CLEAN AVIATION

Gust Load Alleviation Research: Results from CleanSky 2 and Ongoing Investigations in Clean Aviation

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Acknowledgement:

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Agenda

- Motivation for active gust load alleviation
- Overall concept
- Overview of the past developments, followed by the continuation in Clean Aviation
    - Sensor from the AWIATOR project
    - Wind Reconstruction
    - Control Design and Performance evaluation
    - New developments in terms of sensor hardware
- Maturation and demonstration strategy in Clean Aviation

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Gust Loads & Alleviation

- Aircraft structure are designed to withstand the loads expected to be encountered during the life of all aircraft of this type/model

- The loads induced by gust often dominates the load hierarchy for major parts of the wings and that increasing the aspect ratio tend to worsen this situation

- By alleviating the loads induced by gusts and turbulence, the mass of the aircraft can be reduced

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Ambition in Clean Sky and Clean Aviation

- High ambition to transform tomorrow’s aviation towards a sustainable and climate-neutral future
  ➔ aims at pushing the different technologies as far as possible and needed

“as possible”

- To be determined based on the considered system

“as needed”

- For gust load alleviation, as long as gust loads are sizing the structure reducing the gust loads allows reducing the mass of the aircraft
- When gust loads are lower than other loads (e.g. maneuver loads) or would lead to designs that are violating some constraints (e.g. manufacturing), then a further reduction does not yield mass reduction

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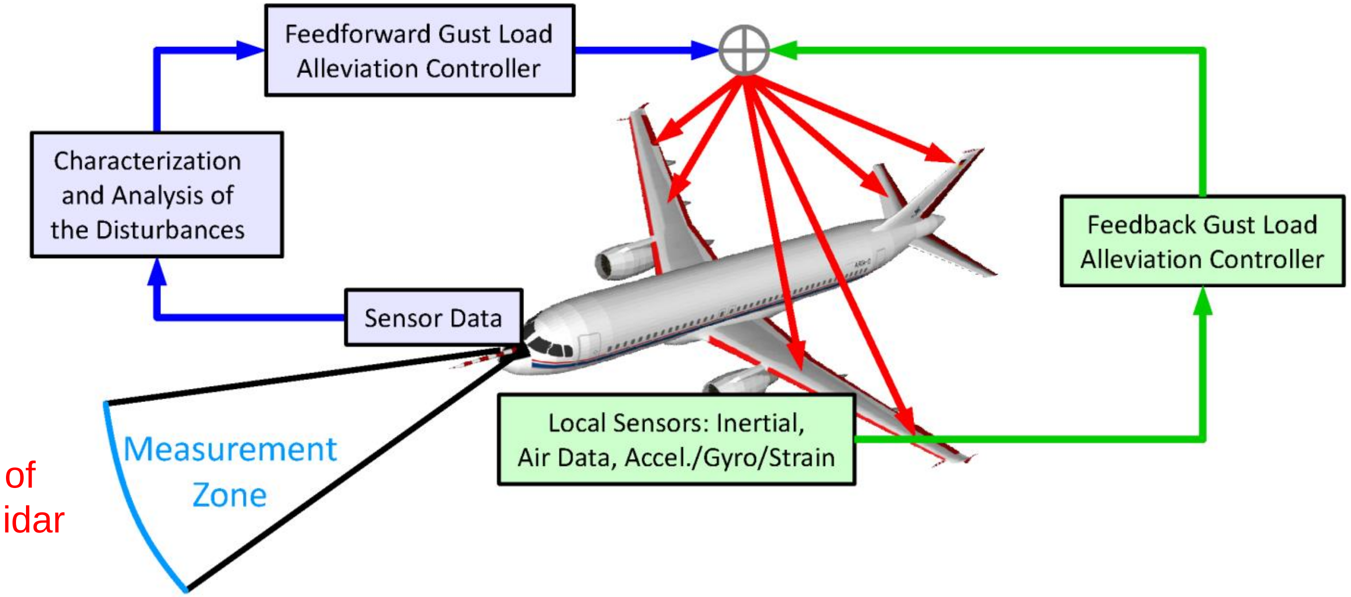
Gust Load Alleviation – *Feedback vs. Feedforward*



Measurement ahead of the aircraft only with lidar

Feedforward gust load alleviation

Can anticipate the forthcoming gusts
➔ can alleviate loads through pitching commands
➔ can trigger e.g. ± open-loop spoiler deployment
➔ expected to enable significantly higher gust load reductions

Feedback gust load alleviation

Can act on the flexible modes (e.g. to damp them)
Reacts to the real motion of the aircraft
Would ultimately alleviate what was not or imperfectly alleviated by the feedforward function

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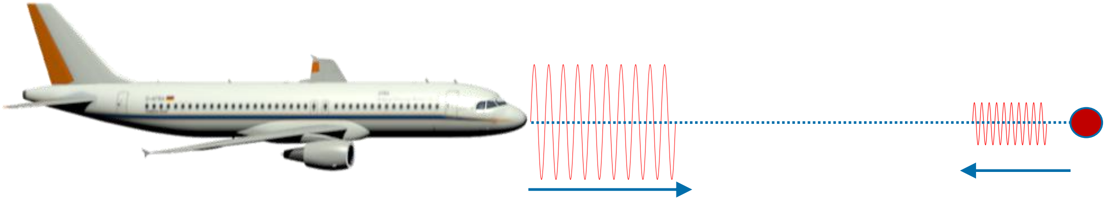
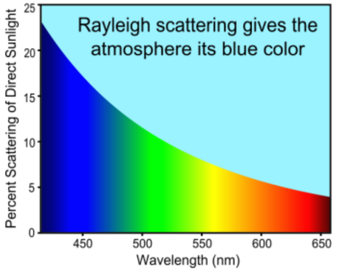
Lidar Sensor: Measurement Principle



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)

Direct Detection

- “Direct” analysis of the frequencies/wavelengths contained in the backscattered signal (via optical interferometer) and comparison with emitted laser frequency/wavelength
- Can work with a backscattered signal having a fairly wide spectrum ➔ also applicable with backscattering on molecule of the air (Rayleigh scattering)



Intensity: $I \sim \frac{1}{\lambda^4}$

→ the shorter, the better, so often **UV-wavelength** is used

Heterodyne Detection

- Analysis of the wavelength via heterodyning, i.e. the mixing of the backscattered signal with the source
- Requires the backscattered signal to be concentrated at one wavelength
  ➔ requires the received signal to have been scattered back by aerosols (Mie scattering)
  ➔ requires comparatively longer wavelength for efficient backscatter from aerosols
  $I \sim \lambda$ → **infrared wavelengths used**
  (also comfortable regarding laser technology)

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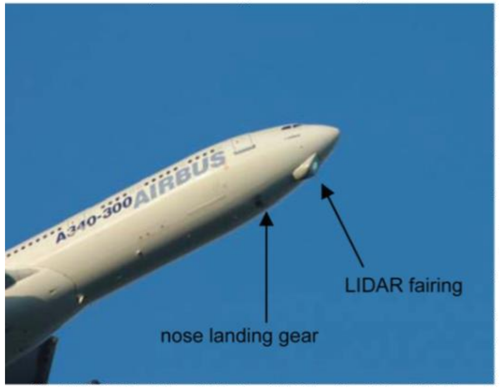
Direct Detection Lidar: In-Flight Demonstration

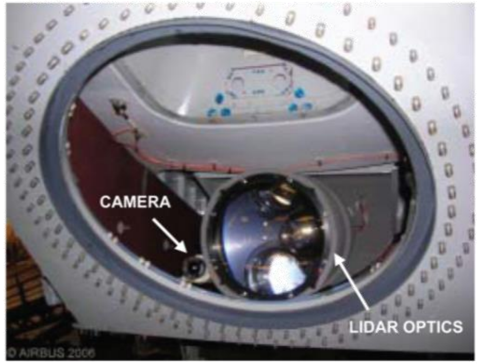
In-Flight Demonstration:

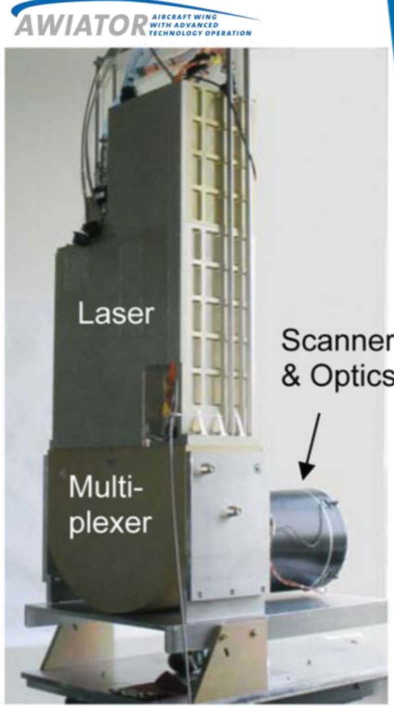
- On DLR ATTAS (2004)
- Improved system tested on A340-300 (2006)
- Capacities of the sensor demonstrated

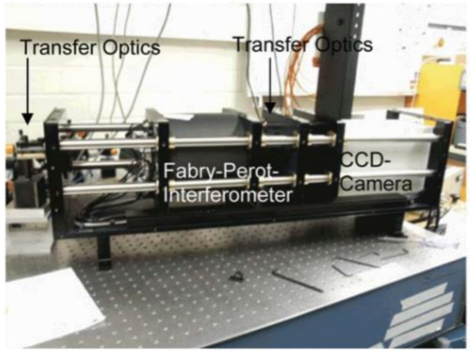
However:

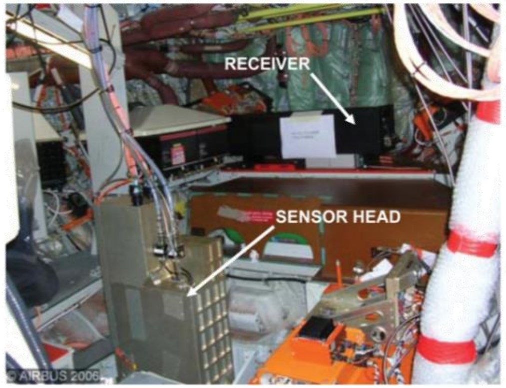
- Offline processing (onboard FPGA-based processing not demonstrated)
- Not coupled (in-flight) with a load alleviation function











Illustrations from
Rabadan, G. J., Schmitt, N. P., Pistner, T., Rehm, W. (2010). Airborne lidar for automatic feedforward control of turbulent in-flight phenomena. Journal of Aircraft, **47**(2), 392-403. doi: 10.2514/1.44950

Very good results showing a possible implementation of such lidar sensor for gust load alleviation (GLA).
Series of open questions remaining, especially on the optimal way to process and use the sensor measurements for GLA, but also on the optimization of the sensor design itself (scan, pulse repetition frequency, binning, interferometer type, ...)

