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 aircraft separation, and (iii) the observation of the influence of different aircraft configurations on the vortex life time in the project AWIATOR.

1. INTRODUCTION

As a consequence of lift, aircraft produce a downdraft beneath the wings air. Because of the shear between the subsiding and the unaffected air wake vortices are rolled up. The behaviour of that wake vortices is a major issue in aeronautical research. Besides other topics in this context (contrails, fuel consumption), wake vortices are a matter of safety and risk management because following aircraft may be endangered.

Trailing wake vortices can be measured by Doppler radar [1], continuous wave (CW) Lidar [2] and coherent Doppler lidar. To measure with coherent Doppler lidar is rather new [3, 4, 5], but the method has been proven to be successful in a number of studies [6, 7, 8].

This paper gives a brief overview about the coherent Doppler lidar instrument that is used by DLR, the measurement technique, some campaigns as examples, and correlated results.

2. MEASUREMENT REQUIREMENTS AND INFLUENCE OF METEROLOGIC CONDITIONS

In the atmospheric boundary layer the 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. 1, left) [9]. 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 signal to noise ratio 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 generating conditions or (iii) in a hazy atmospheric layer. Here limiting factors are either the finite time of smoke generation or the prediction of these rare 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.

3. LIDAR SYSTEM AND MEASUREMENT GEOMETRY

The DLR lidar system consists of a wind tracer transceiver from Lockheed Martin Coherent Technologies. 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.

3.1. 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 signal to noise ratio requiring a close range and high volume covered at a higher range. The elevation angles are adapted to the altitude of the aircraft and range from 0° to 50°. Therefore, wake measurements Out-Of-Ground-Effect (OGE) as well as In-Ground-Effect (IGE) are possible.

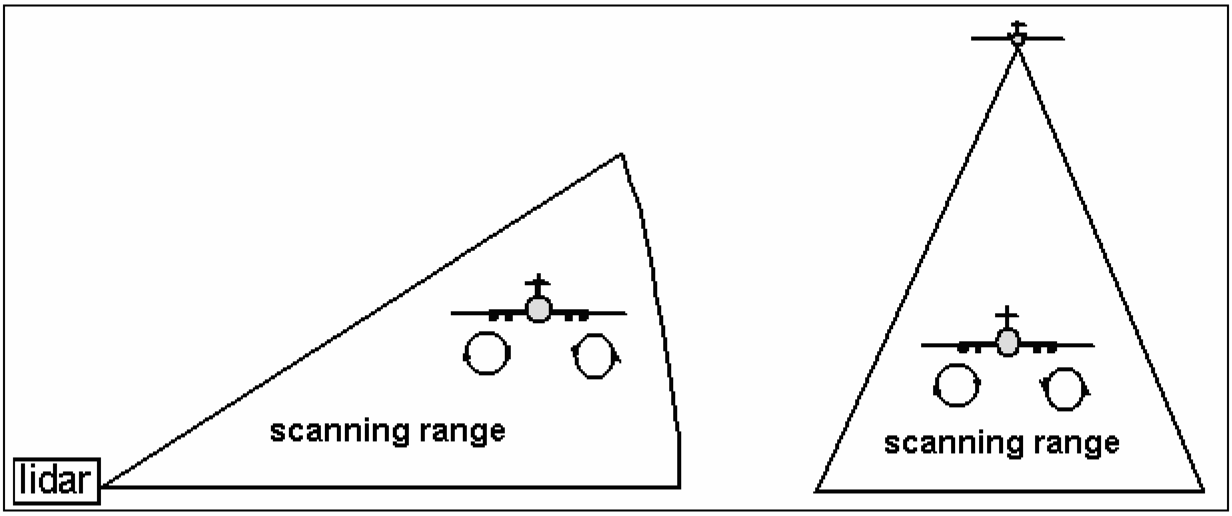

FIG 1. Scan pattern for ground based (left) and airborne (right) wake vortex measurements.

3.2. Airborne measurements

As mentioned above the Falcon F20 aircraft is used as platform for airborne wake vortex measurements in a downward looking configuration [10] 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 the scanned cross section. The higher flight level also relaxes safety issues for the operating of several planes close together. The accuracy of navigation is critical. At a 1000 m range the measuring aircraft (Falcon F20) has to be right above the vortex pair with an accuracy of better than +/-400 m laterally. 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.

4. DATA PROCESSING

Data processing is performed offline in a four stage processing procedure. For high quality results of the circulation strength the homogeneity of the backscatter coefficient has to be monitored closely. Therefore, automated handling is not advisable. The final products of the processing are the position of the centre of each vortex and its circulation strength.

