GROUND-BASED AND AIR-BORNE LIDAR FOR WAKE VORTEX DETECTION AND CHARACTERISATION

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OVERVIEW

In the last two years several ground based and airborne wake vortex campaigns have been performed with the DLR coherent Doppler Lidar. The objectives of those campaigns were (i) measurements for comparison with the wake vortex prediction and monitoring system WSVBS, (ii) the measurement and description of wakes generated by the new Airbus A380 aircraft and a reference aircraft for the ICAO landing separation, and (iii) the observation of the influence of different configurations on the vortex life time in the project AWIATOR.

1. INTRODUCTION

The investigation of aircraft wake vortices by means of coherent Doppler lidar is rather new [1, 2, 3], but the method has been proven to be successful in a number of studies [4, 5, 6]. In the atmospheric boundary layer these measurements can be performed with a ground based lidar. In the typical configuration, the lidar performs an elevation scan with the line of sight (LOS) perpendicular to the vortex axis (Fig. 1a) [7]. A low scanning speed of 2° or less per second is sufficient because the vortex is moving relatively slow in the lidar coordinate system. The advantage of this setup is also a generally high aerosol load and humidity in the atmospheric boundary layer, leading to a high backscatter coefficient and high quality vortex measurements. The disadvantage however is the property of the boundary layer itself. The atmosphere near the ground is either layered at calm wind conditions and low turbulence or it is well mixed and very turbulent. Both atmospheric conditions have a significant influence on the behavior of wake vortices. In addition, the topology and surface roughness have an impact that is difficult to predict if a vortex is generated in proximity to the surface.

In the free atmosphere the conditions are generally more homogeneous, compared to the boundary layer, and close to neutral stratification. However, the main drawback here is mostly the lack of aerosol particles resulting in a pretty poor SNR making good lidar measurements impossible. This restriction can be overcome by (i) using smoke generators at the generating aircraft or by flying (ii) under contrail conditions or (iii) in a hazy atmospheric layer. Here the big issue is either the limited time of smoke generation or the rare occurrence of these conditions. For wake vortex observations in the free troposphere, the Doppler Lidar is installed in the DLR research aircraft Falcon F20 in a downward looking configuration (Figure 1b) [8]. Then, the Falcon is flying 600 to 1000 m (1800 to 3000 ft) higher than the generating aircraft and along the wake track. In this case the geometry for the vortex measurement is better suited because both vortices are separated according to the LOS of the lidar. The scanning speed needs to be higher due to the virtually high relative movement of the vortex in the lidar coordinate system.

2. LIDAR SYSTEM AND MEASUREMENT GEOMETRY

The DLR lidar system consists of a wind tracer transceiver from Lockheed Martin Coherent Technologies (formerly CTI). It is operating at approximately 2.02 micron wavelength with 1.5 mJ energy and a repetition rate of 500 Hz.

The DLR custom build scanner in front of the transceiver consists of two Silicon wedges that can be turned independently by two stepper motors. Thus it is possible to address each LOS direction inside a cone with +/- 30° opening angle. Such a scanner is compact and - compared to a mirror scanner - insensitive to vibration.

The data system follows the strategy of early digitizing, which means the heterodyning signal is directly digitized together with a timestamp. All other housekeeping parameters are also stored in their original data format together with a timestamp in a separate computer. This computer also controls the scanner. This strategy offers maximal flexibility during the offline data processing especially for the correction of time and frequency jitter of the transmitted pulse, or the suppression of pulses where the seeding was not optimal. The correction of any offsets or systematic errors of housekeeping parameters is also easily possible. Thus at wake vortex measurements with a maximum range of 2 km the data rate is roughly 250 MByte per minute that can be handled by a regular commercial computer with SCSI hard disk. During the measurements preliminary results with reduced resolution (called quick-looks, e. g. see Fig. 4) can be investigated.

Data processing takes place offline in a four stage processing that will be described shortly in the next chapter. For high quality results of the circulation strength the homogeneity of the backscatter coefficient has to be monitored closely. Therefore, an automated processing is not advisable. The data products of the processing are the position of the centre of the vortex and its circulation strength.

2.1. Ground based measurements

For ground based wake vortex measurements, the lidar is ideally placed in 1000 m distance normal to the flight path of the wake vortex generating aircraft. This distance is a trade-off between high resolution and good SNR requiring a close range and high volume covered at a higher range. The elevation angle ranges from 0° to 50° depending on the altitude of the generating aircraft. Therefore, wake measurements in Out-Of-Ground-Effect (OGE) as well as in In-Ground-Effect (IGE) are possible.

