Next Generation Scanning LIDAR Systems for Optimizing Wake Turbulence Separation Minima

Ludovic Thobois*  Jean-Pierre Cariou
(LEOSPHERE, Orsay, France)

Abstract: Numerous studies have been performed to better understand the behavior of wake vortices with regards to aircraft characteristics and weather conditions over the past ten years. These studies have led to the development of the aircraft RECATegorization (RECAT) programs in Europe and in USA. Its phase one focused on redefining distance separation matrix with six static aircraft wake turbulence categories instead of three with the current International Civil Aviation Organization (ICAO) regulations. In Europe, the RECAT-EU regulation is now entering under operational implementation at several key airports. As proven by several research projects in the past, Light Detection And Ranging (LIDAR) sensors are considered as the ground truth wake vortex measurements for assessing the safety impact of a new wake turbulence regulation at an airport in quantifying the risks given the local specificities. LIDAR’s can also be used to perform risk monitoring after the implementation. In this paper, the principle to measure wake vortices with scanning coherent Doppler LIDARs is described as well as its dedicated post-processing. Finally the use of WINDCUBELIDAR based solution for supporting the implementation of new wake turbulence regulation is described along with satisfying results that have permitted the monitoring of the wake vortex encounter risk after the implementation of a new wake turbulence regulation.

Key words: Wake turbulence; Wake vortices; Light Detection And Ranging (LIDAR); Algorithm; Circulation; Data collection; Safety case; Risk monitoring

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I Introduction

Today, wake turbulence hazard is a major concern for the air traffic management. ATM has to face to a continuous and significant air traffic growth and specific air traffic management of heavy and super heavy aircrafts, while at the same time reducing its costs and improving the safety. One worldwide emerging solution is to improve the runway throughput by modernizing current conservative International Civil Aviation Organization (ICAO) regulations on aircraft distance separations established sixty years ago.

For ten years, many research Light Detection And Ranging (LIDAR) systems have been used for better understanding wake vortices behaviors within large range of wind and turbulence conditions. All these studies1–3 helped to design new concepts of wake separations between aircrafts thanks to the proven capabilities of LIDAR systems to assess the risks of wake vortex encounters through the circulation retrievals. The recategorization project, called RECAT, has been launched by a joint initiative EUROCONTROL – FAA in order to renew and optimize the out-of-date currently applied ICAOCONTROL – FAA in order to renew and optimize the out-of-date currently applied ICAO regulations on distance separation. The RECAT Phase 1 consists in defining a new distance separation matrix composed of six static aircraft categories instead of three for the current ICAO-PANS wake turbulence scheme. A European version, RECAT-EU has been developed by EUROCONTROL4. The impact on the risk of wake vortex encounters is

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*Communication author: Ludovic Thobois.
E-mail: ludovic.thobois@free.fr.
evaluated by a severity metric based on the rolling moment induced on the following aircraft by the circulation (strength) of the wake vortices generated by the leading aircraft. Extensive studies of wake vortex behaviors have been performed through the realization of numerous wake vortex data collections and simulations. The wake vortex data collections were realized with scanning coherent Doppler LIDARs at several airports including London Heathrow airport and Paris-Charles de Gaulle airport and representing more than 200000 wake vortex tracks. The data analysis focused on the wake vortex behaviors in reasonable worst case conditions defined as the longest tracks (lasting 5 adimensional time) and in ground proximity (at one wingspan of altitude). These conditions allow to evaluate the risk where and when it matters following the results of statistical studies analyzing the risk of wake vortex encounters. When combining wake vortex data and air traffic data, a statistical dimensionless decay model of the wake vortex circulation in reasonable worst case conditions for each aircraft has been developed. Recent studies showed that this model in such conditions fits relatively well for several wake vortex database collected at different airports. Based on all these studies, the safety case of RECAT-EU has been realized and presented to the European Aviation Safety Agency (EASA) which validated it as a basis to update current ICAO wake turbulence scheme.