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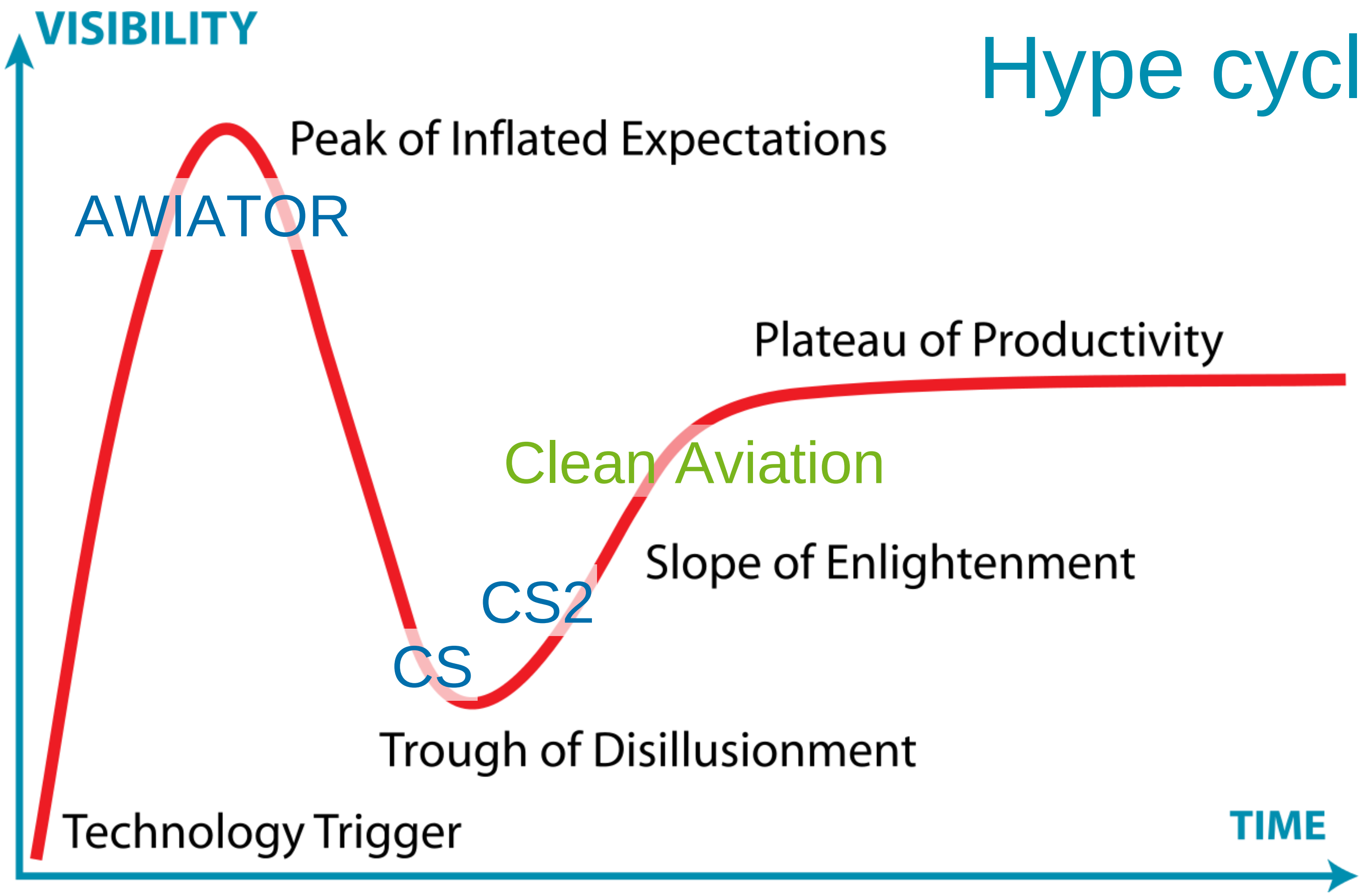
Post AWIATOR: A hard time for lidar-based gust load alleviation



Disclaimer
Placement of the different project along the hype cycle is purely subjective and based on the authors' impression from the time spent working in the Clean Sky and Clean Sky 2 projects.

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Work Performed in CleanSky and CleanSky 2

- **CleanSky – Smart Fixed Wing Aircraft**
  - Two main improvement directions identified compared to the AWIATOR approach
    - Wind reconstruction algorithm
    - Multi-objective optimization for load alleviation function design

- **CleanSky 2 – Airframe ITD – TS-A-4 / NACOR**
  - New implementation of the wind reconstruction algorithm
    → highly optimized and with deterministic execution time and memory footprint
  - Improved load alleviation function design methodology / workflow
    → model management, model reduction, discretization, load envelope computation, etc.
    design based on a new multi-channel structured discrete time H_∞ preview control formulation
  - Evolution regarding the lidar sensor design/technology and its modelling (specific end-to-end simulator + generic/versatile simulator for toolchain use)
  - Start building a simulation toolchain for systems/concurrent-engineering studies

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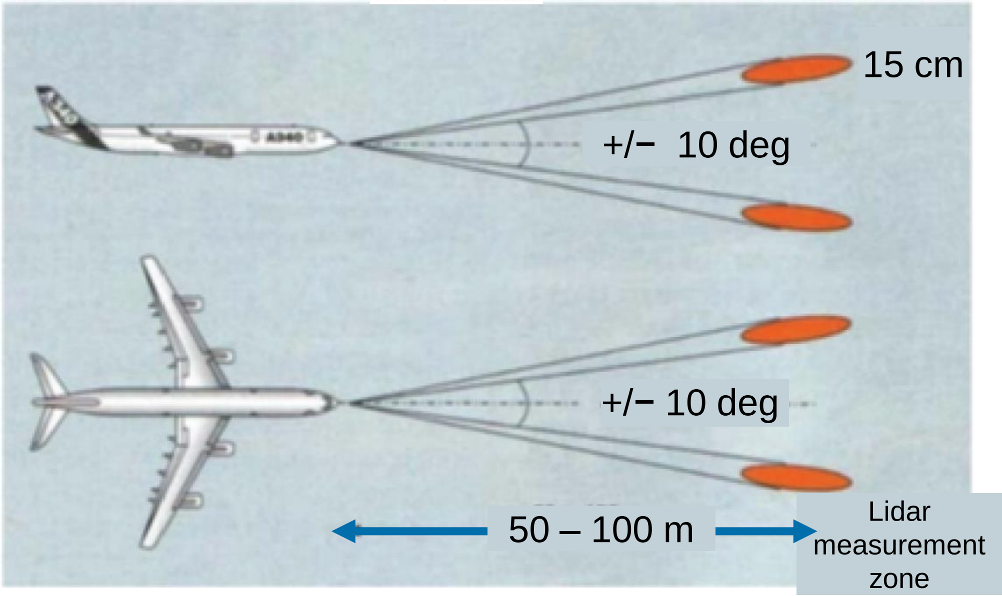
Wind Reconstruction in AWIATOR

REMINDER: Role ➔ Estimate the 3D wind ahead of the aircraft from the lidar measurements

IN AWIATOR



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Determination of the Vertical Wind in AWIATOR

Four measurements volumes (top-left/right & bottom-left/right)
➔ slightly overdetermined least-squares problem
(3 wind components vs. 4 non-collinear meas.)

Noise: std. dev. 1.5 m/s in LoS → 4.3 m/s vertical/transversal
@ 60 Hz @ 15 Hz

x 2.9

at 39,000 ft

IDENTIFIED POTENTIAL IMPROVEMENT DIRECTIONS

- Take time delays & aircraft motion between measurements into account
- Estimate “wind profiles” based on higher number of measurements (e.g. along LoS) instead of independent wind estimates at “one location” → also offers better smoothing possibilities without additional phase-lag

