Conditional reduction of ICAO wake turbulence separation minima on final approach

5th International Conference on Research in Air Transportation
University of Berkeley, California, May 22-25, 2012

Nicolas Bourgeois
Université catholique de Louvain (UCL)
Institute of Mechanics, Materials and Civil Engineering (iMMC)
Bat. Stévin, Place du Levant, 2
1348 Louvain-la-Neuve, Belgium
nicolas.bourgeois@uclouvain.be

Dr. Peter Choroba
Eurocontrol Experimental Center (EEC)
Centre de Bois des Bordes, BP 15
F-91222 Brétigny-sur-Orge, France
peter.choroba@eurocontrol.int

Pr. Grégoire Winckelmans
Université catholique de Louvain (UCL)
Institute of Mechanics, Materials and Civil Engineering (iMMC)
Bat. Stévin, Place du Levant, 2
1348 Louvain-la-Neuve, Belgium
gregoire.winckelmans@uclouvain.be

***Abstract*—An intensive LIDAR measurement campaign of aircraft wake vortices (WV) in the landing phase of flight has been carried out at London Heathrow Airport. The WV trajectory and circulation as well as wind intensities have been collected. The possibility of reducing current ICAO wake turbulence minimum separations in case of favourable wind conditions is assessed by comparing the wake vortex encounter (WVE) risk associated to calm wind conditions to the WVE risk in these propitious conditions. An original approach used to quantify the frequency and the severity of the potential WVE is presented. As some of the WV are stopped being tracked before they effectively become insignificant, it is also decided to fit and extrapolate each WV circulation evolution using a two-phase decay model. First, the computed severity-frequency curves provide generic results, and indicate that a 0.5NM reduction is possible in case of "pure" headwind equal to 9-10 knots and "pure" crosswind equal to 7-8 knots. The potential local application of these conditional reductions is also evaluated at two European hubs, London Heathrow and Paris Charles de Gaulle. The resulting head- and crosswind thresholds are very similar to those obtained for the generic analysis. Yet, in addition to this theoretical study, a complete safety assessment has to be performed before such thresholds can be used operationally to reduce separation.**

I. Introduction

The two counter-rotating wake vortices (WV) generated by any flying aircraft constitute a potential risk for the following aircraft. The rolling moment induced by WV can indeed be very hazardous, going from a recoverable and almost unnoticed upset to a loss of control leading potentially to fatal consequences. Wake-vortex aircraft separation minima were empirically established in the 1970s by the International Civil Aviation Organization (ICAO) in order to minimize wake vortex encounter (WVE) risk [1]. In this study, the potential WVE is defined by WV of a certain circulation strength, at the time spacing of the specific pair, which may be encountered by the follower aircraft. The quantification of the real impact of such WVE is very complex and far beyound the scope of this paper. The separations depend on the leader and follower aircraft masses. Some pairs are not concerned by these wake turbulence (WT) separation rules and are separated according to standard runway and radar separations. During final approach (the phase of flight on which we focus), ICAO WT separations are expressed by distance.

These separation minima are today one of the limiting factors in the Air Traffic Management (ATM) of the most congested airports. The ICAO WT separations were designed for all weather conditions while it has been proven that WV transport and decay strongly depend on meteorological conditions (wind, turbulence and stratification) and on the ground proximity [2], [3]. Those separations are implicitly over-conservative in most favourable conditions [4], from the WV decay and transport point of view. The capacity is thus unnecessarily constrained in such weather conditions, hence it is aimed to reduce separations. The potential benefits of such separation reductions would consist of a temporary increased runway throughput, reduction of airborne delays and improved runway resilience.

Several studies already have investigated the possibility of reducing separations in certain favourable conditions. In the context of the S-Wake project, the assessment of the appropriate WV separation distances for aircraft on the approach glide path has been studied. The severity of encounters was related to possible risk event classes [5]. In the framework of the CREDOS project, Dengler *et al.* [6] obtained crosswind thresholds lying within 3.5m/s and 4.6m/s to clear in 60s a 150m-flight corridor with a 95% probability. The investigation concerned departing aircraft and was based on correlation between crosswind and lateral vortex drift velocity enabling to transport the WV out of the flight corridor. It is also worth mentioning that the Wake Independent Departure and Arrival Operations (WIDAO) study, led by EUROCONTROL, allowed to successfully relax the wake turbulence constraint at Paris Charles de Gaulle Airport, finally allowing closely spaced parallel runways to operate in wake independent segregated modes [7]. The proposed methodology for risk assessment in WIDAO was quite similar to that employed in this paper and had to ensure that an acceptable level of safety was maintained despite the expected increase in WVE risk. It is also worth to add that the operational applicability of such reduced ICAO WT separations will be conditioned to the wind predictability. Several wind forecast studies have been carried out in the context of the Wake Turbulence Mitigation for Arrivals (WTMA) project, see e.g. [8].

This paper aims to evaluate the possibility of reducing current ICAO WT separations minima for approach phase in favourable wind conditions and to determine the wind criteria that would allow it. Being based on LIDAR (Light Detection And Ranging) measurements as many other studies, it also exploits most of the measured wake vortex tracks, including the short tracks that would normally not be used, by extrapolation consistent with basic WV physics. After briefly explaining the consequences and the major issues of reducing separation (Section II), the relative WVE risk assessment is described (Section III); it is performed by comparing severity vs. frequency curves for a defined baseline and the investigated concept. Section IV explains the methodology used to fit and extrapolate circulation measurements and the underlying reasons of such an approach. The WVE risk is assessed from these extrapolated curves and the concept of generic and local curves is introduced (Section V). Sections VI and VII finally present the results valid generically and locally.

