CLEAR AIR TURBULENCE DETECTION AND CHARACTERISATION IN THE DELICAT AIRBORNE LIDAR PROJECT

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ABSTRACT

We report on a development of a long-range airborne UV high spectral resolution lidar, intended for the detection and characterisation of clear air turbulence (CAT). The detection of turbulence is based on the measurement of density fluctuations associated with the movement of turbulent air masses. These density fluctuations are measured by the variations in the molecular backscatter coefficient which is determined from the lidar signal by spectrally separating it from the aerosol backscatter.
After an introduction, we review the CAT detection principle and describe the lidar system design. We then present the expected performance of the system and give an overview on the planned measurement campaign.

1. INTRODUCTION

In the aeronautics sector, the detection of clear air turbulence is getting more and more into focus. With the exception of very rare events, CAT do not present a major risk to air safety. However, turbulence encounters are the major cause of injuries to passengers and flight crews in non-fatal airline accidents. The total cost due to these incidents is estimated to more than 100 M$ per year in the U.S. alone (FAA data).

Turbulent events associated to weather patterns such as thunderstorms and cloud boundaries in general may typically be avoided by the use of weather forecast and airborne radar. In contrast, forecast of CAT is restricted to the provision of probability of occurrence charts over vast areas that may not be avoided by aircraft (e.g. in the vicinity of jet streams). Given its nature of arising in clear air, CAT defy the detection by radar that rely on the backscatter of electromagnetic waves at water droplets.

For this reason, lidar methods have come into focus of aeronautics industry and authorities. Albeit this topic had been studied in the late 60s (in particular in the U.S., see for instance [1; 2]), it has been abandoned for years.
Lidar methods have been used for a long time for the characterisation of turbulence (such as wake vortices) or gusts over short distance. These lidar systems typically rely on the backscatter at aerosols and measure the Doppler shift due to air movement with either coherent or incoherent methods. The European AWIATOR programme demonstrated the principle of a 3-D determination of the windfield ahead of an aircraft with an airborne direct detection (i.e. by fringe-imaging) UV lidar [3] based on molecular backscatter. This is the first step of implementing an active control for maintaining steady flight in turbulent conditions. The long-term objective of this type of airborne lidar is the extension to longer distances, for the detection of CAT and subsequent warning of the flight crew.

The most important parameter of turbulence for aircraft is the vertical wind speed since it directly changes the angle-of-attack of the air flow and thus the lift coefficient. The vertical wind speed defies direct measurement by the Doppler effect due to the marginal projection of the lidar line of sight over the vertical axis (at long distances).
Therefore, CAT may only be measured indirectly, by quantifying the density fluctuations associated to moving airmasses. This approach has been theoretically studied in the European FP6-programme FLYSAFE and is reported in [4]. The present DELICAT project (EC FP7 programme) intends to build and fly such a technology demonstrator lidar.

The principle is to measure air density via the molecular backscatter coefficient with a UV lidar. For this purpose, a high-finesse etalon separates the molecular backscatter from spurious background aerosol backscatter whose spectrum is considerably narrower. Two detection systems (analogue and photon counting) insure the long-range capability of the lidar system. Currently, this lidar system is under construction and test; a dedicated CAT measurement campaign will be performed on the NLR (Nationaal Lucht- en Ruimtevaartlaboratorium, the Netherlands) Cessna Citation II aircraft in 2011.

The following chapter gives a short introduction to CAT meteorology and the measurement principle. Chapter 3 describes the lidar system while Chapter 4 shows the expected performance in CAT detection. Chapter 5 gives an outlook on planned campaigns and activities.

2. CAT DETECTION WITH LIDAR

The clear air turbulence investigated here is associated to two main mechanisms: Overturning and breaking of internal gravity waves as in the lee of orography (mountain waves) and jet stream induced disturbances (Kelvin-Helmholtz instabilities). For the matter of lidar detection, a relationship between the vertical wind speed w and the air temperature T and thus density ρ may be derived [4]:

$$\frac{\Delta\rho}{\rho} = -\frac{\Delta T}{T} = w\frac{N}{g} \, , \tag{1}$$

with N being the Brunt-Väisälä-frequency (measure of stratification stability) and g the gravity acceleration.
For the determination of Equation 1 one has to know N. This quantity may be determined from the vertical gradient of air density ahead of the aircraft (by use of this very lidar). For the purposes of the DELICAT project, N will be measured in-situ during ascent and descent of the aircraft, assuming that N remains roughly equal on the horizontal scale. Typical values for N are 0.01 rad/s and 0.02 rad/s for troposphere and stratosphere, respectively.

