Aeronautics LIDAR applications

Airborne LIDAR Detection of Clear Air Turbulence (CAT)

>> The DELICAT FP7 project

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Introduction:

DLR – Institute of Atmospheric Physics – LIDAR group

- LIDAR group – developing and operating lidar instruments for atmospheric research
  - Trace gases (O$_3$, CH$_4$, CO$_2$, H$_2$O): CHARM-F, MERLIN, WALES
  - Aerosols: WALES
  - Wind: 2µm & 1.6µm coherent systems (LM), ADM demonstrator (A2D)
- Operating on DLR’s research aircraft: HALO G550, Falcon 20, Do228
Introduction:
LIDAR – LIght Detection And Ranging

- Emission of laser pulse into atmosphere

- Backscatter by:
  - Molecules (Rayleigh process)
  - Aerosols (Mie process)

- Collection of backscattered radiation with telescope and detector

- Range-resolved analysis of signal w.r.t. intensity / polarisation / spectrum
  - Aerosols (Backscatter/HSRL/Depol)
  - Trace gases (DIAL)
  - Wind speed (Doppler heterodyne / HSRL)
LIDAR for aeronautics applications

Safety

- ACARE: **Strategic Research and Innovation Agenda (SRIA)**
- ACARE / EC: **Flightpath 2050**

**Strategic Research & Innovation Agenda**

1. Overall, the European ATS has **less than one accident per ten million commercial aircraft flights**. For specific operations, such as search and rescue, the aim is to reduce the number of accidents by 80% compared to 2000 taking into account increasing traffic.

2. The environment and other hazards from the air traffic scheme are precisely evaluated and risks are properly mitigated.

**Flightpath 2050**

**Europe’s Vision for Aviation**

**Goals:**

1. Overall, the European air transport system has **less than one accident per ten million commercial aircraft flights**. For specific operations, such as search and rescue, the aim is to reduce the number of accidents by 80% compared to 2000 taking into account increasing traffic.

2. Weather and other hazards from the environment are precisely evaluated and risks are properly mitigated.

**4.5 Air vehicle operations and traffic management**

The airspace in the year 2050 has evolved considerably. Apart from the continuous growth of the number of aircraft and an increased demand for air travel, there are **new forms of flying vehicles and aerial applications**. These are integrated seamlessly into the air traffic scheme. New technologies and applications introduce new safety challenges. In addition, airspace is even more crowded. Consequently, air traffic management concepts evolve along with the growing demand to achieve safety and security goals. Instead of a number of mostly isolated aircraft moving through airspace, there is a multitude of different co-operative and uncooperative elements in the all-encompassing data space incorporating aircraft movements, trajectories, live performance, vehicle status information as well as copious other kinds of data. This leads to enhanced scenarios where awareness and innovative mechanisms to

**4.5.3 OPERATIONAL MISSION MANAGEMENT SYSTEMS AND PROCEDURES**

Operational mission management systems and procedures are concerned with protection and responses that facilitate hazard risk management through use of the appropriate tools, including atmospheric models. They enable the optimisation of trajectories to ensure hazard and collision avoidance throughout all flight phases and with the earth’s surface. They also enable the safe access and integration of non-commercial flights, personal air vehicles and UAV within airspace and airports and ensure that commercial space operations are merged safely with traditional atmospheric flight operations and airspace structures. Innovative usage concepts are used to maximise the utilisation of scarce resources such as airspace, runways and parking.

To support accurate mission planning, a complexity assessment modelling capability is available together with models to identify and predict meteorological and other environmental hazards affecting flights.

In order to ensure hazard avoidance while in-flight and on the ground, systems and new traffic services are coupled with **on-board sensor technology** that monitor atmospheric conditions, airspace environment, traffic proximity and flight data. This is supported by intelligent
LIDAR for Aeronautics
Applications: Atmospheric / weather hazards

Near field (10s -100s m): Mitigation
- Wind vector field
  → Gusts
  → Wake vortices
  → Turbulence
- Air speed

In-situ:
- Air data (T, p, ..)

Far field (15-30 km): Awareness
- Icing conditions (glaciated, liquid..)
- Volcanic ash
- Clear Air Turbulence (CAT)

→ Vision: One instrumentation for multiple targets (Wx hazards)

→ Research implementation: Separate tracks

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LIDAR for Aeronautics
Near field applications: Gust & WakeVortex mitigation

- Short range scanning LIDAR for wind field estimation
- Direct detection UV LIDAR OR coherent heterodyne LIDAR
- Wind speed determination by Doppler frequency shift

**Concept demonstrated** in EC FP6 AWIATOR project (Airbus)
- Instrument tested on DLR ATTAS and Airbus A340

**DLR IPA continuing from 2014 on** (instrumental developments in L-bows)
LIDAR for Aeronautics
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Awareness

Mitigation

Airborne Wx-Lidar

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Far field application: Hazardous icing conditions

*High altitude glaciated icing conditions*
- Ci-like crystals – high number density
- Radar dBZ = 0
- Ice accretion on pitot tubes, wing and turbine leading edges (AF447)
- Possible engine rollback and flameout

LIDAR measurement
- Backscatter / depolarisation measurement
- Identification of ‘benign’ and ‘hazardous’ Ci-levels
- Distinction of cloud types: SCLD, …
LIDAR for Aeronautics
Applications: Atmospheric / weather hazards

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Far field application: Volcanic ash & Mineral dust

Eyjafallajökull 2010:
- Lidar measurements with 2µm-wind lidar on DLR Falcon

Future:
- LIDAR-based determination of ash concentration (mg/m³)
- VADAS project in H2020
+ Mineral dust
LIDAR for Aeronautics
Applications: Atmospheric / weather hazards

Near field (10s -100s m): **Mitigation**
- Wind vector field → Gusts → Wake vortices → Turbulence
- Air speed

*In-situ:*
- Air data (T, p, ..)