II. Reduction of ICAO WT separation minima

A 0.5NM reduction of ICAO WT separations is here investigated. Its applicability will be conditioned to the head- and/or crosswind intensities. Those wind thresholds will be derived from the data analysis.

By reducing current separations, two undesired consequences exist:

- the time available for wake decay is reduced. This has a negative impact on the *severity* of the possible WVE;
- the time available for wake transport laterally out of the runway axis is reduced. This has a negative impact on the *frequency* of the potential encounters.

However, strong winds have positive repercussions:

- the background atmospheric turbulence associated to medium or strong wind enhances the wake decay compared to low wind conditions. This has a positive impact on the *severity*;
- in case of strong headwind, the vortices tend to be moved backwards, i.e. below the glide path. This positive effect is here not accounted for as the proximity of the ground, causing a systematic rebound, could counteract it. In case of strong crosswind, it is obvious that the lateral transport of the wake is increased. This effect positively impacts the *frequency* of WVE and is taken into account by the presence of a lateral corridor.

It is aimed to define, for a 0.5NM reduction, the wind thresholds from which the positive effects in terms of severity and frequency sufficiently mitigate the negative ones, in order to satisfy the safety condition described in the next section.

III. WVE risk assessment methodology

First of all, a ±100m-width safety corridor (centred on the runway axis) is defined, outside which we consider it is unlikely to find an aircraft. The LIDAR scanning plane being about 1500m away from the runway threshold (see Fig. 1), aircraft are supposed to be precisely aligned on the ILS, hence the chosen width of 200m is considered to be conservative. Secondly, a correspondence between ICAO WT distance-based separations (DBS) and time has to be established. Indeed, studying the WV behavior of an aircraft for a certain distance separation between this aircraft and a follower is done by analysing the severity (i.e. circulation in the present case) of WV lying in the LIDAR scanning plane at a certain life time. We consider a reference approach true airspeed (TAS) depending on the follower WT category. The ground speed is of course dependent of the headwind component, so that the time separation is computed for each case (e.g., we have $t_{\text{sep}} = 99$s for the Heavy-Heavy pair when assuming a reference approach speed of 145kts, in case of no headwind and considering the ICAO WT DBS of 4NM).

The WVE risk is evaluated in a relative way, as there is still no worldwide agreement on the approach for an absolute risk assessment. A relative risk assessment is performed by comparing the WVE risk anticipated from implementation of the proposed change to wake turbulence separation, with the WVE risk observed for a baseline considered tolerably safe today. Indeed, ICAO WT separation minima are considered safe, hence it is also the case for those separations applied during calm wind conditions. Calm wind conditions are considered as the worst-case conditions in terms of WV behaviour; they are here defined by a total wind lower than 5 knots. That defines the baseline.

In order to assess the WVE risk, CCDF (Complementary Cumulative Density Function) curves of circulation are computed. For a certain circulation Γ, $CCDF(\Gamma)$ is defined as the probability to observe, assuming certain wind conditions, at a time t_{sep}, a wake vortex i with a circulation higher than Γ standing in the lateral corridor. For the baseline, that can thus be mathematically formalized by writing:

$$\begin{aligned} CCDF(\Gamma) &= \mathcal{P}\left(\left(\Gamma_i(t_{\text{sep}})>\Gamma \cap y\leq 100\right) | Tw<5\right) \\ &= \frac{\mathcal{P}\left(\Gamma_i(t_{\text{sep}})>\Gamma \cap y\leq 100 \cap Tw<5\right)}{\mathcal{P}(Tw<5)}, \end{aligned} \quad (1)$$

with $y = \min(|y_p|, |y_s|)$ [m] the closest WV (p and s standing for port and starboard WV) to the runway axis and Tw [kts] the total wind. It has to be stressed that the probability is conditioned to specific wind conditions, as we do not want to reflect the probability of observing certain wind conditions into $CCDF(\Gamma)$ but the WVE risk associated to these conditions. In this paper, any CCDF curve is thus coupled with conditions on the wind.

Any new operational concept (e.g. current ICAO WT separations minima reduced of a 0.5NM for a to-be-defined minimum required wind) is considered safe if the baseline CCDF remains above the concept curve over the whole circulation spectrum, i.e.:

$$CCDF(\Gamma)_{\text{Baseline}} > CCDF(\Gamma)_{\text{Concept}} \quad \forall \Gamma. \tag{2}$$

In other words, the risk related to the new concept may not be greater than the current accepted risk under low wind conditions.

The $CCDF(\Gamma)$ is a frequency/probability practically computed as a ratio between a numerator (all favourable cases) and a denominator (all possible cases). The numerator is an accounting of all tracks meeting the previously described conditions. It actually lists all the tracks likely to cause a wake vortex encounter. Being divided by the number of all tracks meeting the same wind conditions (i.e. the denominator), this number gives the $CCDF(\Gamma)$; Eq. (1) can be equivalently rewritten by:

$$CCDF(\Gamma) = \frac{N\left(\Gamma_i(t_{\text{sep}}) > \Gamma \cap y \leq 100 \cap Tw < 5\right)}{N(Tw < 5)} \tag{3}$$

with $N(...)$ the number of tracks meeting the described conditions. This is actually an upper bound of the WVE probability as a WV lying in the lateral corridor at a certain time corresponding to the minimum ICAO WT DBS (distance-based separations) will not necessarily induce an encounter for the follower aircraft.

