

# Improving the mitigation of wind hazards in ATM operations with Ground-based Wind Doppler LIDARs

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**Abstract**— Weather is one of the major causes of flight delays and accidents. Among all the weather conditions for aircrafts, wind and wind hazards like wake vortices and wind shears require to be monitored with high spatial and temporal resolution sensors in order to reduce their impact on air traffic for improving safety and / or for optimizing ATM. Among the different available sensor technologies, Doppler LIDAR sensors as remote sensors allow to obtain high spatial (5m to 200m) and temporal (1 Hz to 20 Hz) resolution and accurate wind measurements (typically 0.5m/s). But the use of these sensors remains relatively limited for ATM and few are used for operational purposes in ATM. This paper presents the developments of a new generation of Doppler LIDAR systems for measuring wind and monitoring wind hazards around airports. Their intrinsic performances in terms of measurement range and accuracy are described. Several applications of such LIDAR technology are then presented like wind measurements, wind shears detection and wake vortices monitoring thanks to several experiments performed on airports. As perspectives the paper proposes the potential benefits of using such atmospheric LIDAR sensors for optimizing air traffic like airport capacities and for improving air traffic safety.

**Keywords**-LIDAR, weather, wind, EDR, wake vortices, wind hazards

## I. INTRODUCTION

Air traffic stakeholders will have to face to a doubling of the worldwide air traffic within the next twenty years, while, at the same time, to improve safety, to reduce ATC costs and thus its efficiency. To reach these objectives, atmospheric conditions and especially air flows in the troposphere must be better taken into account since they have a strong impact on air traffic safety and operations. In terms of safety, several studies have shown that the majority of accidents occurred during takeoff and landing, even though representing one tenth of the flight time. Besides, adverse weather like strong winds, wind shears, and turbulence represent one of the major causes of accidents. In Europe, such a study [1] has shown that half of the ANS related accidents were caused by adverse weather from 2010 to 2012. In terms of ATC delays and corresponding costs, several studies [2][3] have evaluated the impact of weather and have shown that 20% and 70% of the delays in Europe and USA were induced by the weather. Beyond the

different adverse weathers, thunderstorms and convective weather, in-flight icing, strong winds and turbulence (low altitude) contribute the most to delays and thus extra costs for ATC. Global projects for ATM modernization have taken into account the necessity to improve the communication of weather information and its use for all ATC stakeholders through Collaborative Decision Making (CDM) and System Wide Information Management (SWIM). Such new systems require more relevant and accurate weather observations, more reliable weather products and more precise weather forecasts. Weather forecasts require more resolved weather forecast models and more observations assimilation. If considerable progress has been made in the development of modernized systems for exchanging weather information and for improving weather models, current observation systems at airports remain the same in their structure as the ones established in 1953 by International Civil Aviation Organization (ICAO) [4] and World Meteorological Organization WMO [5] whereas, during the same time frame, the air traffic has been multiplied by twenty. The air traffic control has to deal with more traffic and more environmental constraints around airports in urban areas while reaching the highest level of safety as possible.

The measurements of representative winds that affect aircrafts are mandatory to support the decisions of air traffic controllers to manage runways given the wind direction, to adapt airport capacities given the intensity of crosswinds, to allow noise reduction procedures given the intensity of tailwinds, etc.... Several studies have demonstrated the lack of representativity of surface winds [6]. Indeed, air traffic management requires wind information not only for taxi along runways, but for takeoff and landing and thus along takeoff path and final approach up to 1000 feet at least. Furthermore, as a standard, Automatic Weather Observing Systems at airports are equipped for measuring the surface wind (speed and direction averaged during 2 or 10 minutes) with anemometers installed at 10m height.

The detection and forecast of wind shears are crucial for safety and efficiency of ATC at airports where this is a concern. In the 60's, low level wind shear alert systems (LLWAS) have been developed in using network of

anemometers around airports, that are able to determine the differences of wind speed and direction at 20m between the anemometers. Still, these systems cover mainly runways not approaches and the wind shears are computed at 20m not along approach and takeoff paths. Doppler Radar sensors have been developed in different bands (C, S, X) for detecting wind shears in the area of interest but due to their measurement principle, only wind shears occurring under rainy conditions can be detected. For ten years, few scanning Doppler LIDAR sensors have been tested at airports to detect low level wind shears in clear air conditions [24] and very few were deployed operationally [23] due mainly to their costs and reliability.

Among all the aspects limiting these capacities, wake turbulence plays a direct and major role due to the current conservative ICAO regulations on distance separations between aircrafts [17]. Indeed, these regulations have been determined forty years ago in order to prevent the danger for a follower aircraft to encounter wake vortices generated by a leader in the extreme worst weather conditions in splitting aircrafts into three wake turbulence categories. LIDARs are the only sensors capable to detect, localize wake vortices and determine their strength (circulation) as shown by many research projects [18][19][20] that demonstrated in the last decade the capabilities to reduce distance separations thanks to research or / and expensive LIDARs. Today, the current ICAO regulation has been improved through the joint US and EU RECAT project in splitting medium and heavy categories into two subcategories lower and upper. This new regulation accepted by EASA will be now implemented on almost twenty airports in Europe in the next decade but these implementations require to collect LIDAR wake vortex data for assessing the safety with the new rules and for monitoring their risks. In addition to static distance separation concepts where distance separations are fixed, dynamic distance separation concepts have been developed like Time-Based Separation (TBS) or are currently under development. The general idea is adjust dynamically distance separations with weather conditions. To do so, winds, crosswinds and eddy dissipation rate (EDR) measurements are needed since these parameters are well known to have an immediate impact on the decay and finally the lifetime of wake vortices [21][22]. In such weather dependent separation concept, accurate and frequent observations are thus needed in specific area of interest for aircrafts like the approach and the takeoff path.

