4th EASN Association
International Workshop
on Flight Physics and
Aircraft Design

Aeronautics LIDAR applications

Airborne LIDAR Detection of Clear Air Turbulence (CAT)

>> The DELICAT FP7 project

Patrick Vrancken
DLR - German Aerospace Center
Institute of Atmospheric Physics
Oberpfaffenhofen

DLR

Introduction:
DLR – Institute of Atmospheric Physics – LIDAR group

Head: G. Ehret

- LIDAR group – developing and operating lidar instruments for atmospheric research
  - Trace gases (O_3, CH_4, CO_2, H_2O): 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


WALES on HALO


A2D on Falcon


HALO D-ADLR


Falcon D-CMET


Do228 D-CFFU

Introduction:
LIDAR – **LI**ght **D**etection **A**nd **R**anging

- 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. Weather and other hazards from the environment 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.**

stipulating:

- Increase safety
- On-board sensor technology
- Situational awareness w.r.t.
- Atmospheric hazards

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 ever 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 - and requires - increased situational awareness and innovative mechanisms to

4.5.1 SAFETY RADAR

The safety radar comprises innovative methods, processes and services to ensure the identification and detection of safety hazards. It is enabled by the proactive **identification of atmospheric and other external hazards**. Models are developed that enable the identification of hazard probability, impact and mitigation. The safety radar is also underpinned by **behaviour analysis of passengers, staff and personnel** to identify in real-time abnormal behaviour, mobility patterns, etc. to identify hazards to safety. Similar to the personal level, this is extended to **behaviour analysis of airspace and airport use**.

