AIRBORNE DIRECT DETECTION UV LIDAR

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We report on the development of an airborne short pulse direct detection UV lidar. The system data generated are suitable for measurement even at cruising altitudes, where the air is devoid of aerosols. Measurable results in flight-testing were obtained under various flight conditions including rain, dense clouds, and clear air up to 24.000 feet.

1. Introduction

The accurate measurement of the airflow in front of an air vehicle is a very important function for modern high performance military and civil aircraft and helicopters. For military aircraft, the exact value of the true 3D airspeed vector is an essential quantity for the flight control system, especially for thrust vector control. In civil aircraft, the measurement of aerodynamics in front of the aircraft is important for applications as calibration flight testing, mapping of aerodynamic flow, detection of transients in the aerodynamic flow (gusts, turbulences) and others.

For those types of applications coherent Doppler LIDARs were suggested. Various US companies and institutions such as e.g. NASA or Coherent Technologies together with Boeing developed and flight-tested prototypes using IR lasers at 2 microns [1]. More recently, several European programmes such as M-FLAME and I-WAKE have been supporting the development of similar systems, including the investigation of 1.5 micron lasers. These approaches are not suitable for most of the named applications because of the following problems:

- The coherent detection requires a narrow line width of the received signal and therefore backscatter of the laser pulses by aerosols. However, a sufficiently high aerosol density is not available in all global regions and at higher flight levels, as it is shown in fig. 1. Therefore such a system would not generate signals under all flight conditions.
- Pulsed coherent systems generate long pulses (typ. ≥ 400 ns) with low pulse repetition rates, resulting in a poor longitudinal and temporal resolution.

This sensor principle, therefore, is only suitable for long-range warning systems, but not for short-range measurements with high longitudinal resolution.

For safety-critical applications, the measurement scenario must meet at least the following criteria:

- A good longitudinal resolution (i.e. the thickness of the measured air slice ahead) of ~ ± 10 –15 m
- A forward-looking measuring distance of ~50 – 150m in order to ensure that the measured air flow is the one really influencing the aerodynamics of the aircraft
- A temporal resolution > 10 Hz
- In order to measure wind speeds perpendicular to the flight trajectory, the sensor must measure at various angles off the flight axis
- The sensor must be able to produce reliable signals in the absence of aerosols; therefore it must be a molecular backscattering system.

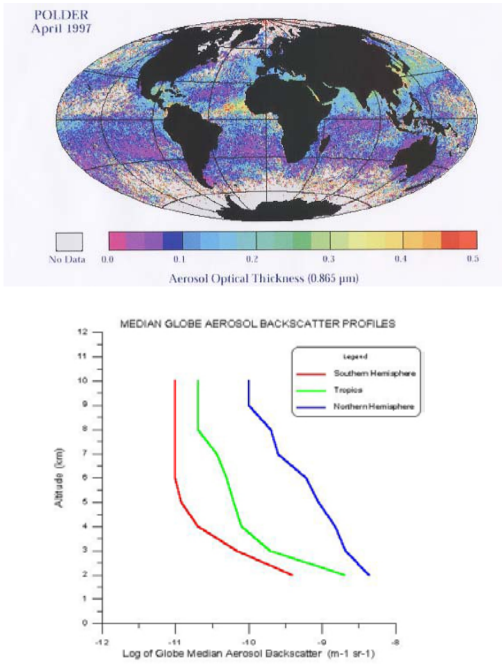

Fig. 1: Aerosol backscatter profiles. Upper: Global distribution; lower: dependence on various altitudes (from M. D. King, EOS, POLDER data 1997)

A sensor system that promises to meet these requirements is a so-called direct detection short pulse UV Doppler LIDAR. This new technology is being investigated by the US companies Ophir [2], Michigan Aerospace [3] and by European consortia, e.g. by Thales and Astrium for space-based atmospheric missions (with large integration times). This contribution describes the first results achieved in flight tests with an airborne high-resolution direct detection short pulse UV Doppler LIDAR, even at cruising altitudes, where the air is devoid of aerosols.

2. Sensor principle

The preliminary requirements for the wind lidar are summarised in table 1. The sensor must be capable of measuring molecular (Raleigh) and advantageously in addition aerosol (Mie) scattering. Fig. 2 shows the two kinds of backscattering signals.