For twenty years, 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 can provide wind measurements for operational purposes [7]. Whereas such LIDAR systems are now widely used in wind energy, this technology remains confidential in aviation weather where only a few LIDARs are used today for wind shears detection [8] and wake vortices measurements [9].

In this paper, the coherent Doppler LIDAR technology based on optical fibers will be described in terms of measurement principle, architecture and data post-processing.

The performances of wind measurements that can be provided by LIDAR wind profilers and scanning LIDARs will be presented (data availability, measurement range, wind accuracy). Their potential applications for wake vortex monitoring and upper wind observations will be discussed through two trials performed at Charles-De-Gaulle airport and Toulouse-Blagnac airport.

## II. COHERENT PULSED DOPPLER LIDARS

For two decades, significant improvements have been performed in Light Detection and Ranging (LIDAR) techniques and especially thanks to the arrival of optical fibers technology. Their low cost and reliable components are widely used in the mainstream telecommunication industry. Thus compact, reliable and accurate atmospheric LIDAR sensors have been developed and industrialized, for example by ONERA, the French aerospace lab and LEOSPHERE Company under the WINDCUBE LIDAR product series.

The basic measurement principle of such pulsed coherent Doppler LIDARs is shown on Figure 1. The laser source emits pulses of light in the atmosphere with a pulsation  $\omega_l$ . The moving particles backscatter light in shifting its frequency. The Doppler shift,  $f_d$  induced is proportional to the particles' radial wind speed  $V_r$  (projection of the wind vector along the laser line of sight). The backscattered light is detected and then processed in order to retrieve the radial wind speed.

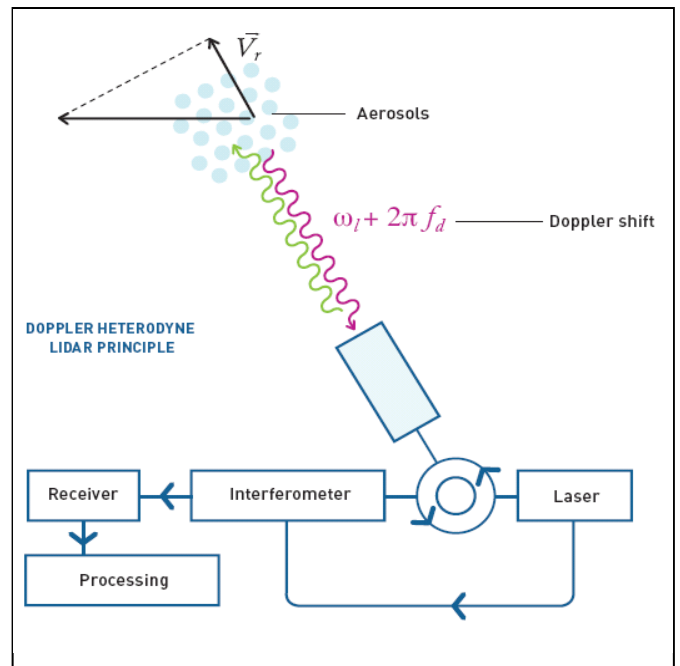


Figure 1. Measurement principle of a Coherent Doppler LIDAR

The fiber technology used in WINDCUBE LIDARs is based on a MOPFA optoelectronic architecture which stands for Master Oscillator Power Fiber Amplifier. The architecture showed in Figure 2 is composed of a continuous laser emitting

in the near-infrared region around  $1.5\mu\text{m}$ . An acousto-optic modulator is used to create laser pulses at the required duration. The pulses are then amplified thanks to a power fiber amplifier EDFA (Erbium Doped Fiber Amplifiers). The emitted and backscattered signals are finally mixed in an interferometer providing a heterodyne beating signal at the Doppler frequency. The use of laser pulses and heterodyne detection allows to reach a high accuracy of wind measurement whatever the distance between the probing volume and the LIDAR and to optimize the detection sensitivity. Flexibility in the MOPFA parameters (energy, PRF, pulse duration) allows to adjust the LIDAR range and resolution according to the measurement requirements [10].