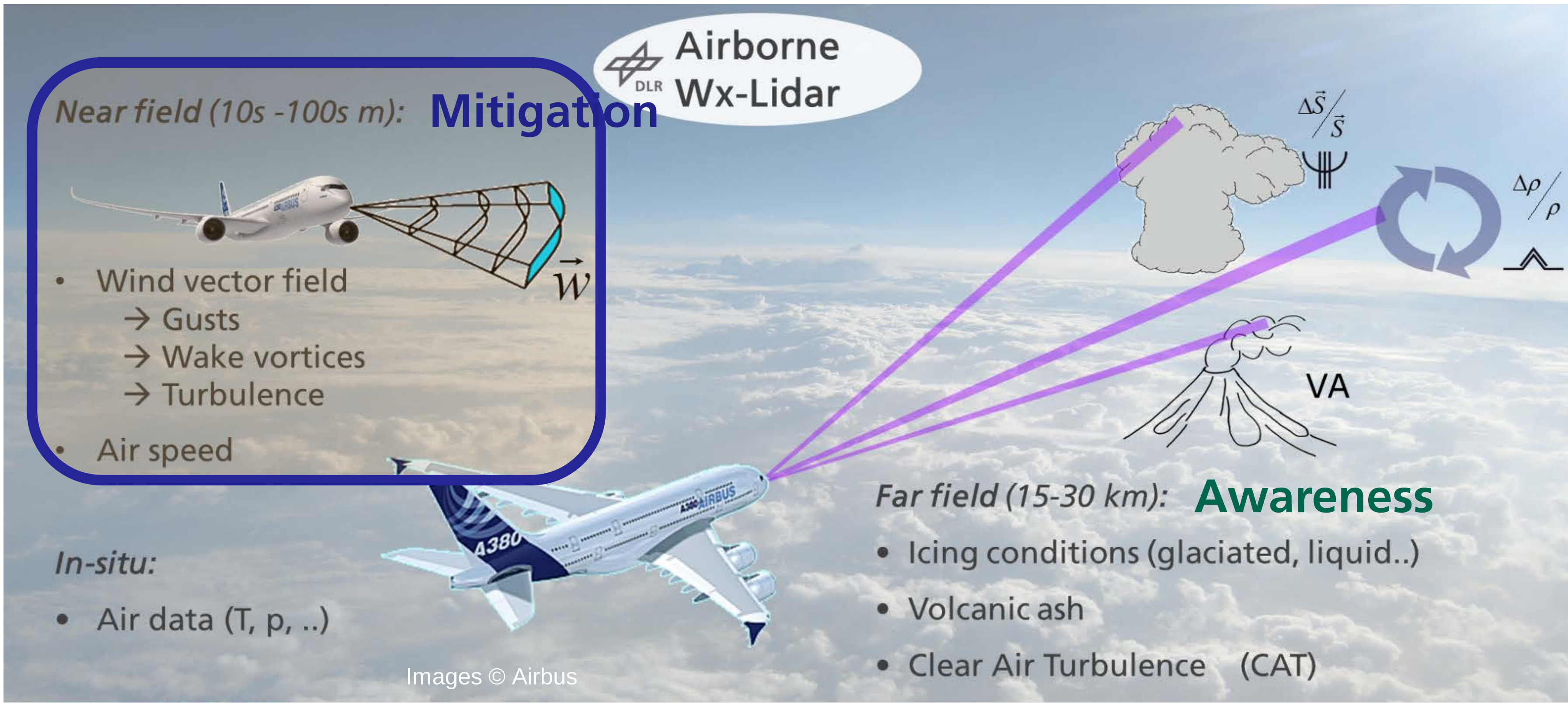
4.5.3 OPERATIONAL MISSION MANAGEMENT SYSTEMS AND PROCEDURES

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

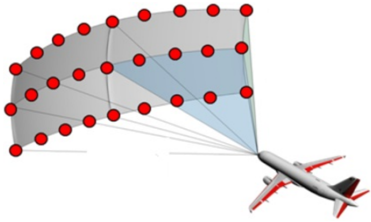


→ ***Vision: One instrumentation for multiple targets (Wx hazards)***

→ ***Research implementation: Separate tracks***

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

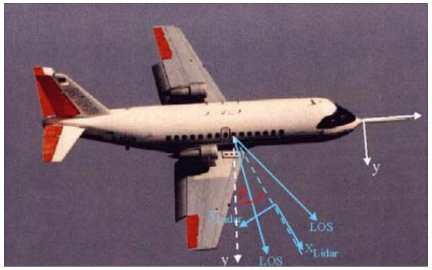
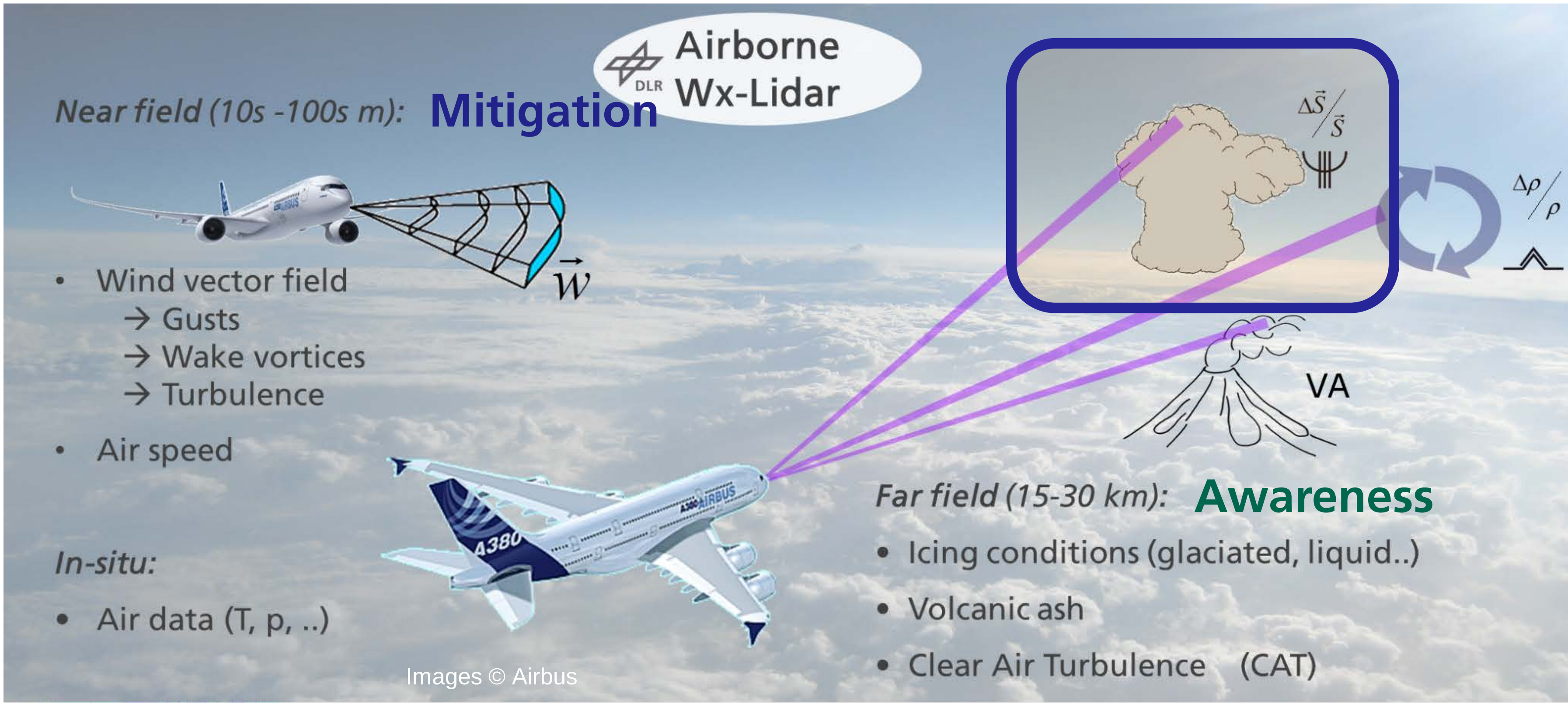


Image © Airbus

Image © Airbus

DLR IPA continuing from 2014 on (instrumental developments in L-bows)