Distance	50 - 150 m
Forward-looking time	0.2 – 0.6 s
Measurement rate	15 Hz for full vector
Longitudinal accuracy	better than ±15 m
field of view	± 10° x ± 10°
wind speed accuracy	~ ± 1 m/s

Tab.1: Preliminary requirements for the wind sensor

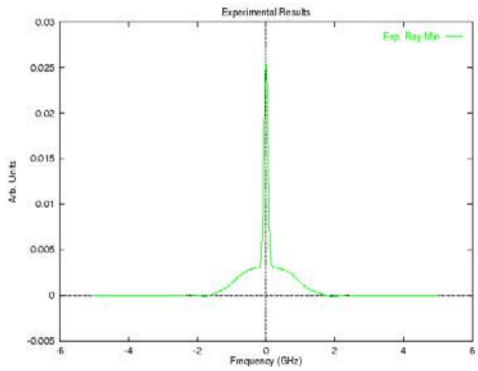

Fig. 2: Signal (principle sketch) for Rayleigh (molecules: broadened spectrum) and Mie (aerosols) scattering. In high altitudes, the Mie peak is negligible**.**

The wavelength shift is measured in an interferometer. The required accuracy of about 1 m/s results in a frequency shift of ~6 MHz for the selected UV wavelength. The thermal broadening of the Rayleigh spectrum is about 600 m/s. Therefore, the frequency shift of the entire curve in fig. 2 must be measured with an accuracy of about 1/600.

The shape of the spectrum also depends from parameters such as temperature, air pressure and aerosol concentration. For obtaining the full 3D wind speed vector the Doppler shift must be determined in at least 3 directions. In our case 4 directions were used for redundancy reasons.

The system consists of a single-frequency tripled Nd:YAG laser at 355nm, a scanning system for beam multiplexing, an optical system for beam transmission and receiving, a Fabry-Perot Interferometer, an image-intensified CCD camera, a data recording and real-time data processing unit and control electronics, see fig. 4.

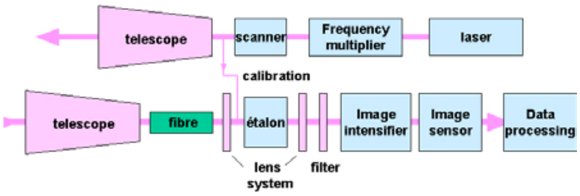

Fig 4: Sensor system architecture

The LIDAR sensor is being realised in two phases. In stage 1 a (flight worthy) system has been built capable of looking ahead 35 m. This was flight-tested in 2004. Stage 2 is the system that will meet the final requirements. It includes, beside other improvements, an upgraded laser at 3W average power and will be flight-tested in 2006.

The laser (see fig. 5) is a single-frequency, third-harmonics Nd:YAG operating at 355 nm, with 300 mW for stage 1 and 3 W for stage 2. It emits pulses of ~ 10 ns width at kHz rates. It was developed by EADS, because suitable devices were not available on the market.

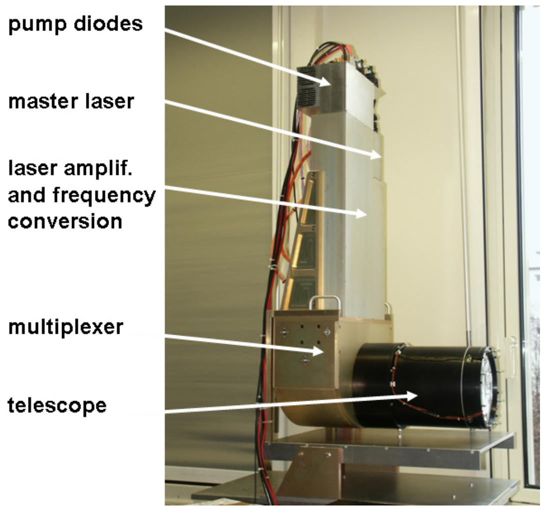

Fig. 5: LIDAR sensor head including the laser

The laser beam is multiplexed in 4 directions by an EADS patented scanning system, which generates a stable focus at the four positions. A full scan is completed with 15 Hz. In the receiver path the backscattered photons are focussed into four UV-fibres and demultiplexed into one fibre, which is connected to the receiver box.

The Fabry-Perot elalon was designed and manufactured by Hovemere. It is capacitance-stabilised and has a finesse of about 5. The Imaging System consists of a modified DiCAM Pro CCD camera with an UV sensitized microchannel plate. The sensor has 640 x 480 pixels; electronic on-chip binning is being used.

3. Theoretical model and evaluation strategy

The backscattered laser light generates, after passing through the etalon, the well-known Airy function:

$$I(\lambda,\theta) = \frac{T^2}{\left(1-R^2\right)} \frac{1}{1+\dfrac{4R}{1-R}\cdot\sin^2\left(\dfrac{\varphi}{2}\right)}$$

with

$$\frac{\varphi}{2} = \frac{2\pi n_{gap}\, h\cdot\cos(\theta)}{\lambda},$$

where T and R are coefficients related to the transmission and reflection properties of the elalon, h is the gap, θ the angle of incidence, and λ the wavelength to be determined.

