Parameter Analysis of a Doppler Lidar Sensor for Gust Detection and Load Alleviation

D. Kiehn[1], N. Fezans[1], P. Vrancken[2], C. Deiler[1]

[1] DLR Institute of Flight Systems
[2] DLR Institute of Atmospheric Physics

International Forum on Aeroelasticity
and Structural Dynamics (IFASD)
Madrid, 15.06.2022

DLR

Motivation

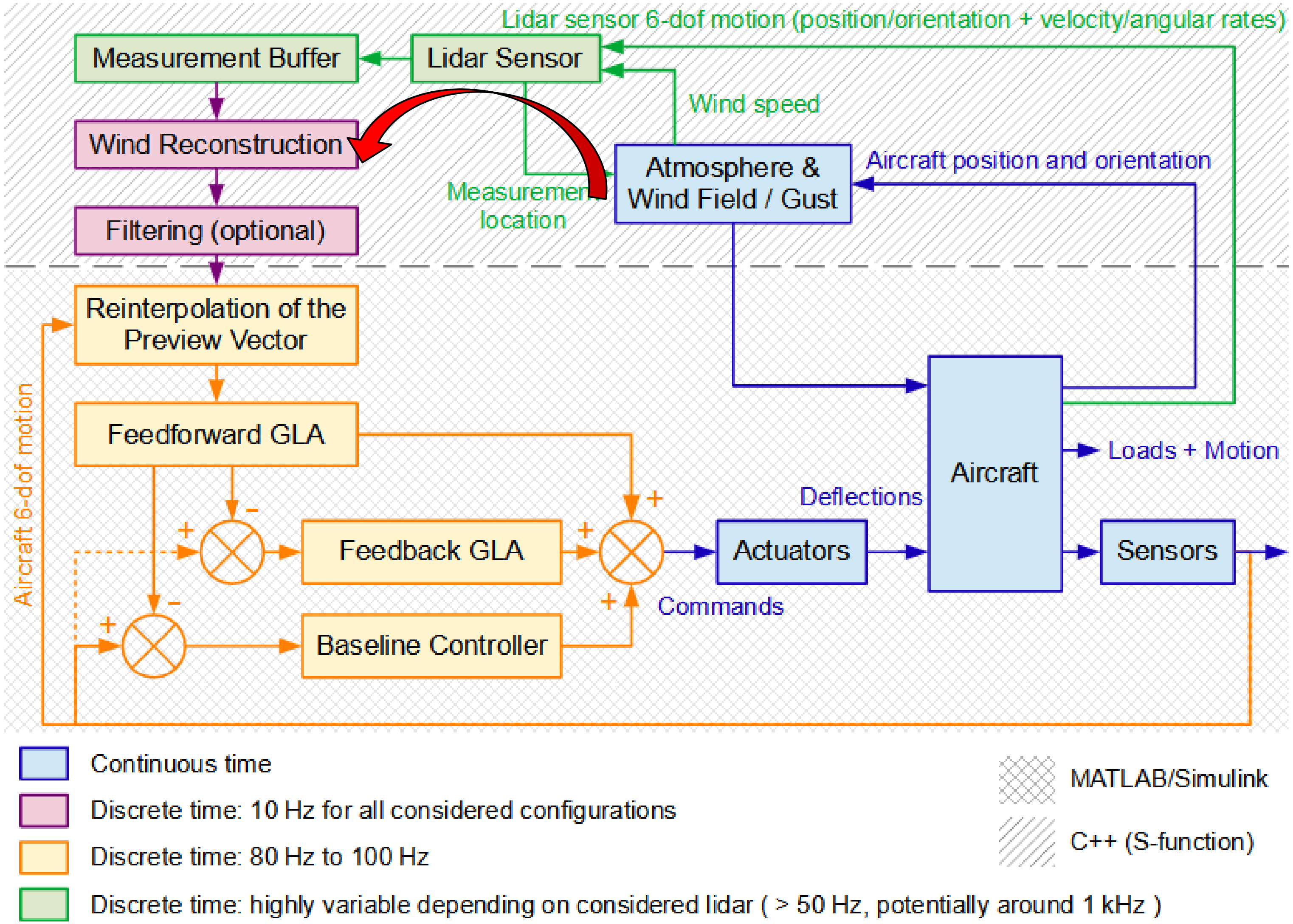
- Feedforward gust load alleviation
  - Anticipate the gust or turbulence before encountering it
  - Potential to reduce aircraft loads (→ weight reduction) and improve passenger comfort
  - Requires a forward-looking sensor such as a lidar

- DLR project COLOCAT (Compact Optical sensors for LOad alleviation of Clear Air Turbulence)
  - Development of a Doppler lidar for load alleviation
    - Difficult definition of requirements
    - Simulation-based evaluation of sensor requirements
    - Sensitivity analysis to determine the impact of sensor parameters on wind measurement/estimation performance

