AST4-CT-2005-012238

FAR-Wake
Fundamental Research on Aircraft Wake Phenomena

Specific Targeted Research Project
Start: 01 February 2005
Duration: 40 months

Final Report on
wake evolution near the ground

Prepared by: G. Winckelmans (UCL, lead)
F. Holtäpfel, T. Gerz (DLR)
A. de Bruin (NLR)

Document control data

<table>
<thead>
<tr>
<th>Deliverable No.</th>
<th>Due date:</th>
<th>Version:</th>
<th>Task manager:</th>
<th>Project manager:</th>
<th>EC Officer:</th>
</tr>
</thead>
<tbody>
<tr>
<td>D 3.F</td>
<td>April 2008 (m39)</td>
<td>1.0</td>
<td>G. Winckelmans</td>
<td>T. Leweke</td>
<td>S. Stoltz-Douchet</td>
</tr>
</tbody>
</table>

Date delivered: 26 May 2008

Project co-funded by the European Commission within the Sixth Framework Programme (2002-2006)

Dissemination Level

<table>
<thead>
<tr>
<th>PU</th>
<th>Public</th>
</tr>
</thead>
<tbody>
<tr>
<td>PP</td>
<td>Restricted to other programme participants (including the Commission Services)</td>
</tr>
<tr>
<td>RE</td>
<td>Restricted to a group specified by the consortium (including the Commission Services)</td>
</tr>
<tr>
<td>CO</td>
<td>Confidential, only for members of the consortium (including the Commission Services)</td>
</tr>
</tbody>
</table>
Contents

1 Introduction 4

  1.1 Global WP overview ............................................ 4
  1.2 Overview of Task 3.1: Dynamics and decay in idealized conditions 5
  1.3 Overview of Task 3.2: Dynamics and decay in real conditions .... 5
  1.4 Overview of Task 3.3: Assessment and advanced real-time modeling 6
  1.5 Report outline .................................................. 6

2 Dynamics and decay in idealized conditions (T 3.1) 7

  2.1 Span loading variations and wake roll-up IGE (D 3.1.1-1) ........ 7
  2.2 3-D instabilities of two- and four-vortex systems IGE (D 3.1.1-2) .. 9
    2.2.1 3D filament simulations of Crow-like instabilities IGE (TR 3.1.1-1) .................................................. 9
    2.2.2 LES of a two vortex system IGE (TR 3.1.1-2) ............... 10
    2.2.3 LES of a four vortex system IGE (TR 3.1.1-3) .............. 11
    2.2.4 Water tank experiments on vortex pairs IGE (TR 3.1.1-4) and additional support work on their numerical simulation .... 11
  2.3 Effect of wind conditions on the evolution of a two-vortex system near the ground (D 3.1.1-3) ................................. 12
  2.4 Quantification of uncertainties in a 2-D vortex pair near the ground with and without cross-flow (D 3.1.1-4) .................. 15
  2.5 Dynamics and decay of spatially-developing two- and four-vortex wakes near the ground (D 3.1.2) ............................. 17
    2.5.1 Delivery of Airbus proprietary wake data measurements IGE (TR 3.1.2-1) .................................................. 17
    2.5.2 Towing tank PIV measurements on two- and four-vortex systems IGE (TR 3.1.2-2) ............................................. 17
2.5.3 Towing tank visualizations of two-vortex systems IGE (TR 3.1.2-3) ........................................... 18

2.5.4 LES calculations of spatially evolving wakes IGE (TR 3.1.2-4) ........................................... 19

3 Dynamics and decay in real conditions (T 3.2) ........................................... 22

4 Assessment and advanced real-time modeling (T 3.3) ........................................... 24

4.1 Improvement of the D2P/P2P ........................................... 24

4.2 Improvement of the DVM/PVM ........................................... 25
1 Introduction

The present report aims at giving a comprehensive summary of the main achievements of WP3 on wake vortex evolution near the ground. A presentation of the previous work on the behavior (transport and decay) of wake vortices near the ground, and knowledge as it was at the beginning of the FAR-wake project, was presented in D3.0 Previous work and present knowledge on wake vortices near the ground. The present report thus concentrates on the “Δ”.

We first recall the main research objectives of WP3, as well as those related to each one of its three specific tasks.