The measured signal consists of the monitor signal and the backscatter signal for each single shot. The monitor signal provides 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 spectra and velocity envelopes, (iii) both vortex core positions, and (iv) both vortex circulation values [9].

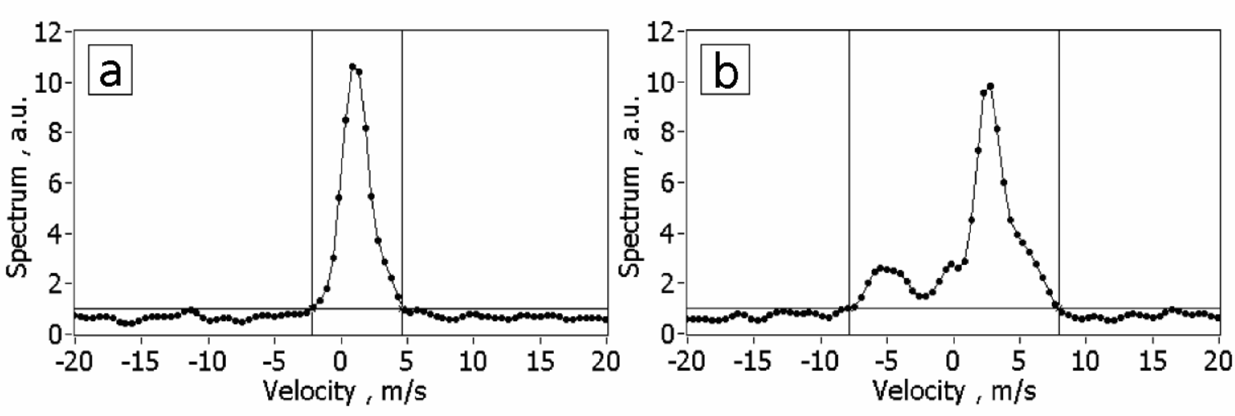

FIG 2. Examples for spectra of ambient turbulence (a) and with the spectral contribution of a wake vortex (b). This contribution here originates from the part of a vortex that rotates towards the instrument, because negative velocities point towards the lidar. Here arbitrary units (a.u.) denote a relative frequency of occurrence of the corresponding velocities.

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 avoid 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 respective positive and negative envelopes of velocities.

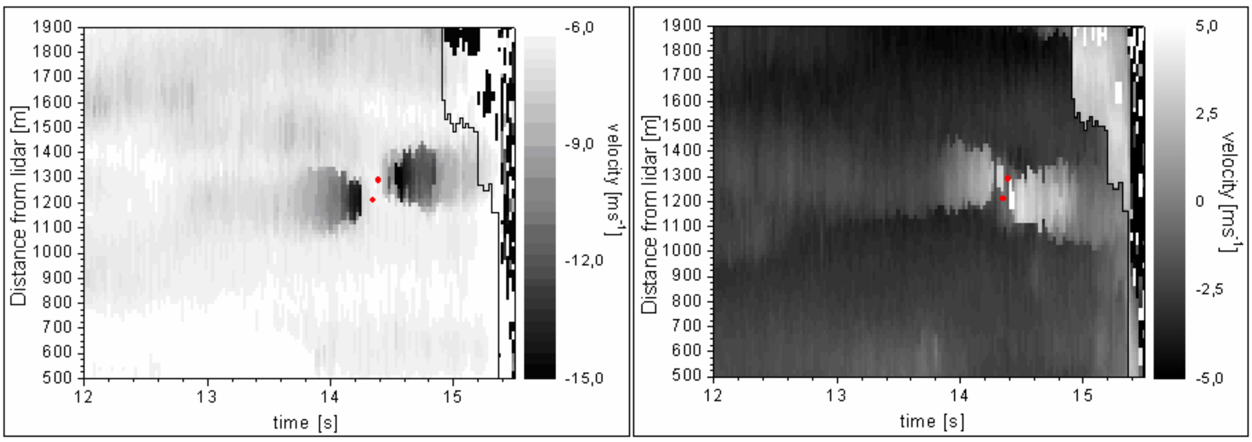

FIG 3. Positive velocity envelopes (right) and negative velocity envelopes (left) obtained from spectral analysis plotted versus distance to the lidar and time. The red dots denote the positions of both vortex cores between the maxima of positive envelopes velocity and the minima of negative velocity envelopes.

In the next step the vortex core position can be derived from the envelopes (see Fig. 3).The values of the positive and negative envelope velocities are plotted versus distance to the lidar and time. The scan has been performed like it is shown in Fig. 1 (left) from top to bottom. The area to the right of the black line is partly influenced by hard target measurements close to the surface or the surface itself.