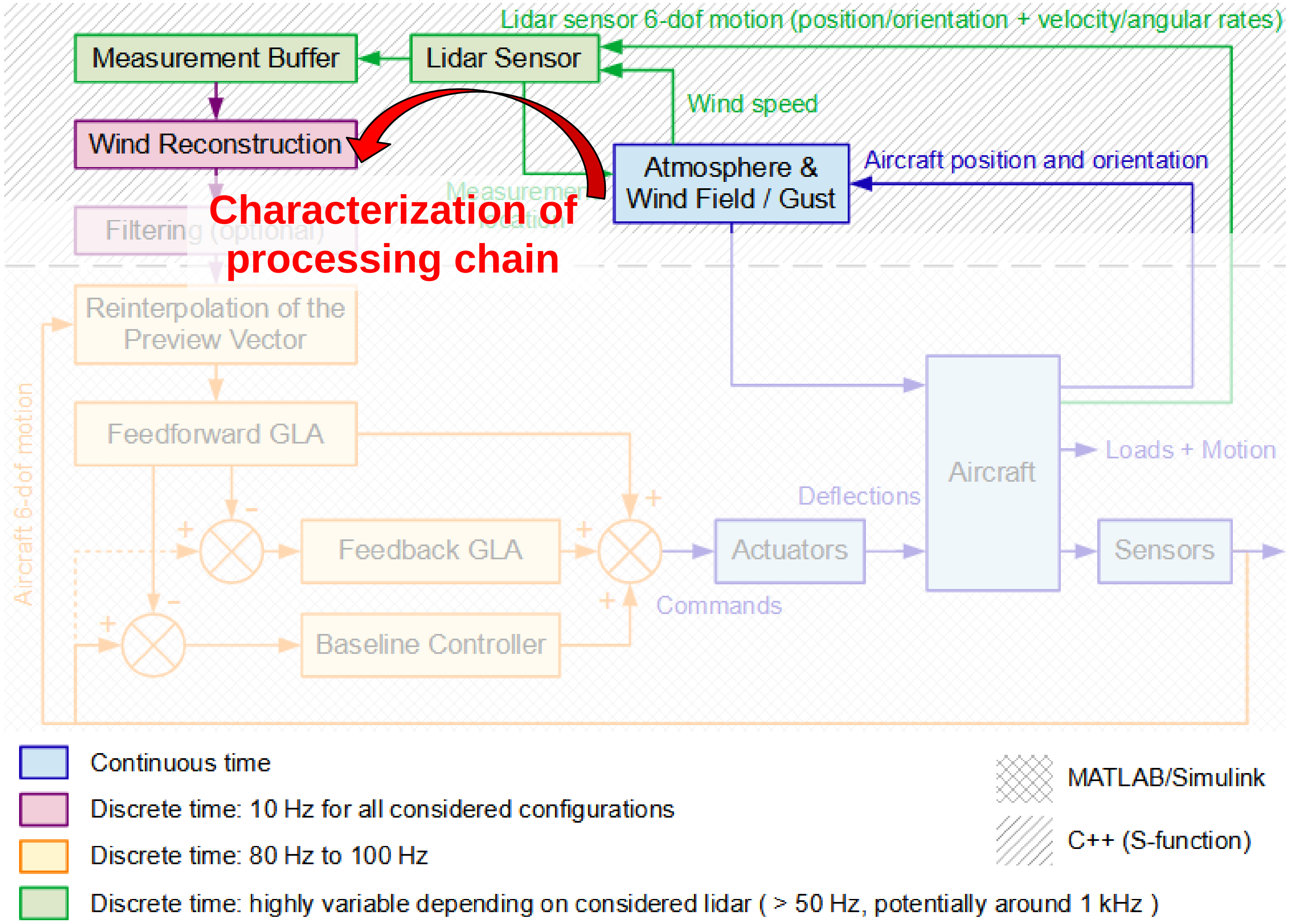
- Simulation framework including:
  - Aeroelastic aircraft model
  - Realistic lidar model
  - Wind reconstruction algorithm
  - Gust load alleviation (GLA) controller

Multi-rate simulation framework

GLA = Gust Load Alleviation



Multi-rate simulation framework



Assumption:

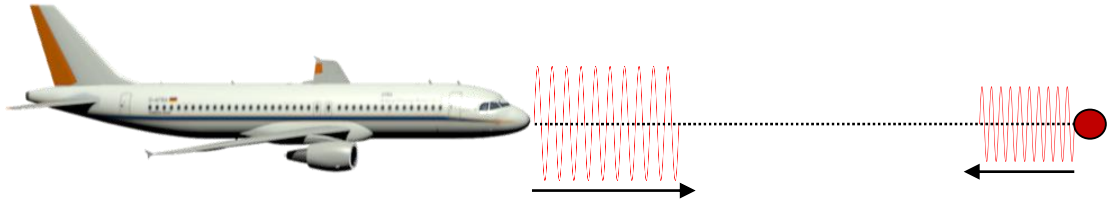
More accurate wind estimation

⇩

Better load alleviation

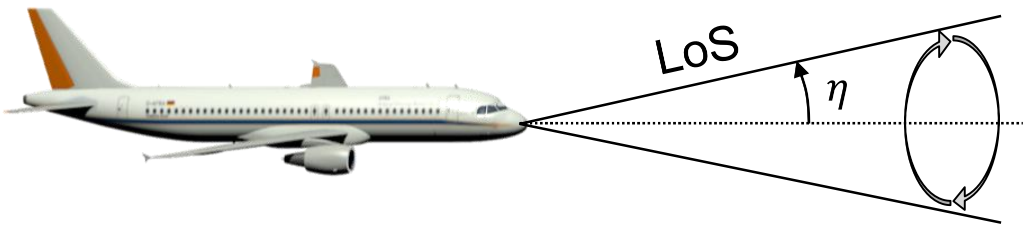
GLA = Gust Load Alleviation

Doppler lidar measurement principle

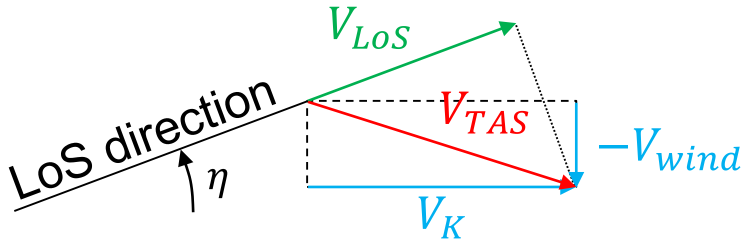


- Doppler lidar: measurement of emitted laser light backscattered by aerosols and air molecules
- Relative velocity between sensor and backscattering particle causes frequency shift (Doppler effect)

- Measurement of relative velocity in line of sight (LoS): components perpendicular to LoS are lost
  - Vertical wind is usually the most relevant for load alleviation
  → Movement of line of sight required (e.g. rotation → movement of the LoS in a cone)