1.1 Global WP overview

Work Package 3 is dedicated to the physics and modeling of wake vortex (WV) transport and decay in the region close to the ground (near-ground effects (NGE) and in-ground effects (IGE)), also possibly combined with wind conditions. The influence of the ground proximity on the wake generation and its roll-up are also investigated.

In a general manner, the NGE region is the region where the WV begin to spread laterally as they get closer to the ground, and the IGE region is the region where they interact more strongly and in a viscous way with the ground, with vorticity being generated at the ground (because of the no-slip condition) and then separating from the ground, to form opposite sign vorticity regions that interact with the primary vortices, leading to rebound of the primary WV system. The interaction also strongly affects the WV system decay IGE. Atmospheric conditions such as crosswind, headwind, wind turbulence among others, further add to the complexity of the problem and the ensuing dynamics.

Because of the complex interactions of the WV system with the ground, the prediction of WV behavior is potentially more challenging than for out-of-ground effect (OGE) cases.

The main objective is a better physical understanding and modeling, including real-time models and probabilistic approaches, of the wake evolution, and its characterization, based on global (macroscopic) quantities. These macroscopic quantities describe, on one hand, the aircraft from which the wakes vortices are shed and, on the other hand, the atmosphere. It is also required to relate the results to those in experimental databases (Task 3.2) and to improve the real-time models (Task 3.3).

In order to gain a clearer picture of the transport and decay behavior of WV in such a complex environment, WP3 was divided into three specific tasks. These are discussed in details in the project’s description of work (DOW), and thus only a brief description of each task will be given here.
1.2 Overview of Task 3.1: Dynamics and decay in idealized conditions

For this task on the dynamics and decay in idealized conditions, we consider WV systems NGE and IGE, as they evolve under idealized and controlled computational and/or laboratory conditions. The objective is to better understand and characterize the principal instabilities and physical mechanisms as the WV interact viscously with the ground and with the secondary counter-rotating vortices originating from the separated boundary layers. Controlled shear and turbulence effects, due to the presence of a turbulent wind, are also studied for two cases: a case with cross-wind and a case with head wind.

The main objectives of this task are:

• Characterize and understand the principal mechanisms and instabilities as the wake vortices interact viscously with the ground.

• Obtain relevant quantitative information on the effect of wind conditions (cross wind and headwind) on wake vortex transport and decay IGE, and quantify the wake vortex behavior dependency on global quantities.

1.3 Overview of Task 3.2: Dynamics and decay in real conditions

In this second task on the dynamics and decay in real conditions, data sets from past field experiments with respect to wake vortices NGE/IGE are analyzed, with the complexity of real atmospheric and surface environments. The aim here is to further analyze all available data, with respect to WV behavior (transport and decay) under given meteorological conditions, and to possibly discriminate between the influence of the atmospheric parameters (e.g., wind, wind shear, and turbulence) and the specific interaction with the ground; this, in relation with global WV transport and decay in the NGE and IGE regions.

Indeed, the transport and decay of wake vortices in the atmospheric boundary layer OGE are dominated by meteorological parameters (crosswind, shear, turbulence, thermal stratification) followed by other effects related to intrinsic instabilities of the vortices themselves. For wake vortices NGE and IGE, the same decay mechanisms should also be effective. The difference with vortices OGE is that, in the vicinity of the ground, the two main vortices produce strong shear (vorticity) layers at the ground surface.

However, the evolution of these secondary boundary layers, their roll-up into secondary vorticity structures, and the interaction between the primary and these newly formed secondary structures may significantly interfere with the conditions of the environment. It is the objective of this task to elaborate and discriminate between these influences and dependencies.

The main objectives here could thus be formulated as:
• Characterize the wake vortex evolution (NGE/IGE) under real atmospheric conditions, in relation with global (macroscopic) quantities and taking into account probabilistic aspects.

• Discriminate between the influence of atmosphere effects (e.g., wind, wind shear, and turbulence) and ground effects for wake vortex transport and decay.

1.4 Overview of Task 3.3: Assessment and advanced real-time modeling

Task 3.3 constitutes the logical “conclusion” process: assessment and advanced real-time modeling: assessment/evaluation of the findings of Task 3.1 and Task 3.2, and translation of the synthesized knowledge into the advanced models for real-time prediction of WV behavior (transport and decay) NGE and IGE: the Deterministic/Probabilistic Two-Phase wake vortex models (D2P/P2P) of DLR; and the Deterministic/Probabilistic wake Vortex Models (DVM/PVM) of UCL. The purpose is to raise the efficiency and accuracy of the real-time modeling tools a step further; hence this task potentially represents one of the most significant applied contributions of this project.