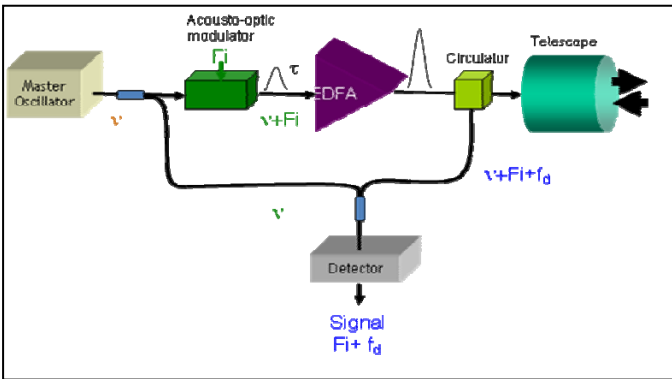


Figure 2. Example of optoelectronic architecture of Pulsed Coherent Doppler LIDARs

The laser wavelength around  $1.5\mu\text{m}$  has been chosen for several reasons: efficient and reliable lasers, good Doppler sensitivity, eye safety, good atmospheric transmission, low power consumption and compactness. Because this technology is based on physics of light propagation, atmospheric conditions have negligible impact on the precision and accuracy of the wind speed retrieval, unlike other remote sensing technologies like sodars.

The measurement is range resolved as the backscattered radiation received at time  $t$  after the emission of the laser pulse has travelled from the LIDAR to the particles at range  $x$  and back to the LIDAR at the speed of light  $c$ . The range gate position is proportional to the time of propagation according to the equation  $x = c.t/2$ . Range resolution is determined by the laser pulse duration and processing parameters, but remains constant along the line of sight allowing for high-resolution measurements. For each laser pulse emitted by the LIDAR system, the signal is divided into time series corresponding to spatial range gates. Spectral analysis is then computed for each range gate, as described on Figure 3. Fourier Transforms are then computed to get the signal spectrum for each range gate. These spectra are then averaged over an accumulation time to improve the estimation of the frequency shift, using a highly accurate Maximum Likelihood Estimator (MLE).

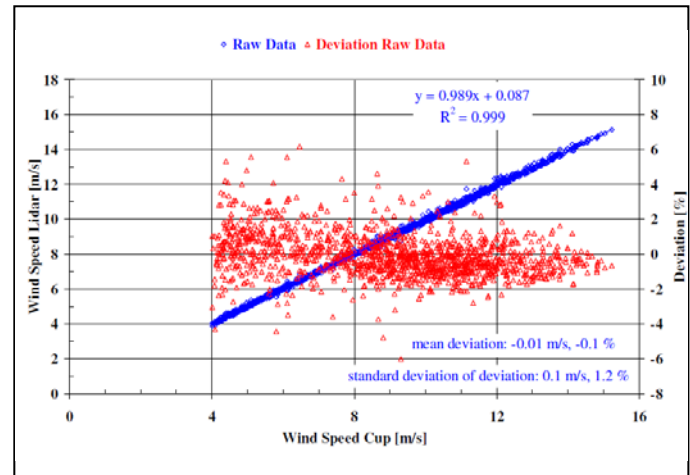
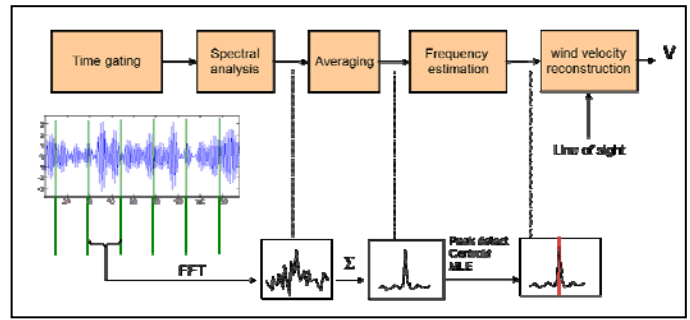


Figure 3. Principle of pulsed heterodyne Doppler wind LIDAR signal processing

Coherent LIDARs measure the radial component of the wind, i.e. the projection of the wind vector along the line of sight (LOS). To provide the different components of the wind vector  $u, v, w$ , the laser beam has to point towards several independent directions and different wind reconstruction techniques can be used [11][12][13][14]. The vertical LIDAR wind profilers embeds usually for example processing algorithms to retrieve the three components, and then the horizontal wind speed ( $V_h$ ) and direction (Dir), based on the Doppler Beam Swinging (DBS) technique. The laser beam successively addresses 5 LOS, one vertical LOS and four tilted LOS pointing North, East, South, West respectively.

### III. MEASUREMENT PERFORMANCES

Performances of new generation Coherent Doppler LIDAR Wind profilers and scanning LIDARs have been assessed during many studies by independent organisms, public research labs, certification companies and private consulting companies. For operational purposes like weather observations for improving the efficiency and safety of air traffic, several parameters must be assessed like the uptime ratio, i.e. the ratio of operational time, the measurement range, i.e. the distance up to which valid wind data are provided, and the accuracy of the wind measurements, i.e. the reliability of the wind data.

### A. LIDAR Wind Profiler

More than 600 Coherent Doppler LIDAR Wind profilers are used worldwide for different purposes but the largest majority for wind energy applications. Such LIDARs allow to measure the wind speed and direction from 40m above ground level to 300m at ten heights (every 25m) and at a frequency of 1 Hz. Usually 10 minutes averaged wind data are used. But 1 Hz wind measurements are provided to retrieve turbulence parameters like turbulence kinetic energy.

