How Future Aircraft May Lose Weight Thanks to Doppler Wind Lidar Technology – the Ultra Performing Wing Project of the EC Clean Aviation Joint Undertaking

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Abstract

In previous issues of this conference, a part of the authors presented novel approaches for the use of Doppler wind lidar in civil aeronautics (Vrancken and Herbst 2020; Vrancken et al. 2021; Vrancken and Herbst 2022). These approaches include considerable advances in terms of technology and data treatment (Fezans et al. 2020) as compared to precursor projects (Schmitt et al. 2007; Rabadan et al. 2010).

An important part of the development cycle from the current state of scientific-grade more experimental status (low technology readiness level TRL of about 3) towards operationally proven status (TRL 6) for the hand-over to industrial partners is the steady maturation of all system components.

Another aspect is equally continuous demonstration and quantitative validation of the required performance of these components along the way.

For that purpose, DLR and ONERA groups teamed up for jointly performing these tasks. Within the UP Wing project (Ultra Performing Wing) of the European Commission financed Joint Undertaking Clean Aviation, a substantial part is devoted to the enhancement of aircraft wing control with the ultimate goal of saving mass. A way to do this is to lower the effective aerodynamical loads that drive the structural design. And the most powerful technique of such control is the feed-forward (contrasting to established feedback control) that ultimately has to rely on wind information ahead which may only be retrieved by Doppler wind lidar (DWL), and due to the high cruise flight levels, by direct-detection (DD) DWL.

On our poster we highlight the different activities focusing on the most critical technology items of DD-DWL maturation.

The project also includes an early demonstration of one possible DD-DWL implementation, namely with the previously (and also in this conference) shown version relying on a fringe-imaging skewed Michelson interferometer as spectral analyzer.

Acknowledgements

The project receives funding from the Clean Aviation project UP Wing (Grant Agreement #101101974), co-financed by the European Commission.

References

Fezans, Nicolas, Patrick Vrancken, Philippe Linsmayer, Christian Wallace, and Christoph Deiler. 2020. “Designing and Maturating Doppler Lidar Sensors for Gust Load Alleviation: Progress Made Since AWIATOR.” In *AEC 2020*. Bordeaux, France.

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Deutsches Zentrum
für Luft- und Raumfahrt e.V.
in der Helmholtz-Gemeinschaft

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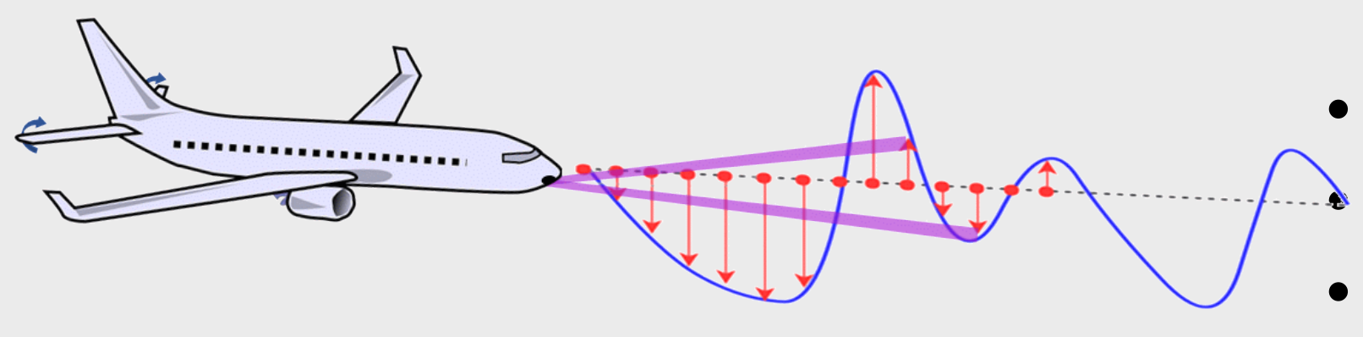
Rationale:

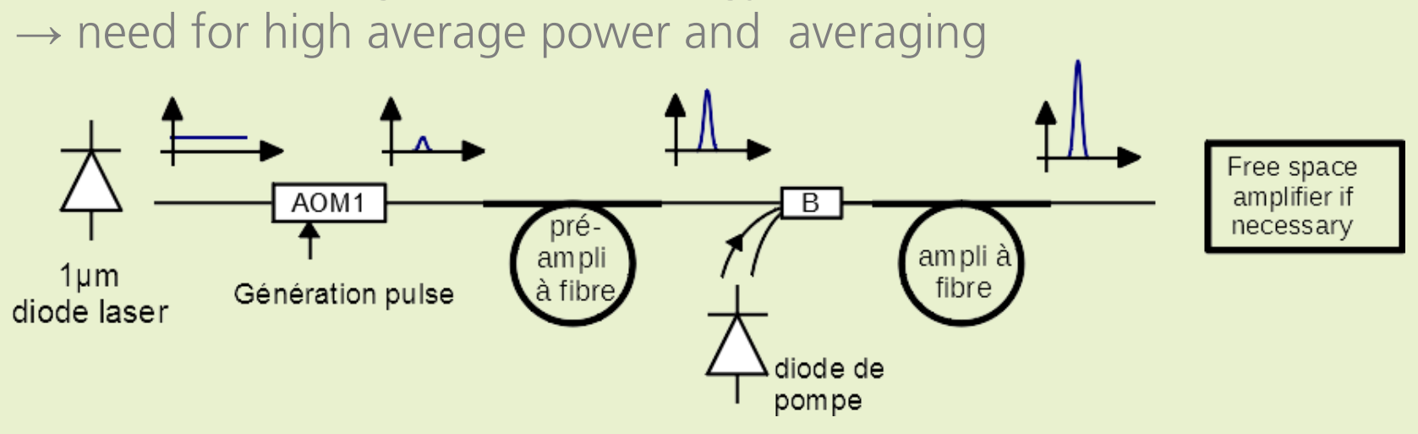


- Goal: Saving structural mass of aircraft wing structure by lowering loads with advanced feed-forward wing control within turbulence = **Lidar-based Feed-Forward Gust Load Alleviation (GLA)**
- Needed: Turbulent gust / wind measurements ahead - retrieved by Doppler wind lidar (DWL)
- High cruise flight levels + system availability requirements (aerosol abundance): UV Direct-detection Doppler Wind Lidar
- For perspectively industrial use: Increase Technology Readiness Level (TRL), i.e. mature technologies, test, and demonstrate

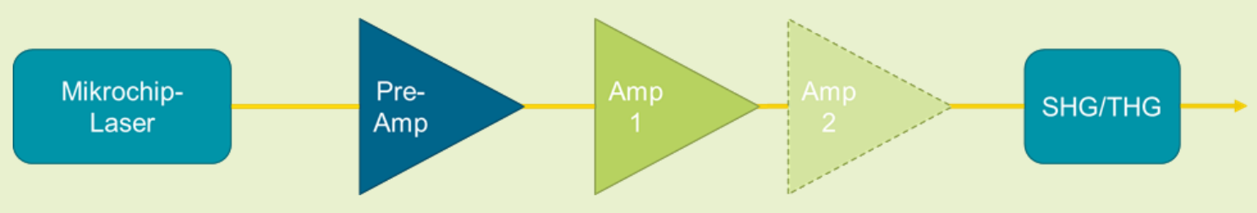
Lidar technology maturation

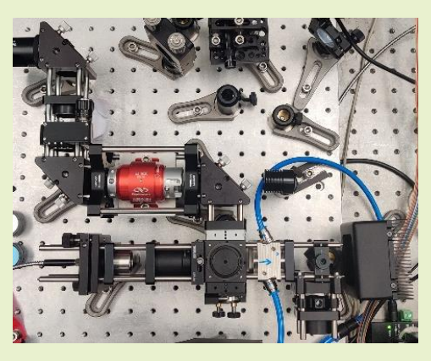
Laser transmitter:

(1) Towards all-fiber sources: Fibered MOPA
- Advantages: efficiency, few alignment, robust to vibration, temporal pulse shaping for optimized detection, path to low cost
- Disadvantages: peak power in fibers limited by nonlinear effects (Stimulated Brillouin Scattering, SBS), low energy per pulse
  → need for high average power and averaging



(2) Flight-test laser – DPSS optimized for application
- DPSS-MOPA architecture
- Goals: > 2.5 W @ 355 nm SLM, 1-3 kHz PRF, 10 ns pulses
- Being integrated in FP7-DELICAT lidar architecture for test flights on NLR Citation 2

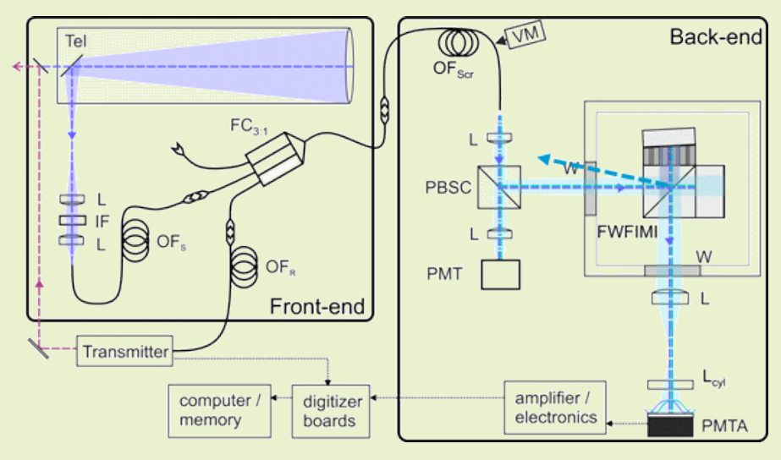


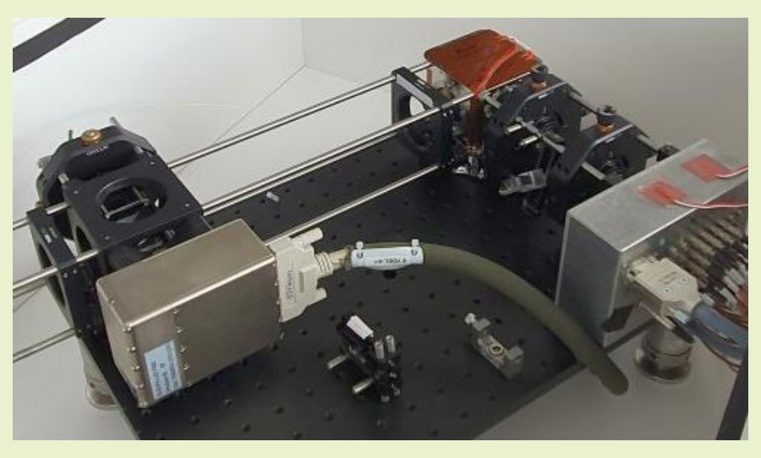


(3) Test and fallback lasers:
- Merion UV injection locked, single frequency laser, 22,5 mJ, 400 Hz, 6 ns
- WALES/DELICAT/AEROLI airborne laser, 80 mJ, 100 Hz, 6 ns

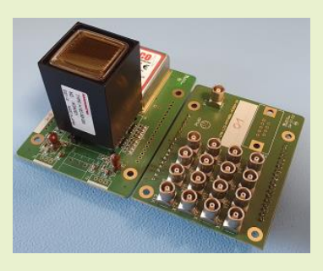
Direct-Detection Doppler Receiver:

(1) Based on Fringe-imaging field-widened Michelson interferometer – flight version