The outer scale L of the turbulence, corresponding to the largest eddy size that can overturn against the stable stratification, amounts to some hundred meters. The characteristic rotation time of these vortices is also given by the Brunt-Väisälä frequency N and amounts to some 5 to 10 minutes. Hence, the density fluctuations associated with the turbulent motion will persist over a time span τ of at least one to two minutes.
As may be inferred from Equation 1, the density measurement has to be performed on the percent level, thus determining a minimum signal-to-noise ratio SNR of 100. During the characteristic time span of the turbulence τ, the lidar system may acquire a sufficiently large dataset for attaining this SNR by averaging (see Chapters 3 and 4).

3. DELICAT LIDAR SYSTEM

The DELICAT lidar system respects the main requirements formulated in [4] which insure a satisfactory CAT detection ratio.
A single-mode laser emits UV laser pulses at a rate of 100 Hz, which are guided over a beam steering system (compensating the aircraft motion) and sent into the atmosphere in the direction of the flight path. At reception, the backscattered signal is composed of a molecular (Rayleigh) and an aerosol (Mie) portion. In order to retrieve the (molecular) air density information the signal spectrum is separated by a Fabry-Perot etalon. Both Rayleigh and Mie signals are fed on two detectors, one working in analogue detection mode for short range, the other in photon counting mode for long range measurements. A synopsis of the system is given in Figure 1. The lidar system is installed in the NLR Citation II aircraft which is equipped with a special optical bay on the fuselage.

3.1. Transmitter

The used laser is the pump laser of DLR's water vapour DIAL system WALES and is described in full detail in [5]. The laser is of the MOPA design, with a monolithic Nd:YAG ring laser as master that runs intrinsically single-mode. It emits IR laser pulses at a rate of 4 kHz and a pulse length of 7.7 ns (FWHM). Its frequency is locked to an I_2 line by feeding a frequency-doubled part through an Iodine absorption cell. The master laser is stabilised to the line centre by controlling the oscillator crystal's temperature. The resulting frequency stability is better than 1 MHz. Part of the laser pulses (at a rate of 100 Hz) is amplified in three power amplifiers, one in double-pass, and two in single-pass. The resulting energy per pulse is then > 400 mJ.

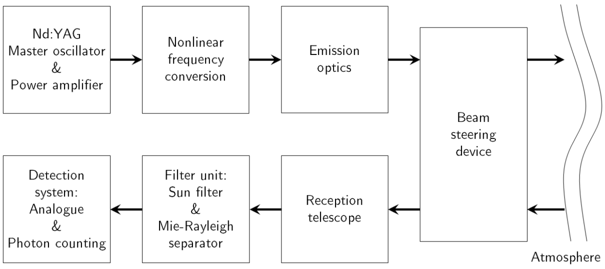

Figure 1: Synopsis of the DELICAT lidar system

For UV conversion, the IR pulses are then fed into a KTP crystal for second harmonic generation. Subsequently, the generated green and the residual IR radiation are guided into a BBO crystal for sum-frequency generation. The resulting 355 nm laser pulses have an energy of $\approx$100 mJ. Part of the beam is sampled and directed onto a photodiode to monitor the pulse-to-pulse energy. The output laser beam is expanded to meet a divergence of 300 µrad.

3.2. Beam steering and coupling to atmosphere

The transmit laser beam is then guided onto a series of two, two-axes controllable mirrors. This system insures the continuous tracking of the (horizontal) aircraft flight path. It allows for the compensation of the necessary change in angle-of-attack due to fuel consumption (lift variation) as well as of short-term attitude fluctuations due to the searched turbulent events themselves. The cut-off frequency of the control is around 1 Hz which has been shown to be enough on the basis of previous flight data with this aircraft.
The beam steering system as well as all subsequent optics are common for both transmit and receive path.

The laser beam is directed through an optical window and onto a 90° bending mirror installed on the outside of the fuselage. These optics are covered by a streamlined fairing that has been developed by NLR for lidar applications. The beam steering device is constructed such that the receive beam is invariant at the centre of the fairing front window, thus insuring an untruncated receive beam whatever the steering angle. The fairing front window determines a useable receiver collection diameter of 140 mm.