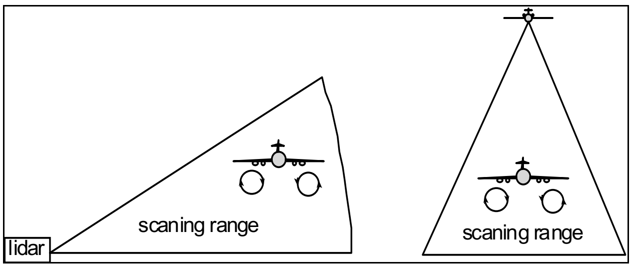

FIG 1. Scan pattern for ground based (left) and airborne (right) wake vortex measurements.

2.2. Airborne measurements

As mentioned above the Falcon F20 aircraft is used as platform for airborne wake vortex measurements in a downward looking configuration [8] and is flying 600 to 1000 m above the flight track of the wake generating aircraft. This distance turns out to be the optimal compromise between resolution and width of cross section scanned. The higher flight level also relaxes security issues of operating several planes close together. The critical issue is the accuracy of navigation. At 1000 m range the measuring aircraft (Falcon F20) has to be right above the vortex pair with an accuracy of better than +/-400 m horizontally. These high requirements for aircraft navigation are difficult to meet due to the advection of the vortices by crosswind, the low visibility of an older vortex (even if seeded by smoke or marked by contrail) and the aircraft velocity of 100 - 200 m/s. In case the vortex of the generating aircraft is seeded by smoke to improve the SNR, the time of the smoke generator is limited to a total of 10 to 20 minutes. Depending on the velocity of the generating aircraft, the required vortex ages, the velocity range of the chasing aircraft with the lidar, and the clearance of the flight control several approaches are possible to optimize measurements during the limited time of smoke generation. Where possible the generating aircraft is flying along the local wind direction to minimize the drifting of the vortex beside the trajectory. The Falcon can fly either the opposite direction if the measurements need to cover a wide range of vortex ages, or it can fly in the same direction with a different speed for a higher density of measurements per vortex age.

3. FOUR STAGE DATA PROCESSING

The measured signal consists of the monitor signal and the backscatter signal for each single shot. By means of the monitor signal it is possible to determine the exact time and frequency of the outgoing pulse that is necessary to analyze the backscatter signal correctly. The four stages of processing consist of the estimation of (i) the Doppler spectra (spectra of the power of coherently detected backscatter signals), (ii) the radial velocity and velocity envelopes, (iii) both vortex core positions, and (iv) both vortex circulations [9].

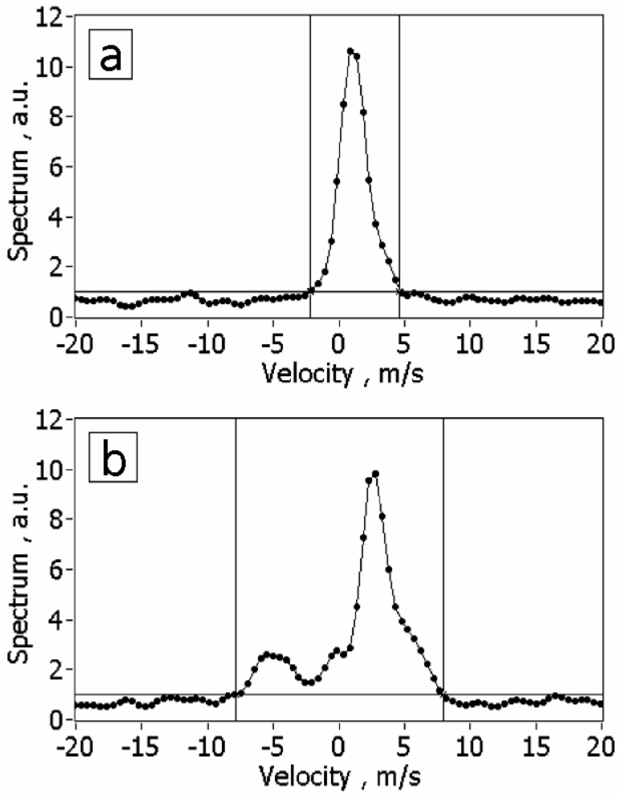

FIG 2. Examples for spectra measured outside of a vortex (a) and below/above a clockwise- / counter- clockwise rotating vortex regarding FIG. 1 (left) or the outer parts of the vortices regarding FIG. 1 (right), negative velocities point towards lidar (b).

At step (ii) the spectra obtained in step (i) are analyzed to achieve both, the radial background velocity and the contributions that are caused by wake vortices (see Fig. 2). The latter become apparent by side peaks or broadening of the mean peaks that have to be above a threshold to suppress noise peaks. Here, the mean peaks are caused by the spectrum of background velocities and the threshold is chosen corresponding to the noise value.