1.5 Report outline

The summary of the accomplishments has been divided according to each respective task. In Section 2, we cover the dynamics and decay in idealized conditions (T 3.1). The dynamics and decay in real conditions (T3.2) is presented in Section 3 and, finally, the advanced real-time modeling (T 3.3) is discussed in Section 4.
2 Dynamics and decay in idealized conditions (T 3.1)

In this section, we consider the work, either experimental or numerical, that relates to Task 3.1 on the dynamics and decay of vortex systems interacting with the ground, in idealized and controlled computational and laboratory conditions. This also included dynamics with added complex effects (span loading variation, rollup IGE, turbulent crosswind, turbulent headwind), yet always in a well defined and controlled environment, thus suitable for specific parametric studies.

The outcome of this task, together with Task 3.2, also served as input to Task 3.3 which concerns the improvement of real-time operational models.

Subtask 3.1.1 focused on wakes with longitudinal uniformity: meaning that the longitudinal direction is homogeneous (i.e., periodic). The activities were:

- studies of wake generation and rollup in proximity of the ground, using a modified lifting line theory, 2-D cross-plane simulations by the viscous vortex method, and water tank experiments;
- studies of 3-D instabilities in WV systems IGE (including intrinsic instabilities) using the vortex filament method (inviscid), advanced large-eddy simulations (LES), and experiments in a water tank;
- studies of the effect of a cross wind, through LES, for two wind conditions.
- studies of the effect of a head wind, through LES.

Subtask 3.1.2 then considered the case of spatially-developing wakes:

- towing tank experiments for two- and four-vortex systems produced by wing models following a constant altitude track above a fixed ground (visualizations and PIV measurements).
- space-developing LES of a two-vortex system IGE.

The summary results are presented below, and are based of the detailed content of the deliverables (themselves sometimes based on the content of detailed technical reports).

2.1 Span loading variations and wake roll-up IGE (D 3.1.1-1)

The influence of the ground proximity on the vortex wake generation and on its roll-up was investigated. The presence of the ground affects the lift coefficient of each wing section, the span loading of the wing and thus the resulting wake vortex sheet. The roll-up of this vortex sheet is also affected by the presence of the ground. The importance of these effects were analyzed in order to determine whether they need
to be taken into account when performing 3-D simulations or when using simplified real-time models.

The influence of the ground proximity on the lift coefficient of an airfoil section IGE was studied, using a vortex panel method taking into account the image panels below the ground. It was shown that the ground influence only becomes significant for $h_0/c$ below 0.5 (where $c$ is the airfoil chord): hence this is negligible for typical commercial aircraft, even in the last phase of landing or in the early phase of take-off.

The span loading of various wings IGE was also obtained, using a modified lifting line theory, taking into account the image vortex system below the ground plane. Three cases were considered: a wing with elliptical chord distribution, a wing uniform chord distribution (rectangular wing) and a wing with “double elliptical” chord distribution (basically a simplified model geometry that leads to a span loading typical of real commercial aircraft in landing configuration). Four aspects ratios were investigated for each wing ($A_R = 7.5, 10, 15, 20$), each at five altitudes ($h_0/b = 0.125, 0.25, 0.5, 1.0$ and $\infty$(OGE)). Useful engineering results results were provided for all cases (see Table 4 of D3.1.1-1): $\Gamma_0/\Gamma_0^*$ (ratio of half plane wake circulation, where the * refers to the value OGE), $b_0/b_0^*$ (ratio of wake vorticity centroid spacing), and $f/f^*$ (ratio of finesse, where the finesse here only refers to the lift to induced drag ratio).