For ten years, many studies have been performed over mid to long periods of measurements more than 6 months to determine the performances of such LIDARs and its benefits for the wind energy sector. A one-year study performed on the FINO1 off-shore platform<sup>3</sup> located in the North Sea in Europe shows that LIDAR Wind profilers can have an uptime ratio above 96% and data availability up to 200m of 92%. It is important to highlight that the data availability at a given range will vary from a site to another and with weather conditions. LIDAR range performances are affected by foggy conditions (visibility lower than 1km) and heavy rains (rain rate above 4mm per hour). Finally, the accuracy of wind speed and direction has been extensively assessed at reference test sites and by independent industrial and research institutes. Statistical analyses against calibrated cup anemometers have been derived. One example is shown on Figure 4. For the first study performed by a certification company [15], the mean difference and standard deviation for wind speed at 135m are 0.03m/s and 0.24m/s. Given all the studies performed, the specified accuracy for wind speed is 0.1m/s and for wind direction 1°.

Figure 4. Example of statistical analyses of the WINDCUBE v2 measurements against calibrated cup anemometers[15].

All the studies performed during the last ten years have demonstrated the high reliability, availability and accuracy of wind measurements with LIDAR wind profilers like the WINDCUBE7v2 against traditional met mast anemometers. Thanks to these studies, the LIDAR is widely accepted within the wind energy industry as a wind sensor capable of replacing met masts. It allows wind measurements with the same quality as met mast and at higher heights while 40m height met masts don't measure the relevant wind for the 80 – 100m wind turbines. In addition, IEC61400 standards have recently evolved in order to integrate LIDAR instruments for the testing of wind turbine power curve and thus have validated it as an operational tool [16].

### B. Scanning LIDARs

The WINDCUBE scanning LIDARs provide high resolution wind measurements of the atmosphere in 3D around the LIDAR. Their configuration in terms of spatial and temporal resolution and scanning patterns can be adjusted according to the needs. Spatial resolution can be adapted from 5m (with range gate overlapping) to 200m. Temporal resolution can be adapted from 0.05s to 10s. Different scanning patterns can be used such as Plan Position Indicator (PPI), an azimuth scan at

a constant elevation angle, Range Height Indicator (RHI), a vertical (elevation) scan at a constant azimuth, stairing Lines of Sight (LOS) and Doppler Beam Swinging (DBS). The scanning speed can be configured from 0.1°/s to 18°/s. Radial wind speeds can be measured up to 13km with a resolution of 200m and an accumulation time of 1s for the WINDCUBE400S scanning LIDAR for example.

Such a LIDAR has been deployed in the South of Paris, Palaiseau, France during 6 months. The results show an uptime ratio of 94% of the radial wind speed measurements. The performances in terms of measurement range have been assessed. When considering all weather conditions, a measurement range of 8km is obtained 80% of the time and 10km half of the time. As any other atmospheric sensor like radar and since LIDAR signal comes from the backscatter of atmospheric aerosols/particles, LIDAR data availability depends on atmospheric conditions. LIDAR measurements capacities will be nominal under clear air conditions. In case of fog, ie. visibility below 1km, the range will be lower since the atmospheric extinction is higher and thus the intensity of the backscattered LIDAR signal will be reduced quicker with distance. In case of rain, the water droplets will induce an additional atmospheric extinction to the aerosols and thus will also induce a reduction of range. Clear air conditions are defined in [4] and consist in:

- A visibility higher than 10km.
- No rain: Rainfall is 0 mm.
- No cloud.

The measurement range of a LIDAR should be determined for these clear air conditions or less restrictive conditions when considering clouds above the altitude of measurement. This filtering may take into account the Planetary Boundary Layer (PBL) height (usually between 1 to 2 km) in keeping the conditions where PBL height is above the altitude of measurements of the LIDAR beam. Following these definitions, the filtered ranges obtained for the same period are 9km at 80% and 11.5km half of the time. It is higher than the unfiltered range computed under all weather conditions even the non-friendly LIDAR conditions.

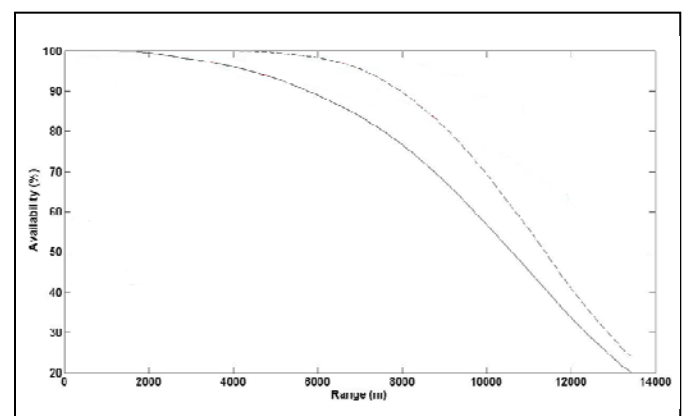


Figure 5. Unfiltered (line) and filtered (dash line) statistical ranges obtained for two months (right).