The gains in airport capacities brought by the RECAT-EU scheme have been demonstrated at pioneer airports and have been simulated for many other airports. Basically for European busiest airports with a significant ratio of heavies’s air traffic, the gains should reach between 2 and 5%. In Europe, deployments of these new wake turbulence regulations on more than fifteen airports are scheduled until 2025 according to the Pilot Common Project (PCP) regulation framework [REG (EU) No 716/2014]. In addition, other static or dynamic concepts like Time-Based Separation have also been developed. TBShas been deployed at London Heathrow airport in 2015 and will be deployed within 2025 on numerous European airports.

For the implementations of wake turbulence regulations, the use of scanning coherent Doppler LIDARs is required since it is the only one proven sensor able to provide the ground truth wake vortex data. Even if LIDAR can measure only under clear air conditions, it has been shown that wake vortex behaviors are the same whatever the weather conditions are LIDAR-friendly or non-LIDAR-friendly. If several years ago, wake turbulence programs were considered to be at research stages, they are now entering into operational phases with extensive deployments at airports. This requires using more reliable and cost-effective LIDAR sensors. Today, new Light Detection and Ranging LIDAR technique, more precisely the coherent Doppler LIDAR technology based on fiber lasers, has been developed and industrialized. This technology is based on the same principle of measurements than the old technology based on solid state or gas lasers. Fiber based LIDAR sensors have already been validated to provide accurate wind measurements for operational purposes especially in the wind energy where they are becoming standard sensors. They have also been used for monitoring wake vortices in the framework of applied research projects and first step of operational projects.

This paper will propose a methodology to use scanning coherent Doppler LIDAR sensors for providing relevant characterization of the wake vortices in terms of detection, localization and circulation in the scope of the implementation of new wake turbulence regulation. A robust and accurate wake vortex algorithm in adequation with the targeted operational uses will be described. Its preliminary evaluation on limited datasets will be presented. Finally, this solution has been deployed at Paris-Charles de Gaulle airport. Preliminary analysis of first data collected at this airport will be presented and discussed.

2 Principle of Wake Vortex Measurements with Doppler LIDars

For the deployment of a new wake turbulence regulation, the scanning coherent Doppler
LIDAR provides the characterization of the wake vortices in terms of detection, localization and circulation. The fiber based coherent Doppler LIDAR technology allows to adapt easily the parameters of the configuration like the spatial and temporal resolutions and the scanning patterns in order to monitor the wake vortices in an optimal way. Besides, the compactness of such LIDAR sensors allows to install them quickly at an airport on multiple runways, at different altitudes and during takeoff or landing following the requirements defined in the safety assessment. In addition, the blind zone with such a LIDAR is much lower which allows to have more flexibility in the LIDAR position. Fig. 1 shows the typical setup of a fiber based scanning LIDAR for measuring wake vortices to a runway. The LIDAR scans vertically (Range Height Indicator-RHI scans) and perpendicularly to the runway. This allows to measure directly the velocities induced by the wake vortices which are oriented in the same plan. This ensures the LIDAR to measure accurately the wake vortex circulation (strength).

The location of the LIDAR along the runway direction will be defined for collecting relevant wake vortex data at one wingspan of altitude where the Wake Vortex Encounter (WVE) risk is the highest of the wake vortices (one wingspan). The distance from the LIDAR to the runway will be mainly constrained by the area of interest for monitoring wake vortices and by the LIDAR specifications. For RECAT-EU, as the safety assessment is based on the longest tracks corresponding to the reasonable worst case conditions, the wake vortices that must be monitored are the ones that remain relatively close to the runway during their lifetime. This area of monitoring can be set to a length of 500 m corresponding to 250 m for each side of the runway. Vertically, the same reason implies given the distance of the area of interest from the LIDAR to fix an appropriate swept angle which allows to follow wake vortices rebounds occurring at the shortest distance. The minimum elevation angle should be as close as possible to 0° in order to monitor the wake vortices descent at the lowest altitude, theoretically around half of initial wake vortex span \(b_0\). The main constraining LIDAR specifications are the length of the blind zone (typically 80 m for fiber based coherent LIDARs) and the maximum distance at which accurate wind and wake vortices measurements can be performed. This parameter depends on the specified spatial resolution. For a resolution of 5 m, the maximum distance will reach 900 m where as for a resolution of 10 m, the maximum distance can reach up to 1.5 km.