In practice, this function must be modified: Firstly, the thermal broadening due to the Doppler shift of the Brown´s molecular movements has to be considered, secondly the mixture of molecules and aerosols must be taken into account, and thirdly, artefacts of the optical system such as vignetting and off-centre beam axis position must be modelled. The resulting function is quite complex; shortly speaking, it contains parameters describing the position of the maxima of the rings, the width of the rings dependent on the air parameters, and parameters modelling the optical artefacts.
In order to obtain the desired accuracy for the backscattered wavelengths, given the expected low photon counting rates, it is not sufficient to just estimate the position of the rings by simple geometrical considerations. These parameters must be determined with subpixel accuracy. Therefore it is necessary to fit the above-mentioned modified Airy function with the unknown parameters to the interferogram data. The system parameters, which are constant over time, are determined using a calibration signal gathered from time to time. Fig. 7 shows measured interferograms for clear air, hazy layer and clouds (note here the smaller lines due to high amount of thermally non-broadened aerosol backscatter).

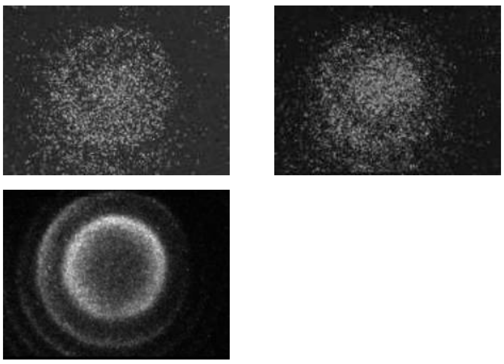

Fig. 7: Interferograms. Upper left: At clear air high altitude (low photon counts, pure molecular backscattering). Upper right: hazy layer. Lower: dense clouds.

4. Flight tests

The sensor was installed in the cabin of the DLR ATTAS VFW 614 test aircraft (fig. 8, fig. 9).

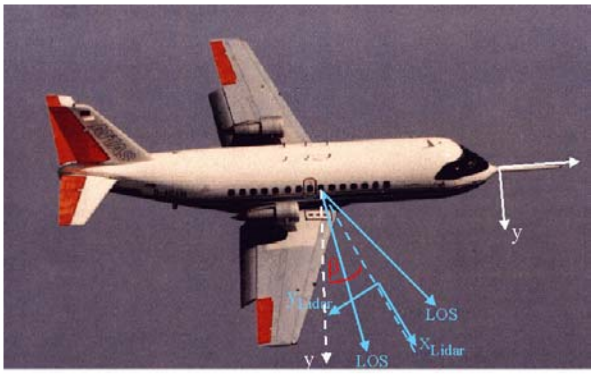

Fig. 8: Sensor installation position in ATTAS

One of the cabin windows was exchanged for a UV transmissive window with anti-reflexive coating at the laser wavelength. The symmetry axis of the sensor was tilted against the x-axis of the aircraft by β=19°, resulting in measurement directions of 61° and 81° from this axis.
Several flight tests with a duration of about 10 hours were performed. Different flight envelopes including flight levels up to 24.000 feet and speeds between 120 and 240 knots were covered. The weather conditions varied from clear air to dense clouds at various altitudes.

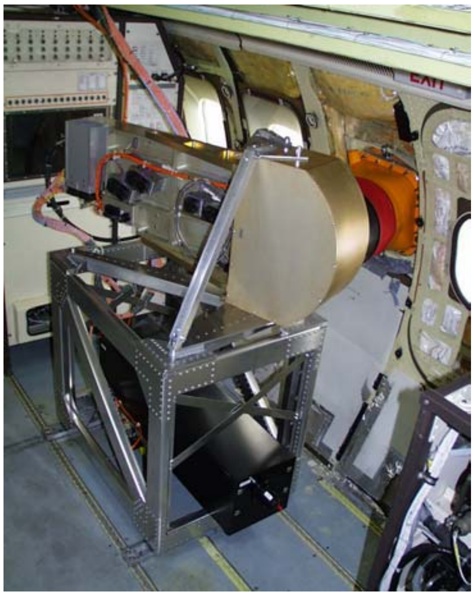

Fig. 9: Integration of the turbulence sensor in the ATTAS aircraft of DLR. Upper box: LIDAR sensor head; lower box: fibre coupled receiver with etalon and camera

5. First results and outlook

The evaluation of the data shows the following results:

- At all flight levels up to 24.000 feet interferograms could be recorded. At higher flight levels, the aerosol backscatter signal is reduced by a factor 10^{-3} compared to ground level, and is therefore by a factor $5*10^{-3}$ weaker than the molecular backscatter signal. This proves that the sensor is able to perform in a pure molecular environment.
- Sensor signals were also obtained in dense clouds, where the visibility was less than 5 m. The strong Mie scattering outweighed the effect of absorption of the laser beam by orders of magnitudes.
- Even in rain and ice, good sensor signals were received. Because of the gated viewing, raindrops on the window did not disturb the measurement.