LIDAR for Aeronautics
Applications: Atmospheric / weather hazards

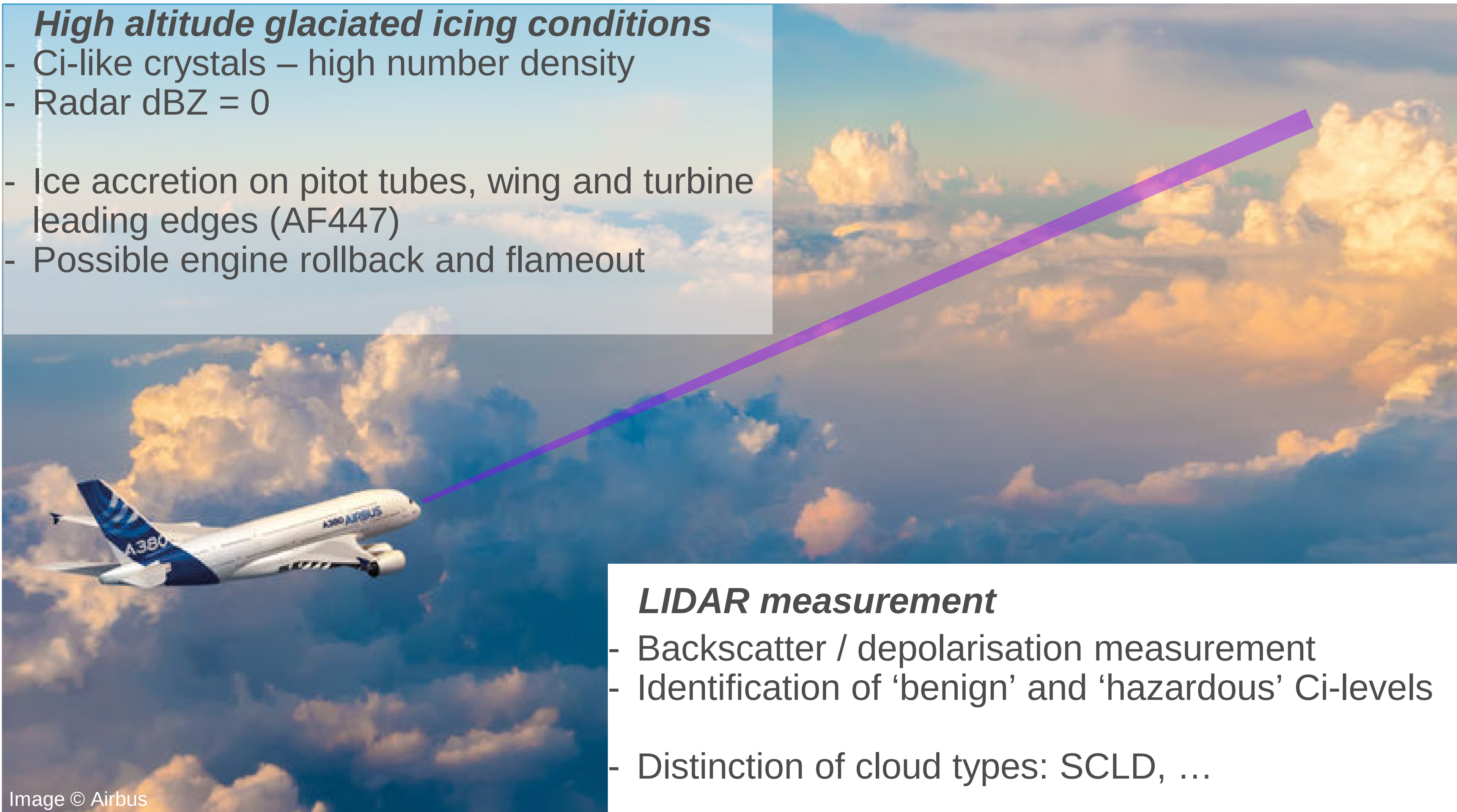


LIDAR for Aeronautics
Far field application: Hazardous icing conditions

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

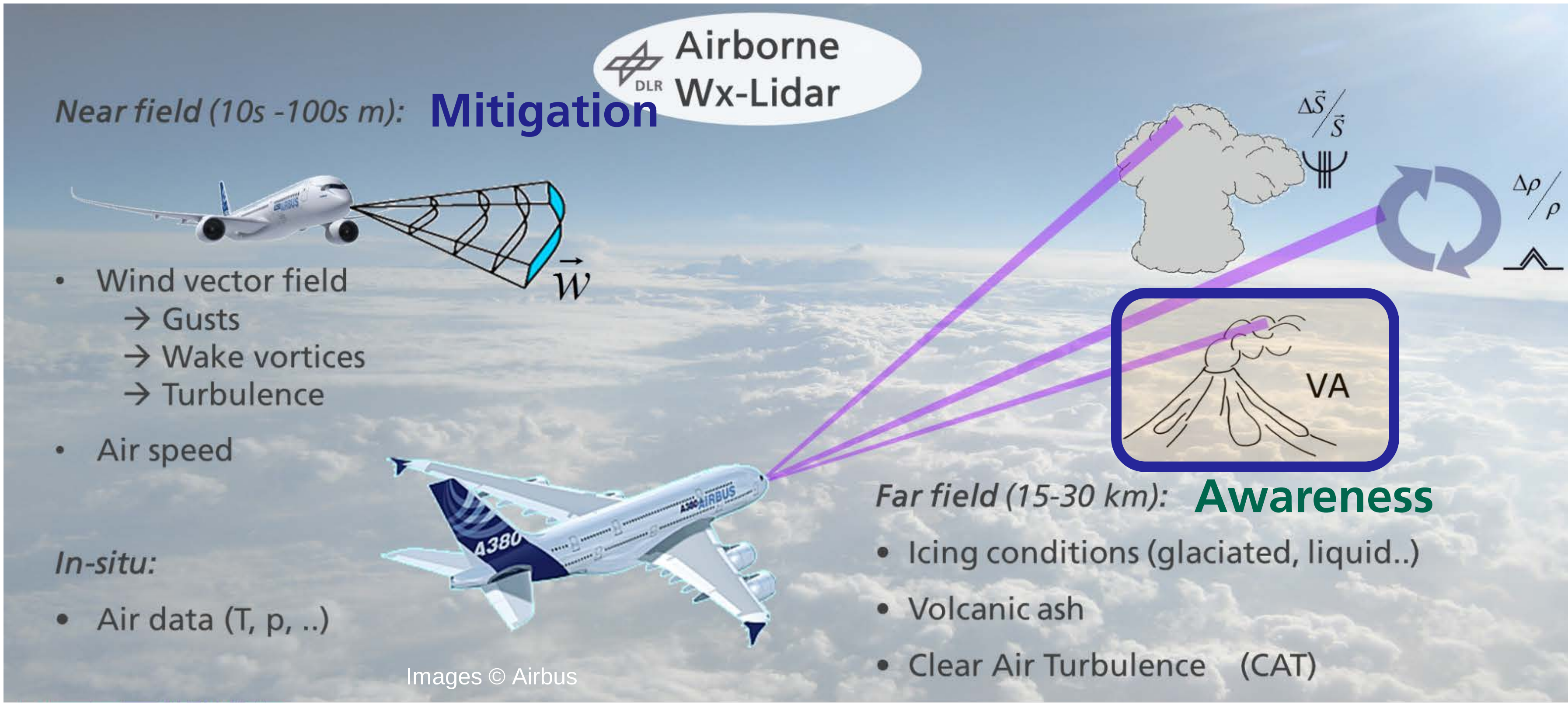


LIDAR measurement

- Backscatter / depolarisation measurement
- Identification of ‘benign’ and ‘hazardous’ Ci-levels