2-D direct numerical simulations (DNS) of wake roll-up IGE were then conducted. The previously obtained span loadings were used to determine the wake initial condition used for each DNS. Indeed, even if the vorticity distribution along the vortex sheet is not significantly modified IGE, the effect of the ground proximity on the roll-up itself still needed to be investigated. The cases of the elliptical wing with $A_R = 10$, at $h_0/b = 0.125, 0.25, 0.5, 1.0$, and at $Re = \Gamma_0^*/\nu = 10^4$ were studied. Obviously, the vortex dynamics IGE are completely different from those OGE, due to the existence of secondary vorticity emanating from the separation of the boundary layer. However, if one examines the roll-up process itself, it happens very fast compared to the global vortex-ground interaction, and it is not really affected by the ground proximity, at least for $h_0/b > 0.25$. For those cases, one could likely replace the vortex sheet by the already rolled-up vortex system OGE and obtain roughly the same dynamics. For lower altitudes, it was shown that part of the vortex sheet strongly interacts with the boundary layer before being rolled-up into the primary vortex.

The Reynolds number effect was then also investigated, for the case $h_0/b = 0.25$ at $Re = 5 \times 10^3, 10^4, 2 \times 10^4$ and $10^5$. The effect on the wake vortex 2-D dynamics and topology were discussed. It is however likely that the complex dynamics at high Reynolds observed in those 2-D simulations would not be observed in 3-D: indeed, the separating boundary layer then indeed rapidly becomes unstable in 3-D and does not create those small, high intensity, 2-D secondary vortices; instead they create 3-D small scales, and thus 3-D turbulence (see the results of 3-D simulations in D3.1.1-2). Finally, the case of the double-elliptic wing was also investigated, as it is a realistic model of the span loading for a real aircraft wing in landing configuration, with flaps deflected.
2.2 3-D instabilities of two- and four-vortex systems IGE (D 3.1.1-2)

This deliverable was made of four detailed technical reports. The numerical investigations and the experiments carried in these four studies yield a better understanding on the physics of aircraft wake vortices IGE. High quality visualizations, gained by experiments and numerical simulations, also provide useful information about the behavior of such vortex systems IGE. Quantitative diagnostics concerning vortex dynamics and decay were obtained: they are also of great value to support the operational modeling tasks (Task 3.3). We consider that the target of this first subtask has been achieved: a better understanding and characterization of the physical mechanisms and instabilities of wake vortices put in idealized conditions and interacting with a smooth ground. We here summarize the main outcomes.

2.2.1 3D filament simulations of Crow-like instabilities IGE (TR 3.1.1-1)

The purpose of this work was to investigate two vortex systems (2VS) in ground effect (IGE) and using the vortex filament method (thus inviscid, long wave, wake vortex dynamics IGE: no reconnection of the vortex tubes possible, and no viscous interaction with the ground possible). Two different vortex systems were investigated in the scope of this study.

The first one aimed to reproduce the experiment carried at CNRS-IRPHE: a “thick” vortex pair created IGE and with a forced, long wave, instability (yet shorter than the Crow instability wavelength). The second one concerned aircraft like wake vortices (i.e., thinner vortex cores) IGE and with a forced Crow instability.

The main outcome of the first simulation is a characterization of the long wave-length instabilities in 2VS near the ground. The numerical results (trajectories and development of the instability) are seen to be in good agreement with the experimental ones. This highlights the fact that, up to the viscous reconnection and/or the viscous interaction with the ground, the vortex filament method yields results which are fully consistent with the physics.

The second case concerns aircraft like wake vortices. It allowed to conclude that the long wavelength Crow instability IGE is very similar to that out of ground effect (OGE). The major difference is a modification (by tilting) of the perturbation plane angle when the vortices come under significant influence of their image. They eventually continue the Crow instability with their image only. The growth rate of the Crow mode is seen to decrease during the transient phase, and is found to be the same when out of the transient: when OGE and when the vortices continue the Crow with their image only. Parametric studies were conducted, by varying the initial perturbation level. They allowed to conclude that, for each perturbation level and up to the time of vortex reconnection, the temporal evolution of the perturbation (plane angle, growth rate) is universal.
2.2.2 LES of a two vortex system IGE (TR 3.1.1-2)

In this study, large eddy simulations (LES) of a 2VS IGE were performed. The LES are here “wall-resolved” (as opposed to LES with ad hoc “near wall closure” modeling). The code uses fourth order finite differences and is energy conserving (in absence of viscosity and/or SGS modeling). The Reynolds number was taken as high as possible: \( Re = 20000 \), which is indeed high yet is not very high. Recall that the Reynolds number only affects the slow laminar decay phase of the vortices. The fast decay phase of the vortices starts when the secondary vortices (those generated at the ground and rolling-up around the primary vortices) become turbulent and interact with the primary vortices, leading to a turbulent 2VS IGE: that phase is independent of Reynolds number, at least when \( Re \) is “high enough”. It is believed that \( Re = 20000 \) is indeed high enough, and thus that the fast turbulent decay rate of the 2VS IGE obtained by the present LES is indeed the same as that for wake vortices at higher \( Re \) (and thus also applicable to aircraft wake vortices).