η: Scan angle

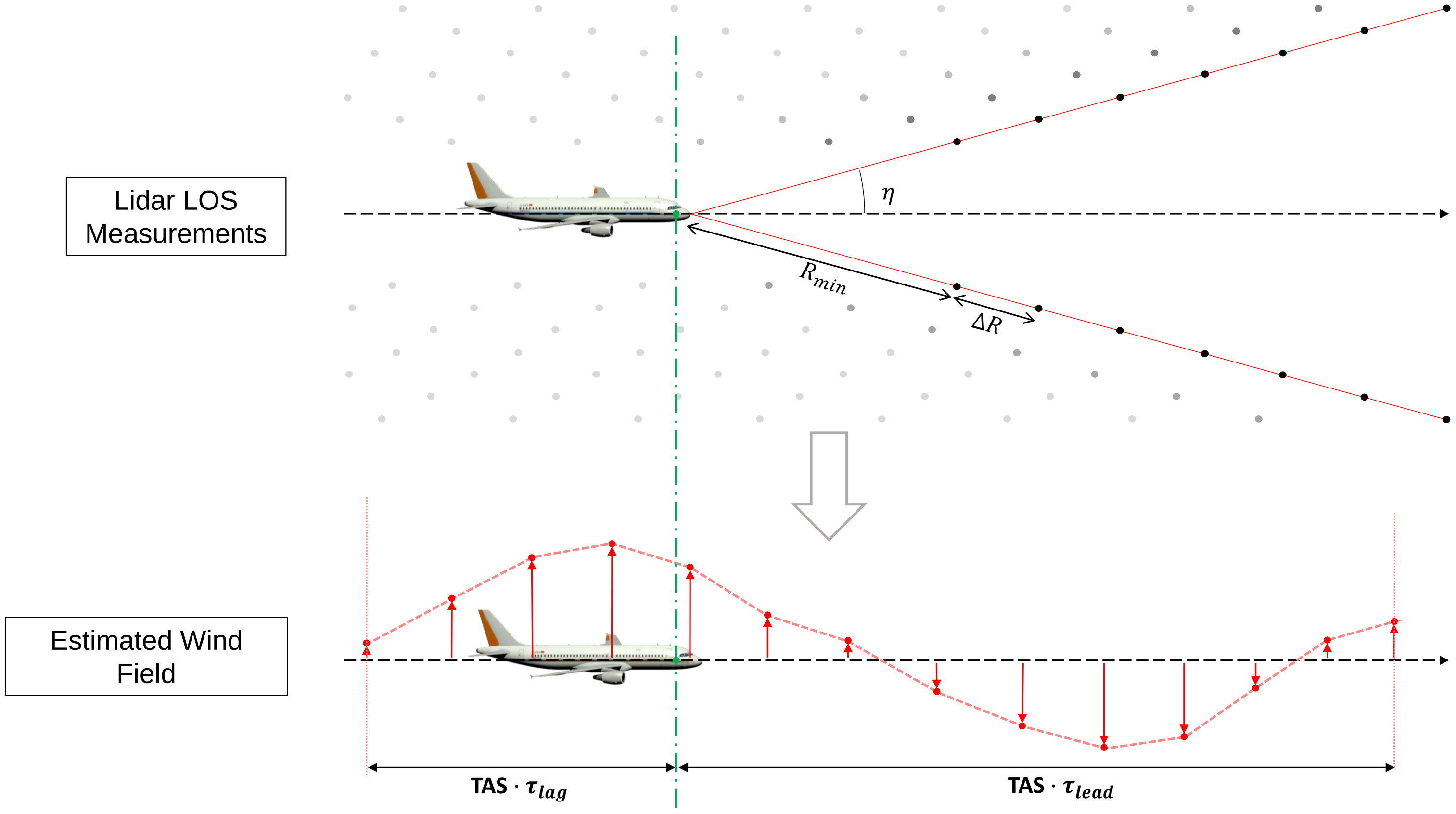


Wind reconstruction based on lidar measurements

- Lidar only measures the wind component in LoS direction
- Measurements are noisy

} Optimization problem

- Wind reconstruction algorithm estimates most probable wind field (*least-squares* problem)
  - Gauss-Newton algorithm with Tikhonov regularization to enforce a certain degree of smoothness in the resulting wind profile (penalty on first and second derivatives)

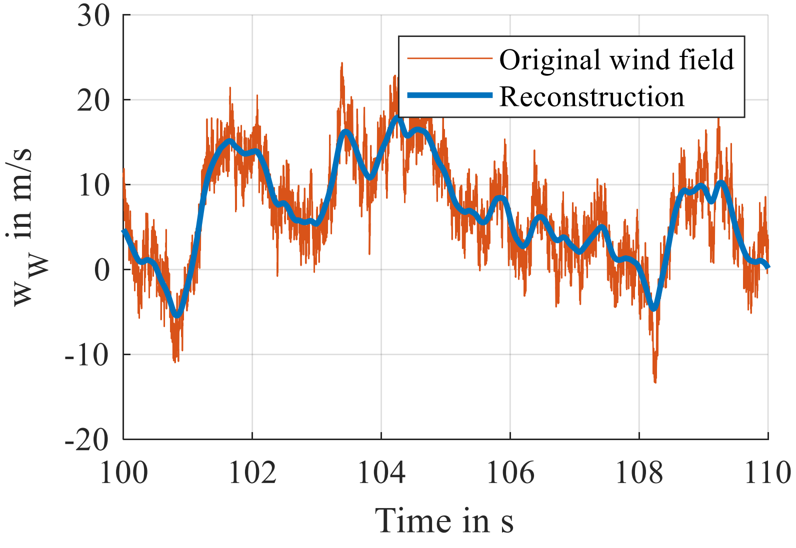


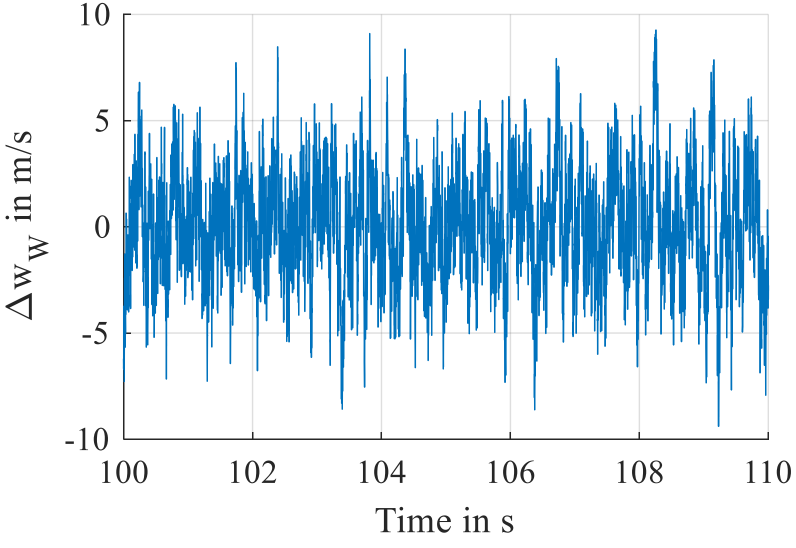
Lidar performance evaluation metric (1/2)