Besides, basic measurement constraints are linked to the typical characteristic scales of the phenomena of interest. For localizing wake vortices with an error smaller than 10 m the cores of the wake vortices, the spatial resolution of the LIDAR should be 5 m at least. For retrieving accurately their circulation, at least one point in each core is required. This leads to a constraint on vertical resolution of 2 m and allows to get about 10 points of wind measurements along one WV diameter (20 m typical). This allows to “resolve” the wake vortex velocity profile. Given their typical duration, a sufficient update rate must also be used (0.1 Hz at the minimum or 10 s) in order to monitor the circulation decay. Given all these constraints, the scanning scenario of a scanning coherent Doppler LIDAR for providing wake vortex data can be determined.

Following the defined scanning scenario, different levels of data will be collected by the LIDAR sensor: the raw data which are the spectra data representing all the Doppler frequencies or velocities acquired in one probing volume of each line of sight, the radial wind data which correspond to the averaged velocity determined for each
probing volume of each line of sight and the wake vortex data which correspond to the presence, the localization and the circulation of wake vortices per scan. Radial data provided by coherent Doppler LIDARs with short pulses, i.e. high range resolution can well represent the velocities profiles of wake vortices.

Among all the different types of existing wake vortex algorithms\cite{10,14–16} in this study, an algorithm based on the optimization of a fit of a wake vortex analytical model on radial wind speeds\cite{11} has been chosen for this accuracy and robustness. This algorithm consists in three main parts:

- Detection of vortices: on every RHI scan, the algorithm detects the presence or not of wake vortices given a threshold on radial speed dispersions.

- Localization of vortices: in case presence of vortices is notified, the algorithm will intend to localize the core of the vortices in a Cartesian grid. The localization uses advanced image processing technics as well as a tracking window to narrow the search area applied on the maps of radial wind speeds. The localization of each wake vortex of one pair is performed independently. The initial tracking window is based on the distance from the LIDAR position to the middle of the runway and for subsequent time steps the two windows are moved independently based on the average crosswinds measured by the Lidar. The accuracy of the localization depends on the resolution of the data at any given location, while the precision depends on the turbulence present in the atmosphere. Hence, higher the amount of turbulence, lower the precision of the algorithm. A history of one wake vortex track is saved to filter out unexpected behavior in the data.

- Circulation of vortices: The circulation / strength is then determined for the two wake vortices by using a least square iterative approach for fitting a Hallock-Burnham wake vortex analytical model on the radial wind speeds near the core location\cite{11}. This approach has been tweaked to be able to calculate vortex circulation strengths even for one single vortex, mostly at the edge of the RHI scan. The sensitivity of the circulation strength depends on the accuracy of the localization of the vortex cores. Based on sensitivity analysis, it was observed that an accuracy of at least 5 m, is necessary for accurate circulation strengths.

For all these steps, the algorithm estimates the cross wind vertical profile for each scan in order to remove it from the radial wind speeds and to keep only the wind speeds induced by the wake vortices.

3 Wake Vortex Data Collection at Paris-Charles de Gaulle Airport

Paris-Charles de Gaulle airport is the second biggest airport in Europe and the ninth worldwide with 66 million of passengers in 2015. Due to the significant increase of air traffic, the airport needs to increase its capacities and especially the runway throughput of its two pairs. As shown in Fig. 2, a WINDCUBE200S scanning coherent Doppler LIDAR from LEOSPHERE and its wake vortex algorithm are then used to collect wake vortex data. The LIDAR has been installed to measure the wake vortices of the runway 27R used for landings in case of westerly winds (roughly 70% of the wind conditions at the airport).