The results show that the subgrid-scale (SGS) modeling strategy plays an important role. Two LES were carried: one using the classical Smagorinsky SGS model, and one using the “filtered Smagorinsky” SGS model (a “multiscale” model, where the local eddy viscosity is computed using only the high frequency content of the local LES field: itself obtained using an efficient grid-based filter). Both models used explicit near-ground damping of the SGS viscosity: something required to ensure that the SGS viscosity has the proper near ground behavior. The impact of the model is indeed found to be significant, on the kinetic energy and on the \( \Gamma_{5-15} \) evolutions. In view of the diagnostics based on energy, circulation and modal energy, the filtered Smagorinsky model, which is based on a flow scales discrimination, clearly outperforms the Smagorinsky model. Indeed, the filtered Smagorinsky model is seen to be inactive during the gentle, laminar phase of the simulation; it only acts where and when required.

A comparison was also done with a direct numerical simulation of the same flow, performed at \( Re = 5000 \) (a DNS: thus a full Navier-Stokes solution, no SGS modeling required). It is found to present strong similarities with the LES at \( Re = 20000 \), also in term of instability mechanisms. However, the secondary and primary vortices interaction at \( Re = 20000 \) generates much more complex tridimensional vortical structures and turbulence. As expected, the high Reynolds number case also leads to a fast turbulent decay phase that happens earlier. The decay rate is also found to be a bit larger; yet, the difference is small. It is thus believed that we have indeed reached, by LES at \( Re = 20000 \), the universal (i.e., valid for \( Re \geq 20000 \)) turbulent decay rate of wake vortices after rebound IGE. It is thus expected that the present LES results (energy and circulation decay rate, vortex trajectories), are representative of what should be expected at values relevant to aircraft wakes. This is also partially confirmed by comparisons to data, measured by lidar, of large aircraft wakes IGE. It is also worth noting that the present results were also most useful to successful work, carried in Subtask 3.3.1, on the improvement of the operational models for wake vortex transport and decay IGE.
2.2.3 LES of a four vortex system IGE (TR 3.1.1-3)

In this contribution, a wall-resolved LES of a wake vortex modeled by a counter-rotating four vortex system (4VS) IGE and at $Re = 20000$ was performed. The parameters are $\Gamma_2/\Gamma_1 = -0.3$ and $b_2/b_1 = 0.3$ (i.e., a canonical case which was also studied in the literature and the FP5 AWIATOR projects for 4VS out of ground effect (OGE)). The SGS model used is a “dynamic mixed model”: here, the local eddy viscosity is computed using the full LES field (thus not multiscale), and the coefficient in front of the model is obtained dynamically (also ensuring a proper near-ground behavior).

The post processing and the visualizations gave a good understanding of the behavior of the 4VS system in terms of vortex dynamics and flow topology. The important conclusion is that the development of the instabilities is different from that in a 2VS. Indeed, at early times, the weaker vortices are deformed by their interactions with the ground and with the stronger vortices. This here leads to the rapid growth of instabilities and to a turbulent 2VS flow before the classical 4VS instabilities (i.e., the so-called “Omega loops” on the weaker vortices) have time to develop. The evolution of $\Gamma_{5-15}$ exhibits a decay at very short time, and the time scale of this decay is smaller than the 4VS in infinite domain. The key mechanism of destruction of the system is the secondary vorticity from the weaker vortices combining (because of same sign) with the secondary vorticity generated at the ground. This vorticity field becomes unstable and produces small scales faster than in the case of the 2VS IGE. Indeed, in the case of the 2VS IGE, the ground generated secondary vorticity orbited more around the primary vortex before becoming unstable). This is confirmed by energy and enstrophy diagnostics.