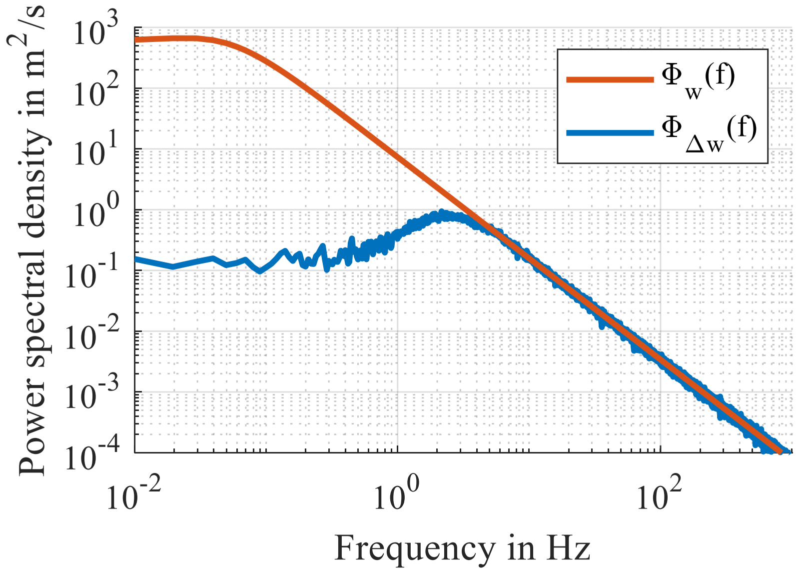
- Simulated flight through continuous turbulence (here: von Kármán spectrum as used in CS 25.341)
- Estimation of the vertical wind
- Error between estimation and actual turbulence is analyzed in frequency domain

subtraction

Power Spectral Density (PSD)