IV. EGLL DATA COLLECTION AND ANALYSIS

A. Description of the LIDAR measurements campaign

The present work is based on the analysis of the EGLL-1 database. The measurement campaign started in October 2008 and ended in December 2010, and was jointly run by EUROCONTROL and NATS. The whole campaign concerns aircraft during final approach. The Lockheed Martin Coherent Technologies (LMCT) LIDAR was installed at London Heathrow Airport, at about 1500m of the runway threshold (see Fig. 1), corresponding typically to an ILS altitude of ≈ 80m (≈ 260ft). The scanning concerns only West operations, i.e. runways 27L and 27R. The database contains 121,636 tracks (among which 883 Super Heavy; 54,516 Heavy and 66,237 Medium in the sense of ICAO WT categories).

B. Shortcomings of the LIDAR data

Among the very large number of WV tracks in the database, some of them are not directly usable as they stop with a significant last circulation value before reaching the time in which we are interested. The "rate of tracking" η is defined as the proportion of tracks that are usable at a time corresponding to the ICAO WT DBS: they are either still alive at this time, or the tracking stopped with a last measured no significant circulation ($\Gamma_{\text{last}} \leq 200\,[\text{m}^2/\text{s}]$). It is plotted on Fig. 2 for the Heavy-Heavy pair in function of several head- and crosswind thresholds. The stronger the wind, the worse the rate of tracking (this effect being dramatically more important for headwind than for crosswind). Regardless of the wind, the rate of tracking indicates that more than 30% of the initial tracks are stopped being tracked before the considered time separation, despite having still a circulation larger than $200\,[\text{m}^2/\text{s}]$. They would normally not be used when computing statistics for the Heavy-Heavy pair, yet they constitute a considerable amount of tracks (more than 18,000). In order to add even more value to the already valuable database, it is suggested to extrapolate the good quality short tracks, even if no point older than the studied time separation is measured.

C. Fit and extrapolation of circulation data

In order to be consistent with WV basic physics, it was chosen to fit and extrapolate circulation using a two-phase decay model [9], [10]. Each phase is analytically described by a decreasing exponential function characterized by coefficients α_1 and α_2, using Γ_0 as initial circulation. The transition between the two phases occurs at $t = t_d$ which can be viewed as a measured time-to-demise (as used in the Sarpkaya approach [9]). The mathematical expression of the fit $\Gamma^*(t)$ can be written as:

$$\Gamma^*(t) = \begin{cases} \Gamma_0 \, \exp(-\alpha_1 \, t) & \text{for } t \leq t_d, \\ \Gamma_0 \, \exp\left((\alpha_2 - \alpha_1)t_d - \alpha_2 \, t\right) & \text{for } t \geq t_d. \end{cases} \tag{4}$$

Four parameters (Γ_0, α_1, α_2 and t_d) have to be determined by minimizing the residues between the fit $\Gamma^*(t)$ and the data $\Gamma(t)$ in the least squares:

$$res = \sum_{i=1}^{N} \left(\Gamma^*(\alpha_1, \alpha_2, t_d, \Gamma_0; t_i) - \Gamma(t_i)\right)^2. \tag{5}$$

This multi-variables minimization problem without constraint is solved for each individual track (port and/or starboard vortex) for which at least one vortex is still within the lateral corridor after a time corresponding to the radar minimum separation. The circulation of tracks having both WV out of the lateral corridor within this time is not investigated. The radar minimum separation corresponds to a time separation of 58s when conservatively assuming a reference landing speed for the follower aircraft of 155kts.

Individual extrapolations can be as good as the quality of measurements is, as illustrated by Fig. 3 showing two examples of fits obtained with measurements which can be qualified of good (up) and poor (down) quality. As some tracked points have no physical sense, it is also the case for the related fits. Some simple filters on the results (i.e. on Γ_0, α_1, α_2 and t_d which are the solutions of (5)) can avoid working

Fig. 1. Location of the LIDAR and of the measurement planes for the EGLL-1 campaign (the background photograph is from ©Microsoft Visual Earth).

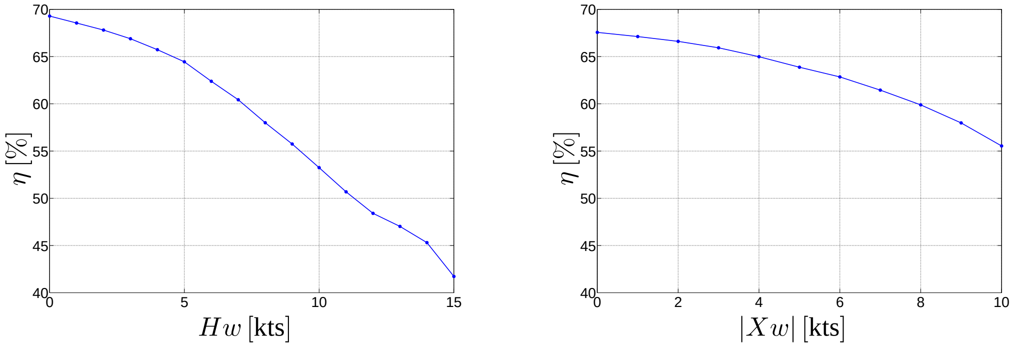

Fig. 2. Rate of tracking (η) as a function of headwind (left) and crosswind (right) thresholds for a time corresponding to the Heavy-Heavy pair ICAO WT DBS of 4NM.