- Distinction of cloud types: SCLD, …

LIDAR for Aeronautics
Applications: Atmospheric / weather hazards



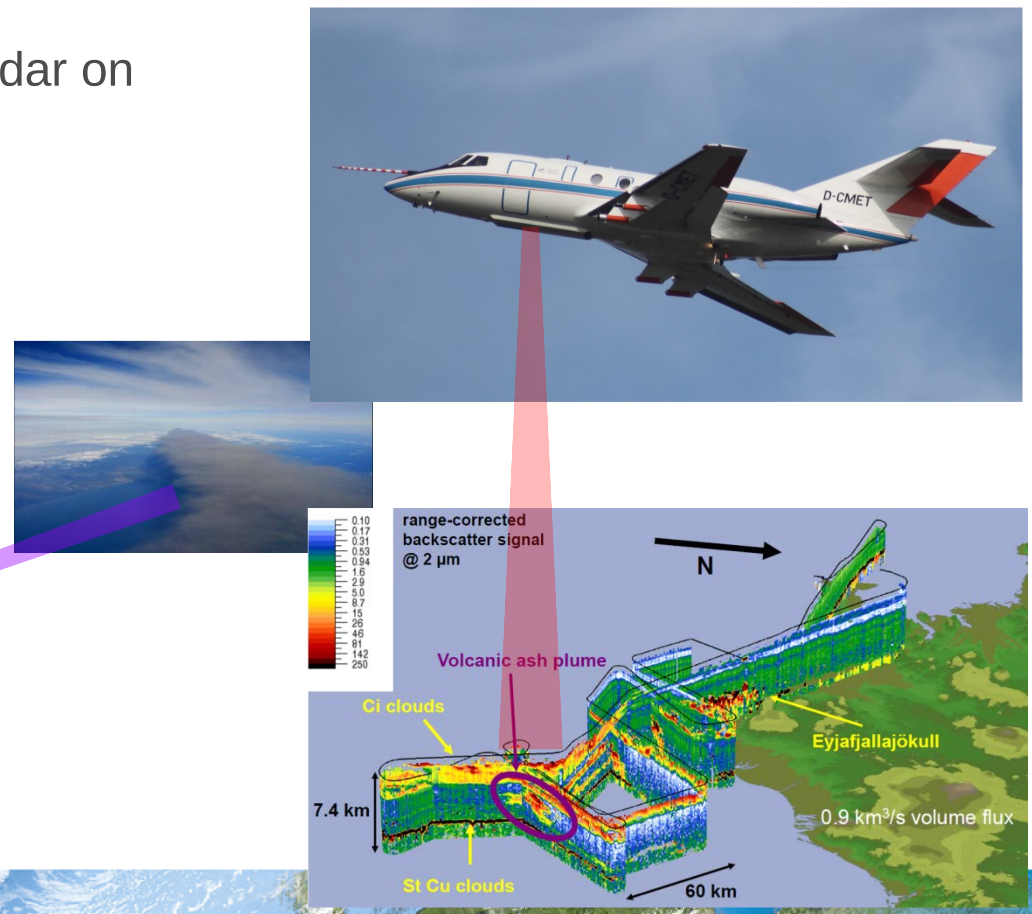
LIDAR for Aeronautics
Far field application: Volcanic ash & Mineral dust

Eyjafalla 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



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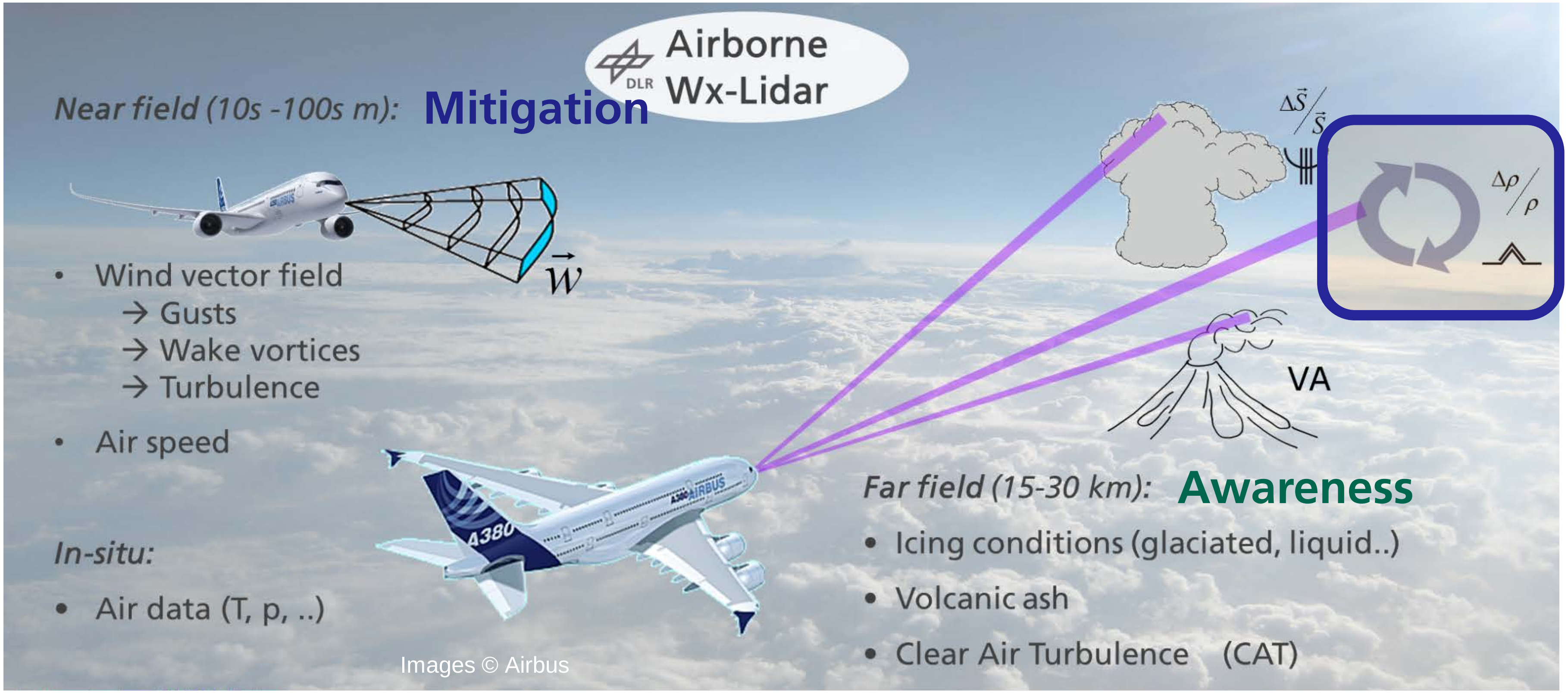
LIDAR for Aeronautics
Applications: Atmospheric / weather hazards