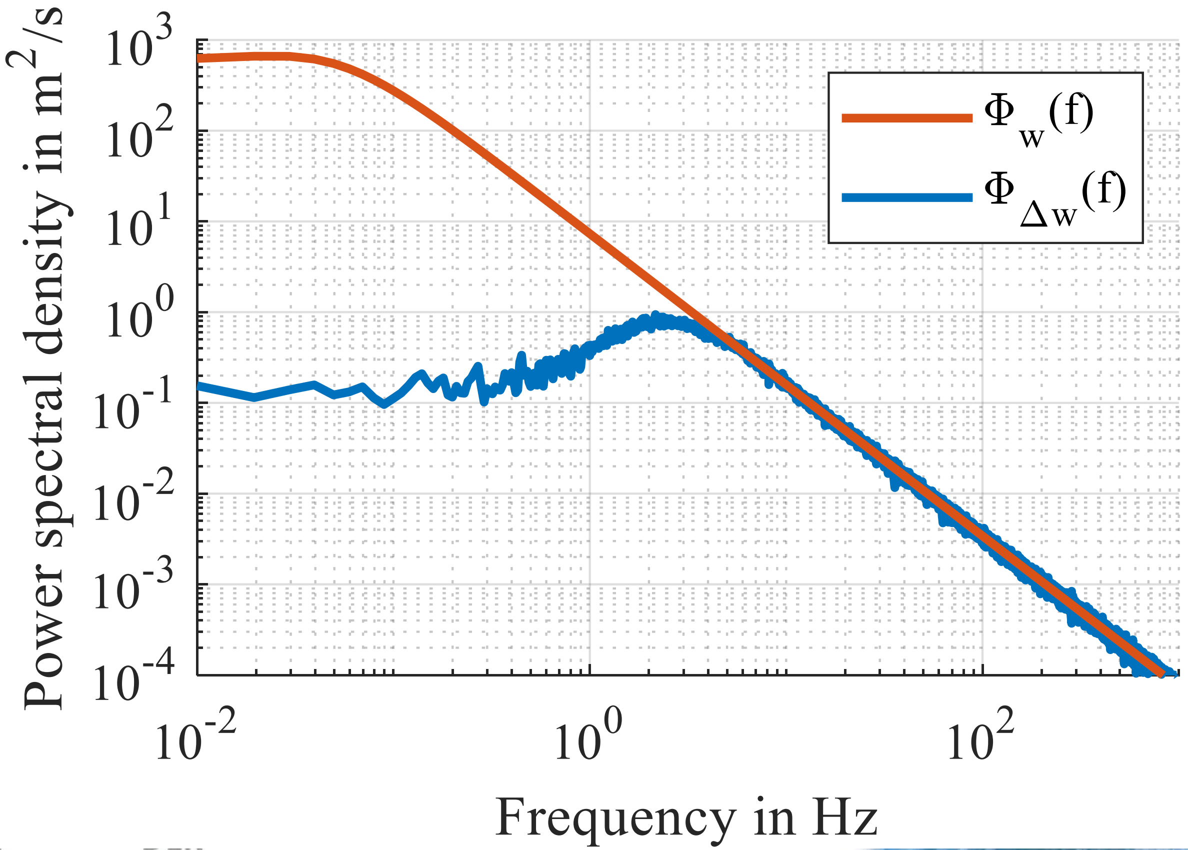


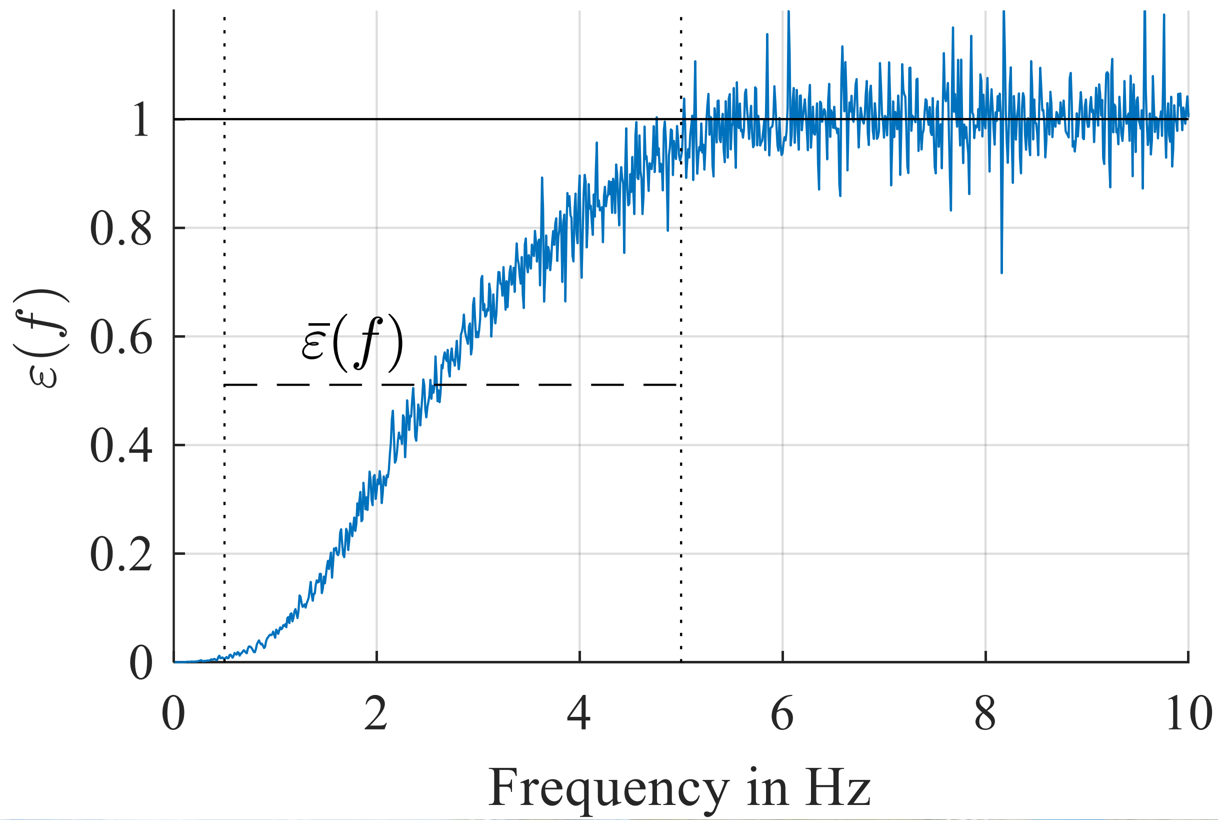


Lidar performance evaluation metric (2/2)

- PSD of error signal is compared to PSD of original turbulence signal
- Relative spectral error $\varepsilon(f)$ describes loss of spectral power (transfer function)
- Mean spectral error $\bar{\varepsilon}(f)$ in frequency band (0.5 - 5 Hz) as single evaluation criterion

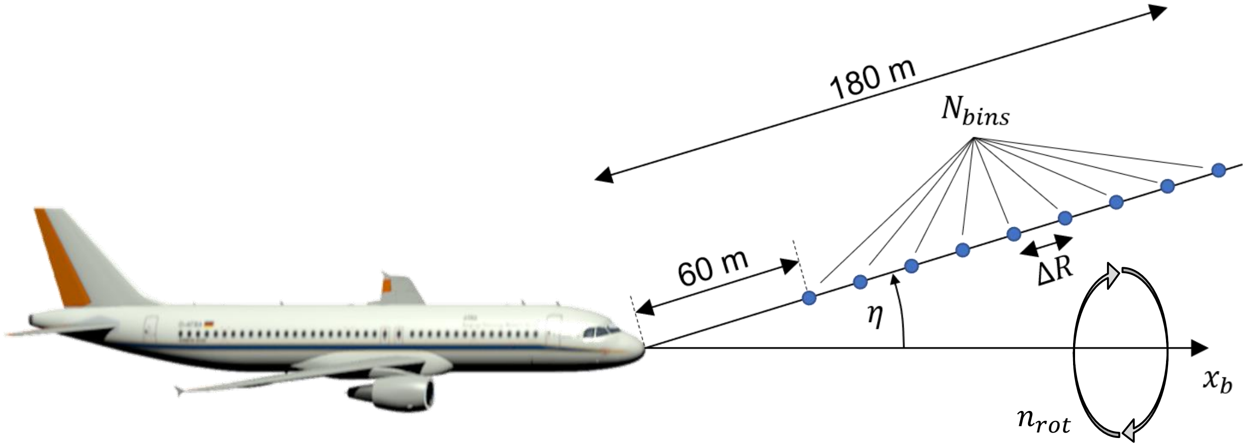
$$\varepsilon(f) = \frac{\Phi_{\Delta w}(f)}{\Phi_{w}(f)}$$





First parameter study: setup

- Variation of:
    - Number of measurements per laser pulse N_{bins}
    - Rotational speed n_{rot}
    - Scan angle η