Both figures show two velocity minima or maxima, respectively. Both pairs of minimum and maximum velocity are caused by one of both vortices. In between each pair the position of the vortex cores can be found, in Fig. 3 these are marked with red dots.

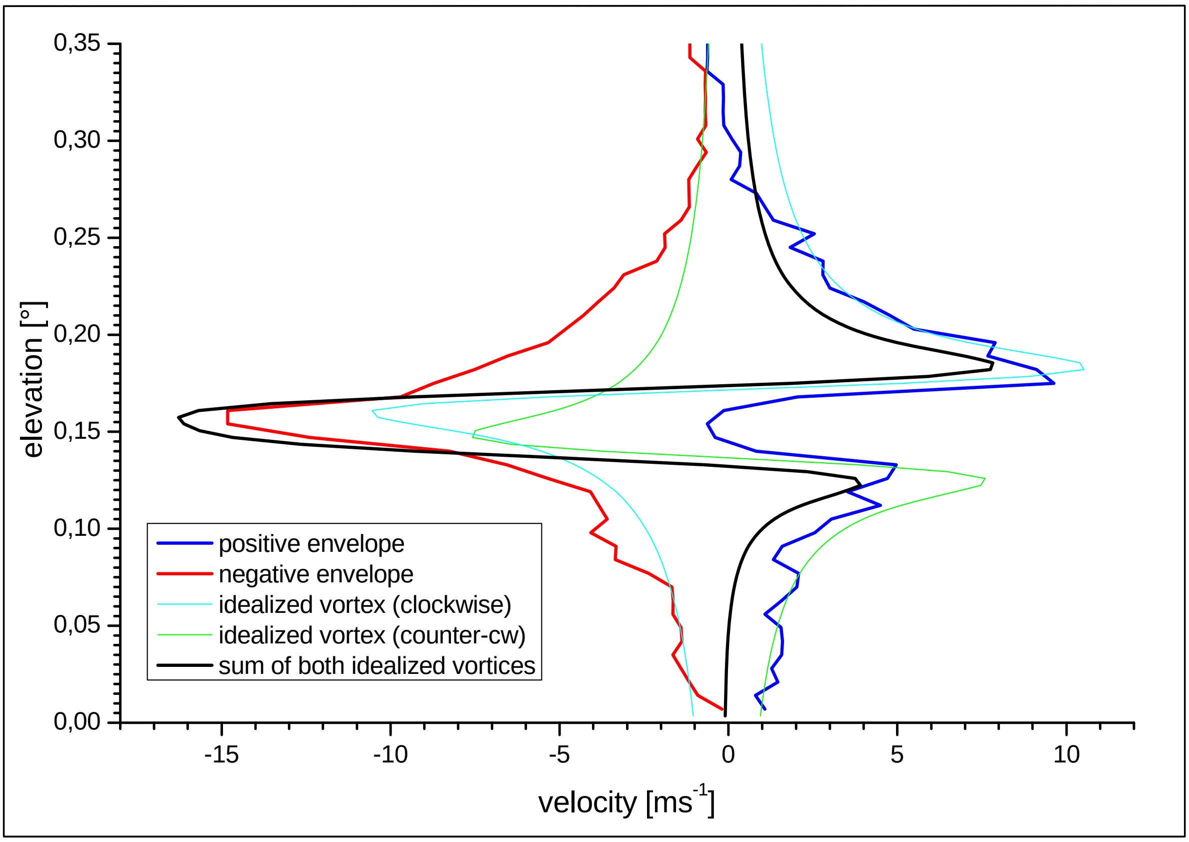

FIG 4. Velocities induced by a vortex pair. Shown are positive and negative envelope velocities at vortex core distance versus altitude and velocities of idealized synthetic vortices to illustrate the contribution of both vortices to the measured envelopes.

The vicinity of the vortex core position can be used to find the circulation value (velocity times the vortex radius integrated between 5 m and 15 m from vortex centre). The envelope velocities at vortex core distance above and below the core (see Fig. 4) are used for the integration where the contribution of the background velocities mutually are cancelled out between both sides of the vortex [11, 12]. In Fig. 4 the discrepancy between the positive envelope and the idealized vortex at lowest levels is caused by the contribution of the other vortex.

5. WAKE VORTEX MONITORING

At Frankfurt Airport (Germany) a high number of measurements have been performed with the focus on wake vortex displacement in the context of WSVBS [13, 14, 15] (*Wir-*

belschleppen-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 [16] that are used for dynamical adjustment of aircraft separations.