#### IV. APPLICATIONS OF COHERENT DOPPLER LIDARS FOR AIR TRAFFIC MANAGEMENT

The accuracy of scanning LIDARs wind measurements has been assessed during a campaign conducted along with Denmark Technical University (DTU) during summer of 2013 in comparison to a certified met mast. First, the accuracy of the radial wind speed was performed and compared with the wind speed projected on the LIDAR beam (see Figure 6). The mean difference on radial wind speed measurements between the LIDAR and the anemometer was 0.09m/s and the standard deviation was 0.2m/s.

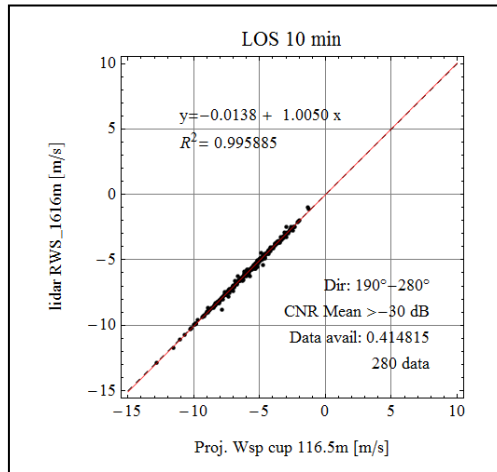


Figure 6. 10 minute radial velocity comparison with tower measurements projected on the line of sight

A PPI scan pattern of 45° is used to provide radial wind speed measurements that are post-processed to retrieve the two horizontal components of the wind [13]. The mean difference for horizontal wind speed between the scanning LIDAR and the met mast at 116m above ground level is 0.36m/s with a standard deviation of 0.56m/s.

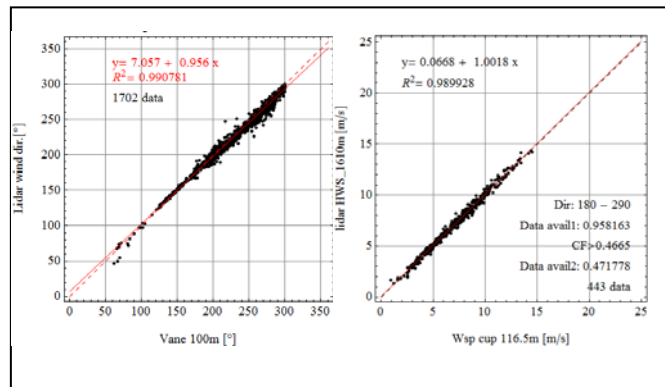


Figure 7. Ten minute averaged wind direction (left) and wind speed (right) compared to a standard IEC met mast at DTU.

The studies performed show that the wind speed measurements from scanning Doppler LIDAR are reliable and maintain as good accuracy traditional measurements.

##### A. Upper Wind measurements at airports

Currently, in ICAO standards [4] wind information at airports consist in surface wind measured by cup anemometers at 10 to 20m above ground level.

A WINDCUBE7v2 LIDAR wind profiler has been installed at Toulouse airport from April to June 2014 in the framework of the UFO European FP7 project to provide vertical profiles of averaged wind speed and direction and also turbulence. The Figures 11 and 12 show respectively the evolutions from April to May 2014 of the wind speed and wind direction at 40m (red) and 200m (blue) for the LIDAR in comparison to the AWOS wind data. The general trends agree between the surface wind and the winds at 40m. Strong differences can be observed for wind speeds at 200m with a systematic bias. For the wind direction, the bias is slower but there are many cases where the differences between the surface wind direction and the wind direction at 200m can reach 180°.

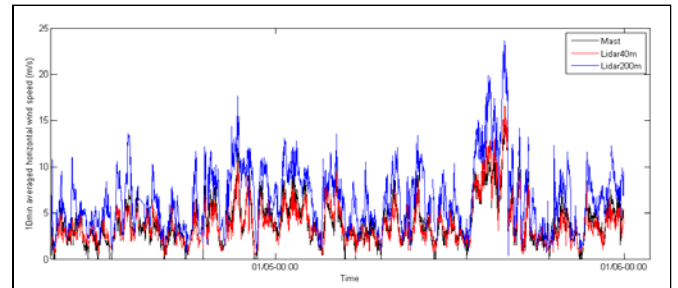


Figure 8: Time series of wind speed measurements of the LIDAR at 40m (red) and 200m (blue) and AWOS wind speed (black) during April and May 2014 at Toulouse airport

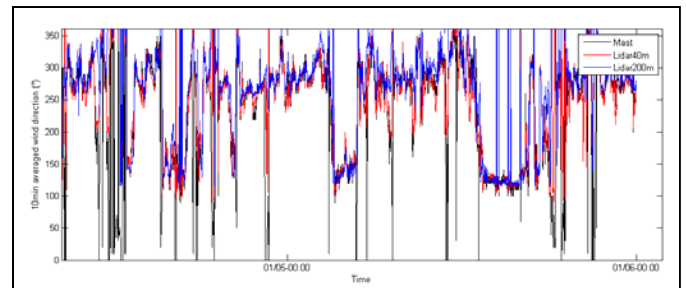


Figure 9: Time series of wind direction measurements of the LIDAR at 40m (red) and 200m (blue) and AWOS wind speed (black) during April and May 2014 at Toulouse airport

The differences between the upper winds and the surface wind are computed for each altitude available from 40m to 200m every 20m in terms of mean difference and standard deviation for the wind speed and wind direction. Figure 10 shows the results for the wind speed. A difference of 1 m/s maximum can be observed between the surface wind and the wind at 40m, 60m and 80m. This difference increases with altitude and can reach up to 2.5m/s at 200m. The standard

deviation between surface and upper winds is also increasing with altitude. The minimum standard deviation at the lowest altitude is 2 m/s.