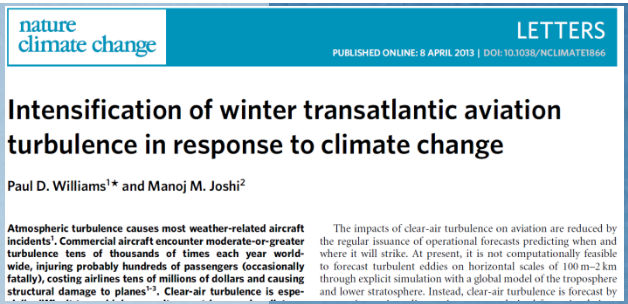


LIDAR for Aeronautics
Far field application: Clear Air Turbulence (CAT) & WV

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


nature climate change

LETTERS

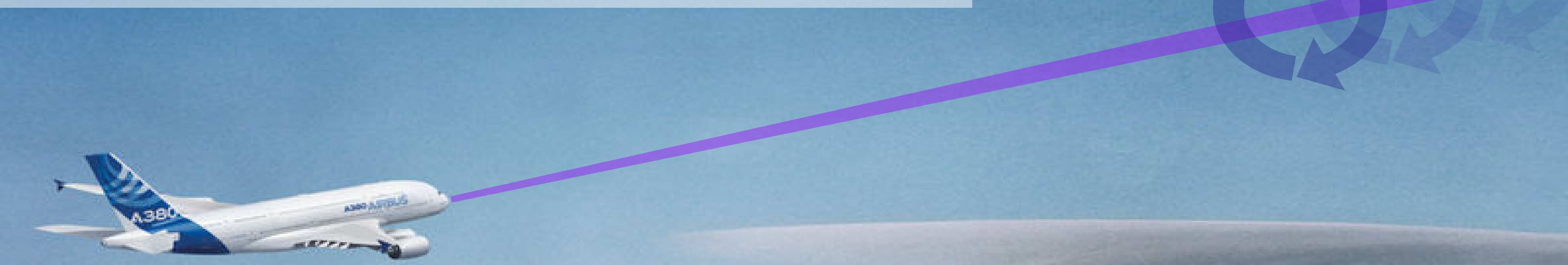
PUBLISHED ONLINE: 8 APRIL 2013 | DOI:10.1038/NCLIMATE1866

Intensification of winter transatlantic aviation turbulence in response to climate change

Paul D. Williams[1]* and Manoj M. Joshi[2]

Atmospheric turbulence causes most weather-related aircraft incidents[1]. Commercial aircraft encounter moderate-or-greater turbulence tens of thousands of times each year worldwide, injuring probably hundreds of passengers (occasionally fatally), costing airlines tens of millions of dollars and causing structural damage to planes[1-3]. Clear-air turbulence is espe-

The impacts of clear-air turbulence on aviation are reduced by the regular issuance of operational forecasts predicting when and where it will strike. At present, it is not computationally feasible to forecast turbulent eddies on horizontal scales of 100 m–2 km through explicit simulation with a global model of the troposphere and lower stratosphere. Instead, clear-air turbulence is forecast by



LIDAR measurement

- Doppler wind speed measurement
- Indirect measurement:
  Air density fluctuations

➔ DELICAT (EC FP7)

SEVENTH FRAMEWORK PROGRAMME

DELICAT

Demonstration of **Li**dar-Based **CAT** (Clear Air Turbulence) detection

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D. Nicolae INOE
…

DLR

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)

- **Consortium of twelve European partners**: Thales (lead), DLR, CNRS/LATMOS, ONERA, Météo France, NLR, RAS/Inst. of Atm.Ph., Hovemere Inc., INOE (Romania), Laser Diagnostics Instruments, Warsaw University/ICM, Airbus (EADS/IW).

- Envelope: 5.6 M€, grant by EC: 3.8 M€
  Start: 01/04/2009, end 31/03/2014

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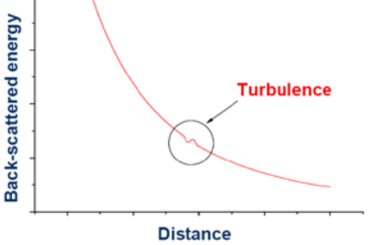
Lidar-based CAT detection: Basic concept

w ⊥ LOS && insufficient aerosols at cruise altitude
→ Coherent Doppler lidar not usable

➔ Indirect measurement:
Air temperature / density fluctuations = backscatter fluctuations (molecular)

$$\frac{\Delta\rho}{\rho} = -\frac{\Delta T}{T} = w\frac{N}{g}$$



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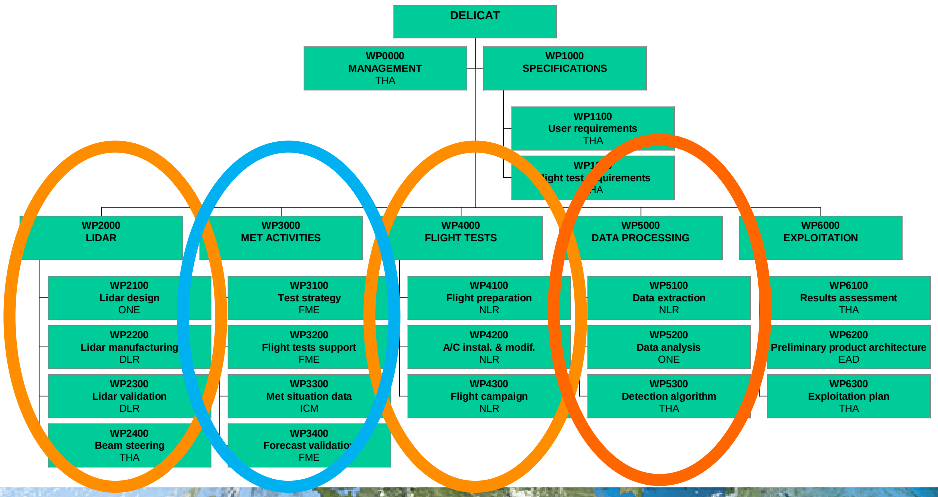
Lidar-based CAT detection: Main project goals