2.2.4 Water tank experiments on vortex pairs IGE (TR 3.1.1-4) and additional support work on their numerical simulation

The behavior of 2VS IGE was investigated experimentally at various Reynolds numbers in the range $Re = 1900 \ldots 5500$. The experiments were performed in a water-tank where straight uniform vortices were generated by the impulsive rotation of two long flat plates. The generated vortices had a relatively fat core $(r_c/b_0 \approx 0.2)$ compared to real aircraft wake vortices $(r_c/b_0 \approx 0.05$ or less). The behavior of the vortices was studied qualitatively using Laser-Induced Fluorescence (LIF) visualizations as well as quantitatively using Particle Image Velocimetry (PIV) measurements. The experiments were performed using two initial heights: $h_0 = 6 b_0$ and $h_0 = 2 b_0$.

The main part of this work is about the interaction of the vortex pair with the ground, using the initial height $h_0 = 2 b_0$. The observed dynamics is initially two-dimensional and dominated by the rebound phenomenon in agreement with the literature. The trajectories and the time-histories of the circulation were obtained from the PIV measurements. These diagnostics were shown to be Reynolds number dependent. The experiments also clearly showed the development of short-wavelength instabilities on the secondary vortices that quickly make the flow fully
three-dimensional and very complex. Another short-wavelength instability was observed on the primary vortices at the highest Reynolds numbers. This centrifugal-type instability is due to the generation mechanism and is not specific to the interaction with the ground.

The highest initial height was used to validate the generated “initial” flow. It was also used to investigate the development of the Crow instability and the interaction with the ground of the resulting periodic vortex rings.

Numerical simulations of the experiment at $Re = 3500$ were performed by UCL (not funded by FAR-Wake). First, a 2D simulation (using a “vortex particle method” combined with an immersed boundary approach) reproduced the whole experiment including the generation of the vortices by the flapping plates. Second, a 3D DNS (using a code based on 4th order finite differences) was performed using a simplified setup to study the onset of instabilities in the system. The results of the simulations are found to be in very good agreement with those of the experiment, both qualitatively and quantitatively. The rebound trajectory and the time-history of the circulation are correctly predicted. The 3D DNS also shows the development of short-wavelength instabilities on the secondary vortices. Those are elliptic instabilities as revealed by the careful analysis of numerical results. The comparison between the simulations and the experiment was presented at the 18ème Congrès Français de Mécânique. A copy of that paper was put in the deliverable.

2.3 Effect of wind conditions on the evolution of a two-vortex system near the ground (D 3.1.1-3)

This deliverable reported about time-developing large eddy simulations (LES) of a longitudinally uniform two vortex system (2VS) IGE with realistic cross-wind (CW) and head-wind (HW) conditions. These simulations were jointly defined and shared between UPS-IMFT and CENAERO/UCL. Thus, in spite of the fact that the two approaches were different (same approach as in TR 3.1.1-2 for CENAERO/UCL, same approach as TR 3.1.1-3 for UPS-IMFT) in terms of numerical method, grid resolution and sub-grid scale modeling, the initial conditions as well as the post processing tools were the same.

The fully turbulent 3-D wind was itself obtained by LES. It was then supplemented with a 2VS analytically defined and representative of an aircraft wake after the roll-up has been completed. The present approach is thus not trivial: complex, time-dependent, turbulent winds presenting typical mean (i.e., time-averaged) velocity profiles and turbulence statistics profiles are used as the atmospheric system interacting with the 2VS. This is as opposed to the oversimplified (and non-physical) approach where one uses a mean RANS-type wind profile as the atmospheric system interacting with the 2VS. The objective was to significantly improve the physical reality of the LES, and thus also significantly improve the understanding of the

---

1M. Duponcheel, C. Cottin, G. Daeninck, T. Leweke, G. Winckelmans, Experimental and Numerical Study of Counter-Rotating Vortex Pair Dynamics in Ground Effect, 18ème Congrès Français de Mécânique, August 27-31, 2007, Grenoble, France
transport and decay mechanisms encountered in realistic atmospheric wind conditions.