As for the wind speed, the global comparison for the wind direction reveals the same logarithmic trends with errors up to 180°. Even if averaged errors of surface winds can be relatively small, its dispersions are much higher compared to upper winds. In addition, for managing air traffic at a given airport, wind conditions in real time are the most important since many decisions of ATM will be linked to local and real time observations of wind speeds and wind directions. The benefits of such advanced upper wind observations will be to optimize the runway management, i.e. to decide to change runway direction when needed not only when surface wind direction is changing but when upper wind direction also changes. For airports in urban areas, local procedures, involving tailwind landings for reducing noise emissions, are discussed but rarely put in operations due to the uncertainty on surface winds, which are not representative of upper winds in such complex terrain.

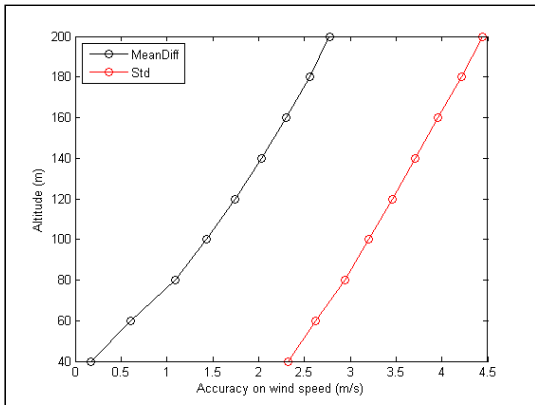


Figure 10: Mean difference (black) and standard deviation (red) of wind speed measured by the surface anemometer with the altitude of the LIDAR measurements from 40 to 200m

### B. Wake turbulence applications

As explained previously, airport capacities are mainly limited by aircraft distance separations imposed to avoid wake vortex encounters.

Leader / Follower	A380-800	HEAVY	MEDIUM	LIGHT
A380-800		6 NM	7 NM	8 NM
HEAVY MTOM ≥ 136 tons		4 NM	5 NM	6 NM
MEDIUM 7 tons ≤ MTOM < 136 tons				5 NM
LIGHT MTOM < 7 tons				

RECAT-EU scheme	"Super Heavy"	"Upper Heavy"	"Lower Heavy"	"Upper Medium"	"Lower Medium"	"Light"
Leader / Follower	"A"	"B"	"C"	"D"	"E"	"F"
"Super Heavy"	3 NM	4 NM	5 NM	5 NM	6 NM	8 NM
"Upper Heavy"		3 NM	4 NM	4 NM	5 NM	7 NM
"Lower Heavy"		(*)	3 NM	3 NM	4 NM	6 NM
"Upper Medium"						5 NM
"Lower Medium"						4 NM
"Light"						3 NM

Figure 11: Current applied ICAO regulations [17] (top) and new RECAT-EU regulations [25] (bottom) for horizontal distance separations given wake turbulence categories of follower and leader aircrafts

Thanks to in-depth statistical analyses of hundreds of thousands of wake vortex LIDAR data, the new RECAT-EU regulation has been developed. This regulation allowed to decrease for some aircraft categories the horizontal distance separations compared to current ICAO regulation (see Figure 11) and thus allowed to increase the number of slots per hour for airports. Many European airports will deploy this kind of new regulation to improve their traffic while a high level of safety. For implementing such a new regulation at a given airport, performing a safety assessment based on LIDAR wake vortex data permits to determine quantitatively the risk of wake vortex encounters at the targeted airport relatively with the current risk with the current distance separations regulation. Such a safety assessment allows taking into account all the local specificities. Many airports have for example specific air traffic rules that could require to be adapted with the implementation of the future regulation. Besides, local wind and turbulence conditions can lead to different statistics of local behaviors of wake vortices and thus a different risk of wake vortex encounters. After the implementation, a risk monitoring can be performed to verify and understand the potential events of wake vortex encounters. In addition, weather dependent separation rules, which are currently under development, require to have more wind and turbulence observations for optimizing distance separations with real time and local atmospheric conditions. A margin will be added to the minimum distance separations in taking into account the uncertainty of atmospheric information.

In this context, new generation of scanning Doppler LIDARs have been evaluated in the framework of the SESAR work package 12.2.2 led by Thales Air Systems and in partnership with ONERA the French aerospace agency. In the project, the goal was to study the behaviors of wake vortices with wind conditions and then to develop a wake vortex advisory system capable of adjusting in real time distance separations between aircrafts in taking into account weather conditions.