![Fig. 2 Picture of the WINDCUBE200S LIDAR installation at Paris-Charles de Gaulle airport](C)1994-2020 China Academic Journal Electronic Publishing House. All rights reserved. http://www.cnki.net
performed when the scan is going down in order not to deform the shape of the wake vortex which are usually going down. The measurement points along the beams of the LIDAR are setup in order to have the target vertical and range resolutions in the area of interest defined as 250 m on each side of the runway. As indicated in Fig. 3, as the LIDAR is located at 350 m from the runway center, the wake vortex can be monitored between 100 m to 600 m with the target resolutions. But it is important to mention that the LIDAR acquires data from 60 m to 800 m. This leads to acquire 158 measurement points per line of sight. Given the altitude of the aircrafts (80 m above the ground), the swept angle of the RHI scan has been defined in order to be able to measure wake vortices very close to the LIDAR at 100 m of altitude. It has been fixed to 24°. Following the requirements of 8 s of update rate of wake vortex data, the scanning speed is thus imposed to 3.75°/s taking into account 1 s for the scanning head to come back to the starting position. To reach the vertical resolution of 2 m, an angular resolution of 0.19° must be used that leads to an accumulation time per beam of 50 ms. The WINDCUBE Lidar is configured in the wake vortex mode with specific pulses and analysis windows and with the use of range gate overlapping in order to reach the targetted range resolution of 5 m.

In order to collect, archive and post-process the huge amount of data collected, the LIDAR is directly connected to a wake vortex server that archives all the data collected, post-processes the spectra data into radial data in a first step and into vortex data in a second step. In total, 17 hours of wake vortex measurements are performed per day.

For the first five months of the campaign, 10721 aircrafts landed on the targeted runway when the LIDAR was measuring. In Fig. 4, it shows that a low percentage of aircrafts are missed by the LIDAR collection. Knowing the number of expected wake vortex measurements per day, the uptime ratio of the LIDAR wake vortex collection can be estimated. The global uptime ratio is 90%.

The wake vortex database is then merged with the corresponding aircraft database in order to perform the data analysis given the aircraft type and wake turbulence category.

### 4 Analysis of Wake Vortex Database

During this campaign, the performances of the wake vortex data collection by the WINDCUBE200S LIDAR have been evaluated. Several parameters have been defined:

- Track duration, defined as the maximum time at which the algorithm is able to compute the circulation of wake vortices during the follow-up of one aircraft. No quantitative reference is available for this parameter even if statistical at least 2% of the tracks should be longer than 2 min.
- Hit rate, defined as the probability to detect, localize and compute the circulation of a pair of wake vortices on at least the first scan of a track.
- Vortex span, defined as the initial distance between the two vortices cores (just after the merge of marginal WVs) for one aircraft. The vortex span provided by the LIDAR data will be compared to the theoretical vortex span computed as $\pi/4 \, b$ for all aircrafts.

- Initial circulation, defined as the maximum circulation of the vortices in a wake vortex track. It is compared to the reference initial circulation defined previously.

- Vortex circulation decay, which corresponds to the decrease of the circulation (strength) of WVs versus time during their follow-up. The expectations for this parameter are that the averaged decay for each type of aircraft follows qualitatively the expected trends.

In theory, the evaluation should have been performed for only Heavy and Jumbo aircrafts and only for measurements performed in friendly LIDAR conditions, i.e., an aeronautical visibility above 10 km and no rain (rain rate strictly equal to 0 mm/h). But the analysis presented in this paper has been performed for all aircrafts and for all weather conditions, except the ones for which the LIDAR signal was too weak and thus for which the LIDAR data were not usable (i.e., fog and moderate to heavy rain conditions).