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 (see Fig. 6). Three different azimuth directions have been chosen to cover the last nautical mile before the touch-down zone. This corresponds to the most critical area because there wake vortices can not descend significantly below the flight corridor. Consequentially, most encounters occur at heights below 100m [17, 18]. 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.

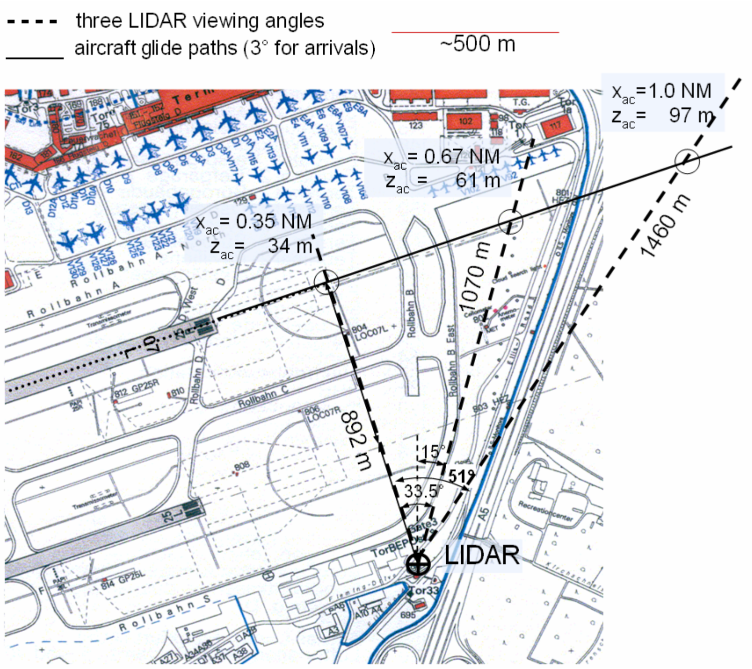

FIG 5. Measurement scheme at Frankfurt airport, Germany. x_{ac}, z_{ac} denote the distance to touch-down zone and the height of landing aircraft in the three vertical scan planes of the LIDAR (dashed lines); The local operation center of DWD (German weather service) and the meteorological profiler were situated between both extended runway centrelines. Map reprinted by courtesy of Fraport AG.

Figure 6 shows three results of vortex core position displacements obtained during this campaign as an example. Each pair of vortices was generated by the same aircraft at different distances to the touch-down zone corresponding to different initial altitudes. It is obvious, that the right vortices first subsided and then rebounded while the left ones remained in lower altitudes. At the time of measurement a weak crosswind to the right side has been present, which is responsible for the asymmetric vortex rebound.