The horizontal bars in Fig. 2 denote the threshold while the vertical bars indicate the positive and negative velocity envelopes. In the next step the vortex core position can be found easily by means of the envelopes. The circulation can be calculated considering background velocities and noise threshold values [9, 10].

4. MEASUREMENTS FOR WSVBS

At Frankfurt Airport (Germany) a high number of measurements have been performed with the focus on wake vortex displacement in the context of WSVBS [11,12,13] (*Wirbelschleppen-Vorhersage- und -Beobachtungssystem,* German for Wake Vortex Prediction and Monitoring System).

Therefore, wake vortex transport has been tracked for the monitoring of the predictions of a probabilistic vortex model [14] that is used for dynamical adjustment of aircraft separations.

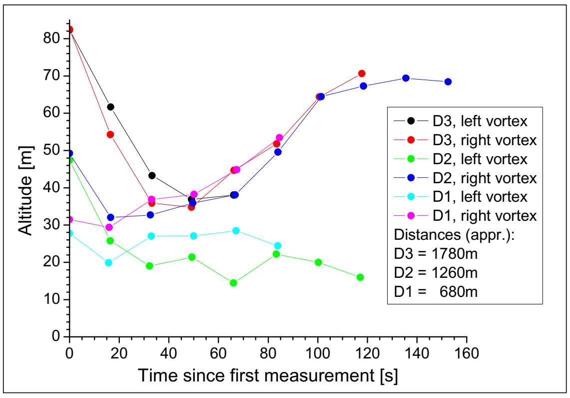

FIG 3. Altitude of vortex cores over time at different distances (D1-D3) to the touch-down zone for a single aircraft on 30th Jan, Frankfurt, Germany.

These measurements between December 2006 and February 2007 covered a variety of meteorological and ambient conditions with a real traffic mixture. The lidar site was situated laterally to the glide slope of the runways 25R and 25L and close to the touch-down zone. Three different azimuth directions have been chosen to cover the last nautical mile before the touch-down zone. The elevation angles have been reduced to a range from 0° to 6° (up to 8° for the outermost azimuth direction) to obtain a high temporal resolution for the landing aircraft. Approximately vortices of 1100 heavy aircraft have been monitored.

Figure 3 shows three results of vortex core position displacements obtained during this campaign as an example. Each pair of vortices was generated at a different distance to the touch-down zone corresponding to different initial altitudes.

5. AIRBUS A380 VORTEX MEASUREMENTS

The DLR Doppler lidar system has been used to asses the wake vortices of the new Airbus A380. In that context DLR acted as a subcontractor for Airbus.

The measurements for the A380 started in April 2005 by looking towards the glide slope of the airport Blagnac during the normal flight test program of Airbus with only a few landings a week. This set of measurements confirmed the value of Doppler lidar measurements for the characterization of wake vortices. In consequence, a regular measurement series started with measurements in different altitudes above ground in order to study the wake vortices at IGE as well as OGE. Sodar and RASS wind profiler were used to probe the atmosphere in terms of wind, temperature, and eddy dissipation rate (EDR). To get a comparison with existing aircraft, most of the measurements were done in a way that the passes of the A380 alternated with passes of other heavy aircraft in order to obtain comparable results under similar atmospheric conditions concerning turbulence, temperature stratification, and cross wind. Those measurements were observed by a member of Eurocontrol and/or the FAA.

The behaviour of a wake vortex pair generated by an aircraft at cruising altitude is also a point of consideration. Because smoke generators commonly did not work at cruising altitudes, meteorological conditions with persistent contrails have to be searched.

Therefore, airborne measurements took place, where the A380 and another heavy aircraft were flying during appropriate conditions at cruising altitude in parallel so that the wake vortices could be measured and the results could be compared against each other. The vortices of both generating aircraft were measured starting directly behind the aircraft up to a distance of 25 nm, which corresponds to a vortex age of roughly 4 minutes.

Some additional ground based measurements have been performed with the focus on measurements in a very calm atmosphere.

The result of these measurements will be reflected in the final update of the ICAO guidance regarding A380 wake turbulence separations

6. AWIATOR A340-400 MEASUREMENTS

Another interesting topic is whether static or dynamic settings of flaps can have an influence on the vortex strength or lifetime. One idea is that instabilities are introduced in the wake vortex that cause the rapid decay phase to start earlier. [15] Experiments on a model in a water tank do not answer all questions. Again, the Doppler lidar is currently the only instrument that can probe high-accuracy wake vortex characteristics in the atmosphere generated by a real aircraft.