Overall, 7511 wake vortex tracks have been collected by the WINDCUBE200S LIDAR since its installation. Among them, 932 tracks start with an aircraft hit meaning that for the first scan of these tracks the corresponding aircraft was “hitted” by the laser beam. The others (6579) correspond to a first detection. The majority of these tracks (65%) has been obtained for medium aircrafts which is coherent with the aircraft fleets of the airport. 353 tracks correspond to Jumbo aircrafts and 2372 to heavy aircrafts. The database is composed of 31228 scans which corresponds to an averaged track duration of 4 scans, roughly 30s but there are many tracks that last one to two scans especially in case of strong crosswinds. Nevertheless, 756 tracks last more than 2 min (15 scans) which represents 10% of the total tracks and still 39 tracks (representing 0.5%) above 3 min. The details of the track duration are shown in Fig. 5.

Considering all type of aircrafts and all weather conditions, 70.06% of the aircrafts landed on runway 27R have been tracked by the vortex algorithm of the LIDAR. The hit rate corresponding to only the detection of wake vortices is much higher (above 90%). The number can be explained by the difficulty in some adverse weather conditions and for the smallest aircrafts (smallest medium for Paris-Charles de Gaulle airport) to localize and compute the circulation even for the first scan. Nevertheless, this global performance has to be considered as a good performance given the fact that the algorithm has been applied in an automatic way to the entire dataset without any adjustments after the calibration period of one month.

The accuracy of initial vortex spans and initial circulation obtained for Heavy and Jumbo categories are gathered in the Tab. 1 below. The preliminary results are very good according to the fact that the algorithm was launched automatically to the entire dataset and according to the uncertainties on the reference values especially for the initial circulation. Mean errors lower than the spatial resolution of 5 m are obtained. This can be explained by the fact that the localization of the wake vortex cores is performed by image processing which allows to localize wake vortices between two range gates. The correlation graphs for the circulation are shown on Fig. 6 for both Heavy and Jumbo aircrafts.

The analysis of the circulation decays for heavy and jumbo aircrafts have started. Qualitatively, the curves obtained correspond to the expectations to have a decay in two slopes as shown in Fig. 7. Further analysis will be performed to verify that these curves fit the two exponential decay analytical model for each aircraft.
As an example of vortex track, Figs. 8 and 9 represent a pair of wake vortices generated by a Jumbo aircraft the 20th of November in case of low crosswinds. Fig. 8 shows the time evolution of the characteristics of the wake vortices. The trajectories of the cores of this pair show a rebound of the vortices at 40 s after the initiation of the wake vortices. The left vortex is advected by the low crosswinds and is approaching the LIDAR. After its rebound, the right vortex remains above the runway even 2 minutes after. The spatially resolved velocity measurements performed by the scanning LIDAR are presented in Fig. 9. The high resolution of 5 m horizontally and 2 m vertically allow to visualize the wake vortices and the vertical structure of the crosswinds and their evolution in time.

5 Conclusion

Improving the runway throughput becomes a major concern for airport and air navigation authorities given the strong and continuous increase of the worldwide air traffic. Years of research in the field of wake vortices show the possibility to reduce current ICAO-PANS wake turbulence horizontal separation distances between aircrafts by quantifying in-depth the wake vortex encounter risks in order to keep the same level of
safety. The results are the new series of wake turbulence regulations like the RECAT family based on the recategorization of the wake turbulence categories of aircrafts. These studies showed also the capabilities of the new LIDAR sensor technology to provide ground truth wake vortex data to better understand wake vortices behaviors with regards to weather conditions. Moving to operational implementations at many airports, new wake turbulence regulations require modern and cost-effective scanning coherent Doppler LIDARs in order to ease the process of implementation and to quantify the local risk in the framework of the local safety assessment and risk monitoring. This paper describes a generic methodology for using scanning LIDARs in the context of the im-

**Fig. 8** Time evolutions of the positions in X and Z (top left), the vortex span (top right) and of circulations (bottom) of a pair of wake vortices generated by a Jumbo aircraft the 20th November 2015.