with those tracks. The most trivial of them is to require that α_2 is positive, ensuring a decreasing second-phase of decay. The same condition could be imposed for α_1, as it is physically impossible to see the circulation durably increasing, but the beginning of a track is regularly noisy and potentially presents an increasing first-phase. This does not mean that the whole track has to be discarded; hence we consider a less restrictive constraint by keeping tracks with α_1 belonging to the 95%-envelope of all computed α_1. Filters on the dimensionless residues res/Γ_0 and Γ_0 are also applied.

The dimensionless mean results obtained for several dimensionless total wind (Tw/V_0) bands show the influence of the wind intensity on the wake vortex decay (see Fig. 4); $V_0 = \frac{\Gamma_0}{2\pi\, b_0}$ [m/s] defines the initial descent velocity, with b_0 [m] the initial spacing between the two WV (and practically approximated by the difference between the two WV lateral positions given by the LIDAR measurements). The results conform to the basic WV physics indicating that the decay of the WV is increased with the turbulence of the atmosphere. Close to the ground, the atmospheric turbulence (the main factor impacting the WV decay, together with the stratification level and the ground vicinity) is directly related to the total wind intensity. The succession of slow and rapid phases of decay are however not as clearly distinguishable as usual. This is mainly an effect of the averaging process.

Let us also add that no extrapolation of the lateral WV position has been considered; we conservatively assume that the WV lateral positions after the last measured point remain constant.

D. Implications of extrapolating circulation

As the number of tracks is significantly increased by the use of the extrapolation technique (see Fig. 2 indicating that about 30% of the normally lost tracks will be taken into account), the frequency of the potential WVE can only increase. The consequences on the CCDF curves are thus observed by a trend to principally move upward. As the safety criterion (2) is expressed relatively, the question of knowing whether the extrapolation technique is more conservative than the “classic” one has to be answered by comparing the relative WVE risk growths for both the baseline and the concept curves. It can *a priori* be supposed that the concept curve will be the most affected by stopped tracks and thus will incur the greatest

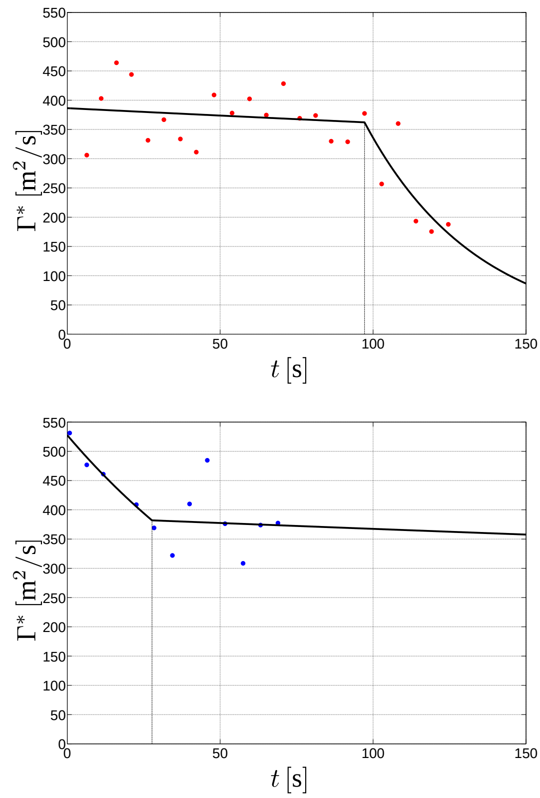

Fig. 3. Two examples of extrapolations of $\Gamma(t)$ obtained from good (up) and bad (down) quality measurements.

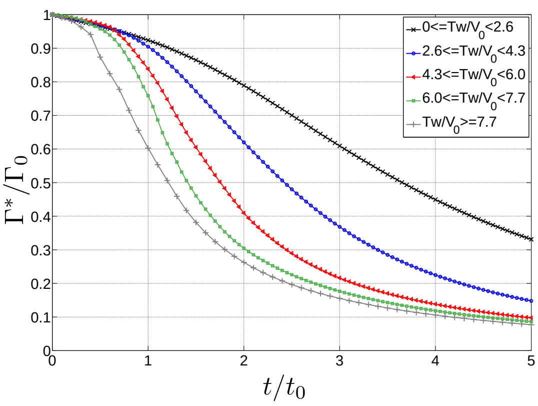

Fig. 4. Results of the extrapolations of $\Gamma(t)$ for both port and starboard vortices (Heavy aircraft): dimensionless mean results of $\Gamma^*(t)/\Gamma_0$ for several dimensionless total wind bands.

CCDF jump when adding extrapolated tracks, as the baseline limits to cases in calm wind conditions. Considering a simple example with strong headwinds confirms that the baseline (less concerned by the dead short tracks, as it could be expected) increases to a lesser extent than the concept curve (see Fig. 5), implying a more constraining safety criterion when using the extrapolation technique. This example also shows that the 0.5NM reduction satisfies the safety criterion when using "raw" data whereas it does not when using extrapolation. It thus appears that the use of extrapolated tracks is conservative.