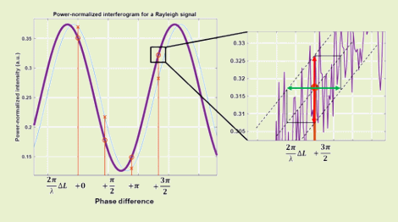


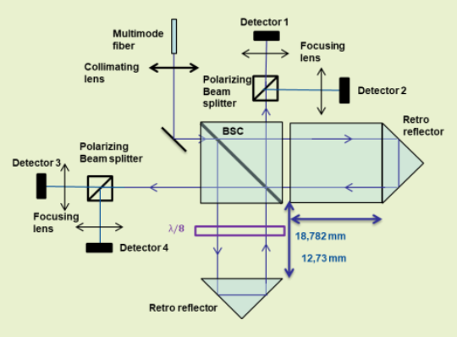


(2) Michelson receiver upgrades / 2nd generation
- Bistatic telescope architecture (adapt overlap)
- Optical mode scrambling (fiber etc.)
- Michelson reflected channel
- Interferometer architecture
- Efficient imaging
- Detection optimization
- Robust data analysis, real-time capable



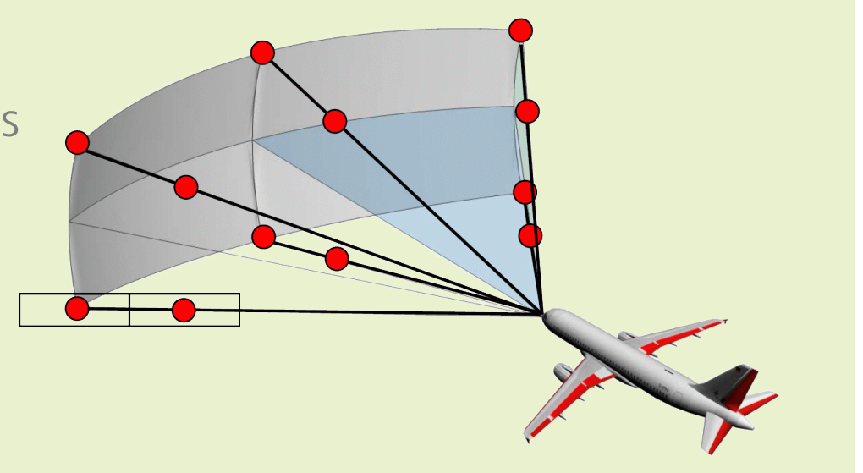
(3) Parallel project: Quadrature-Mach-Zehnder receiver
- Similar theoretical performance as Imaging Michelson(Mach-Zehnder ~2.4 $\sigma_{v_{LOS}, ISA}$
- Only four detectors
- Lab version + monolithic



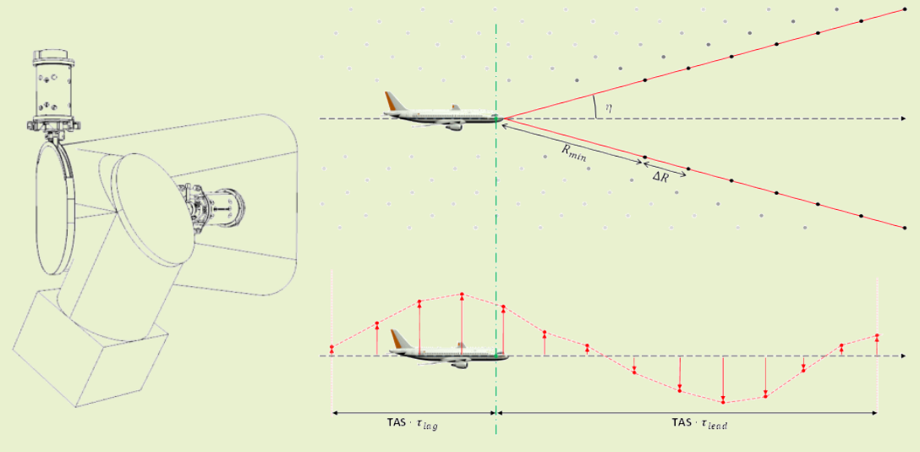


Tx/Rx beam direction:

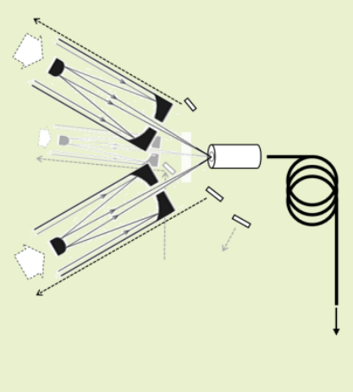
(1) Application: ahead vertical and lateral wind LOS projection
- Iterative study on requirements on
- n° of directions,
- Angles (error, validity, integration constraints
- Speed of scan / switch
- Monostatic/bistatic, on-/off-axis
- Movables (mirrors, etc.), active-optic, holographic

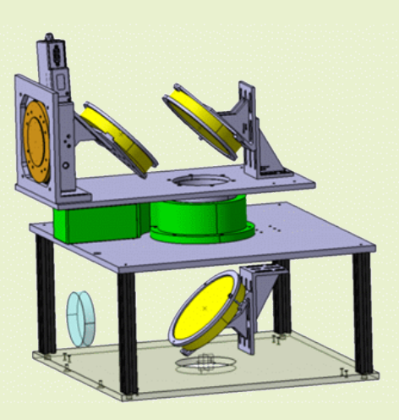


- Continuous scan
- Few, discrete directions



(2) Test purposes
- Turret system
- Fixed directions (biplexer)



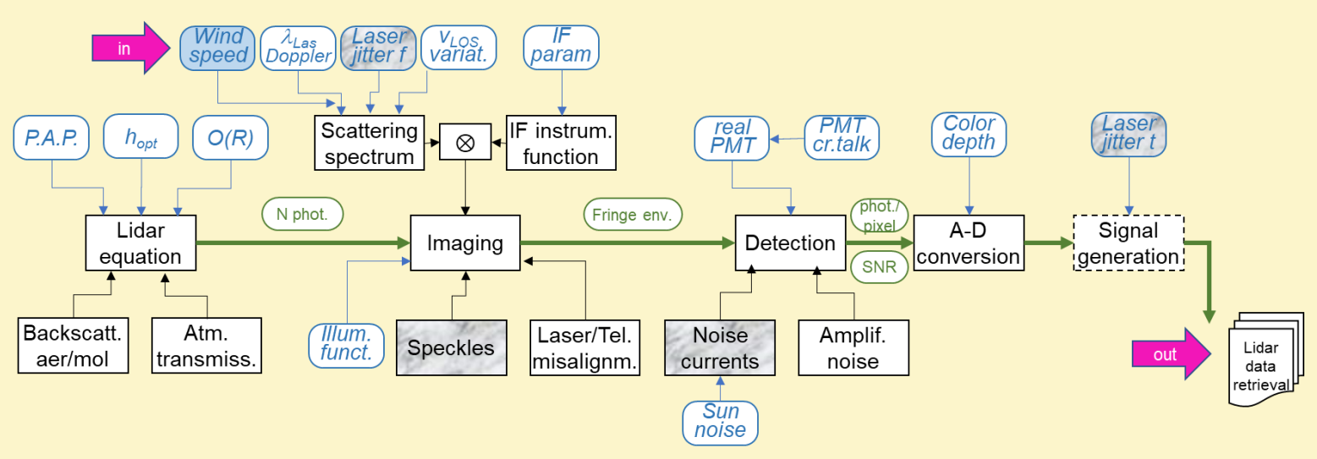


Simulation support

Lidar simulation

(1) Simplified analytical approximation for overall GLA simulation
- LOS Doppler wind distribution based on:
- main lidar design variables Range R, range resolution ΔR, measurement rate $r_{refresh}$, laser power and aperture product $P.A.P.$
- lidar 'constants'
- atmosphere / mission
- $\sigma_{v,av} = \left(\frac{R^2 \cdot r_{refresh}}{P.A.P. \cdot \Delta R}\right)^{1/2} \cdot \frac{\kappa_{real} \cdot \kappa_{TIF}}{(e \cdot \eta_{opt} \cdot \rho_{det})^{1/2}} \cdot \left(\frac{k_B \cdot T(h)}{m_{air} \cdot \beta_{atm}(h,\lambda)}\right)^{1/2}$

