adaptive following the “smart lidar” concept!
- Think on how we can convince others!

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[4] R. A. Pielke and H. A. Panofsky. "Turbulence characteristics along several towers". In: *Boundary-Layer Meteorology* 1 (2 1970), pp. 115–130. ISSN: 0006-8314.

[5] Y. Chen, D. Schlipf, and P. W. Cheng. "Parameterization of wind evolution using lidar". In: *Wind Energy Science* 6.1 (2021), pp. 61–91. DOI: 10.5194/wes-6-61-2021.

Please contact us if you have further questions!

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