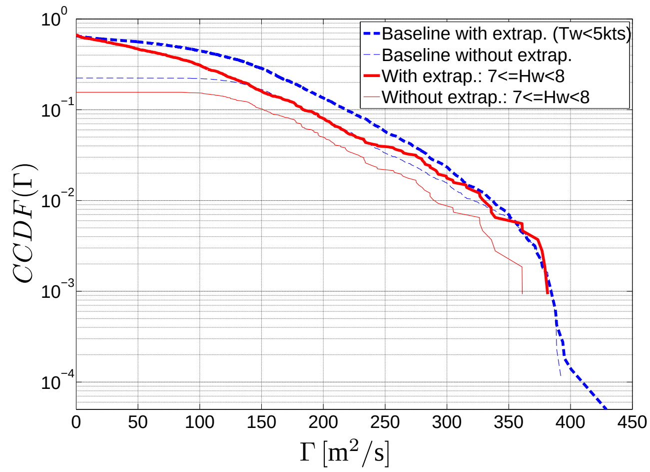

Fig. 5. CCDF curves obtained with (thick curves) and without (thin curves) extrapolated circulation tracks for a 0.5NM reduction (Heavy-Heavy pair).

V. Local and generic CCDF curves

A. Local validity of CCDF computed with "raw" data

When assessing the WVE risk for a new concept in function of wind conditions, it is aimed to define a wind criterion from which the concept is considered safe and can be activated (a buffer related to accuracy of short-term wind forecast would still need to be added). Such a wind constraint is intended to be expressed as a "greater-than" criterion. Working with such a criterion implicitly induces that the CCDFs computed from data without any other consideration are only valid locally. Indeed, CCDF curves obtained from "raw" data (yet they consist of extrapolated circulation data) are highly dependent of the wind distribution at the measurements location. Let us consider the following simple example: for a certain circulation $\Gamma = \bar{\Gamma}$ and for a crosswind threshold $|Xw| > 6$ kts, all WV are for sure out of the lateral corridor, i.e. $CCDF(\bar{\Gamma}) = 0$. One aims to compute $CCDF(\bar{\Gamma})$ for $|Xw| \geq 5$ kts, knowing that, between 5 and 6 knots, at least one of the two WV still stands within the lateral corridor and has a circulation larger than $\bar{\Gamma}$; one has thus $CCDF(\bar{\Gamma}) = 1$ for $5 \leq |Xw| \leq 6$ kts. Let us consider the two crosswind distributions described in Table I (a bullet corresponding to one piece of data). For two different wind distributions, the CCDF computation for the wind condition $|Xw| \geq 5$ kts gives two different results, being only valid for the particular wind distributions resulting from the measurements campaign (i.e. strongly dependent of the period during which the LIDAR was used and of the place where it was located). It could however be aimed to remain generic in terms of results. They might then characterize the WV physics and not the frequency at which this physics is observed at a certain location.

B. Generic CCDF computed with wind band criterion

In order to obtain such generic results which do not depend of the local wind distribution, one would like to dispose of an identical number of cases for each investigated wind condition, i.e. a uniform wind distribution. The local wind

	$\|Xw\|$ [kts]		
	5-6	>6	
Distribution 1	•	• • •	$\Rightarrow CCDF(\bar{\Gamma})$ = 1/4
Distribution 2	• • •	• • •	$\Rightarrow CCDF(\bar{\Gamma})$ = 1/2

TABLE I
SIMPLIFIED EXAMPLE OF TWO CROSSWIND DISTRIBUTIONS AND OF THE RESULTING CCDF COMPUTATION. COMPUTATION OF $CCDF(\bar{\Gamma})$ FOR $|Xw| \geq 5$ KTS.

distribution would not affect results in this case. The solution is to consider wind bands and to compute for each of them a CCDF curve being considered as generic. Applying the concept at a certain airport would then allow to take into account the local wind distribution. An implicit assumption is that the wind distribution is uniform within each wind band. This is obviously not the case, but the narrower the bandwidth is, the closer to uniform the distribution can be assumed. The counterpart is that statistics are in this case less well converged. It is also worth mentioning that wind banded CCDFs are actually both generic and local, as wind distribution is assumed uniform in both cases. They are thus supposed to be valid in any LIDAR scanning plane standing at the same distance of the threshold and being crossed with the same traffic mix as in the EGLL-1 database.

C. Construction of local results

The application of the concept into a certain airport imposes that this is validated locally (with a complete local safety case). The wind distribution has a huge influence on the frequency with which all the possible circulation evolutions occur, and thus with the WVE frequency of a certain severity at a certain moment. Computing local CCDF valid at the measurement location, with a "greater-than" wind criterion is straightforward (as explained in Section V-A) as soon as the distribution coming from the wind measurements during the campaign is representative of the local wind distribution. The present campaign having been led for almost two full years, it can reasonably be considered that this condition is fulfilled. What would be interesting is to be able to construct, from the generic results, the local CCDF curves for any other location than EGLL. It simply comes back to add wind banded generic curves and weight each of them by the local distribution. We simply consider the example of the pure headwind concept; we aim to compute the local CCDF for all headwinds larger than 4kts. It can be mathematically formalized in the following way, assuming a bandwidth of 1kt:

$$\begin{aligned} CCDF(\Gamma) \;=\;& \mathcal{P}(4{\leq}Hw{<}5\,|\,Hw{\geq}4)\cdot CCDF(\Gamma\,|\,4{\leq}Hw{<}5)\;+ \\ & \mathcal{P}(5{\leq}Hw{<}6\,|\,Hw{\geq}4)\cdot CCDF(\Gamma\,|\,5{\leq}Hw{<}6)\;+ \\ & \ldots + \\ & \mathcal{P}(15{\leq}Hw{<}\infty\,|\,Hw{\geq}4)\cdot CCDF(\Gamma\,|\,15{\leq}Hw{<}\infty). \end{aligned} \tag{6}$$