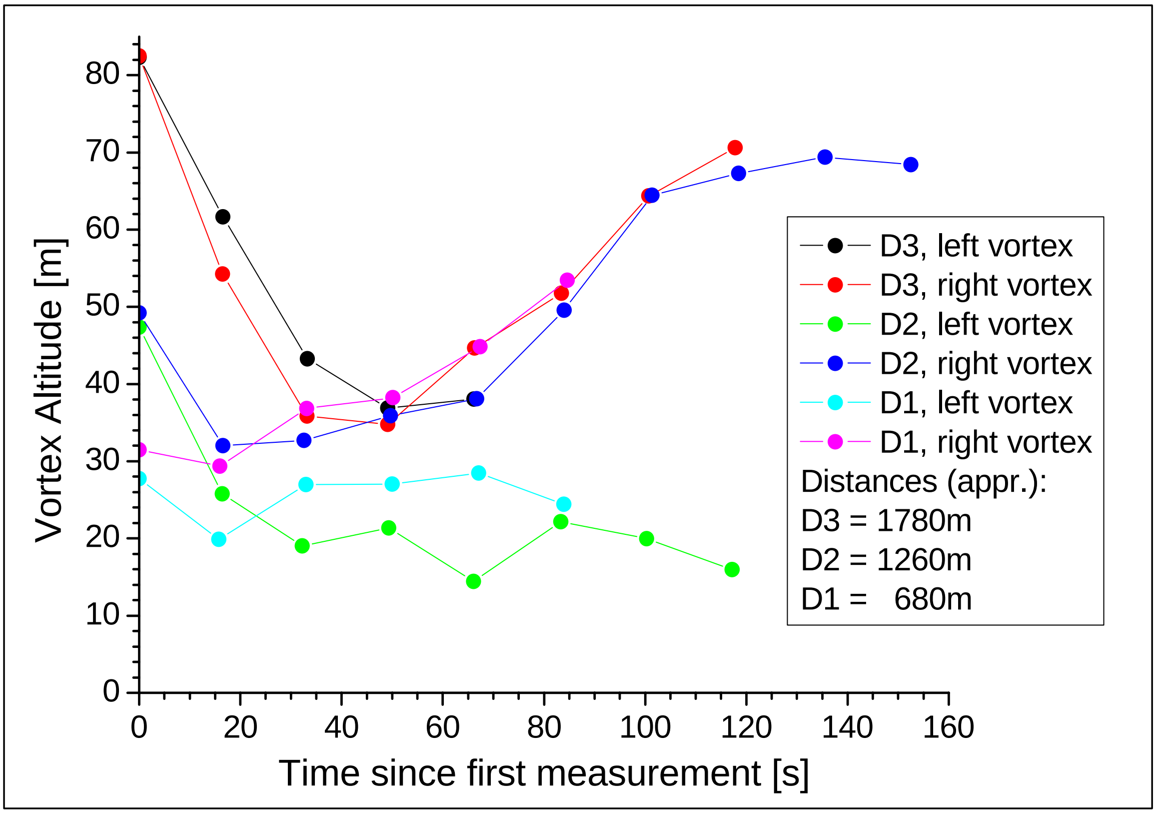

FIG 6. Altitude of vortex cores over time at different distances (D1-D3) to the touch-down zone for a single aircraft on Jan 30th, 2007, Frankfurt, Germany.

6. EFFECTS OF AIRCRAFT CONFIGURATIONS

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 early rapid decay [19]. Experiments with a model in a towing tank are limited by Re number effects and the size of the tank. 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 vortex generator. It was flying above the atmospheric boundary layer at approximately 3000 m altitude where the temperature is still high enough to allow the operation of smoke generators. The lidar was installed on the DLR Falcon F20 looking downward. Four sets of flights were performed in total on two days.

Airborne wake vortex measurements basically imply that the scanning plane is not perpendicular to the vortex axes because of the movement of the lidar flying with the aircraft, i.e. the different scans are cutting the vortices in a zigzag pattern.

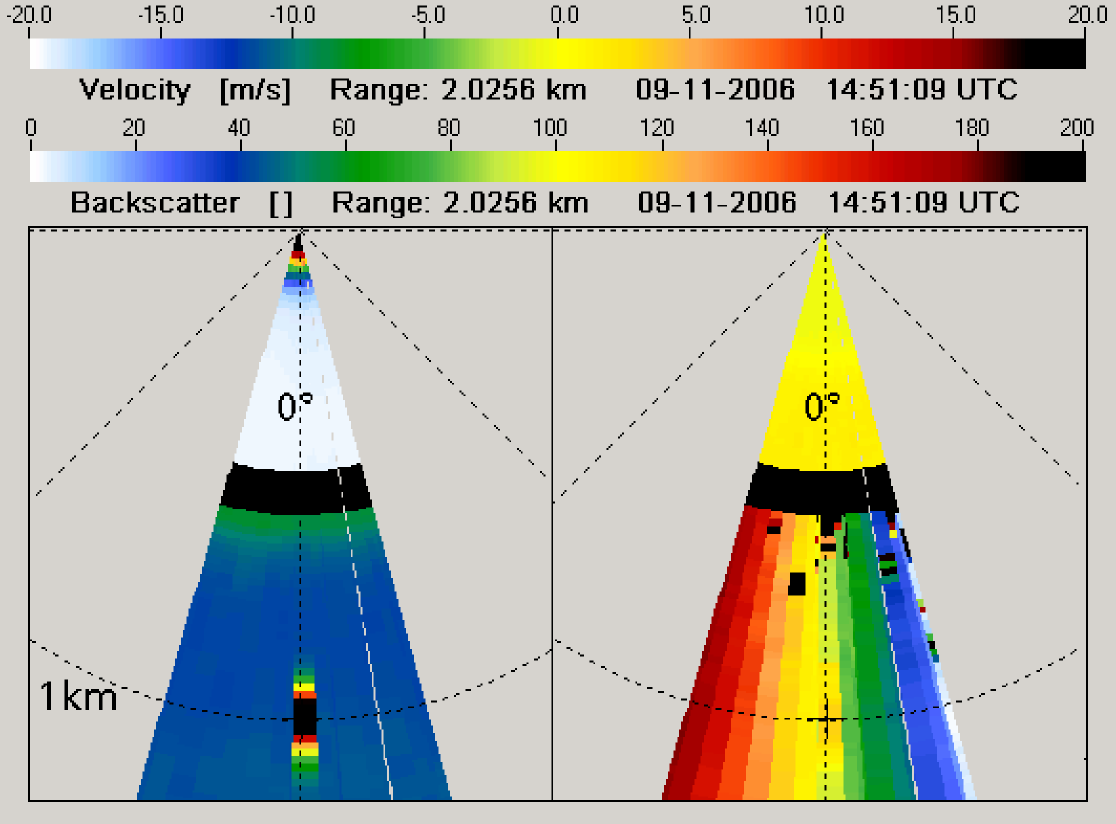

FIG 7. Quick-looks (preliminary figures obtained during the measurements) of backscatter (left) and velocity (right) for a single scan during the AWIATOR campaign, see corresponding colour codes above.