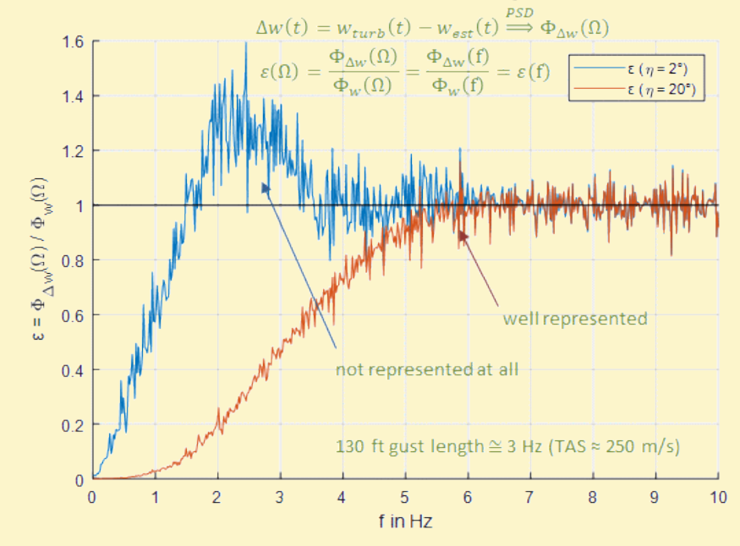
(2) Physics-based end-to-end simulation
- to date: Monte-Carlo-like simulation on main lidar design drivers / perfo impacts
- Simplified optical system
- Atmospheric and fiber speckle effects
- Noise processes (laser, electronics etc.)
- Synthetic signal → full data analysis including fringe fit



- Future additions of atmosphere interaction, light propagation, imaging errors, detector model, environmental effects → + advanced ata analysis

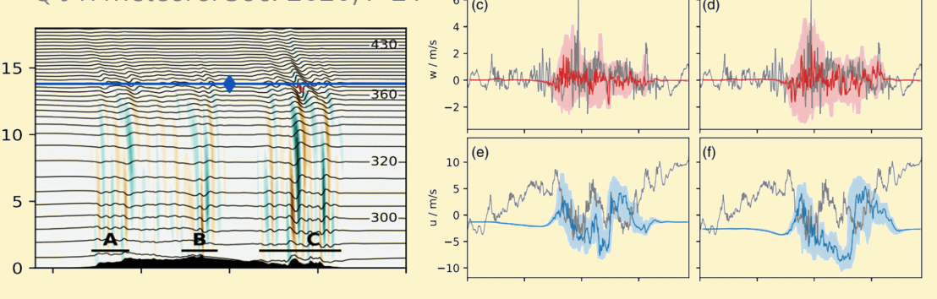
Wind reconstruction algorithm (WRA)

- Buffering of noisy line-of-sight wind measurements
- Maximum likelihood estimation of wind profile (Gauß-Newtonian)
- Tikhonov-regularization
- Frequency domain analysis
- Sensitivity studies (lidar parameters) for optimization, e.g.: scan cone angle η
- Input for controller design



'Realistic' clear air turbulence data

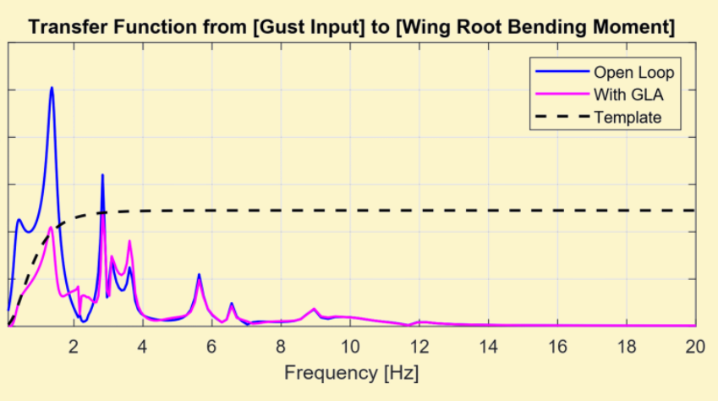
- Flight experiments 1D, 2D data (in-situ noseboom + nadir Doppler lidar)
- CFD study of 3D geophysically produced turbulence:
- Choice of case studies
- Data field generation
- Analysis of turbulent parameters relevant for WRA/GLA
- Investigation of WRA properties and performance in simulated complex 3D turbulence fields