For such investigations, the influence of the atmosphere on the wake vortices has to be as small as possible. Consequently, those measurements took place above the atmospheric boundary layer. An A340-300 from Airbus with smoke generators mounted below both wings was used as generating aircraft. It was flying approximately at 3000 m altitude (where the temperature is still high enough to allow the operation of smoke generators) but high enough to be outside the atmospheric boundary layer. The lidar was again installed on the DLR Falcon F20 looking downward. Four sets of flights were performed in total on two days.

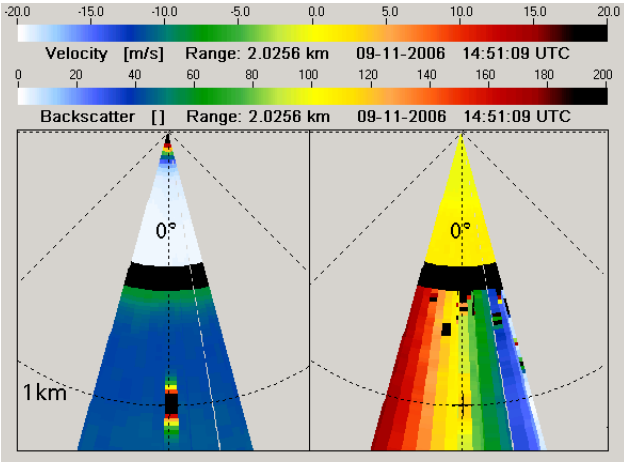

FIG 4. Quick-looks (preliminary figures obtained during the measurements) of backscatter (a) and velocity (b) for a single scan during the AWIATOR campaign, see corresponding colour codes above.

By performing airborne measurements one has to deal with the fact that the scanning plane is not perpendicular to the vortex axes because of the movement of the lidar situated inside the aircraft with time, i.e. the different scans are cutting the vortices in zigzag pattern.

To measure alternatively perpendicular to the vortex axis the double wedge scanner control has been modified such that the LOS points forward at the beginning of a scan and backward at the end. This mode has been operated during the AWIATOR measurements for the first time. The implementation can be seen in Figure 4. The backscatter (a) shows the vortex clearly, because of its seeding with smoke, while the vortex signature inside the rainbow-like velocity plot (b) gets hidden because of the alternating contribution of the flight speed to the measured velocities.

Three different wing configurations have been tested against one standard setting (baseline). At those flights the A340 and the Falcon with the lidar were flying in opposite direction. At a flight level below the A340 a Fairchild Metro II from NLR, equipped with video cameras, was flying in the same direction and straight below the Falcon aircraft. This way a correlation of the vortex parameters obtained from the lidar measurement with the optical appearance of the smoke seeded wake vortex pair is possible.

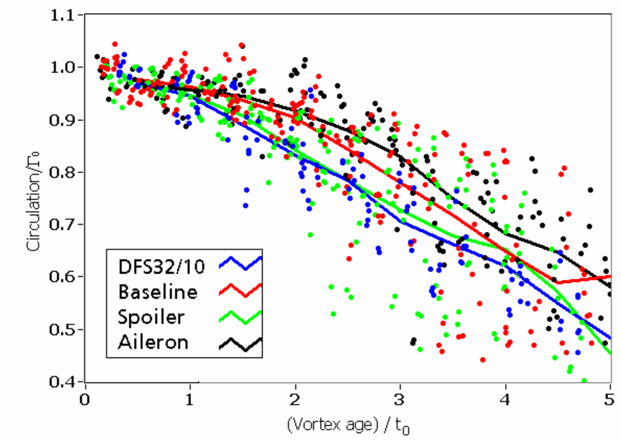

FIG 5. Normalized circulation against vortex age for four different wing configurations. Red colours denote the baseline configuration.

Figure 5 shows the result of the circulation strength as a function of vortex age for the four different configurations. Shown are the single data points as well as a mean curves derived from all eight single measurements for each configuration. Detailed information about the different configurations can be found in reference [15].

CONCLUSIONS

Doppler lidar is the leading instrument for measuring wake vortices of real aircraft because of its high accuracy, the possibility of fast scanning at different ranges and the usage at different platforms and measuring geometries.

This paper has shown that:

- Congested airports can benefit from these measurements by lidar participation on a safety net.
- Very detailed investigations of wake vortices of single aircraft (A380) are possible with DLR lidar.
- The influences of flap setting modifications increase the knowledge of wake vortex behaviour.

ACKNOWLEDGEMENTS

The measurements in Frankfurt 2006/2007 were funded by the DLR project Wirbelschleppe.
The wake vortex measurements on the Airbus A380 were performed under Airbus contract.
The A340-300 measurements were funded by the European Union AWIATOR program contract no. G4RD.CD200200836.

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