Designing and Maturating Doppler Lidar Sensors for Gust Load Alleviation: Progress Made Since AWIATOR

CLEANSKY

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DLR

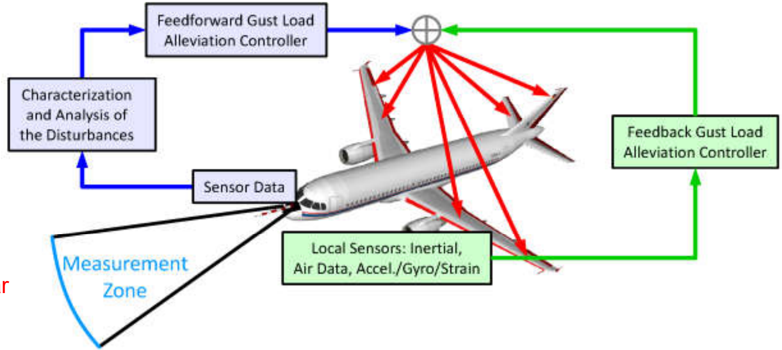
Outline

- Introduction
  - Gust load alleviation and link to improvement of aircraft energy efficiency
  - Lidar-based versus non-lidar-based gust load alleviation
- AWIATOR developments and demonstrations
- DLR post-AWIATOR contributions
  - Lidar sensor and measurement post-processing
  - Load alleviation function
  - Systems engineering
- Conclusions and outlook

Gust load alleviation and link to improvement of aircraft energy efficiency

- Gust loads are usually sizing some of the most heavy portions of the wings
- With suitable maneuver load alleviation function, the next largest loads on those parts are often quite significantly lower *(order of magnitude 8-10% lower)*
- Alleviating the gust loads such that they are not sizing anymore
  ➔ potential mass savings
- Mass saving would be about 1–2% of the MTOM on a flexible long-range airliner configuration and mission

Lidar-based versus non-lidar-based gust load alleviation



Measurement ahead of the aircraft only with lidar

Feedforward gust load alleviation

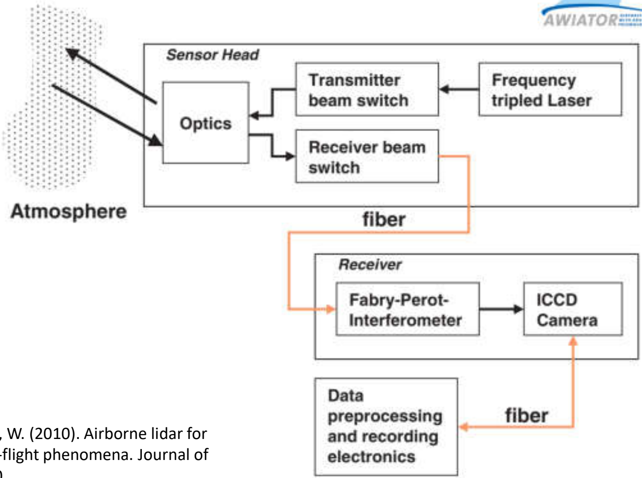
- Can anticipate the forthcoming gusts
  ➔ can alleviate loads through pitching commands
  ➔ can trigger e.g. ± open-loop spoiler deployment

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

Lidar-based versus non-lidar-based gust load alleviation

What are (Doppler) lidar sensors?



Sketch of the direct detection Doppler lidar sensor developed in **AWIATOR**

Illustration 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

AWIATOR: Overall objectives

Large European 5th RTD framework project

Objectives:

- reduce the vortex hazard, by this decrease the separation distance behind a large aircraft by 1 nm;
- apply specific flight procedures using new devices validated in this project, by this reduce noise by 2 EPNdB;
- increase cruise performance (L/D +2%, Fuel Burn –2%) by new devices and **load control** strategies;
- increase low speed performance by using new devices and **load control** strategies, in detail increase L/D by 2.5;
- **decrease new aircraft structural weight by applying new load control strategies, in detail reduce weight by 5% using existing devices and by 10% using new devices;**
- aerodynamic characteristics, systems and structures will be optimized in a multi-disciplinary approach by controlling lift distribution, wake vortex, and wing loads.