The first terms of the right-hand side are simply given by the local headwind distribution. We should actually speak of "partial" headwind distribution as we consider the probability of having a headwind within a certain band, at the condition that it is larger than 4kts. The second terms designate the generic headwind banded CCDF curves, aiming to present a universal character. As the total number of bands is finite, we consider that all cases with $Hw \geq$ 15kts constitute a unique band. The same methodology applies for any local curve, and thus also for the baseline. The considered wind distribution is then the total wind, and the generic curves are those related to CCDFs by total wind bands.

VI. GENERIC RESULTS FOR THE HEAVY-HEAVY PAIR

A. Headwind concept

We here examine the possibility of a 0.5NM reduction for the Heavy-Heavy pair in case of strong headwinds. This corresponds to 12s of reduction in case of no headwind and assuming a reference approach speed of 145kts. We analyse generic results, i.e. headwind banded CCDF curves. We arbitrarily limit the crosswind component to 2kts, as we aim to evaluate whether the supposed enhanced WV dissipation in case of strong (head)wind can mitigate or not the increased WVE risk due to the separation reduction. Considering only pure headwind excludes most of the cases with WV transported out of the corridor. The effect of reducing separations has thus theoretically only an impact on the severity of the potential WVE. Graphically, the CCDF curve of a same case is thus supposed to move to the right due to the reduction, but the total risk (i.e. $CCDF(0)$) does not increase. This is confirmed on Fig. 6 by comparing the curves without (thin red) and with (thick red) reduced separation. The CCDF curves for two headwind bands of interest indicate that a 0.5NM reduction meets the safety condition expressed by (2) for headwinds between 9 and 10 knots.

B. Crosswind concept

The same principle as for the "essentially headwind" concept is now considered; we investigate "essentially crosswind" cases by limiting the headwind component to 5kts. When the crosswind increases, the probability of having the WV blown out of the lateral corridor is increased. As for the headwind, any strong crosswind means that the background atmospheric turbulence is also supposed to be strong, hence the resulting decay is accelerated. Reducing separation for pure crosswind cases implies thus that the WVE are potentially more frequent and more severe: the CCDF moves both upward and rightward (see Fig. 7). This double negative impact on both severity and frequency appears to be mitigated for crosswinds enclosed between 7 and 8 knots. The WVEs for the reduced WT separations are of course more frequent and more severe than the case with no reduction, yet they are acceptable according to the safety criterion (2).

VII. LOCAL RESULTS FOR THE HEAVY-HEAVY PAIR

The application of the concept locally requires to validate the reduced separation for the specific local wind distribution.

It is operationally aimed to establish a wind threshold from which the separation reduction mode can be activated. It is expected from the generic curves that, for the Heavy-Heavy pair, these wind thresholds should not be higher than 10 and 8 knots respectively for headwind and crosswind conditions. Considering larger winds can indeed only have a positive influence on the WV decay and on the frequency of laterally transported WV.

As described in (6), the local wind distribution and the generic CCDF curves are required to compute the local CCDF curves. We compare these local CCDF curves for two of the busiest airports in Europe: London Heathrow (EGLL) and Paris Charles de Gaulle (LFPG). The local wind distributions are respectively based on the EGLL-1 and on the LFPG-1 databases. The total wind distributions being not strictly equivalent for both locations, the baselines for the two airports are slightly different. The headwind case (Fig. 8, left) shows that the 0.5NM reduction could be applied at both London Heathrow and Paris CDG as soon as the headwind is larger than 9 knots. The concept curves for $Hw \geq 8\,$kts (not shown here) clearly cross the related baselines. The crosswind curves (Fig. 8, right) indicate that the 0.5NM reduction can be considered at EGLL as soon as the measured crosswind is larger than 6 knots. The crosswind distribution at EGLL is thus such that the mitigation effects, getting more important with the crosswind, are frequent enough to have a crosswind threshold smaller than the one that could have been expected from the generic results, i.e. a threshold between 7 and 8 kts. Concerning the CDG airport, the local CCDF curves tend to show that the 0.5NM is not possible from the same threshold as in EGLL. A threshold of 7 knots (not shown here) appears to be necessary. It has to be kept in mind that the local CCDF curves quantify the WVE risk for a wind distribution supposed to be representative of the local wind conditions over a certain period. This also constitutes the validity limitation of such a curve, as any difference between the distribution used for the computation and the practically observed distribution will induce a modification to the theoretical and "forecast" CCDF, as the frequency of the favourable events (enhanced decay and/or lateral transport of the WV) can potentially be affected.