- 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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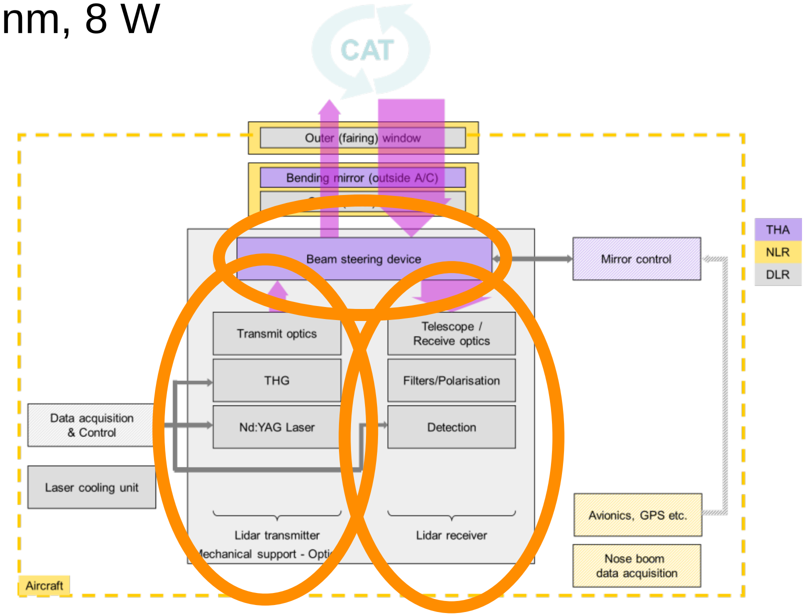
Test aircraft PH-LAB (NLR – Dutch Aerospace Lab)

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

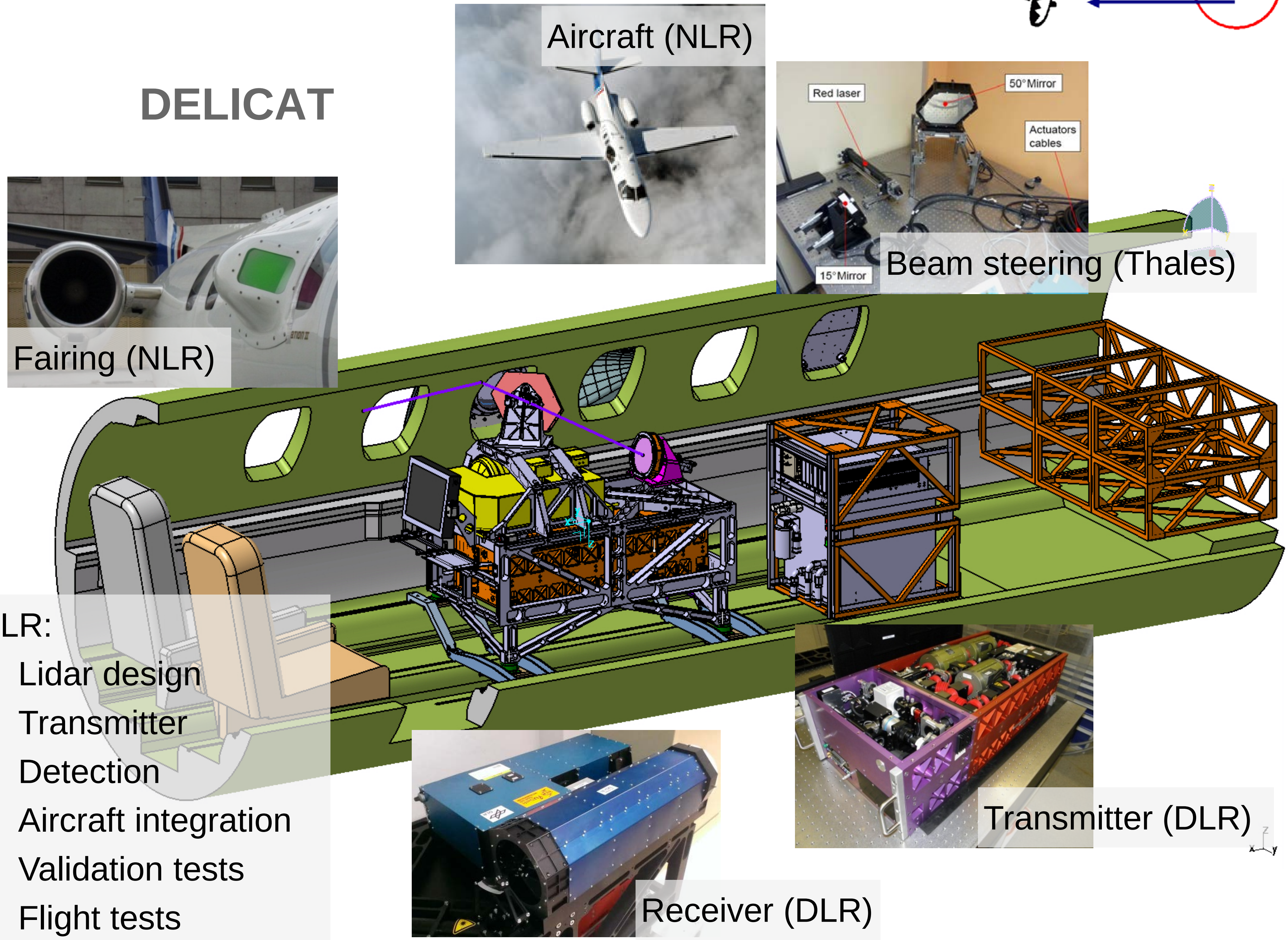
- Front looking fairing
  for directing laser beam on trajectory

DELICAT
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)



DELICAT



DLR:

- Lidar design
- Transmitter
- Detection
- Aircraft integration
- Validation tests
- Flight tests

DELICAT
Lidar on PH-LAB

- Installation and calibrations in June 2013

- STC on 16/07/2013


Ministry of Infrastructure and the Environment
Civil Aviation Authority - Netherlands

SUPPLEMENTAL TYPE CERTIFICATE

This approval is issued to:	Nationaal Lucht- en Ruimtevaartlaboratorium NLR Anthony Fokkerweg 2 1059 CM Amsterdam The Netherlands
Number:	SA1301NL
Date of application:	25 April 2012
Issue Date of application:	16 July 2013
Aircraft and Type:	Cessna 550 s/n 0550-0712
CAA-NL Type Certificate:	T-0056-1991
Type Certificate country of origin:	A22CE -USA
Certification basis:	See associated technical documentation
Description of the Change:	The DELICAT modification consists of the installation of a nose boom, an additional Total Air Temperature sensor, flight test instrumentation in the cabin and a LIDAR (laser) system: with several equipment items in the cabin, an optical window panel assembly, an optical mirror assembly on the outside, protected by a fairing, and a cooler window panel assembly.