AWIATOR: Load control

Two main development targets:

–5% load reduction using **existing devices** (i.e. no unconventional control surfaces or sensors, no lidar)

➔ Various “passive” and “active” functions where developed in AWIATOR and rapidly brought to production aircraft (now TRL 9)

–10% load reduction using **new devices**

- New Trailing Edge Devices (TED)
- Lidar-based gust load alleviation ← topic for this presentation

AWIATOR: Achievements on lidar-based gust load alleviation

In-Flight Demonstration:

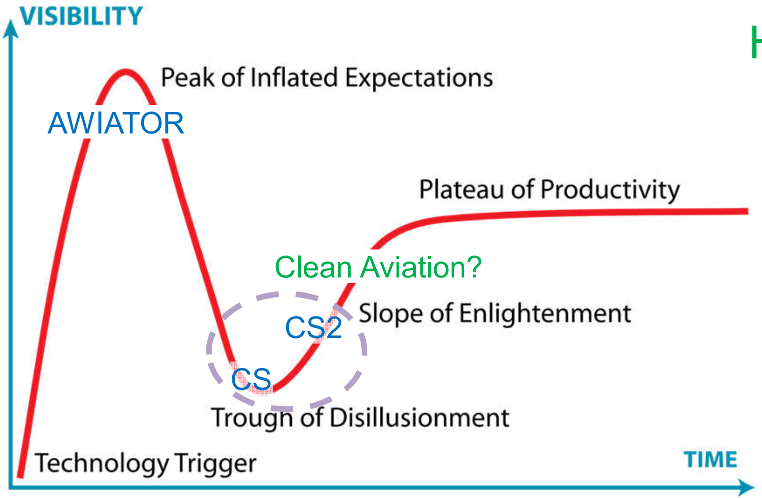
- On DLR ATTAS (2004)
- Improved system tested on A340-300 (2006)
- Capacities of the sensor demonstrated

To the best of my knowledge:

- Offline processing (though some FPGA developments are mentioned in papers)
- 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

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



Hype cycle

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 CS and CS2 projects.

Post AWIATOR – Overview

- **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 – TS-A-4 / NACOR & LuFo V-2 Con.Move**
  - 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
  - New ideas regarding the lidar sensor design and its modelling (end-to-end simulator)
  - Start building a simulation toolchain for systems/concurrent-engineering studies

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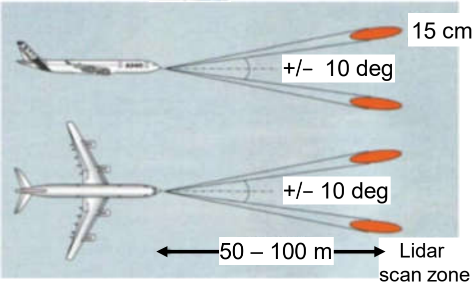
Post AWIATOR: Improvement to the wind reconstruction

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 (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 @ 60 Hz → 4.3 m/s vertical/transversal @ 15 Hz

x 2.9

at 39,000 ft

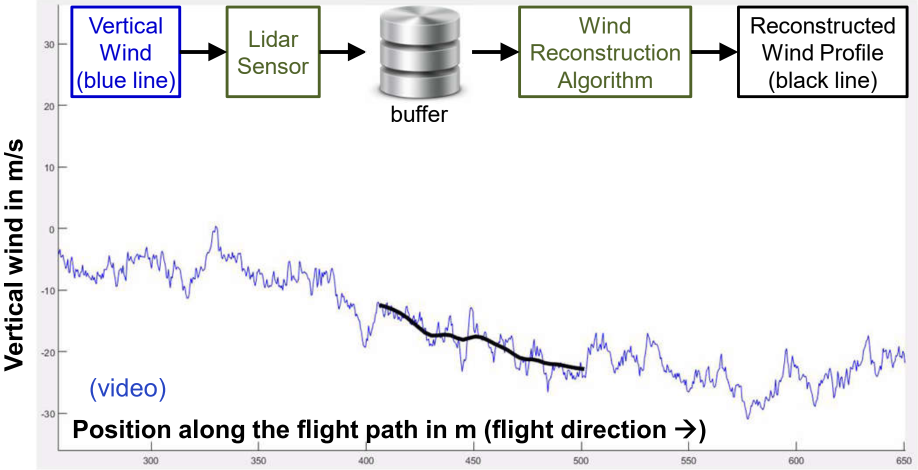
IDENTIFIED POTENTIAL IMPROVEMENT DIRECTIONS

➔ Take time delays & aircraft motion between measurements into account

➔ Estimate "wind profiles" based on higher number of measurements instead of independent wind estimates at "one location" → also offers better smoothing possibilities without additional phase-lag

Post AWIATOR: Improvement to the wind reconstruction

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



Limited spatial resolution

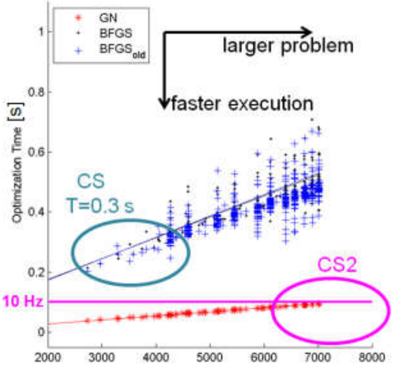
- Good for anticipating the large-scale gusts
- Cannot really measure the small-scale gusts

Post AWIATOR: Improvement to the wind reconstruction

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

Proposed and tested in CleanSky, optimized (new implementation) in CleanSky 2
→ now highly optimized and with **deterministic execution time and deterministic memory footprint**