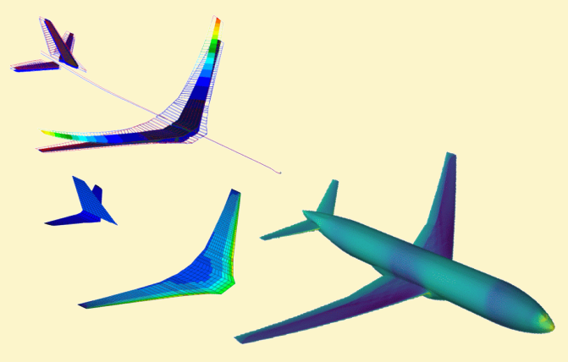
Courtesy of Wilms et al.
Q J R Meteorol Soc. 2020;1–21

Flight controller

(1) Controller optimization:
- via cost functions = 'performance channels'
- Multi-goal optimization = multiple p.c.
- geometry-specific, load type – specific
- (Frequency-specific) weighting by filtering



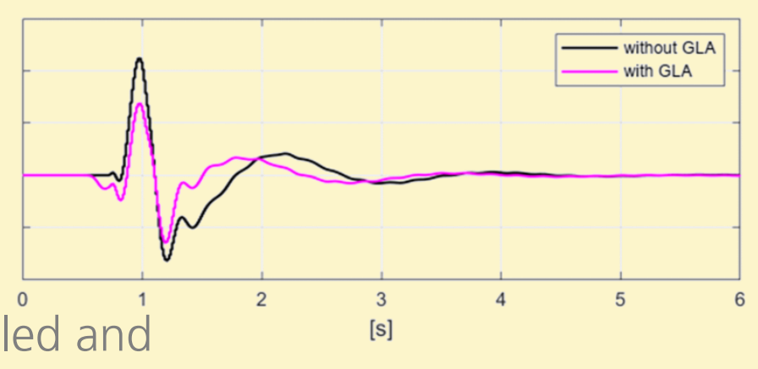
(2) Controller synthesis:
- Discrete-time, reduced-order, multi-channel H_∞ techniques
- Robust control due to minimization of H_∞ -norm



Aircraft models + flight points:

- Models: GBJA – Generic business jet aircraft, GLRA – Generic long range aircraft, Airbus XRF-1, NASA CRM – Common research model (+Fermat)
- Different flight points (Altitude, Ma-number) + mass configurations
- Derivation of aero-elastic model

Load analysis & results



- Frequency and time responses
- Full order or reduced order model complexity
- Time responses of configurations in fully coupled and multirate simulation (i.e. in continuous time), allowing e.g.
- XRF-1 baseline controller 25 Hz, load alleviation 100 Hz, lidar + WRA 10 Hz