VIII. Conclusions

In this theoretical study, the extrapolation of early terminated wake vortex tracks was used to extend the scope of the data set for assessment of potential conditional reduction of ICAO WT separations. This approach allows to provide a more conservative analysis than that usually considered. A safety corridor of $\pm$100m has been considered. The Heavy-Heavy pair has been used as an example for the whole investigation. Two generic wind thresholds respectively for "essentially headwind" and "essentially crosswind" conditions have been identified for a 0.5NM reduction (9-10 and 7-8 knots), and are supposed to characterize the WV behavior for these wind conditions. The local application of the separation reduction is made possible by integrating the local wind distribution into the generic results. Two examples of local 0.5NM reductions at London Heathrow and Paris Charles de Gaulle Airports were given, and the methodology to identify the specific and local wind thresholds enabling the separation reduction for any other airport has been explained. An important disclaimer to the present investigation is that the wind criteria found using the described methodology shall not be applied directly without proper adaptation of the local operational concept for conditional reductions of WT separations and without development of a local safety case. Reducing separations requires to fulfil much more demands than providing frequency and severity curves for potential WVEs. This is thus only an input as one of the basic evidences to the full safety assessment process.

Acknowledgment

This study is sponsored by EUROCONTROL's research grant "University support to P6.8.1". The LIDAR data used in this study was provided by EUROCONTROL and NATS. The work presented contributes to initial assessments required for validation of Weather Dependent Separations concept (WDS) and it also relates to potential short-term operational improvements such as CROPS (Crosswind operations). Thanks are also addressed to project colleagues for numerous discussions and useful comments.

References

[1] Procedures for Air Navigation Services—Air Traffic Management. International Civil Aviation Organization. *Doc. 4444, ATM/501*, Montreal, 2001.

[2] P. R. Spalart. Airplane Trailing Vortices. *Annual Review of Fluid Mechanics*, 30:107-138, 1998.

[3] T. Gerz, F. Holzäpfel, and D. Darracq. Commercial aircraft wake vortices. *Progress in Aerospace Sciences*, 38:181-208, 2002.

[4] M. Frech, T. Zinner. Concept of wake vortex behavior classes. *Journal of Aircraft*, 41:564-570, 2004.

[5] A. C. de Bruin *et al.* S-Wake–Assessment of Wake Vortex Safety–Publishable Summary Report. National Aerospace Laboratory (NLR). May 2003.

[6] K. Dengler, F. Holzäpfel, T. Gerz, A. Wiegele, I. De Visscher, G. Winckelmans, L. Bricteux, H. Fischer and J. Konopka. Crosswind thresholds supporting wake-vortex-free corridors for departing aircraft. *Meteorological Applications*, May 2011.

[7] Principles and guidance for wake vortex encounter risk assessment as used in the Paris CDG–Wake Independent Departure and Arrival Operations (WIDAO)–Safety Case. EUROCONTROL, November 2010.

[8] C. Engholm, D. A. Clark, V. Andleigh, S. Huang, F. Robasky. Probabilistic Wind Forecasts for WTMA-S. *WakeNet3-Europe*, 28-29 February 2012.

[9] T. Sarpkaya. A new model for vortex decay in atmosphere. *37th Aerospace Sciences Meeting & Exhibit*, Reno NV, January 1999. Paper AIAA 99-0761.

[10] T. Sarpkaya, R. E. Robins, and D. P. Delisi. Wake-vortex eddy-dissipation model predictions compared with observations. *38th Aerospace Sciences Meeting & Exhibit*, Reno NV, January 2000. Paper AIAA 2000-0625.

[11] J. C. Kaimal, J. C. Wyngaard, I. Izumi and O. R. Cote. Spectral Characteristics of Surface Layer Turbulence. *Quart J. Roy. Meteorol. Soc.*, 98:536-589, 1972.

[12] G. Winckelmans, I. De Visscher, T. Lonfils, O. Desenfans, L. Bricteux, M. Duponcheel and N. Bourgeois. UCL operational tools for predicting aircraft wake vortex transport and decay: The Deterministic/Probabilistic wake Vortex Models (DVM/PVM) and the WAKE4D platform. Version 2.2, January 15, 2010.