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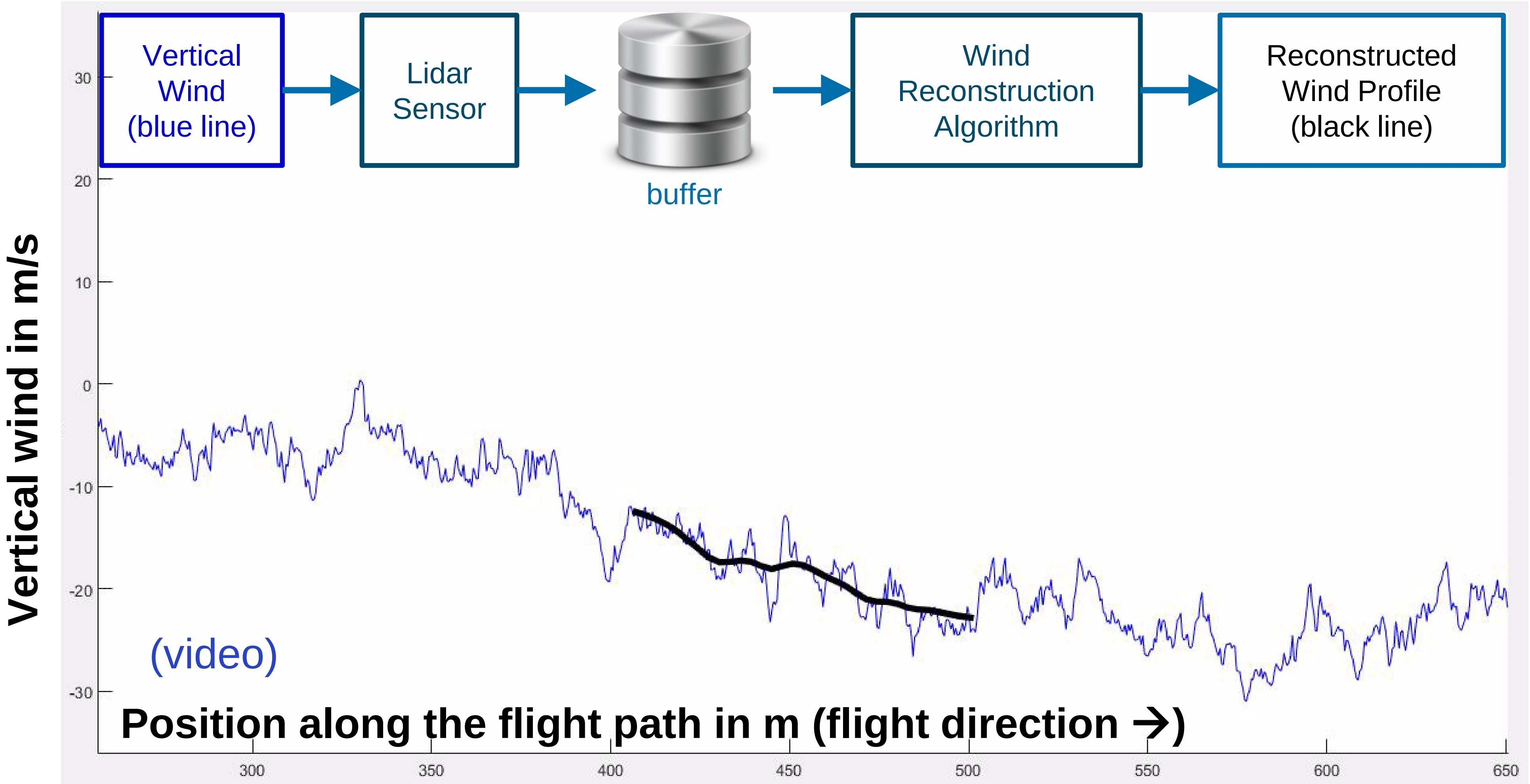
Wind Reconstruction Developed in CleanSky

New approach for the determination/reconstruction of the wind ahead of the aircraft


Vertical Wind (blue line) → Lidar Sensor → buffer → Wind Reconstruction Algorithm → Reconstructed Wind Profile (black line)

(video)

Limited spatial resolution

- Good for anticipating the large-scale gusts
- Cannot really measure the small-scale gusts

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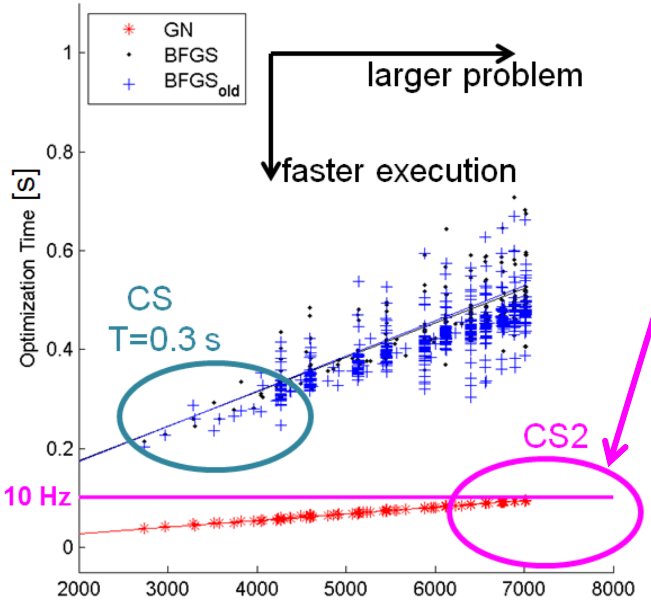
Improvement of the Wind Reconstruction in CleanSky 2

Approach proposed and tested in CleanSky was optimized in CleanSky 2
→ **deterministic execution time and deterministic memory footprint**



Number of line-of-sight measurements contained in the measurement buffer

10 Hz for wind profile updates in CS2:
not to be confused with a signal sampling rate!

In cooperation with TU Braunschweig / SE^{2}A Excellence Cluster:

- Optimal tuning method for smoothing/regularization parameters

Way forward in Clean Aviation:

- Develop and test recursive formulation (equivalent but even more efficient)
- Generate realistic 3D turbulence cases and test the wind reconstruction algorithm on these cases
- If needed, improve the algorithm (3D cases, dealing with outliers, etc.)
- Investigate 3D wind reconstruction capability and its robustness when varying the scanning pattern

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Work Performed in CleanSky and CleanSky 2

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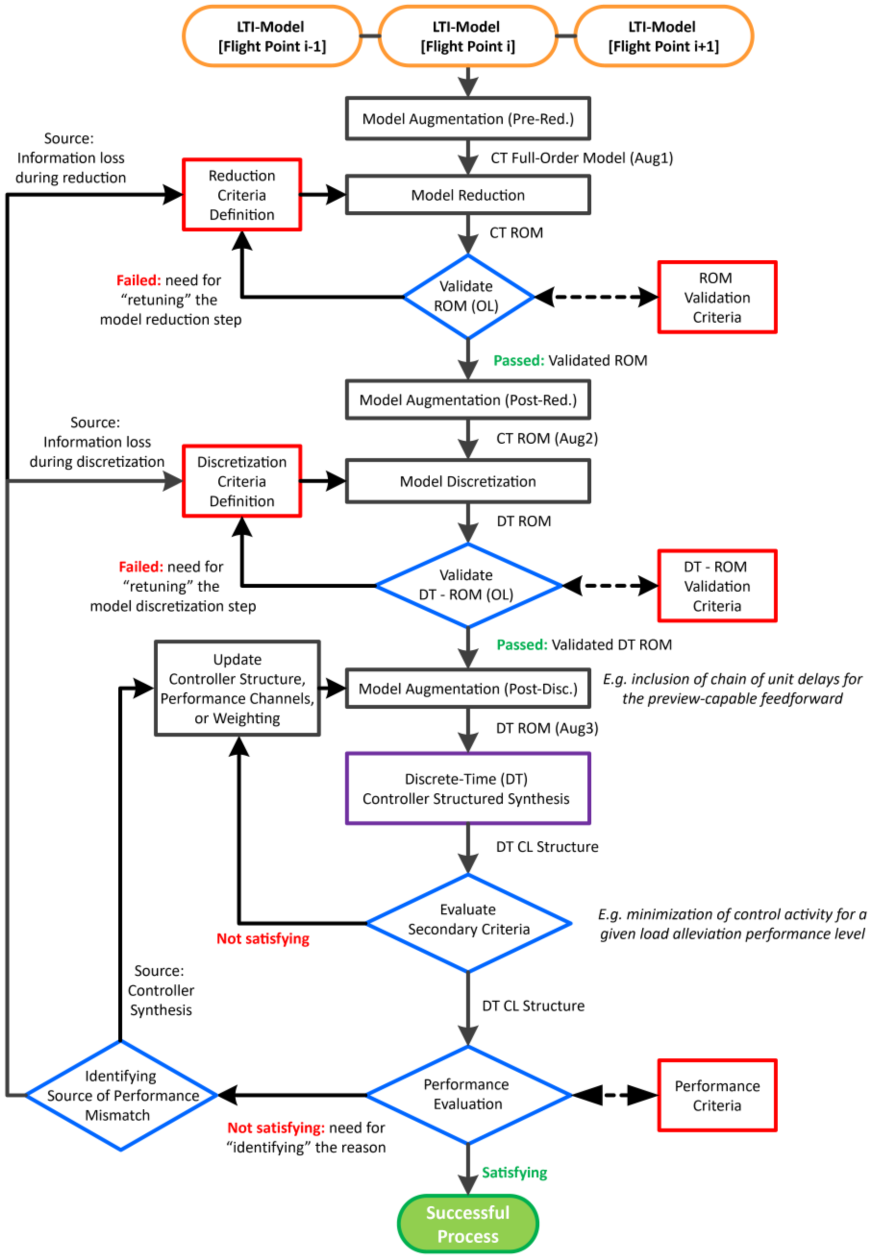
Gust Load Alleviation Control Design Methodology

Multi-model

Models are reduced and discretized prior to synthesis

Synthesis directly in discrete time

Iterative adjustment of some of the criteria based on the results obtained on the full nonlinear simulation (to account for effects that are loss or imprecisely represented in the linear design model)