3.3. Receiver

Upon return and after being fed through the beam steering device, the light falls into a Cassegrain telescope of 140 mm diameter. The collimated beam is guided through an electro-optic modulator (Pockels cell) which protects the subsequent detectors from the inevitable back-reflection at common transmit-receive optics.

The beam is then directed into the filter assembly. A narrow interference filter of 0.2 nm is used to block a big part of sunlight. The Mie-Rayleigh separator is very similar to the ALFA device studied for the EarthCARE mission, described in detail in [6].
The system consists of two high-finesse Fabry-Perot etalons. The first, with a free spectral range (*FSR*) of 0.45 nm and a bandwidth of 12 pm further reduces the amount of noise by sunlight. After passing through the first etalon, the light is reflected by a polariser and passes through a quarter-wave plate before falling on the second etalon.
The second etalon separates the spectral parts of molecular and aerosol signal, with an *FSR* of 4.2 pm and a bandwidth of 0.22 pm. In contrast to ALFA, the optical path difference between the etalon plates is thermally controlled on account of the vibration environment in the aircraft. The line centre of this etalon is precisely matched on the laser line, taking into account the Doppler shift due to the air speed.

The central part of the signal spectrum is the aerosol backscatter and passes through the etalon, is then split and guided on two detectors, one in analogue detection mode, the other in photon counting mode (see below).
The reflected part (i.e. the wings of the Rayleigh spectrum) corresponds to the molecular signal and passes again through the wave plate and thus through the polariser.
It is then split and fed onto an analogue detection device (for short range) and a photon counter (for long range), respectively. The analogue detection module is also used in WALES [5] and is based on a Hamamatsu bialkali photomultiplier tube (PMT). The sampling rate of the subsequent data acquisition is 10 MHz which corresponds to a spatial resolution of 15 m and thus allows to resolve CAT features as discussed in Chapter 2.
The photon counting device is based on a Hamamatsu super-bialkali PMT and a 50 MHz counter.

3.4. Aircraft

The lidar will be integrated in the Cessna Citation II (PH-LAB) of NLR. It is a twin turbofan engine aircraft with a maximum ceiling of 43,000 ft and a maximum cruise speed of 200 m/s. Considering the DELICAT equipment, the maximum endurance will be about four hours.

4. SIMULATIONS

In order to evaluate the CAT detection performance of the DELICAT experiment a comprehensive simulator has been developed. It uses a full atmosphere parameterisation including localised turbulent events together with aircraft trajectory realisation. The simulator is composed of four parts:

1. 3-D atmospheric parameters including turbulence: Air density and temperature, Mie and Rayleigh atmospheric backscatter coefficients, atmospheric extinction and horizontal wind.
2. Aircraft position and lidar line of sight angle versus time obtained from typical aircraft trajectory statistics (including pitch and yaw angles).
3. Atmospheric parameters projection on lidar line of sight for each aircraft position; backscattered signal simulation along lidar line of sight for each laser shot and detected signal taking into account signal transmission in Mie and Rayleigh channels and noise sources for analogue and photon counting detectors.
4. Signal processing for turbulence signal recovery.

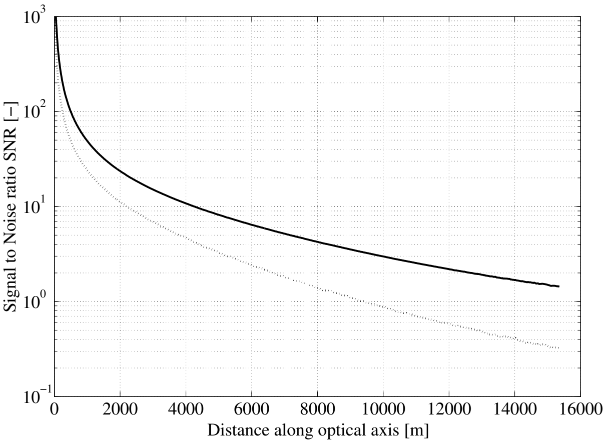

Figure 2: Signal to noise ratio for Rayleigh (solid line) and Mie channel in analogue mode (dotted)