In order to measure nonetheless 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 strategy compensates the the aircraft flight speed such that the laser beam cuts the wake vortices effectively perpendicular to the flight direction. This mode has been operated during the AWIATOR measurements for the first time. A drawback of this method can be seen in Figure 7. The backscatter (left) shows the vortex clearly, because of its seeding with smoke, while the vortex signature inside the rainbow-like velocity plot (right) is hidden because of the alternating contributions 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.

The video of the vortices seeded by smoke taken from NLR have been "stitched" to an image shown in Fig. 8 (Courtesy of A. de Bruin). Clearly visible are the different stages of vortex deformation, linking, and ring formation. The effluence of smoke indicates vortex bursting phenomena occurring at various locations along the vortices, corresponding to different vortex ages.

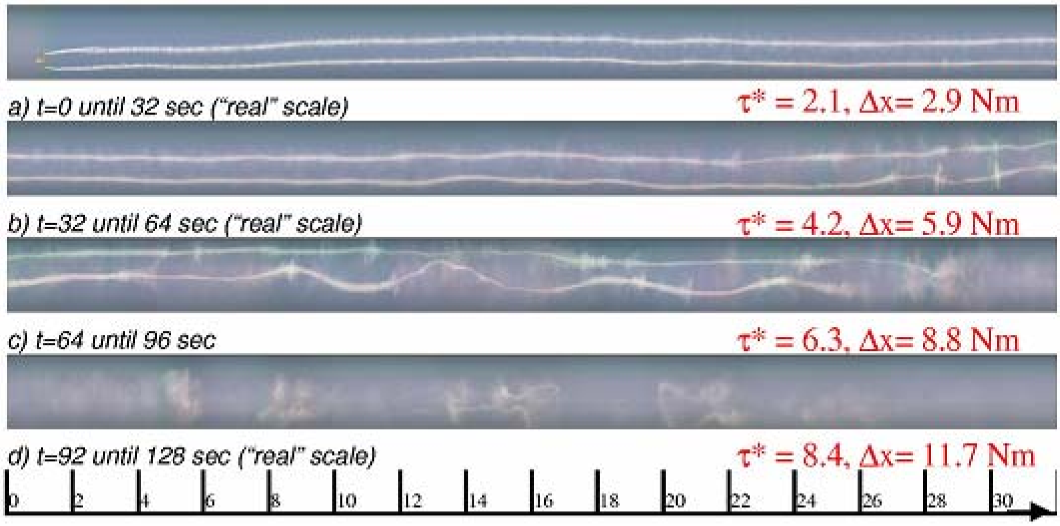

FIG 8. "Stitched"- video image of smoke traces taken from NLR aircraft flying below the Airbus. Timescales are given in seconds and normalised age of vortex τ^*.