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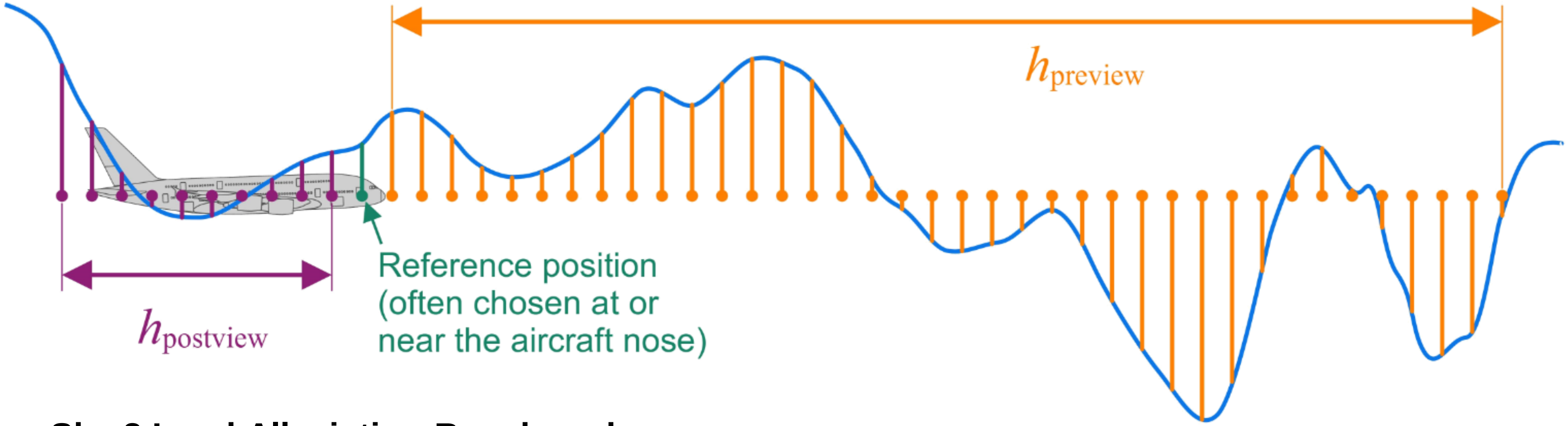
Preview Control for Gust Load Alleviation

- **Preview control:** class of control techniques making use of information known in advance, that is related to a future time (e.g., disturbance or reference)
  → Can be used to optimize (offline) the optimal reaction (control commands) to the entire wind profile
- Formulation used:



Reference position (often chosen at or near the aircraft nose)

In the the case of the **CleanSky 2 Load Alleviation Benchmark**

$h_{\text{preview}} = 35$ and $h_{\text{postview}} = 10$ → wind profile is provided to the controller as a 46-element vector

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Preview Control for GLA: Results from CleanSky 2

Structured controller based on preview-control formulation and in discrete time (80 Hz)

$$K_{\mathrm{ff}}(z) = \underbrace{\begin{bmatrix} \overline{F}_{\mathrm{elevators}}(z) & 0 & 0 \\ 0 & \overline{F}_{\mathrm{ailerons}}(z) & 0 \\ 0 & 0 & \overline{F}_{\mathrm{ailerons}}(z) \end{bmatrix}}_{\text{fixed (not tunable)}} K_{\mathrm{tunable}}(z) \longleftarrow$$

K_{tunable} has 3 outputs, (h_{total} + 1) inputs, 4 states

$h_{\mathrm{total}} = h_{\mathrm{preview}} + h_{\mathrm{postview}}$ = 35 + 10 = 45 → 46 inputs

➔ 350 parameters to tune

$F_{\mathrm{elevators}}(z)$ and $F_{\mathrm{ailerons}}(z)$ obtained by discretizing the following continuous-time filters

$$F_{\mathrm{elevators}}(s) = \underbrace{\frac{s^2}{(s+0.05\cdot 2\cdot\pi)\,(s+0.1\cdot 2\cdot\pi)}}_{\text{high-pass}} \underbrace{\frac{1}{\left(\frac{s}{6.0\cdot 2\cdot\pi}+1\right)^2 \left(\frac{s}{7.0\cdot 2\cdot\pi}+1\right)^2}}_{\text{low-pass}}$$

$$\overline{F}_{\mathrm{elevators}}(s) = \frac{F_{\mathrm{elevators}}(s)}{||F_{\mathrm{elevators}}(s)||_\infty}$$

$$F_{\mathrm{ailerons}}(s) = \underbrace{\frac{s}{(s+0.1\cdot 2\cdot\pi)}}_{\text{high-pass}} \underbrace{\frac{1}{\left(\frac{s}{7.0\cdot 2\cdot\pi}+1\right) \left(\frac{s}{8.0\cdot 2\cdot\pi}+1\right) \left(\frac{s}{9.0\cdot 2\cdot\pi}+1\right)}}_{\text{low-pass}}$$

$$\overline{F}_{\mathrm{ailerons}}(s) = \frac{F_{\mathrm{ailerons}}(s)}{||F_{\mathrm{ailerons}}(s)||_\infty}$$

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Preview Control for GLA: Results from CleanSky 2

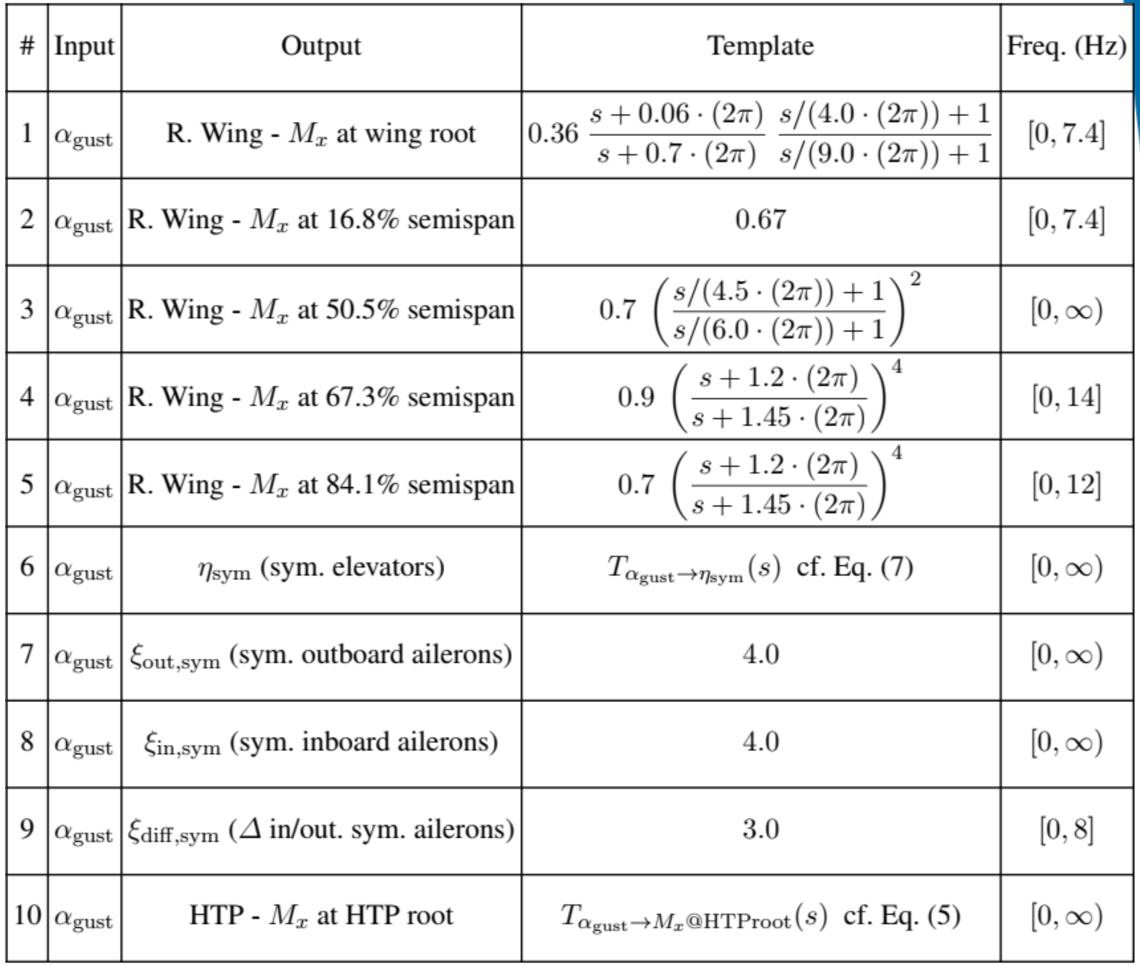
Tuning criteria:

- 10 different H∞ criteria were defined and tuned iteratively
- all 10 criteria were applied to 4 tuning models
- no gain-scheduling (e.g., no adjustment for different loading cases or Mach number)

used to tune the load alleviation performance at different locations along the wing

used to penalize the control activity (cf. structure imposed with the band-pass filters)

used to prevent excessive HTP loads



#	Input	Output	Template	Freq. (Hz)
1	α_{gust}	R. Wing - M_x at wing root	$0.36\,\dfrac{s+0.06\cdot(2\pi)}{s+0.7\cdot(2\pi)}\,\dfrac{s/(4.0\cdot(2\pi))+1}{s/(9.0\cdot(2\pi))+1}$	$[0, 7.4]$
2	α_{gust}	R. Wing - M_x at 16.8% semispan	0.67	$[0, 7.4]$
3	α_{gust}	R. Wing - M_x at 50.5% semispan	$0.7\left(\dfrac{s/(4.5\cdot(2\pi))+1}{s/(6.0\cdot(2\pi))+1}\right)^2$	$[0, \infty)$
4	α_{gust}	R. Wing - M_x at 67.3% semispan	$0.9\left(\dfrac{s+1.2\cdot(2\pi)}{s+1.45\cdot(2\pi)}\right)^4$	$[0, 14]$
5	α_{gust}	R. Wing - M_x at 84.1% semispan	$0.7\left(\dfrac{s+1.2\cdot(2\pi)}{s+1.45\cdot(2\pi)}\right)^4$	$[0, 12]$
6	α_{gust}	η_{sym} (sym. elevators)	$T_{\alpha_{\text{gust}}\rightarrow\eta_{\text{sym}}}(s)$ cf. Eq. (7)	$[0, \infty)$
7	α_{gust}	$\xi_{\text{out,sym}}$ (sym. outboard ailerons)	4.0	$[0, \infty)$
8	α_{gust}	$\xi_{\text{in,sym}}$ (sym. inboard ailerons)	4.0	$[0, \infty)$
9	α_{gust}	$\xi_{\text{diff,sym}}$ (Δ in/out. sym. ailerons)	3.0	$[0, 8]$
10	α_{gust}	HTP - M_x at HTP root	$T_{\alpha_{\text{gust}}\rightarrow M_x\text{@HTProot}}(s)$ cf. Eq. (5)	$[0, \infty)$