For this project, a WINDCUBE200S LIDAR was deployed at Paris-Charles-De-Gaulle (CDG) airport for two experiments in

2011 and 2012. The LIDAR has been configured to monitor the two contra-rotated wake vortices in a perpendicular plane to the runways. A radial resolution of 5m has been used in order to be able to measure the structures of the wake vortices and up to a distance of 800m. Measurement scans were performed every 7 seconds to ensure the proper monitoring of the evolution of the wake vortices. As an illustration of the LIDAR measurements, the figure below shows two examples of maps of radial wind speeds on which wake vortices can be observed for two different aircrafts and for two different setups.

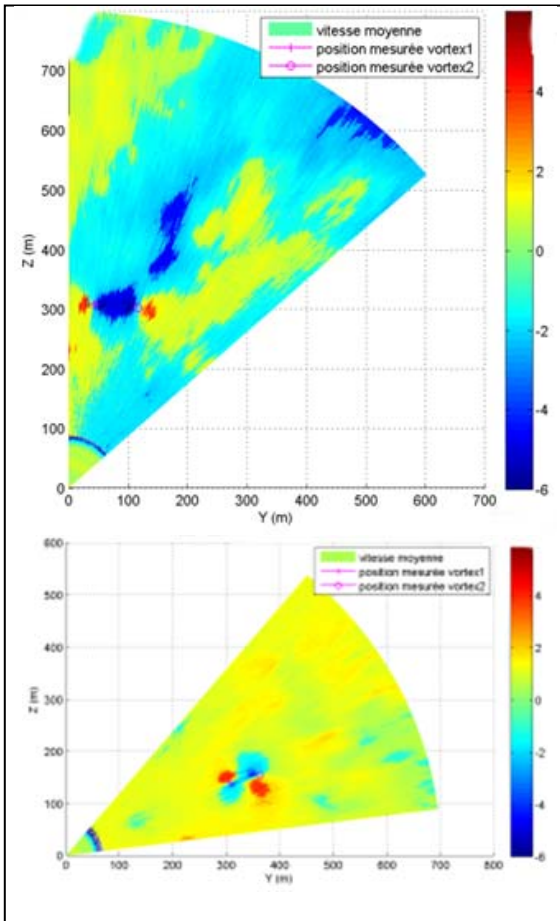


Figure 12: Examples of wake vortex measurements of a WINDCUBE200S for a landing aircraft below the glide path (top) and a takeoff when looking aside (bottom) for the SESAR XP1 trial at Paris-CDG airport

The radial wind data provided the LIDAR are then post-processed by an algorithm that will retrieve wake vortex characteristics such the localization of the cores and the circulation (strength) of each vortex. The obtained accuracy for the localization of the wake vortices is 5m analyzed and shown by Figure 13. The initial circulation retrieved by the vortex algorithm is compared to the theoretical circulation computed thanks to aircraft data (type of aircraft, wingspan, airspeed, estimated weight). The LIDAR with the vortex algorithm was able to retrieve the initial circulation with an error of 20% which is a satisfying result compared to the state of the art.

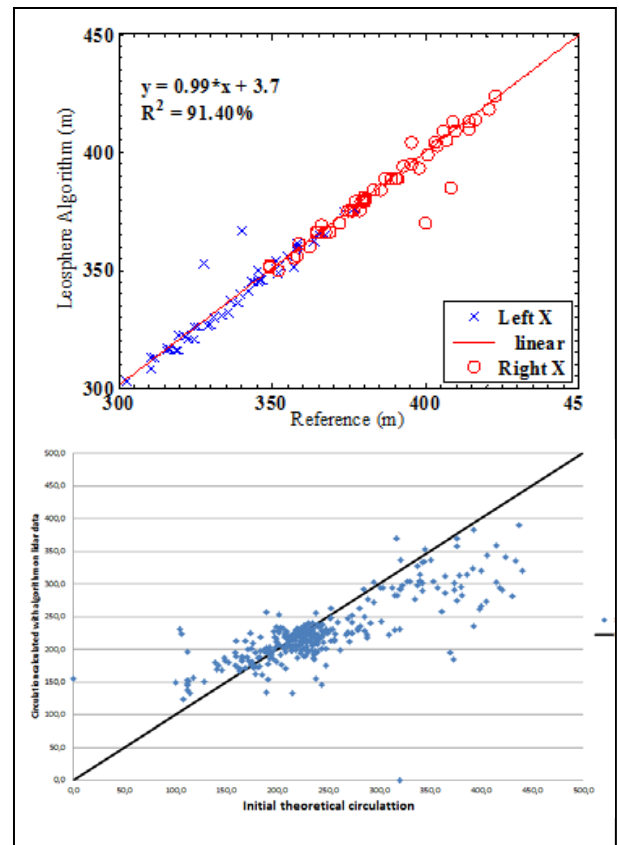


Figure 13: Correlation graphs comparing the localization of wake vortex cores (top) and their initial circulation (bottom) with reference values for the SESAR XP1 trial at Paris-CDG airport