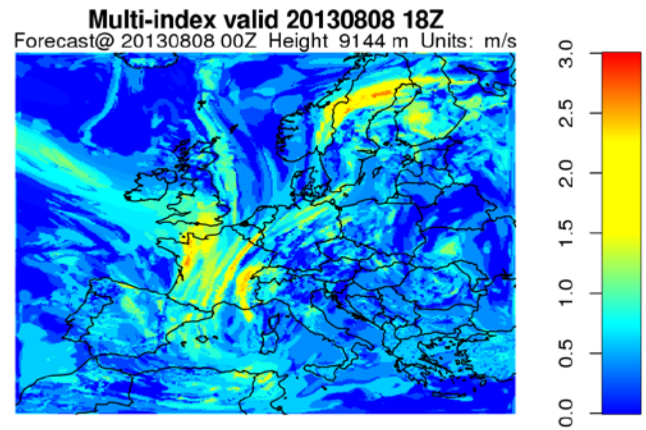
This is to certify that the change in the type design as defined above meets the airworthiness requirements of the certification basis identified above.
This approval is subject to the conditions and limitations on the following page(s).

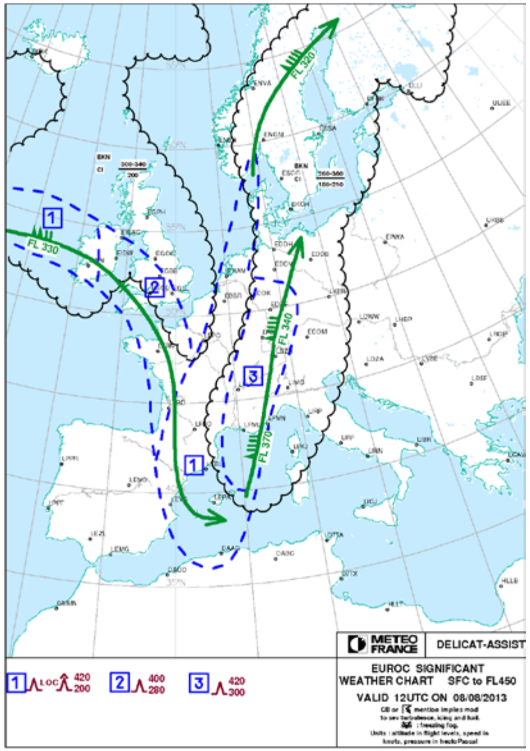
THE MINISTER OF INFRASTRUCTURE AND THE ENVIRONMENT,
on his behalf,
MANAGING DIRECTOR CIVIL AVIATION AUTHORITY THE NETHERLANDS,

Edwin Griffioen.