Far field (15-30 km): **Awareness**
- Icing conditions (glaciated, liquid..)
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Far field application: Clear Air Turbulence (CAT) & WV

Clear Air Turbulence
- Causing 10s M€/$ p.a. to airlines
- Injuries of crew and passengers
- Will increase with climate change
- Intermittent phenomenon, difficult to precisely forecast
- Invisible to weather RADAR

LIDAR measurement
- Doppler wind speed measurement
- Indirect measurement: Air density fluctuations
  ➔ DELICAT (EC FP7)
DELCICAT
Demonstration of Lidar-Based CAT (Clear Air Turbulence) detection

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Knowledge for Tomorrow
DELICAT
EC Aeronautics Research FP7 project

- Goal: Demonstration of technology - Detection of Clear Air Turbulence (CAT) by LIDAR during cruise in far field (15-30 km)


- Envelope: 5.6 M€, grant by EC: 3.8 M€
  Start: 01/04/2009, end 31/03/2014
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Lidar-based CAT detection: Basic concept

\( w \perp \text{LOS} \land \land \text{insufficient aerosols at cruise altitude} \rightarrow \text{Coherent Doppler lidar not usable} \)

\( \rightarrow \text{Indirect measurement:} \)
Air temperature / density fluctuations = backscatter fluctuations (molecular)

\[
\frac{\Delta \rho}{\rho} = \frac{\Delta T}{T} = \frac{wN}{g}
\]

Wind shear: \( s = 2w \Delta z \)
\( Ri = N^2\frac{\rho}{\rho_0} \), \( Ri_c \approx 0.25 \)
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Lidar-based CAT detection: Main project goals

- Design and build lidar system
- Perform flight test campaign of lidar system
- Assess CAT meteorology and provide campaign support
- Retrieve CAT signature from lidar data and develop detection algorithms
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Test aircraft PH-LAB (NLR – Dutch Aerospace Lab)

- Cessna Citation 2
- Ceiling 43,000 ft, max. payload 1300 kg, max. 5.5 h endurance

- Front looking fairing for directing laser beam on trajectory
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Lidar system synopsis

- Laser transmitter (DLR):
  - Nd:YAG, 100 Hz, 40 W, 7 ns, 200 µrad (based on DLR-lidar WALES)
  - Third Harmonic Generation → UV 355 nm, 8 W

- Beam steering system (Thales):
  - Two 2-axis-movable mirrors
  - External front-pointing mirror

- Receiver I (DLR):
  - 6” f/5 telescope
  - Front optics, polarisation optics
  - PMT detection: || (molec.) and ⊥

- Receiver II (Hovemere):
  - idem I
    - high spectral resolution filtering (aerosol backscatter filtering)
    - for ground tests only

- Aircraft integration (NLR+DLR)
Beam steering (Thales)

Aircraft (NLR)

Fairing (NLR)

DLR:
- Lidar design
- Transmitter
- Detection
- Aircraft integration
- Validation tests
- Flight tests
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Lidar on PH-LAB

- Installation and calibrations in June 2013
- STC on 16/07/2013
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Flight campaign 17/07 – 12/08/2013 from Schiphol

Met support:
- Used NWPs:
  - ARPEGE (MF)
  - COAMPS (UW-ICM)
- Turbulence indices
- Combined index analysis (ICM)
- Aeronautics forecaster (MF): Synoptical situation analysis
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Flight campaign 17/07 – 12/08/2013 from Schiphol

- 11 Flights, 33 h

- Calibrations

- Systems verification
  - Lidar
  - Beam steering
  - Aircraft experimental system

→ All systems performed exceedingly well

→ CAT very localised, light and difficult to find
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Data analysis: LIDAR system evaluation

- Fundamental lidar sensitivity:
  - Goal: Detect light-moderate CAT detection
    Necessary density (backscatter) measurement sensitivity $\sigma \leq 1\%$
  - Averaging: $\sigma_M \propto \frac{1}{\sqrt{N_{\text{Shots}}}}$

- Prereq: White noise (detection system)

- Detection noise evaluation by ‘time variance’ analysis
  → Over time: Averaging over lidar shots
  → Spatially: Averaging over range

⇒ Sub-% domain attainable by integrating over $\sim 1s$ and $\sim 100m$

⇒ DELICAT lidar apt for measuring $\geq$ light-mod CAT
  (by analysing signal variance)
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Data analysis: CAT signature retrieval

- Challenge: Few, isolated and weak (< light-mod) CAT events
- Simple signal variance analysis insufficient

Advanced data analysis:
- Backscatter estimation (maximum likelihood) + thresholding
- FIR filtering + adaptive thresholding
- Wavelet covariance analysis

CAT detection possible
- Condition: Absence of aerosols
- OR: Filtering of aerosol backscatter

Development of high resolution spectral filter for aerosol rejection

Within DLR-project L-bows

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Conclusion

- Challenging project:
  - Complexity (LIDAR ↔ aircraft)
  - Delicate (sensitive) systems / instruments
  - Airworthiness certification
  - Scarce and weak CAT yield

⇒ DELICAT project carried out successfully!

- Instrumental development continued within DLR
- Further validation by flight tests necessary

- LIDAR system ‘upgradable’ for other research topics (icing, VA, MD…)

- Thanks to the EC for the support!
LIDAR for Aeronautics - DELICAT

- Thank you for your attention!

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