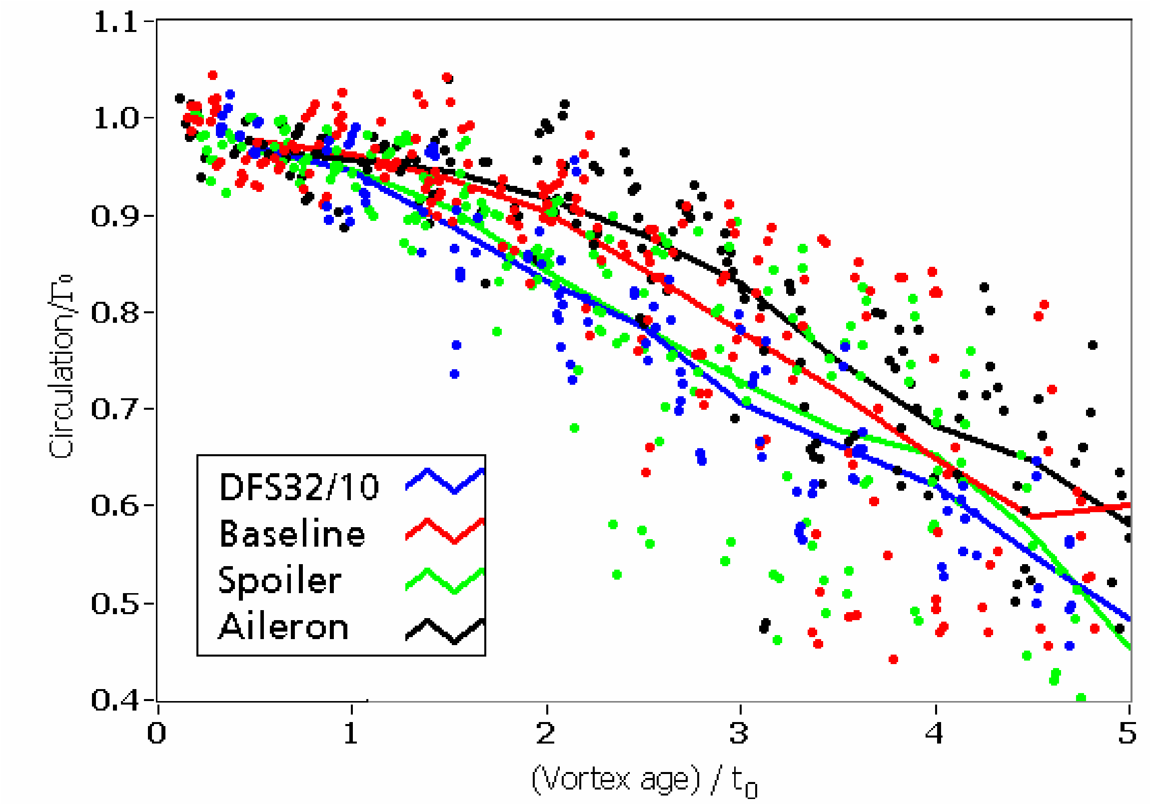

FIG 9. Normalized circulation against vortex age for four different wing configurations. Red colours denote the baseline configuration.

Figure 9 shows the evolution of the circulation strength as a function of vortex age for the four different configurations. Shown are the single data points as well as mean curves derived from all eight single measurements for each configuration. Detailed information about the different configurations can be found in reference [19]. Consideration of the respective meteorological conditions allows to adapt the circulation evolutions to nominal identical atmospheric conditions which in turn enables to identify the most promising aircraft configuration [20].

7. AIRBUS A380 VORTEX MEASUREMENTS

The DLR Doppler lidar system has been used to assess 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 at the airport Blagnac during the normal flight test program 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 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 alternatingly 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 do not work reliably at cruising altitudes, meteorological conditions with persistent contrails had to be searched. Therefore, airborne measurements took place, where the A380 and the heavy reference aircraft were flying during appropriate conditions at cruising altitude in parallel so that the wake vortices could be measured simultaneously 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 is reflected in the present update of the ICAO guidance regarding A380 wake turbulence separations [21].

8. CONCLUSIONS

Doppler lidar is the leading instrument for measuring wake vortices of real aircraft because of its long range and high accuracy. The manuscript describes capabilities of the DLR Doppler lidar focusing on the possibility of fast scanning at different ranges and the usage on different platforms (airborne and ground based) and different measuring geometries.

In particular it demonstrates that:

- The DLR Doppler lidar is an instrument that is able to characterise wake vortices from ground proximity up to the free atmosphere.
- Wake vortex transport can be monitored within the critical height range of up to 100m of the final approach to an airport. Thus, lidar is well suited to monitor wake

vortex predictions of a wake vortex advisory system that aims to increase the capacity of congested airports.
- Lidar is capable to estimate the effects of modifications at the aircraft wings provided that the impact of ambient conditions on vortex decay can be neglected or considered appropriately.
- Very detailed investigations of wake vortices of single aircraft (A380) are possible with DLR Doppler lidar. Air traffic control can benefit due to the categorization of typical circulation strengths for different aircraft types.

In future it is intended to automate the lidar and the processing of the wake vortex algorithm to receive the locations and circulation strengths of wake vortices close to real time.

ACKNOWLEDGEMENTS

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REFERENCES

[1] Marshall, R.E., and Myers, T.J., 1996: Wingtip generated wake vortices as radar target, *Aerospace and Electronic Systems Magazine*, *IEEE*, Volume 11, Issue 12, Page(s):27 – 30, doi10.1109/62.544796.

[2] Köpp, F., Schwiesow, R.L., and Werner, C., 1984: Remote Measurements of Boundary-Layer Wind Profiles Using a CW Doppler Lidar. J. Appl. Meteor., 23, 148–154.

[3] Hannon, S. M., and Thomson, J. A., 1994: Aircraft Wake Vortex Detection and Measurement with Pulsed Solid-State Coherent Laser Radar, *Journal of Modern Optics,* Vol. 41, pp. 2175-2196.