Page 1 of 2 pages

DELICAT
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

DELICAT
Flight campaign 17/07 – 12/08/2013 from Schiphol

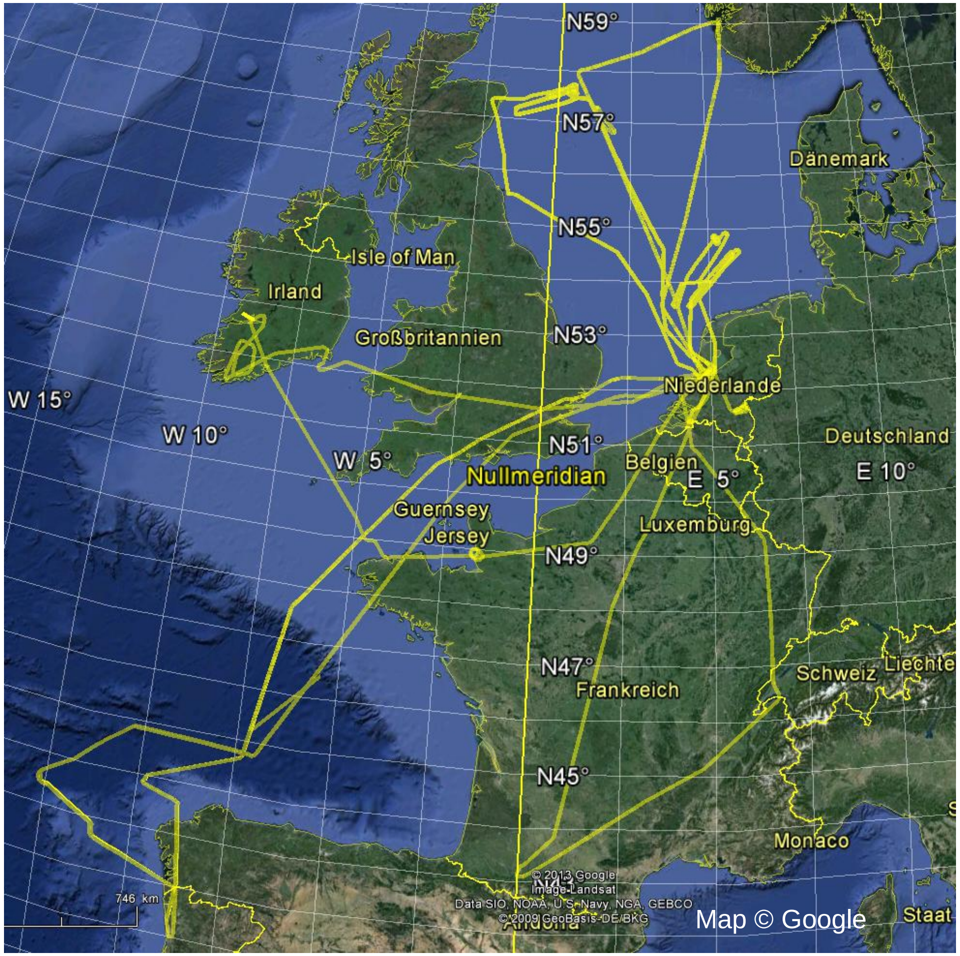
- 11 Flights, 33 h

- Calibrations

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

→ All systems performed exceedingly well

→ CAT very localised, light and difficult to find



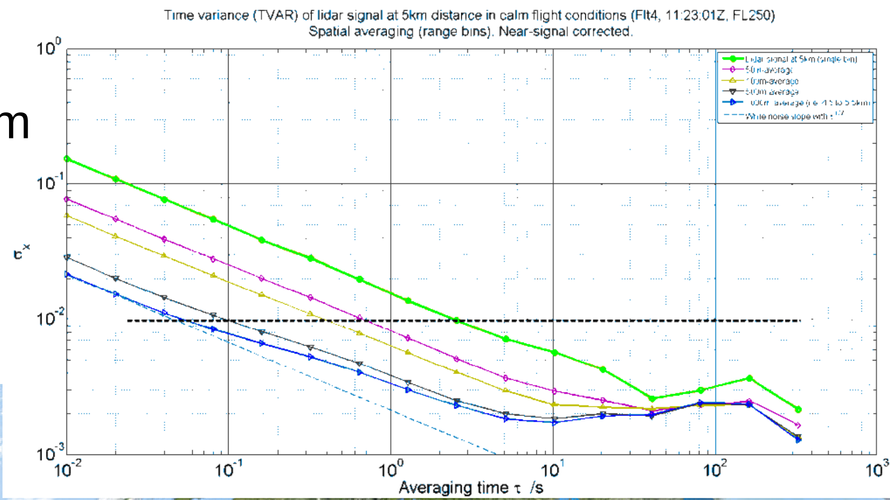
DLR

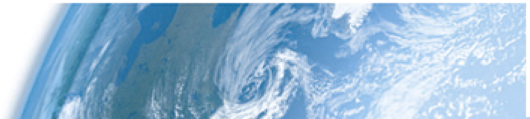
DELICAT
Data analysis: LIDAR system evaluation

- Fundamental lidar sensitivity:
  - Goal: Detect light-moderate CAT detection
    Necessary density (backscatter) measurement sensitivity $\sigma \leq 1\%$
  - Averaging: $\sigma_M \propto {}^{1}/_{\sqrt{N_{Shots}}}$
  - 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 ~1s and ~100m

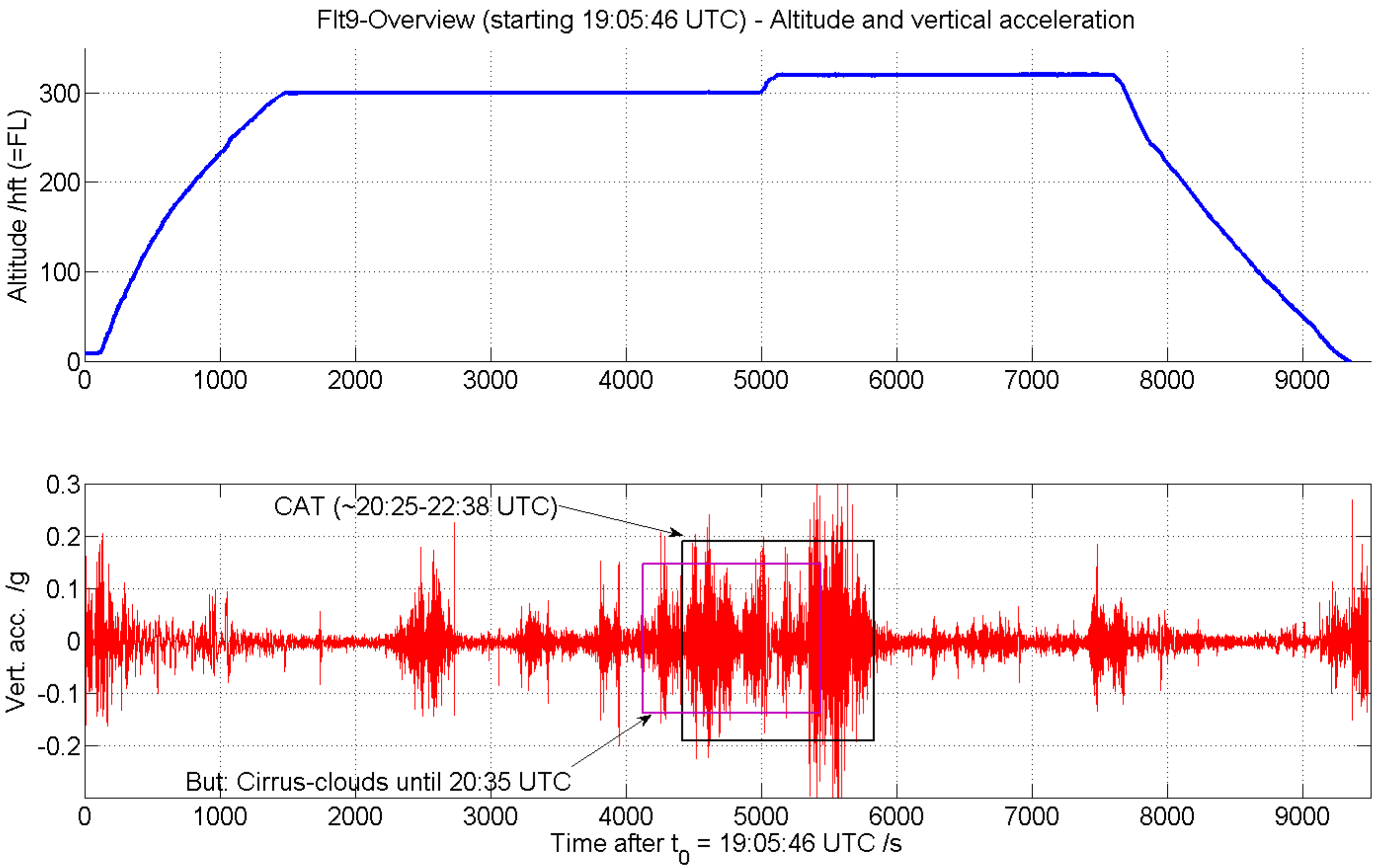
➔ **DELICAT lidar apt for measuring ≥ light-mod CAT**
(by analysing signal variance)





DELICAT
Data analysis: CAT signature retrieval

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



DELICAT
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!

The research leading to these results has received funding from the European Community's Seventh Framework Programme [FP7/2007-2013] under grant agreement n° 233801

LIDAR for Aeronautics - DELICAT

- Thank you for your attention!

- Questions:
  patrick.vrancken@dlr.de

- Website:
  http://delicat-fp7.org/