Figure 10 demonstrates the LIDAR data following the curve of the aircraft onboard reference data system (nose-boom with multi-hole probe) after compensation of a constant offset.

From the preliminary evaluation the following conclusions can be drawn: The accuracy strongly depends on the photon count rate. The signal backscattered by clear air is weak, especially in high altitudes, but still measurable. The low intensity was due to the interferometer throughput, which is much lower than expected. Therefore, because of the low counting rates, the specified wind speed accuracy could not yet be achieved. For stage 2, the interferometer is strongly improved.

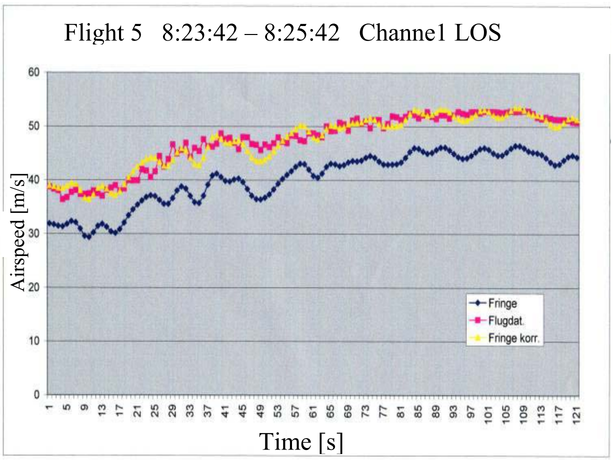

Fig.10: Flight test data from flight Nr.5:. The magenta (upper dark) curve represents the data from the aircrafts reference system, the blue (lower dark) curve the LIDAR sensor raw data, the yellow (upper light) curve the LIDAR sensor data compensated by a constant offset. It is demonstrated that the LIDAR sensor data follow the changes measured by the aircrafts reference system.

In result (see Fig. 11), from flight test 1 using the ATTAS aircraft, a standard variation of the line-of-sight air velocity of 8-12 m/s (flight 5; can be improved by a factor of 2 by summing up 4 interferograms) in clear air could be achieved (depending of flight nr. with different set of parameters), 3-4 m/s (flight 5) in hazy layers, and 1.8-3m/s (flight 4) in clouds. Taking into account a stronger laser and several improvements for the stage 2 system, which shall be flight-tested in autumn 2006 using an Airbus A340 aircraft, a standard variation of 1.8-3 m/s is expected in clear air conditions, and 0.7m/s to 1.5 m/s in clouds (blue (left) and red (right) bubbles of Fig. 10). This expectations are derived from linear extrapolation based on the photon count improvements, thus not taking into account further improvement of systematic errors, which are indicated by vertical black arrows below the bubbles.

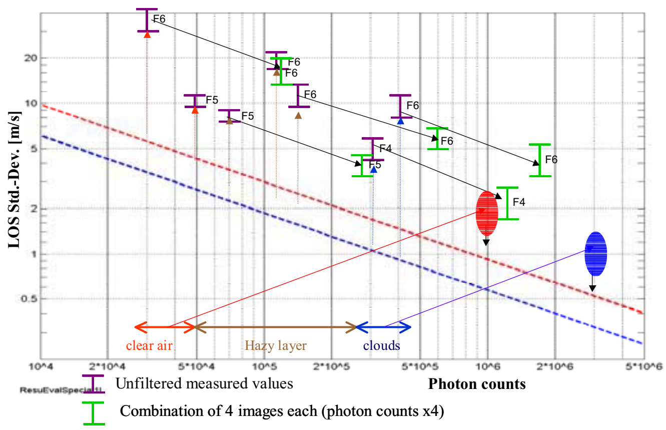

Fig. 11: Measured flight data: LOS standard variations versus photon counts.
Purple (dark) error bars: single interferogram analysis (flight number indicated right of the bar)
Green (light) error bars: Summation of four interferograms.
Red (left)/blue (right) bubbles: estimations for upgraded system in flight tests 2, autumn 2006

To conclude it could be shown that the Rayleigh/ molecular short pulse Lidar is suitable for airflow and turbulence measurement, under flight test conditions up to high altitudes, in clear air and in clouds. We expect to achieve the desired performance due to improvements of the evaluation methods, the receiver system and the upgrade of the laser to the full power.

References

[1] Soreide, D., et al.: Coherent LIDAR turbulence measurement for gust load alleviation. NASA Technical Memorandum 104318 (1996)

[2] www.ophir.com/rayleigh_mie_optical_air_data.htm (2002)

[3] http://www.michiganaero.com/moads/index.shtml (2001)