Test and early demonstration

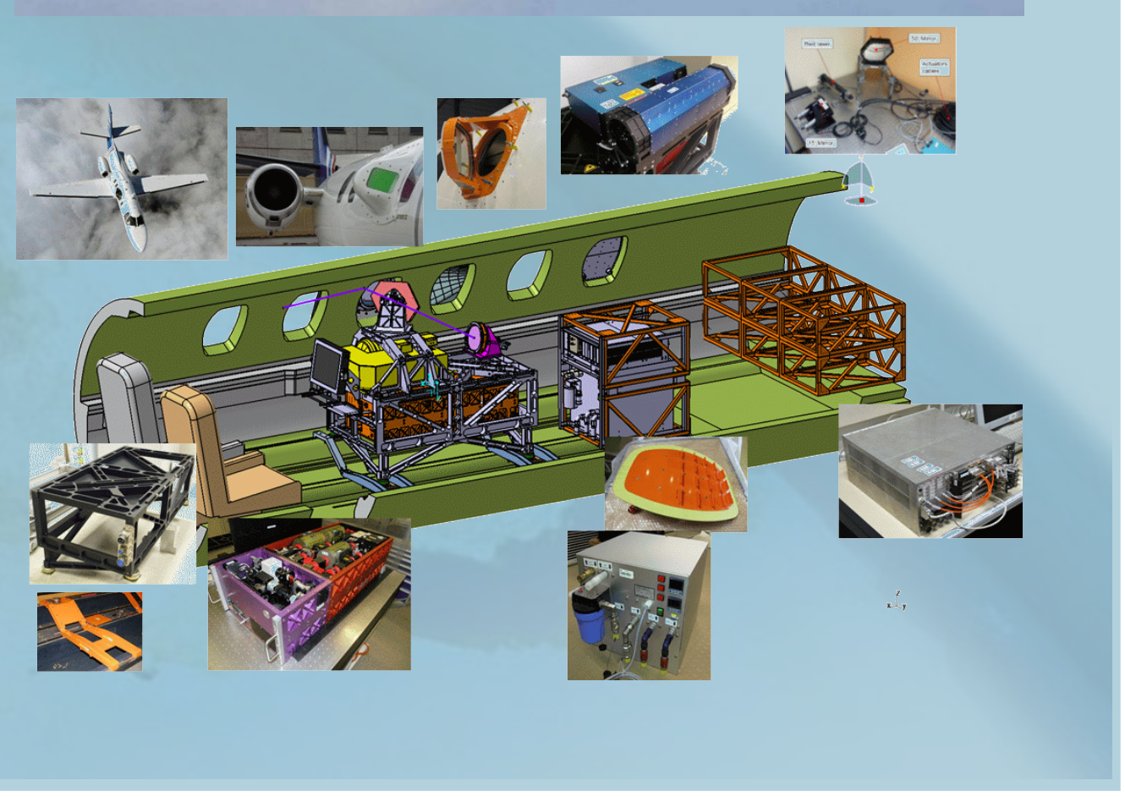
Ground-based high altitude

- Functional testing of respective lidar configurations
- Characterization and sensitivity studies
- High-altitude, mountain-based test facility: Environmental Research Station Schneefernerhaus (UFS) at 2650 m a.s.l.
- Reference (heterodyne detection) Doppler wind lidar(s): Windcube© 200S, in-house fiber-based, 1.6 µm WindTracer© transceiver
- Further reference wind sensors: ultrasonic anemometer(s)
- Aerosol quantification - German Federal Environmental Office (UBA): Nephelometer, particle size distribution, particle counter
  - German Weather service (DWD): Ceilometers
- First campaign 2022 with lessons learned (see talk Philippe Linsmayer)

Early flight tests / airborne validation of DWL functionality

Demonstration UV-Direct-Detection Lidar works according to simulation (and prior ground demo) in flight conditions
- MOPA-DPSS transmitter + Michelson-single-channel receiver + single fixed direction (for LOS only)
- few to none particles / aerosols
- airborne operation
- demo of some functionalities
- = TRL increase of an important part of the lidar technology

Means: measure only wind in line-of-sight of laser beam + compare to air data
- Use existing equipment and flight platform including certification EC/FP7 DELICAT installations
- Forward pointing mirror + aerodynamic fairing
- Nose boom with α and β vanes + 5-hole-probe
- Inertial reference system (IRS/IMU)
- TBD: Aerosol equipment
- Mission: (1) calm air + maneuvers, (2) turbulence



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This work is funded within the framework of the European Clean Aviation Joint Undertaking – Airframe (Grant Agreement 101101974 UP WING) within the research and innovation framework programme of the European Commission.

Co-funded by the European Union

CLEAN AVIATION

4th European Lidar Conference
September 13-15, 2023
Universitatea Babeș-Bolyai, Cluj-Napoca

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