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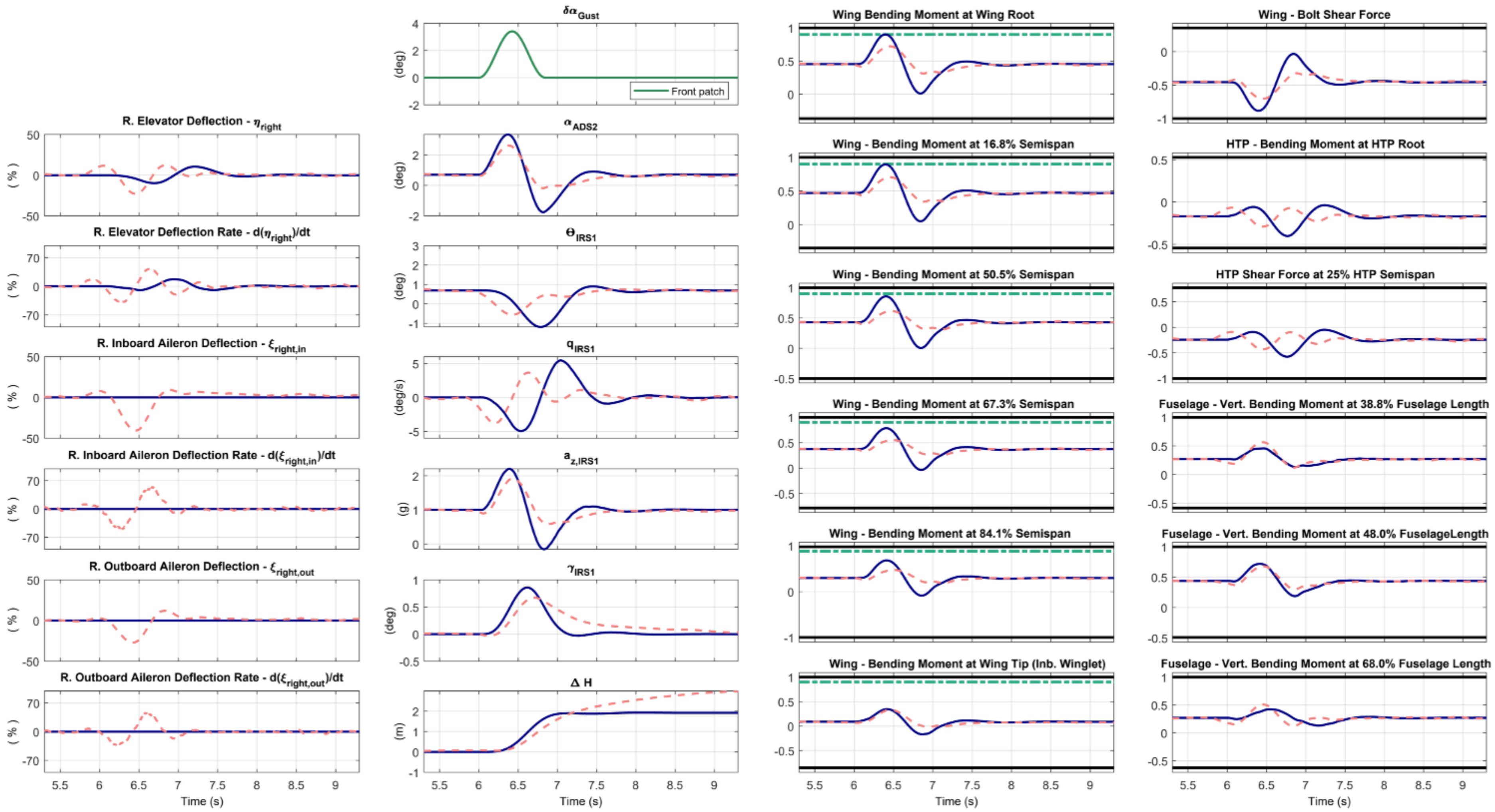
Preview Control for GLA: Results from CleanSky 2

- ▬ Baseline FCS
- ╌ Baseline FCS + GLA
- ▬ Current Limit Loads
- ▬·▬ Target Load Levels

Control Surfaces | "Rigid-body" | Wing Bending Loads | Other Selected Loads



All signs and conventions used follow the definitions from the ISO-1151 standard

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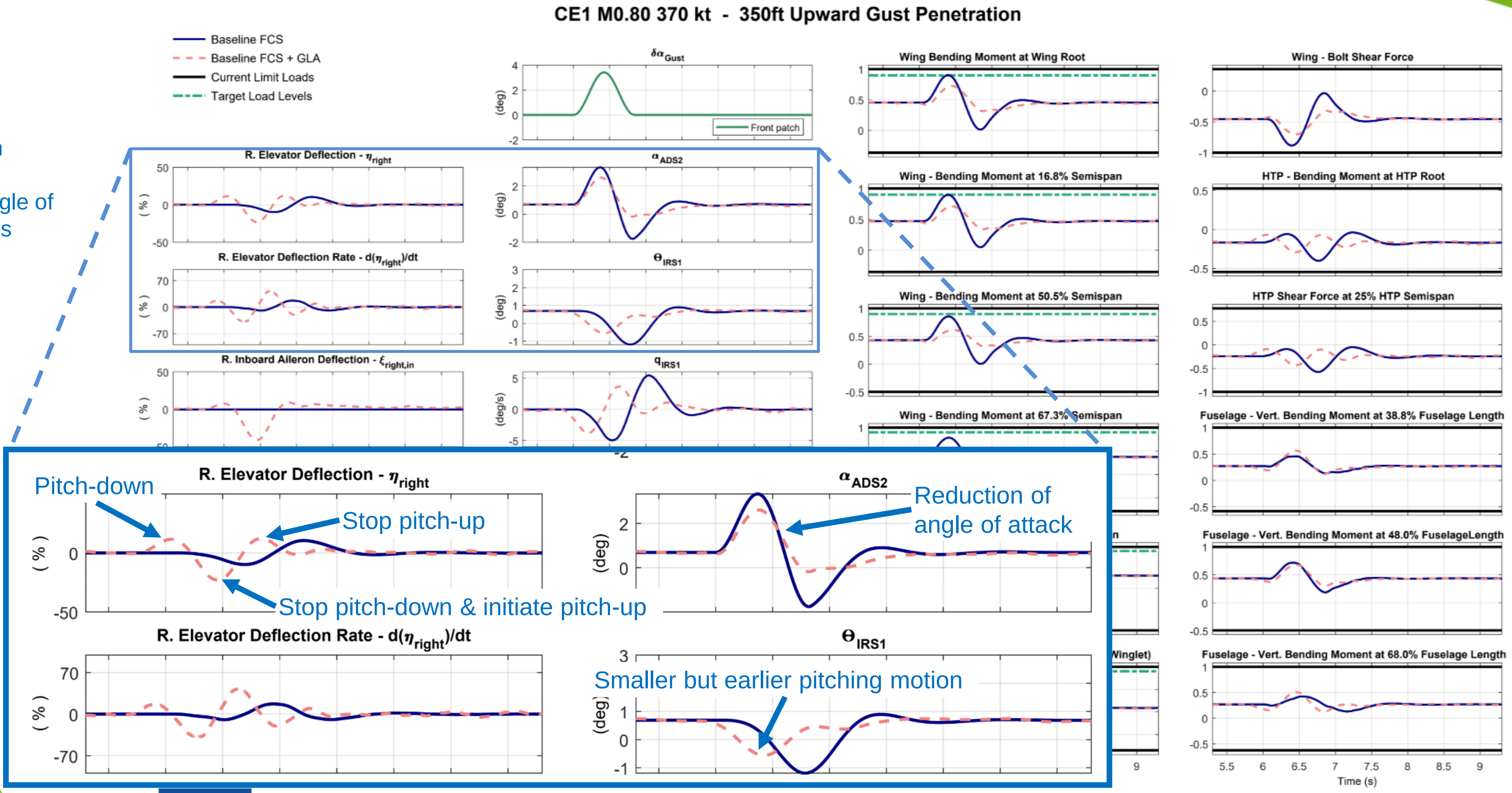
Preview Control for GLA: Results from CleanSky 2