Once the outputs of the LIDAR have been validated, the LIDAR has been used for better understanding the influence of wind on wake vortices transport. In the example below, the turbulence was relatively high in this case and thus the decay of the circulation (strength) was relatively high since the circulation of wake vortices have been decreased of 30% within one minute. The red line indicates the theoretical value of the circulation for the given aircraft. As expected, the circulation is increasing in a first phase where the two wake vortices are generated after the merge of all margin wake vortices. In a second phase, the circulation is decreasing. In addition, due to the crosswind, the two wake vortices have been transported out of the runway (located at 400m from the LIDAR) within a minute. In this case, due to the specific weather conditions, the distance separation might have been reduced. Nevertheless, developing new regulations on wake turbulence require hundreds of thousands of wake vortices tracks, ie. a database representing a sufficient sampling of all aircraft types and all weather conditions. The LIDAR sensor is then able to support the design of new regulations and conditions of implementation. In more operational projects, LIDARs can be used for supporting the safety cases and for

assessing the risks when implementing a new regulation related to wake turbulence on an airport.

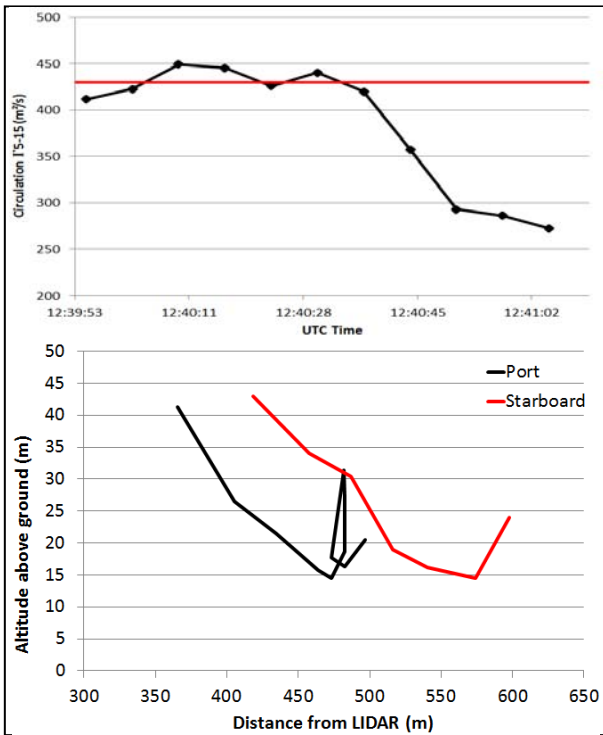


Figure 13. Example of decay of circulation of two wake vortices induced by a heavy aircraft (top) and their trajectories (bottom)

For weather dependent separations, the reduction of separations to be applied on static separations depends on the uncertainty of atmospheric information like headwind in a concept like Time-Based Separation. The more the uncertainty of the wind information is, the less the separations could be reduced since a margin will be set up. Thus the increase of airport capacities, ie. the return on investment, will depend directly on the wind accuracy.

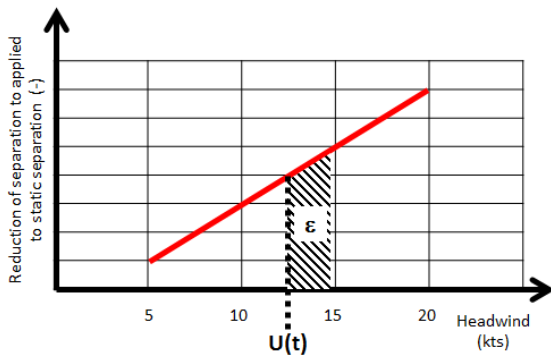


Figure 14. Scheme of the impact of uncertainty on headwind measurements

As shown in this paper, as the accuracy of LIDAR wind measurements is very high, the highest benefits of weather dependent separations should be obtained with LIDAR sensors. In addition, even if LIDAR measurements will be mainly available under clear air conditions, these atmospheric conditions correspond to the conditions during which separations can be optimized. For example, in low visibility conditions (like fog or haze), runway throughputs are not limited by wake turbulence.

## V. CONCLUSIONS

Sustainable growth of air traffic requires to better take into account weather information into ATM. If significant programs have been launched worldwide for modernizing air traffic management, new opportunities are emerging to improve ground-based observations systems thanks to the arrival of new LIDAR technologies based on coherent detection and fiber lasers. These new sensors can ensure more accurate and resolved wind measurements than existing observation systems and than other remote sensing techniques. In this paper, this new technology has been described as well as its demonstrated performances in terms of wind measurements. If these performances are affected by some weather conditions like fog and heavy rains, out of these conditions, the data availability is above 90%, the measurement range can reach up to 10km and the accuracy for wind speeds is better than 0.3m/s. The intrinsic performances of this technology make it of added value for ATM operations like wind and turbulence observations around airports. As this technology is not operating under all weather conditions, it required nevertheless to be combined with other sensors like the standard anemometers used in the AWOS or to RADAR sensors for monitoring severe weather or wind shears that should occur under rainy conditions. In clear air conditions, the benefits of LIDARs have been illustrated for monitoring wake vortices in order to develop new regulations related to wake turbulence and to support their implementation on airports. As any other technology, coherent Doppler LIDAR technology based on fiber architectures will be tested and introduced step and step in the aviation weather community in order to determine its benefits for various aviation weather purposes.

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