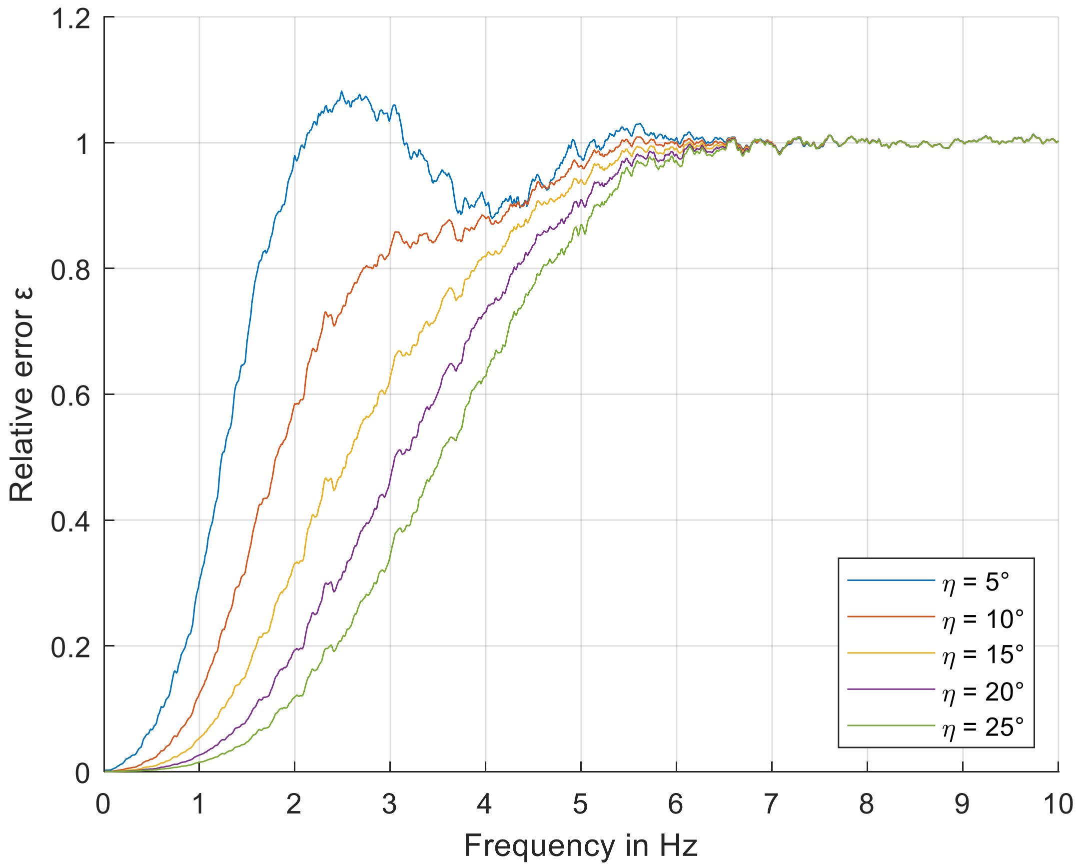


- Higher N_{bins} means more points available for wind reconstruction
- Minimum and maximum measurement distance constant → $\Delta R \sim \frac{1}{N_{bins}}$
- Standard deviation of measurements: $\sigma_v \sim R\sqrt{\frac{PRF}{\Delta R}}$

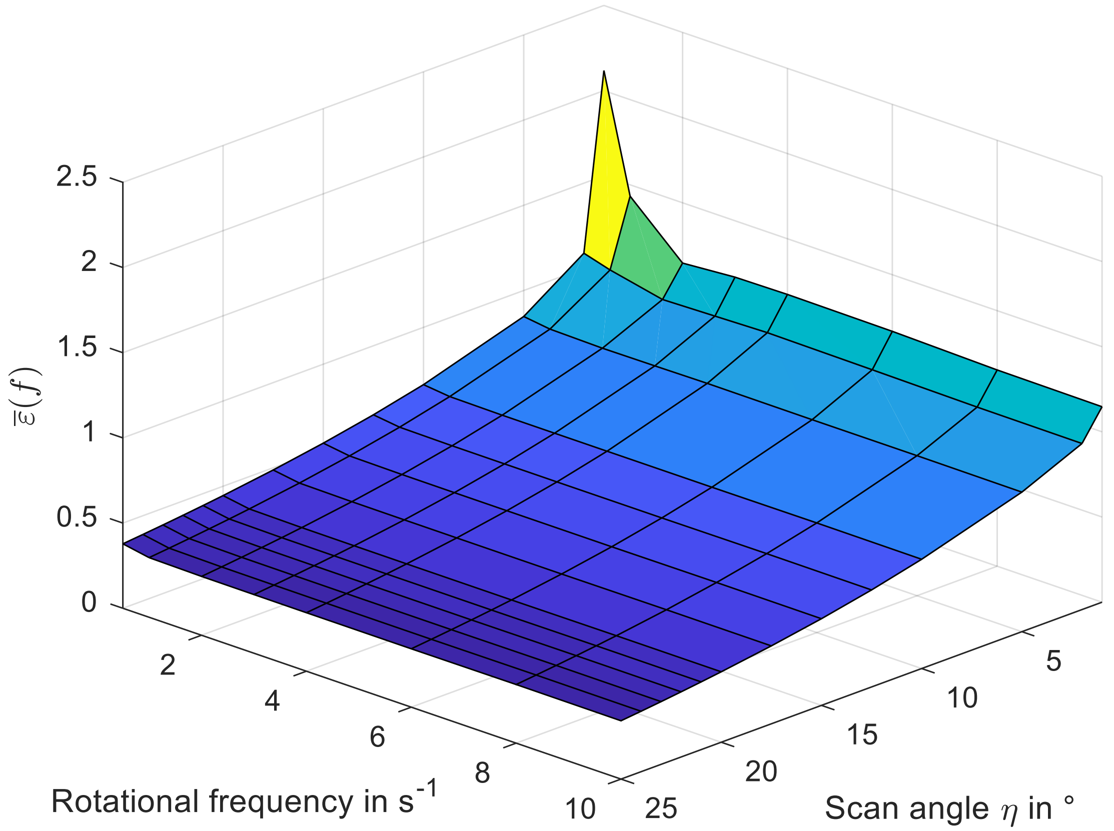
Variation of and N_{bins} is a trade-off between quality and quantity

- Flight point: cruise flight in high altitude (Ma 0.86 at 40,000 ft, TAS ≈ 254 m/s)

First parameter study: results (1/3)

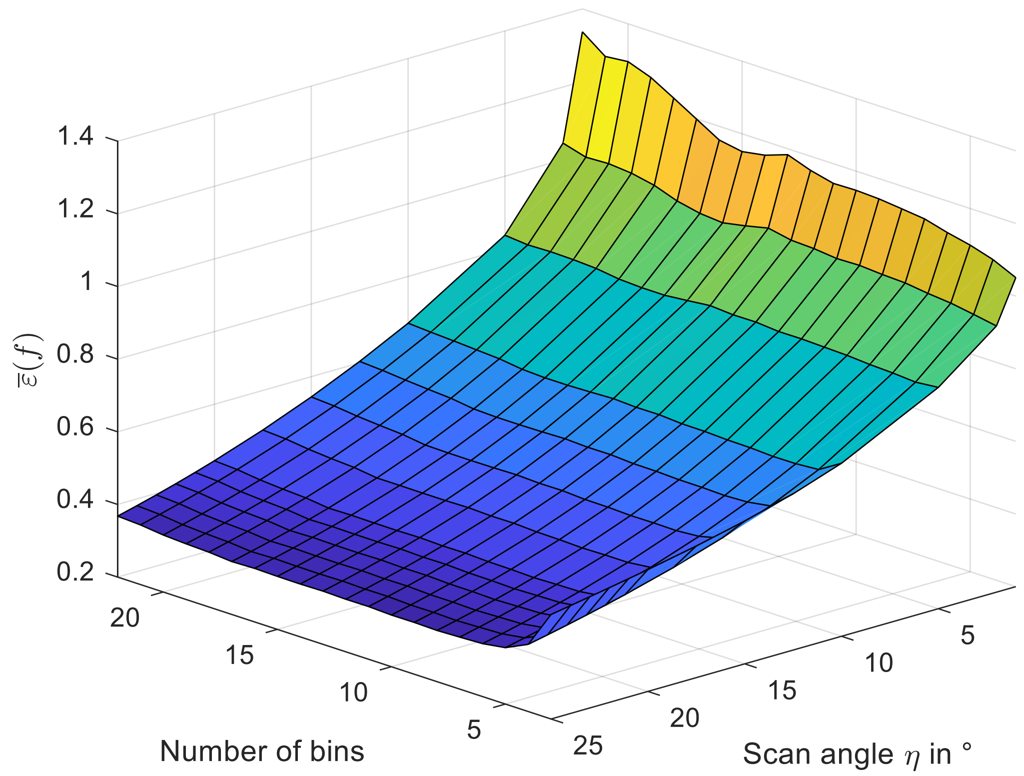


N_{bins} = 10, n_{rot} = 10 s[-1]