350 ft gust

Pitching motion commanded to reduced the angle of attack variations



Pitch-down

Stop pitch-up

Stop pitch-down & initiate pitch-up

Reduction of angle of attack

Smaller but earlier pitching motion

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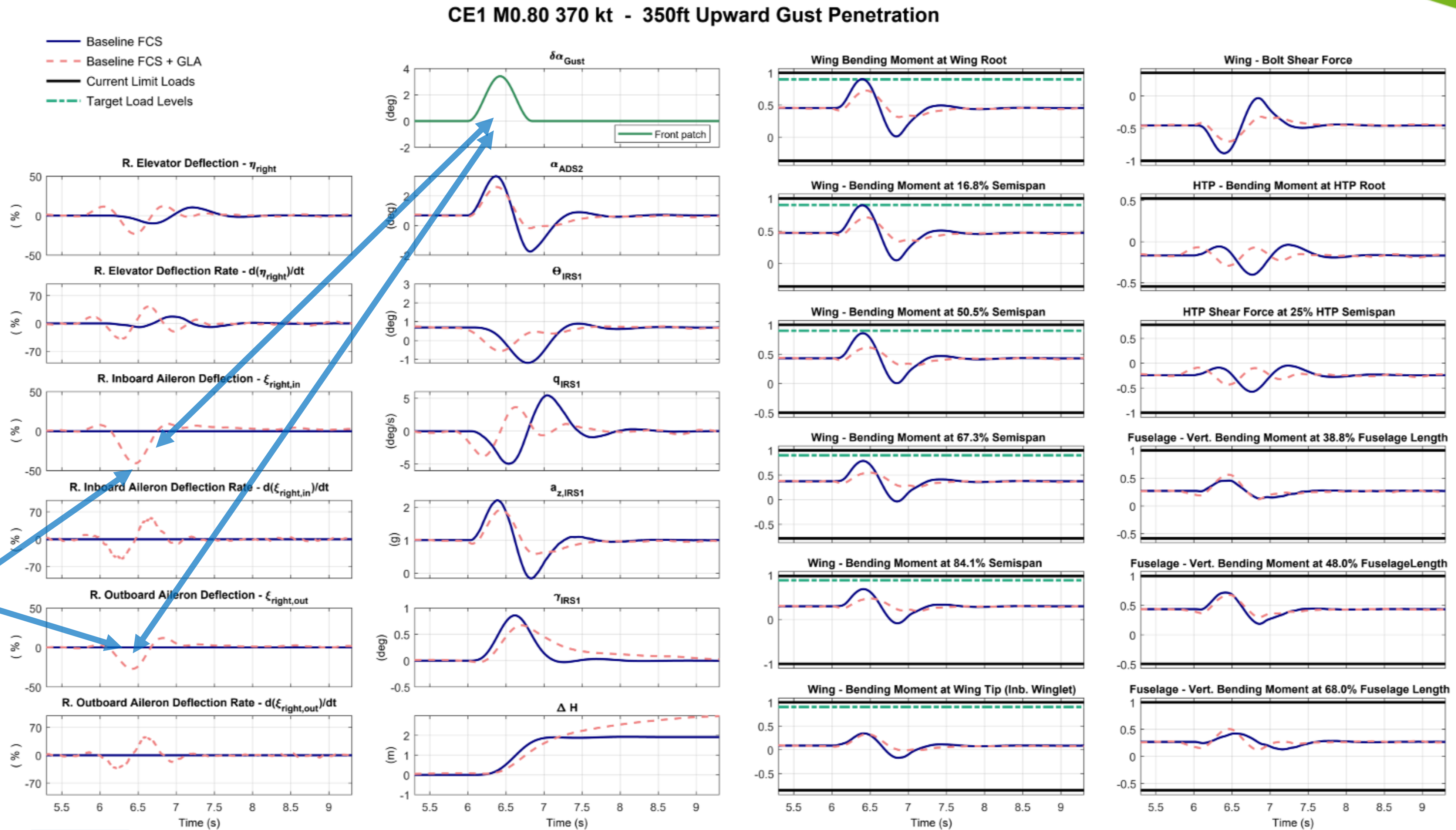
Preview Control for GLA: Results from CleanSky 2

350 ft gust

Pitching motion commanded to reduced the angle of attack variations



CE1 M0.80 370 kt - 350ft Upward Gust Penetration

Ailerons mostly move upwards when the gust arrives at the main wing

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Preview Control for GLA: Results from CleanSky 2

- For all gust scales between 90 and 350 ft:
  - Pitching motion reducing the gust-induced variations of the angle of attack, ...
    ... but with no attempt to fully “cancel” them (would be unnecessary aggressive and probably causing other issues)
  - Aileron deflections are made more or less synchronously with gust-induced velocities at the wing
  - The shorter the gust scale, the harder it is to make significant gains without reaching the rate limits of the actuation systems

- For smaller gusts (30 – 70 ft), the lidar sensor limits the load alleviation performance

- **REMARK**: Test cases are based on the discrete gusts criteria from CS25.341a,
  BUT no assumption of 1–cosine gust shape is made in any of the parts of the system.
  It also works with other shapes of gusts and on continuous turbulence!

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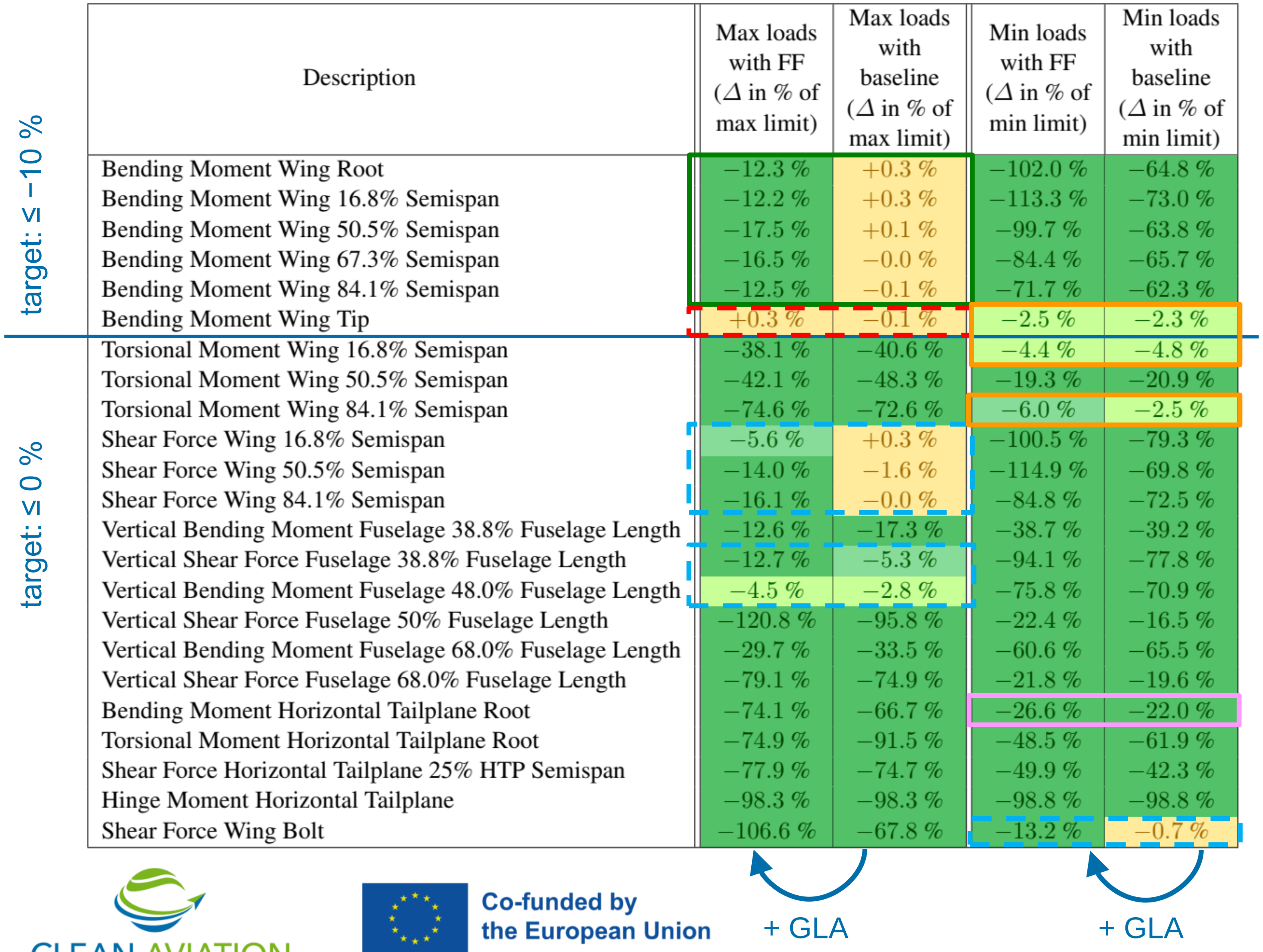
Preview Control for GLA: Results from CleanSky 2



Description	Max loads with FF (Δ in % of max limit)	Max loads with baseline (Δ in % of max limit)	Min loads with FF (Δ in % of min limit)	Min loads with baseline (Δ in % of min limit)
Bending Moment Wing Root	−12.3 %	+0.3 %	−102.0 %	−64.8 %
Bending Moment Wing 16.8% Semispan	−12.2 %	+0.3 %	−113.3 %	−73.0 %
Bending Moment Wing 50.5% Semispan	−17.5 %	+0.1 %	−99.7 %	−63.8 %
Bending Moment Wing 67.3% Semispan	−16.5 %	−0.0 %	−84.4 %	−65.7 %
Bending Moment Wing 84.1% Semispan	−12.5 %	−0.1 %	−71.7 %	−62.3 %
Bending Moment Wing Tip	+0.3 %	−0.1 %	−2.5 %	−2.3 %
Torsional Moment Wing 16.8% Semispan	−38.1 %	−40.6 %	−4.4 %	−4.8 %
Torsional Moment Wing 50.5% Semispan	−42.1 %	−48.3 %	−19.3 %	−20.9 %
Torsional Moment Wing 84.1% Semispan	−74.6 %	−72.6 %	−6.0 %	−2.5 %
Shear Force Wing 16.8% Semispan	−5.6 %	+0.3 %	−100.5 %	−79.3 %
Shear Force Wing 50.5% Semispan	−14.0 %	−1.6 %	−114.9 %	−69.8 %
Shear Force Wing 84.1% Semispan	−16.1 %	−0.0 %	−84.8 %	−72.5 %
Vertical Bending Moment Fuselage 38.8% Fuselage Length	−12.6 %	−17.3 %	−38.7 %	−39.2 %
Vertical Shear Force Fuselage 38.8% Fuselage Length	−12.7 %	−5.3 %	−94.1 %	−77.8 %
Vertical Bending Moment Fuselage 48.0% Fuselage Length	−4.5 %	−2.8 %	−75.8 %	−70.9 %
Vertical Shear Force Fuselage 50% Fuselage Length	−120.8 %	−95.8 %	−22.4 %	−16.5 %
Vertical Bending Moment Fuselage 68.0% Fuselage Length	−29.7 %	−33.5 %	−60.6 %	−65.5 %
Vertical Shear Force Fuselage 68.0% Fuselage Length	−79.1 %	−74.9 %	−21.8 %	−19.6 %
Bending Moment Horizontal Tailplane Root	−74.1 %	−66.7 %	−26.6 %	−22.0 %
Torsional Moment Horizontal Tailplane Root	−74.9 %	−91.5 %	−48.5 %	−61.9 %
Shear Force Horizontal Tailplane 25% HTP Semispan	−77.9 %	−74.7 %	−49.9 %	−42.3 %
Hinge Moment Horizontal Tailplane	−98.3 %	−98.3 %	−98.8 %	−98.8 %
Shear Force Wing Bolt	−106.6 %	−67.8 %	−13.2 %	−0.7 %