[4] Köpp, F., 1994: Doppler Lidar Investigation of Wake Vortex Transport Between Closely Spaced Runways, *AIAA Journal,* Vol. 32. , pp. 805-810.

[5] Constant, G., Foord, R., Forrester, P. A., and Vaughan, J. M., 1994: Coherent Laser Radar and the Problem of Aircraft Wake Vortices, *Journal of Modern Optics,* Vol. 41, 2153-2173.

[6] Harris, M., Vaughan, J. M., Huenecke, K., and Huenecke, C., 2000: Aircraft Wake Vortices: a Comparison of Wind-Tunnel Data with Field-Trial Measurements by Laser Radar, *Aerospace Science and Technology,* Vol. 4, pp. 363-370.

[7] Harris, M., Young, R. I., Köpp, F., Dolfi, A., and Cariou, J.-P., 2002: Wake Vortex Detection and Monitoring, *Aerospace Science and Technology,* Vol. 6, pp. 325-331.

[8] Köpp, F., Smalikho, I., Rahm, S., Dolfi, A., Cariou, J.-P., Harris, M., Young, R. I., Weekes, K., and Gordon, N., 2003: Characterisation of Aircraft Wake Vortices by Multiple-Lidar Triangulation, *AIAA Journal,* Vol. 41, pp. 1081-1088.

[9] Köpp, F., 1999: Wake-Vortex Characteristics of Military-Type Aircraft Measured at Airport Oberpfaffenhofen Using the DLR Laser Doppler Anemometer, *Aerospace Science and Technology,* Vol. 3, pp. 191-199. *Oceanic Technology*, Vol. 21, 2004, pp 194-206.

[10] Rahm, S., Smalikho, I., Köpp, F., 2007: Characterization of Aircraft Wake Vortices by Airborne Coherent Doppler Lidar, *Journal of Aircraft,* Vol. 44 (be published soon).

[11] Köpp, F., Rahm, S., and Smalikho, I., 2004: Characterization of Aircraft Wake Vortices by 2-μm Pulsed Doppler Lidar, *Journal of Atmospheric and Oceanic Technology*, Vol. 21, pp 194-206.
[12] Holzäpfel, F., Gerz, T., Köpp, F., Stumpf, E., Harris, M., Young, R. I., and Dolfi, A., 2003: Strategies for Circulation Evaluation of Aircraft Wake Vortices Measured by Lidar, *Journal of Atmospheric and Oceanic Technology,* Vol. 20, pp. 1183-1195.
[13] Gerz T., Holzäpfel F., Bryant W., Köpp F., Frech M., Tafferner A. and Winckelmans G., 2005: Research towards a wake-vortex advisory system for optimal aircraft spacing, *Comptes Rendus Physique*, Académie des Sciences, Paris, 6, No. 4-5, 501-523.
[14] Holzäpfel, F., Gerz, T., Frech, M., Tafferner, A., Köpp, F., Smalikho, I., Rahm, S., Hahn, K.-U. Schwarz, C., 2007: The Wake Vortex Prediction and Monitoring System WSVBS – Part I: Design, CEAS-2007-Proceedings, Berlin.
[15] Gerz, T. ,Holzäpfel, F., Gerling, W., Scharnweber, A., Frech, M., Wiegele, A., Kober, K., Dengler, K., Rahm, S., 2007: The Wake Vortex Prediction and Monitoring System WSVBS – Part II: Performance and ATC integration at Frankfurt airport, CEAS-2007-Proceedings, Berlin.
[16] Holzäpfel F., 2003: A Probabilistic Two-Phase Wake Vortex Decay and Transport Model, Journal of Aircraft, Vol. 40, No. 2, pp. 323-331.
[17] Critchley, J., Foot, P., 1991: UK CAA Wake Vortex Database: Analysis of Incidents Reported Between 1982 and 1990, Civil Aviation Authority, CAA Paper 91.
[18] Holzäpfel, F., Steen, M., 2007: Aircraft Wake-Vortex Evaluation in Ground Proximity: Analysis and Parameterization, *AIAA Journal*, Vol. 45, pp. 218-227.
[19] de Bruin, A. C., Schrauf G., 2007: Wake vortex results from the AWIATOR project, CEAS-2007-Proceedings, Berlin.
[20] Leweke, T., Le Dizès, S., 2007: Analysis of F/T-1 and F/T-2 LIDAR measurements and smoke visualisations, AWIATOR Technical Report.
[21] ICAO, 2006: Guidance On A380-800 Wake Vortex Aspects, http://www.icao.int/icao/en/ro/apac/2006/RASMAG6/ip02.pdf