In order to evaluate the detected signal in the Rayleigh and Mie channels (P_{Rayout}, P_{Mieout}), the spectral transmission of the filter assembly is computed. As the spectral shape of the aerosol plus molecular backscatter signal (function of temperature and air speed) is known, a transmission matrix may be computed for each laser shot. Equation 2 gives a typical realisation of this matrix:

$$\begin{pmatrix} P_{\mathrm{Mieout}} \\ P_{\mathrm{Rayout}} \end{pmatrix} = \begin{pmatrix} 0.37 & 0.09 & 2\cdot 10^{-12} \\ 0.19 & 0.47 & 2\cdot 10^{-11} \end{pmatrix} \cdot \begin{pmatrix} P_{\mathrm{Aer.in}} \\ P_{\mathrm{Mol.in}} \\ P_{\mathrm{Sun}} \end{pmatrix} \tag{2}$$

The Rayleigh, Mie and Sun signal contributions in each channel are then evaluated for each aircraft position and each laser shot. Subsequently, the signal to noise ratio SNR_i for each laser shot i is evaluated (Figure 2). For

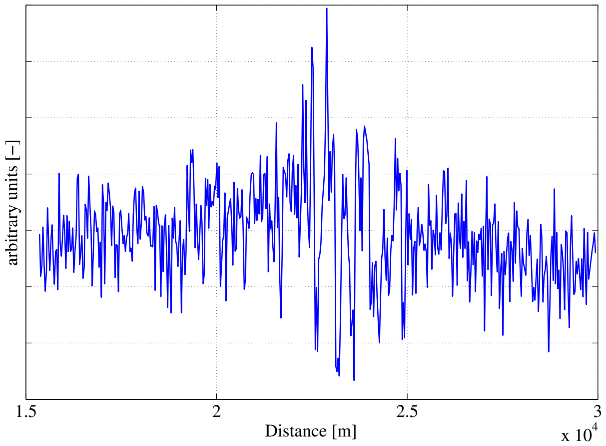

Figure 3: Accumulated signal for 4000 m decision distance

the DELICAT instrumentation, the single shot SNR_i at 10 km distance in the Rayleigh channel typically amounts to about 3.

The transmission matrix, for a given temperature and air speed is then inverted in order to estimate the input molecular and aerosol signals. For each atmosphere slice, lidar signals are added as a function of aircraft advance. We call 'decision distance' the shortest lidar range taken into account in the summation. Figure 3 gives an example of an accumulated signal for 4000 m decision distance. A CAT event is located at 23,000 m in the atmospheric box. With these simulations we see that CAT events may already be detected with the evaluation of the standard deviation of the accumulated signal without further processing. Figure 4 shows the standard deviation of a set of 50 accumulated acquisitions for a 4000 m decision distance, and 20 realisations of atmosphere and aircraft trajectory.

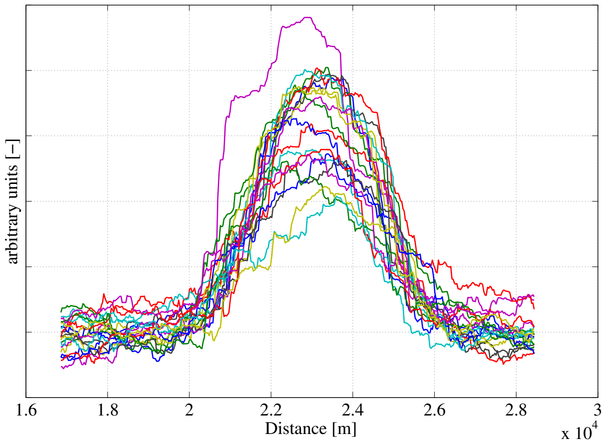

Figure 4: Standard deviation of accumulated lidar signal

5. CAMPAIGN PLANS AND OUTLOOK

In the DELICAT consortium, the partners MétéoFrance and the Interdisciplinary Centre for Mathematical and Computational Modelling (ICM) of Warsaw University develop methods for an efficient CAT prevision and nowcasting. These prognostic algorithms will provide optimum location and timing information to maximise CAT encounter during the flight campaign.
The flight campaign with the Citation II aircraft is scheduled for 2011 and contains 50 flight hours. The aircraft will also provide detailed meteorological data from a nose boom and other sensors. These data will be used for comparison with the lidar measurements.

To summarise, the lidar instrument developed within DELICAT will allow to measure air density fluctuations on the percent level on typical aircraft cruise level. This permits to detect typical clear air turbulence with moderate to severe strength.
Both the spatially high-resolved density information as well as the aircraft-supplied meteorological data will allow to characterise CAT and its occurrence to a today unprecedented level. DELICAT represents an important stepping stone toward future integrated weather lidar for future commercial aircraft.

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