Objectives:

- Wing bending moment −10 % on peak value w.r.t design loads
- All others: ≤ 0 % w.r.t. design loads

Results:

- Target achieved except at wing tip (for which sizing gusts are 30 ft gusts)
- Margins to 0 % for other load stations were usually increased
- Sometimes almost unchanged (e.g., when critical gust are 30 ft and hardly seen by the lidar sensor)
- HTP loads need monitoring during tuning
- Detailed results including worst cases for selected load stations published in

N. Fezans et al.: *“Lidar-Based Gust Load Alleviation – Results Obtained on the Clean Sky 2 Load Alleviation Benchmark”*, IFASD 2022 conference. Madrid, Spain. June 2022. IFASD-2022-155. https://elib.dlr.de/187462/

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Preview Control for GLA: Way Forward in Clean Aviation

- The developed control design methodology is already very mature
  → further developments are not prioritised (compared to other activities, e.g. on the sensor itself)
- This said some improvements will be developed/added:
  - Three improvements developed in parallel to / right after CleanSky 2 will be integrated:
    1. Discrete gust impulse filters (DGIF) from
       D. Cavaliere, N. Fezans: *Recasting Discrete 1-Cosine Gust Requirements as Frequency Domain Specifications for Load Alleviation Control Design*, IFASD. Madrid, Spain. June 2022. IFASD-2022-143. https://elib.dlr.de/193035/
    2. Lidar estimation filters from
       D. Cavaliere, N. Fezans, D. Kiehn: *Method to Account for Estimator-Induced Previewed Information Losses - Application to Synthesis of Lidar-Based Gust Load Alleviation Functions*. Proceedings of the 2022 CEAS EuroGNC conference. Berlin, Germany. May 2022. CEAS-GNC-2022-063.

       D. Cavaliere, N. Fezans, D. Kiehn, J. Schulz, U. Römer: *Linear Modeling of Doppler Wind Lidar Systems for Gust Load Alleviation Design*. Accepted for publication in Journal of Guidance, Control and Dynamics (Dec. 5th 2023).
    3. The automated specification re-tuning from
       D. Cavaliere, N. Fezans: *A Practical Approach to Automated Multiobjective Gust Load Alleviation Control Design in a Structured H_2/H_∞ Framework*. Submitted to the CEAS EuroGNC 2024 conference, to be held in Bristol, UK. June 2024.
  - Direct integration of feedback gust load alleviation functions (both in UP Wing and in CONCERTO)
  - Investigation of dynamic interactions between GLA and flutter control functions to clarify the need for specific certification criteria / means of compliance (CONCERTO)

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Work Performed in CleanSky and CleanSky 2

- **CleanSky – Smart Fixed Wing Aircraft**
  - Two main improvement directions identified compared to the AWIATOR approach
    - Wind reconstruction algorithm
    - Multi-objective optimization for load alleviation function design

- **CleanSky 2 – Airframe ITD – TS-A-4 / NACOR**
  - New implementation of the wind reconstruction algorithm
    → highly optimized and with deterministic execution time and memory footprint
  - Improved load alleviation function design methodology / workflow

    → model management, model reduction, discretization, load envelope computation, etc.
    design based on a new multi-channel structured discrete time H_∞ preview control formulation
  - Evolution regarding the lidar sensor design/technology and its modelling (specific end-to-end simulator + generic/versatile simulator for toolchain use)
  - Start building a simulation toolchain for systems/concurrent-engineering studies

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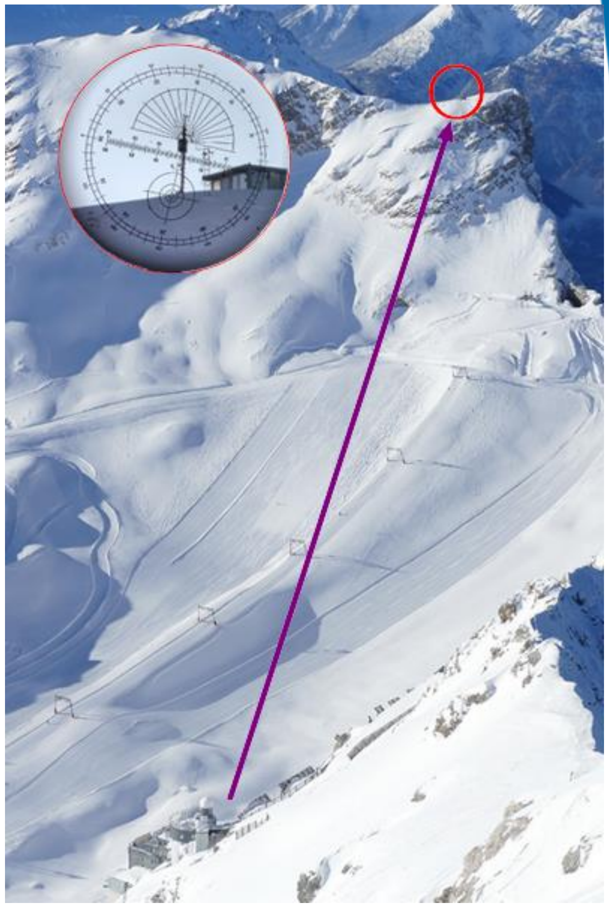
Lidar Sensor for GLA – Detector

- **AWIATOR detector with Fabry-Pérot interferometer**
  (Circular patterns/fringes on a CCD)
  - ➔ Quite good optical efficiency
  - ➔ Quite complex post-processing
  - ➔ Many photosensitive cells → poor signal-to-noise ratio (SNR) for each cell

- **Alternative detector concept developed DLR-projects and CleanSky 2**
  - Michelson interferometer: small prototypes tested in lab (DLR site in Oberpfaffenhofen) and in altitude (mountain lab)
    - Slightly more complex optical construction
    - Almost linear interference pattern
      - → lower number of photosensitive cells → better SNR
      - → simpler post-processing
      - → enables multiple measurements along LoS (line-of-sight) without dividing signal



- P. Vrancken and J. Herbst, “Aeronautics Application of Direct-Detection Doppler Wind Lidar: An Adapted Design Based on a Fringe-Imaging Michelson Interferometer as Spectral Analyzer,” Remote Sensing, vol. 14, no. 14, p. 3356, Jul. 2022, doi: 10.3390/rs14143356.
- P. Vrancken and J. Herbst, “Development and Test of a Fringe-Imaging Direct-Detection Doppler Wind Lidar for Aeronautics,” in EPJ Web of Conferences, 29th International Lidar Conference, Hefei, People’s Republic of China, 2019. doi: 10.1051/epjconf/202023707008.
- J. Herbst and P. Vrancken, “Design of a monolithic Michelson interferometer for fringe imaging in a near-field, UV, direct-detection Doppler wind lidar,” Applied Optics, vol. 55, no. 25, p. 6910, Sep. 2016, doi: 10.1364/AO.55.006910.

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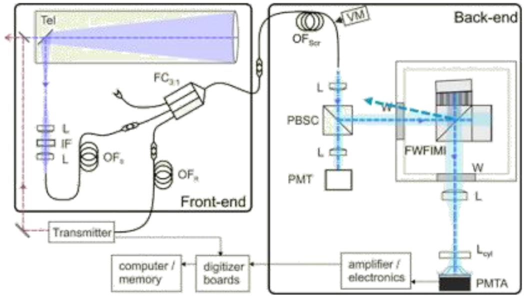
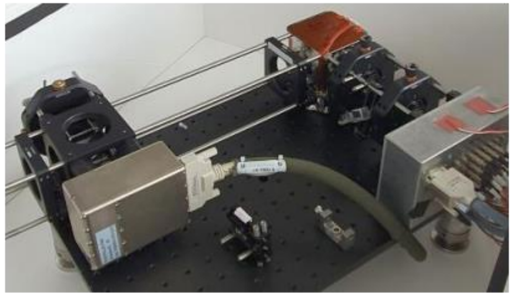
Lidar Sensor for GLA – Detector

Way Forward in Clean Aviation

1. Further Development of Fringe-imaging field-widened Michelson interferometer – flight version

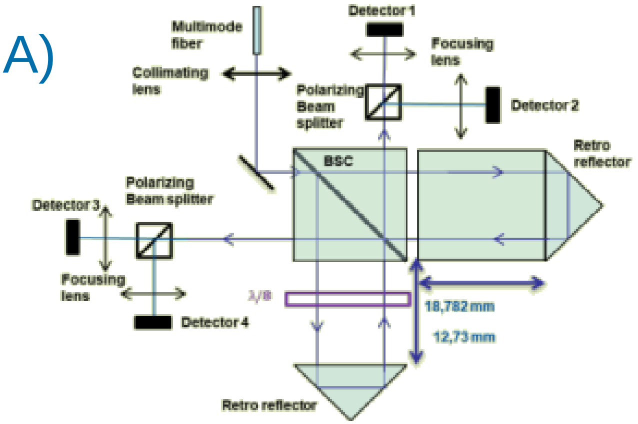




2. Michelson receiver upgrades / 2nd generation
   - Bistatic telescope architecture (adapt overlap)
   - Optical mode scrambling (fiber etc.)
   - Michelson reflected channel
   - Interferometer architecture

- Efficient imaging
- Detection optimization
- Robust data analysis, real-time capable

3. Quadrature-Mach-Zehnder receiver (parallel investigation by ONERA)
   - Similar theoretical performance as imaging Michelson
   - Only four detectors
   - Lab version + monolithic