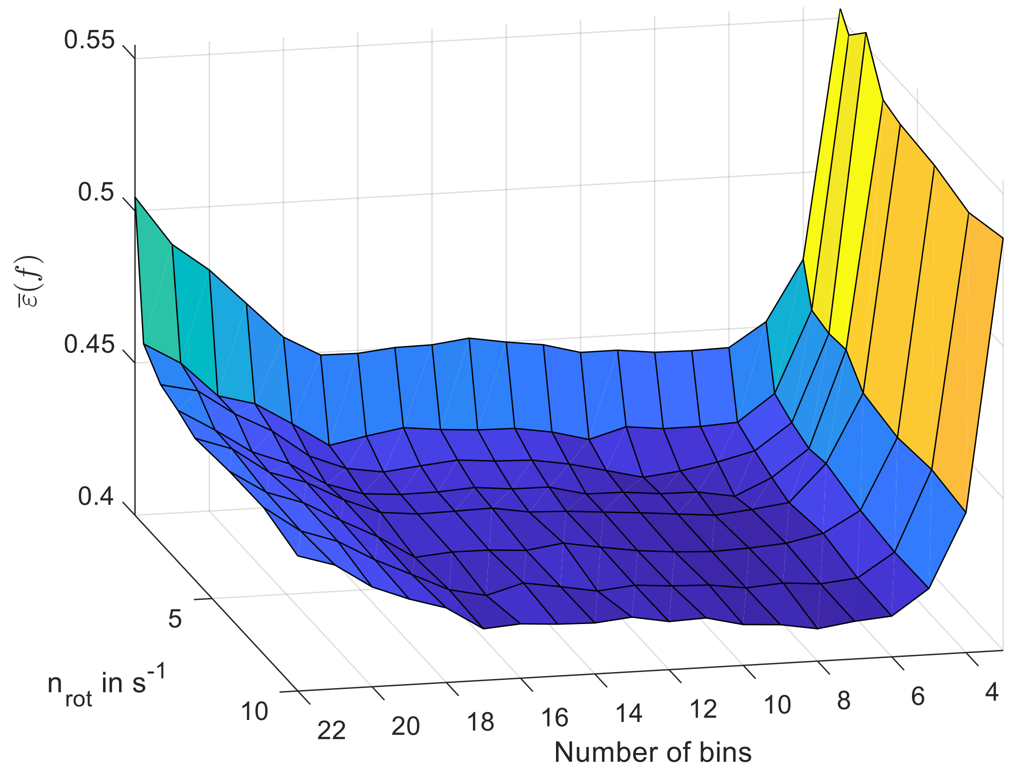


N_{bins} = 10

First parameter study: results (2/3)

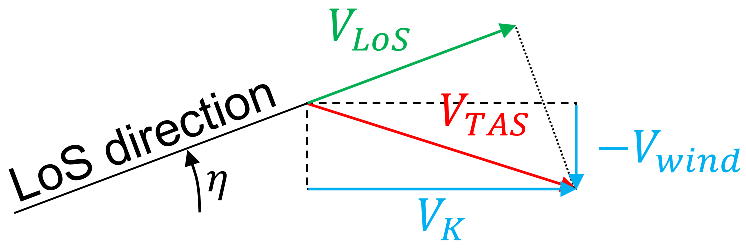


n_{rot} = 10 s^{-1}



η = 20°

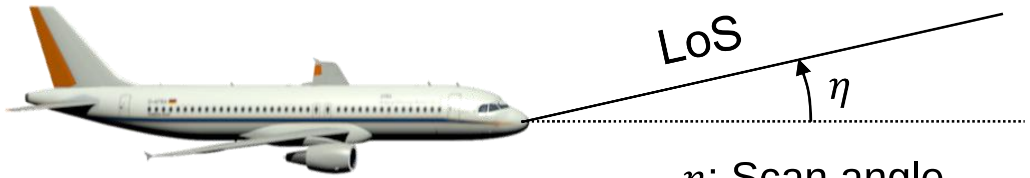
First parameter study: results (3/3)



- Observations:
  - Increasing scan angle improves sensor/algorithm performance
  - Number of bins has relatively small impact for moderate values
  - Rotational speed n_{rot} has small impact

- Impact of scan angle generally expected: higher η → higher projection of vertical wind on LoS → better signal-to-noise ratio

- In CS 25 (and lidar model), wind is only a function of x → performance of higher scan angles is overestimated since real lidar would measure different wind than the aircraft will encounter (higher η = higher vertical distance between measurement point and aircraft)



η: Scan angle

- Large „plateaus" – low parameter sensitivity
- Suspected: regularization too strong → „equalization" of results