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



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

Post AWIATOR – Overview

Skipped due to time constraints
- Uses state-of-the-art modern control techniques
- cf. authors' publications

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Post AWIATOR: Lidar sensor design

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

- **Alternative detector concepts**
  - Michelson interferometer: small prototypes tested in lab, possibly soon in altitude (top of a mountain)
    - Slightly more complex optical construction
    - Almost linear interference pattern
      - → lower number of photosensitive cells → better SNR
      - → simpler post-processing
      - → potentially enables multiple measurements along line-of-sight without dividing signal
  - Mach-Zehnder interferometer: potentially a viable alternative, to be investigated

- **Potential alternative laser sources**
  - Fiber laser + amplification + frequency multiplication
  - Semiconductor laser

Post AWIATOR: Lidar sensor modelling (1/2)

- **Physics-based end-to-end lidar simulation**
  - Describes the sensor based on all physical processes in the sensor subsystems and the atmosphere
  - The model permits to vary the main properties of each subsystem
  - Statistic noise processes are represented at all relevant stages of the detection process

    → Suited for (pre)design of direct detection Doppler lidar sensors
  - Development supported by various ground demonstrations/experiments

"Measurement Characteristics" = **f** (*"Sensor Parameters"* & "Atmosphere Parameters")

Post AWIATOR: Lidar sensor modelling (2/2)

- **Physics-based end-to-end lidar simulation**
  - Describes the sensor based on all physical processes in the sensor subsystems and the atmosphere
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    → Suited for (pre)design of direct detection Doppler lidar sensors
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- **“Surrogate” model of the lidar sensor**
  - Much simpler than the end-to-end simulator
  - Macroscopic representation of the properties and performance of a given lidar sensor configuration *(corresponding macroscopic parameters can be determined using the end-to-end simulation model)*
  - Lightweight and fast → can be integrated in the complete aircraft + controllers + load alleviation + lidar simulation environment

→ Key element for systems/concurrent engineering studies

Post AWIATOR: Towards systems engineering of lidar-based GLA

Assuming some amount of money for improving the sensor, how should it be allocated?

?

?

?

Laser Source

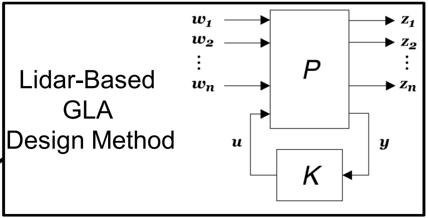
Detector

Other optical component

Post AWIATOR: Towards systems engineering of lidar-based GLA

Assuming a combination of aircraft, lidar, control method…

Laser Source
+ Detector



…what is the best "scan geometry" for this combination of components ?

- Field-of-view
- Range
- Scan pattern
- Laser pulse repetition rate
- Laser pulse energy
- …

Post AWIATOR: Towards systems engineering of lidar-based GLA

Ideal world

Perfect lidar sensor and scan system

→

Very high level of load alleviation
(higher than useful) ✓

System designers' world

Reasonable set of requirements
for the lidar sensor and scan system

→ *Minimum design complexity and costs for fulfilling the requirements*

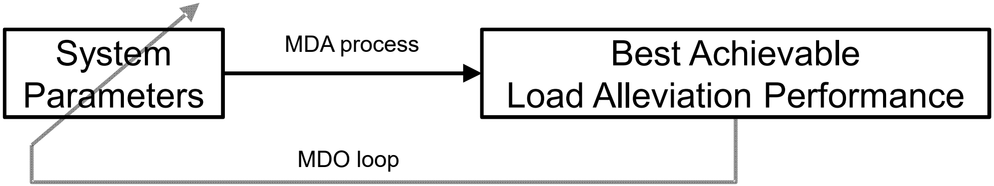
? ←

Reasonable/useful
level of load alleviation

Post AWIATOR: Towards systems engineering of lidar-based GLA

Need for a systems engineering environment

- At least multidisciplinary analysis (MDA)
- Ultimately multidisciplinary optimization (MDO)



DLR started to build such a systems engineering capability for lidar-based GLA.
First results to be expected soon (2021?). Progressive refinements planned afterwards.

Summary and outlook

- AWIATOR remains THE reference programme in terms of direct detection Doppler lidar demonstration
- BUT…
  - DLR has continued working on it since AWIATOR (CS, CS 2, LuFo, DLR-internal activities)
  - Progress has been made this last 15 years (e.g. better understanding of the key parameters, improved algorithms)

    ➔ Even with the same technology bricks than in AWIATOR, we would be able to have significant improvement in terms of load alleviation performance
  - At the same time, the underlying technology bricks have also evolved!
- We (authors) think that it is time to think about "resuscitating" the lidar-based load alleviation topic
- **Major topic for Clean Aviation?**

Questions?

Acknowledgment

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Clean Sky   Clean Sky 2   Federal Ministry for Economic Affairs and Energy

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