**Fig. 9** Maps of radial wind measurements provided by the LIDAR showing the evolution of the pair of wake vortices generated by a Jumbo aircraft the 20th of November at 18:40:58, 18:41:17, 18:41:35, 18:41:54, 18:42:13 and 18:43.
plementation of a new wake turbulence regulation at an airport. It shows how the new fiber based scanning WINDCUBE coherent Doppler LIDARs (with short pulses and short blind zones) can be configured to collect relevant wake vortex data. A wake vortex algorithm based on the estimation of circulation on radial wind data has been developed and presented. Its evaluation on several datasets at several airports and with reference data has been performed and showed that such an algorithm can accurately localize the wake vortices with an error of 5 m and compute their circulation with an averaged error of 20%.

The given WINDCUBE LIDAR-based solution has then been installed at Paris-Charles de Gaulle airport for collecting a huge wake vortex database. The wake vortex data collected over five months have been presented and analyzed. The statistical performances obtained on the localization and the circulation of wake vortices are very good. Finally, the use of such LIDARs for monitoring the risk of wake vortex encounters has been discussed. For the current project, the WINDCUBE LIDAR will continue to provide the ground truth wake vortex measurement swallow to perform the risk monitoring. As a perspective, given the worldwide growing interest to implement optimized wake turbulence regulations, scanning LIDARs must be considered as the ground truth reference and as the chosen tool for supporting the deployments of new regulations at airports from the safety assessment to the risk monitoring stages.

References


Ludovic Thobois received a PhD Thesis from INP Toulouse, France in Fluid dynamics (2006). He studied large eddy simulations of turbulent flows close to surfaces without and with chemistry. He joined in 2011 the advanced research division of LEOSPHERE as the scientific studies manager. He was in charge of developing new post-processing techniques for providing more accurate and relevant observations from LIDAR raw data. He is an active participant of several working groups in Europe in charge of exploring the capabilities of new remote sensors for meteorology and aviation weather applications. He was for example involved in several SESAR workpackages related to the measurements of wake vortex and the detection of wind shear at several airports in Europe including Paris-Charles de Gaulle airport. He is also involved in a COST European action related to the cooperation of European countries in science and technology for the study of remote sensing in future observing networks for weather & climate. He is the author of many articles and presentations in international conferences in the fields of meteorology, aviation weather related conferences. He was also an active participant of the expert groups related to wake turbulence in Europe (WAKENET-EU) and in USA (WAKENET-US).

Jean-Pierre Cariou is Scientific Director at Leosphere and senior scientist in lidar technology. He received an engineer degree in Optics from Institut d’ Optique Graduate School in Orsay in 1981 and a PhD in Astronomy and Spatial Techniques in 1983. At ONERA (French Aerospace Lab), he has been involved in many developments of coherent lidars and laser imagers. During 10 years, he was the head of the Laser and Optoelectronics research group, including 20 scientists. He developed different generations of lidars and participated to studies both in instrumental modeling, source development and instrument design. Since 1995, he has been creating new lidar instruments based on 1.5 μm Erbium doped fiber amplifiers, allowing single mode operation, reliability and cost effectiveness. In 2007, he joined Leosphere as Associate and Technical Director. Since then, Leosphere is developing a family of coherent wind lidars, for wind energy market, meteorology and airport wind hazard monitoring. He is currently heading the Scientific Research & Technologies Department (DRST), including new technologies and signal processing developments, and external cooperation with academic institutions and companies as well. He is author of many articles in the lidar field and tutored 5 PhD theses. Jean-Pierre Cariou has been awarded the 2010 Inventor prize by the Marius Lavet Foundation and the Montgolfier 2013 prize by the SEIN in France.