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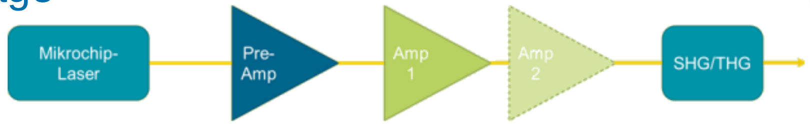
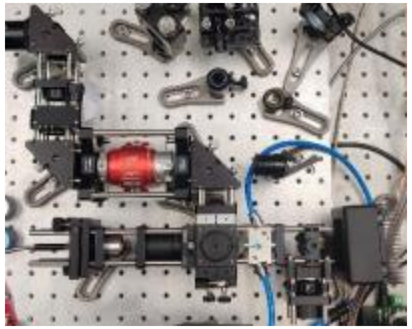
Lidar Sensor for GLA – Transmitter

Way Forward in Clean Aviation

1. Towards all-fiber sources: Fibered MOPA (master oscillator + power amplifier)
    - 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, possibly solid-state boost stage
2. Flight-test laser – Solid-state laser optimized for GLA application
    - Diode-pumped solid state (DPSS)-MOPA architecture
    - Goals: > 2.5 W @ 355 nm SLM, 1-3 kHz PRF, 10 ns pulses
    - Being integrated in EU FP7-DELICAT lidar architecture for test flights on NLR Citation II





3. Test and fallback lasers:
    - Commercial Merion UV injection locked, single frequency laser, 22.5 mJ, 400 Hz, 6 ns
    - DLR WALES/DELICAT/AEROLI airborne laser, 80 mJ, 100 Hz, 6 ns

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Simulation – Lidar-Based GLA

Way Forward in Clean Aviation

- **Simulation of the overall lidar-based GLA**
  - Aeroservoelastic aircraft
  - Simplified Lidar Sensor
  - Wind Reconstruction
  - Control Functions

Simplified analytical lidar performance model predicts noise distribution of LOS Doppler wind measurements based on:

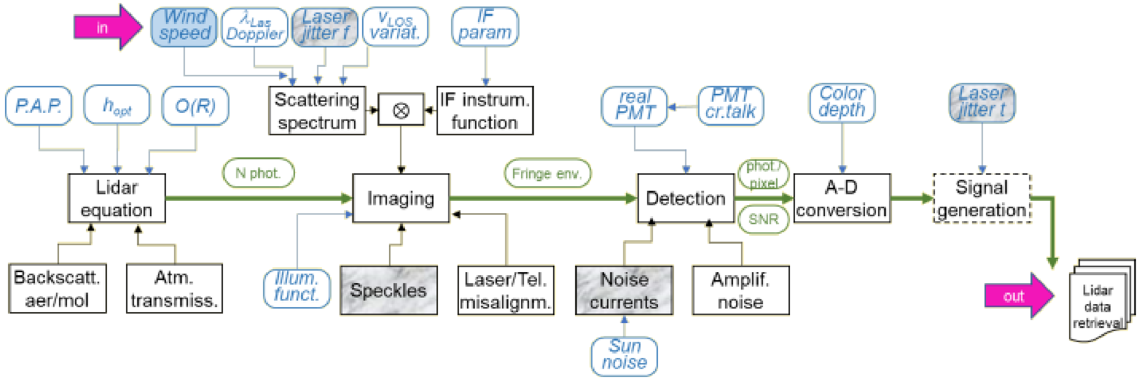
❶ main lidar design variables

❷ some system constants

❸ current conditions (atmosphere)

$$\sigma_{v,av} = \underbrace{\left(\frac{R^2 \cdot r_{refresh}}{P.A.P. \cdot \Delta R}\right)^{1/2}}_{❶} \cdot \underbrace{\frac{\kappa_{real} \cdot \kappa_{TIF}}{\left(e \cdot \eta_{opt} \cdot \rho_{det}\right)^{1/2}}}_{❷} \cdot \underbrace{\left(\frac{k_B \cdot T(h)}{m_{air} \cdot \beta_{atm}(h,\lambda)}\right)^{1/2}}_{❸}$$

- **Physics-based end-to-end lidar simulation**
  - Monte-Carlo-like simulation varying main lidar design drivers and analyzing their impact on performance
  - Simplified optical system
  - Atmospheric and fiber speckle effects
  - Noise processes (laser, electronics etc.)
  - Synthetic signal → full data analysis including fringe fit
  - Future additions: atmosphere interaction, light propagation, imaging errors, detector model, environmental effects



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Clean Aviation – Lidar for GLA Demonstration Strategy

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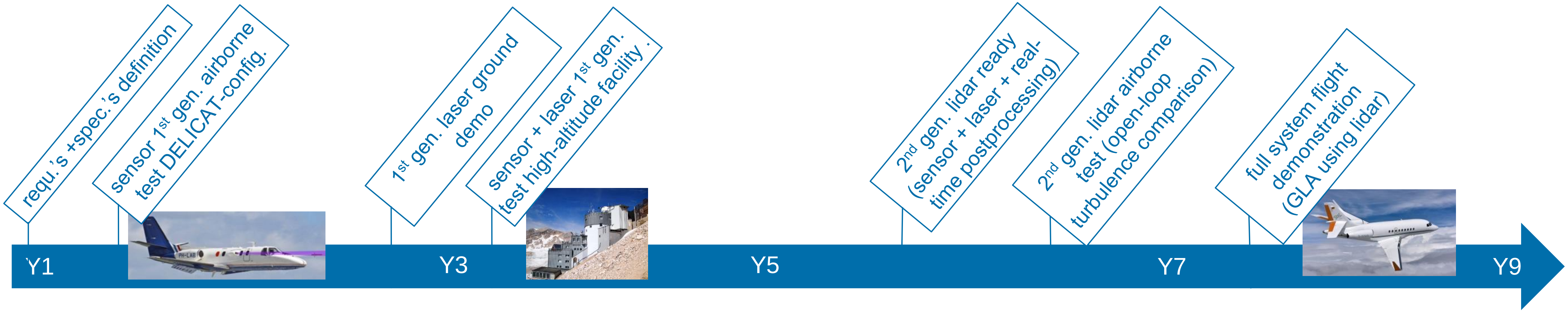
Demonstration Strategy

Various demonstrations in parallel / interlaced over the whole UP Wing project (and after)

- Lab, ground (top of mountain), and in-flight tests/demonstrations
- Various development stages of the systems
- Full system flight demonstration (closed loop, incl. instrumentation for structural loads) not in UP Wing anymore (second phase of Clean Aviation?)


requ.'s +spec.'s definition

sensor 1st gen. airborne test DELICAT-config.

1st gen. laser ground demo

sensor + laser 1st gen. test high-altitude facility .

2nd gen. lidar ready (sensor + laser + real-time postprocessing)

2nd gen. lidar airborne test (open-loop turbulence comparison)

full system flight demonstration (GLA using lidar)

Simplified timeline

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Ground-Based High-Altitude Demonstrations

- Functional testing of respective lidar configurations
- Characterization and sensitivity studies
- High-altitude mountain facility: Environmental Research Station Schneefernerhaus (UFS) at 2560 m ASL
- Reference instrumentation:
  - Heterodyne detection Doppler wind lidar(s): Windcube 200S, in-house fiber-based, 1.6 µm WindTracer transceiver
  - Ultrasonic anemometer(s)
- Aerosol quantification:
  - German Federal Environmental Office (UBA): Nephelometer, particle size distribution, particle counter
  - German Weather Service (DWD): Ceilometers
- First campaign in 2022

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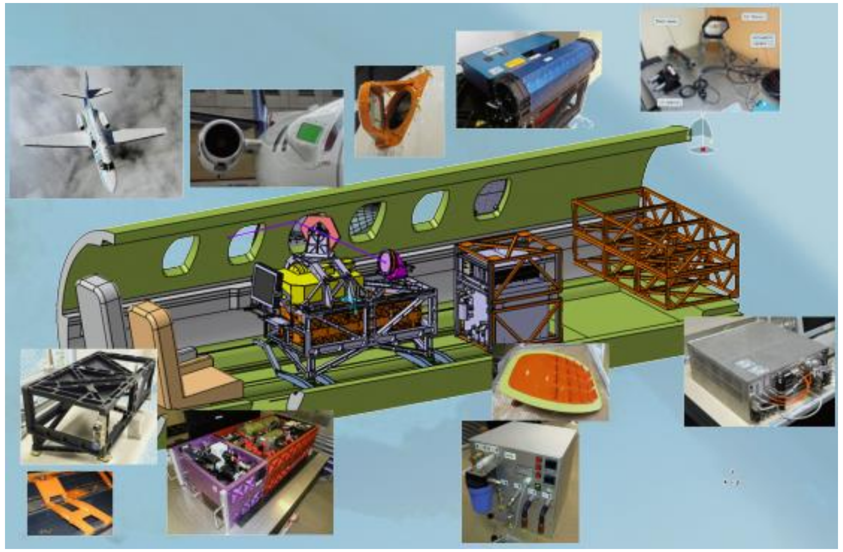
In-Flight Demonstrations

Demonstration of UV-Direct-Detection Lidar Performance

- Validation of performance model (simulation and prior ground demo)
- MOPA-DPSS transmitter + Michelson single-channel receiver + single (aircraft-fixed) direction
- Re-use (as much as possible) of EU FP7 DELICAT equipment and installations
- Significant increase in TRL for an important part of the lidar technology
- NLR Cessna Citation II PH-LAB aircraft with EC FP7 DELICAT modifications (forward-pointing optics in fairing, racks, cooling, …)

- Reference instrumentation: aircraft-carried air data systems
    - Standard air data sensors
    - Nose boom with AoA/AoS vanes and 5-hole probe
    - Partly supported by / fusioned with other sensors (e.g., IMU)
    - TBD: Aerosol sensors
- Conditions:
    - Validation of Airborne operation with few to no particles/aerosols
    - Calm air + maneuvers
    - Turbulence



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Summary

- Ambitious undertaking being pursued in Clean Aviation aiming at enabling future and more efficient configuration (lighter structure, higher aspect ratio wings)
- Probably the biggest effort worldwide towards maturation of direct-detection lidar sensors for gust load alleviation purposes
- Demonstrations balancing the current need for flexibility in the sensor design and the need for testing under real cruise altitude condition with no aerosols
- Long-term goal: TRL 6 by 2030

Questions?

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