Second parameter study: setup

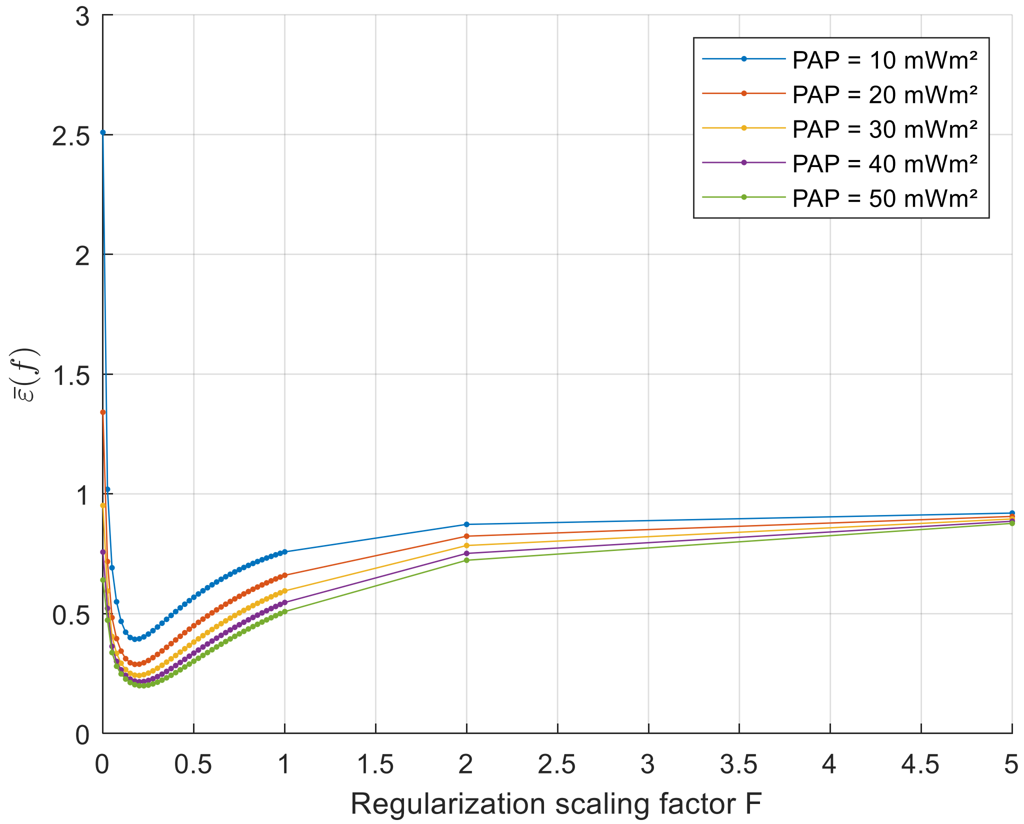
- First study revealed that regularization might have been too strong

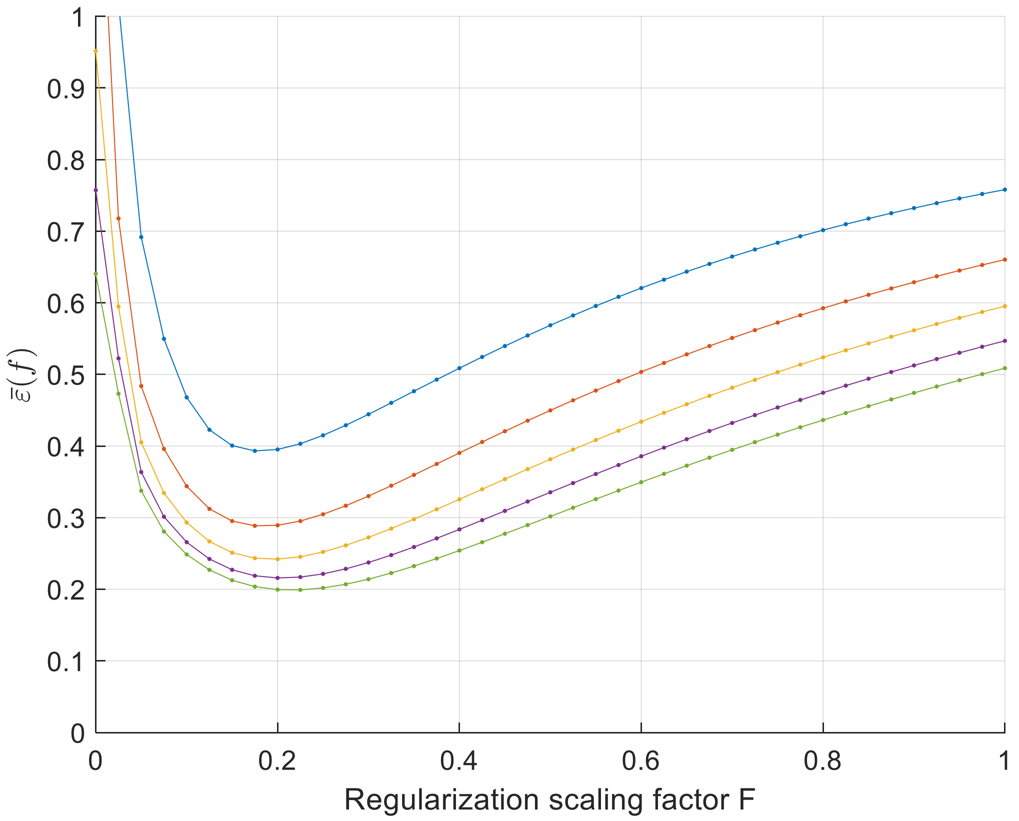
- Variation of regularization parameters
- Factor F: strength of regularization compared to settings used in first study
  - Higher F means stronger regularization, F = 1 represents same regularization (F = 0: no regularization)

- Simultaneous variation of power aperture product PAP
  - Product of receiver area and laser power (good indicator for size/weight/power of the lidar)
  - Higher PAP leads to more precise measurements
    - Measurement standard deviation: $\sigma_v \sim \sqrt{\frac{1}{PAP}}$

- Same flight point as in first study

Second parameter study: results





- Regularization was indeed too high: minimum at F ≈ 0.2
- Spectral error decreases with higher PAP (expected due to lower noise of measurements)
- Minimum spectral error depends on PAP → tuning of regularization parameters based on sensor parameters

Conclusions and future work

- Sensitivity studies conducted for parameters of the lidar sensor and wind reconstruction algorithm

- Lidar parameter with biggest impact: scan angle → high scan angles desired
- Rotational speed of LoS had very little impact
- Number of bins per laser pulse had low impact for moderate values

- Regularization was previously too strong
  - Full potential was not exploited
  - Suboptimal sensor configurations are still useful due to regularization

- Regularization parameters require tuning based on lidar parameters

- Future work
  - Modeling of 3D wind fields (extension of von-Kármán turbulence): more realistic use case
  - Enhancement of sensitivity studies (large parameter space) → optimized sensor design
  - Automatic tuning of algorithm parameters based on lidar sensor characteristics

Thank you for your attention!

German Aerospace Center (DLR)

Institute of Flight Systems
Department of Flight Dynamics and Simulation
Lilienthalplatz 7
38108 Braunschweig, Germany

Institute of Atmospheric Physics
Department Lidar
Münchener Str. 20
82234 Oberpfaffenhofen-Weßling, Germany

Contact:
Daniel Kiehn M.Sc.
Telefon +49-531-295-2959
daniel.kiehn@dlr.de