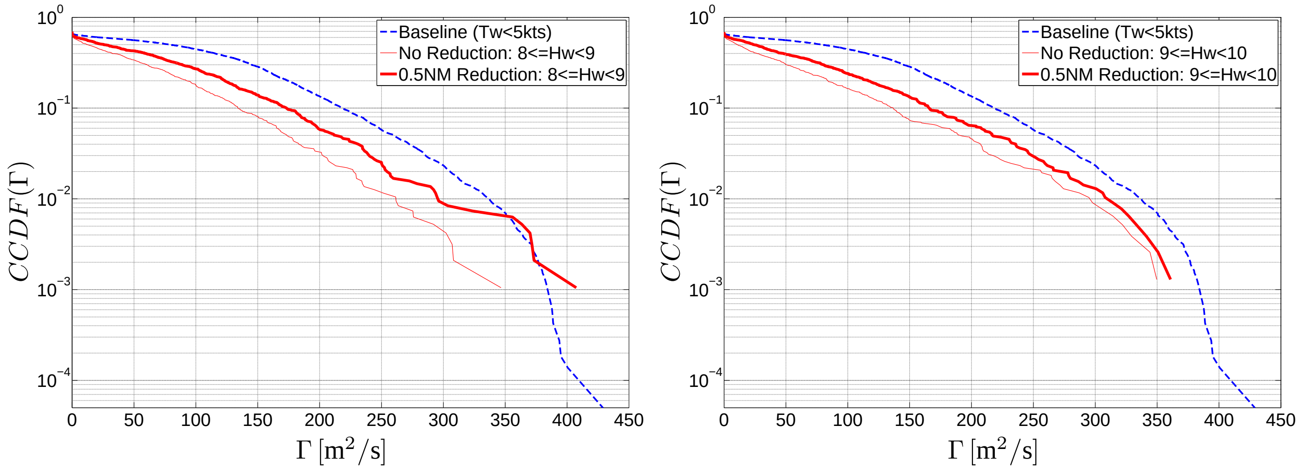

Fig. 6. Generic CCDF curves for "essentially headwind" concept ($|Xw| \leq 2$ kts), for current ICAO WT DBS and a 0.5NM reduction, and for two headwind bands (Heavy-Heavy pair).

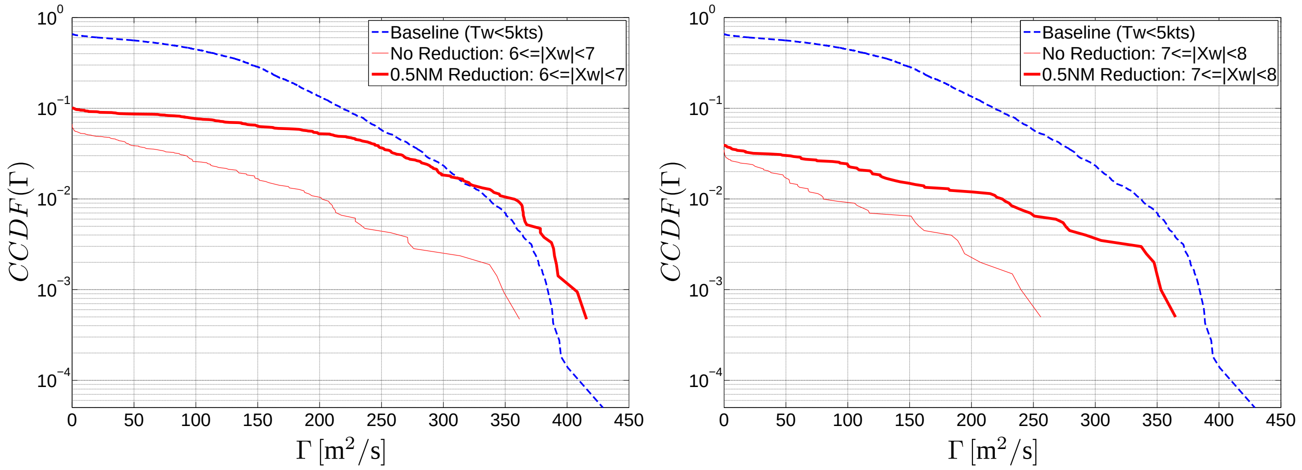

Fig. 7. Generic CCDF curves for "essentially crosswind" concept ($Hw \leq 5$ kts), for current ICAO WT DBS and a 0.5NM reduction, and for two crosswind bands (Heavy-Heavy pair).

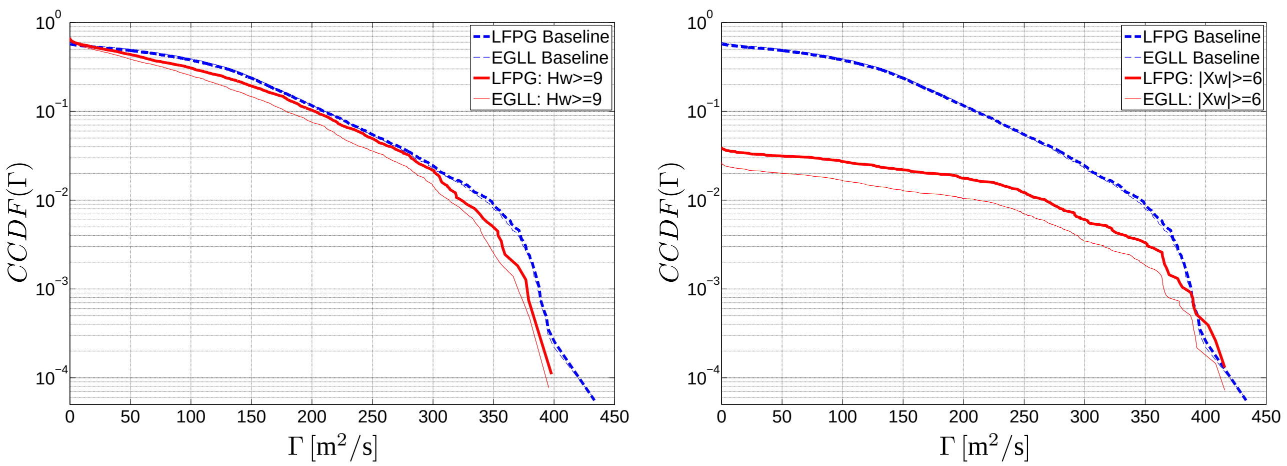

Fig. 8. Local CCDF curves for "essentially headwind" (left) and "essentially crosswind" (right) concepts, both at London Heathrow (EGLL) and Paris Charles de Gaulle (LFPG) airports (Heavy-Heavy pair).