The $R$ parameter is the ratio of the mean wind velocity at the initial height of the 2VS, $U_w(h_0)$, to the initial velocity descent of the 2VS OGE, $V_0$. The other parameter is the initial height, $h_0$, of the 2VS put in the turbulent wind. As for TR 3.1.1-2, all cases investigated were done with $h_0 = b_0$, where $b_0$ is the initial spacing of the wake vortices. The effect of two different cross-winds were investigated by UPS-IMFT ($R = 1$ and $R = 2$) and CENAERO/UCL ($R = 1$). In terms of vortex trajectories, there is a “potentially hazardous situation” as the upwind vortex stays above the runway after rebound; this was the main motivation for focusing on the case $R = 1$ for the cross-wind investigation, by doing two LES. The rebound of the downwind vortex is also more pronounced than that of the upwind vortex (final rebound height significantly higher); it is thus transported a bit faster than the upwind vortex; it could also interfere with a neighboring parallel runway. A head-wind case with $R = 1$ was also investigated by CENAERO/UCL. As for TR 3.1.1-2, those were “wall-resolved” LES, with as high as possible a Reynolds number: $Re = 20000$, which is indeed quite high, yet not very high. Based on the same argument as before, the obtained results are expected to also be representative of what happens for wake at higher $Re$ (and thus also applicable to aircraft wake vortices). Note that, for the case with $R = 1$, the corresponding turbulent wind was well-resolved by the grid (in fact, it was almost a DNS).

For the cross-wind cases, the LES by CENAERO/UCL used a computational box with transverse size $L_y = 8b_0$ (direction of the wind) and longitudinal size $L_x = 4b_0$ (direction of the vortex), and with periodic boundary conditions. The vertical size was $L_z = 3b_0$, with no-slip at the ground and slip at the top. The total number of grid points was 33.6 million. The LES by UPS-IMFT used $L_y = 13b_0$, $L_x = 4b_0$, $L_z = 3b_0$, and the total number of grid points was 15 million. Let’s mention that we do not consider, and thus do not capture, the potential further development of long wavelength Crow-type instabilities IGE (which would require to use $L_x = 8b_0$).

The many results were gathered and analyzed, also outlining of the specific wind effects and the related key mechanisms. They were also usefully compared to the LES results on the same 2VS without wind of TR 3.1.1-3. The quantitative diagnostics, such as the vortex trajectories, circulation evolution and energy evolution were also provided and compared.

The presence of turbulent wind reduces the starting time of the formation of the turbulent secondary vortical structures, as the wind fluctuations trigger the instability of the secondary vortices generated at the ground. There is thus a strong interaction of the primary vortices with these secondary turbulent structures. There is also the engulfment and wrapping, around the primary vortices, of the turbulent wind vortex structures themselves. These effects both reduce the starting time of the fast turbulent decay phase of the 2VS IGE. The turbulent decay rate of the primary vortices is also significantly enhanced by wind effects. This is manifested by the energy and circulation evolutions with time.
For the head-wind case ($R = 1$), we obtain a fast turbulent decay starting time starting at $\tau \approx 1.8$, which correspond to $\approx 0.6$ after the time when the wake vortices are at their lowest position ($\tau \approx 1.2$), and which is faster by $\approx 0.9$ compared to the no-wind case. The decay rate of the vortices is also enhanced compared to the no-wind case. The rebound of the vortices at long times is up to $z/b_0 \approx 1.2 - 1.4$.

For the cross-wind case with $R = 1$, we obtain, for the upwind vortex, a fast turbulent decay starting at $\tau \approx 1.8$, thus $\approx 0.4$ after the time when that vortex is at its lowest position ($\tau \approx 1.4$); for the downwind vortex, we obtain a fast turbulent decay starting at $\tau \approx 1.5$, thus $\approx 0.5$ after the time when that vortex is at its lowest position ($\tau \approx 1.0$). The decay rate of the upwind vortex is similar to that with head wind. The decay rate of the downwind vortex is faster than that of the upwind vortex. The rebound of the upwind vortex at long times is up to $z/b_0 \approx 0.9 - 1.0$; that of the downwind vortex is up to $z/b_0 \approx 1.6 - 1.8$.

For the cross-wind case with $R = 2$, we obtain, for the upwind vortex, a fast turbulent decay starting at $\tau \approx 1.8$, thus $\approx 0.3$ after the time when that vortex is at its lowest position ($\tau \approx 1.5$); for the downwind vortex, we obtain a fast turbulent decay starting at $\tau \approx 1.3$, thus $\approx 0.3$ after the time when that vortex is at its lowest position ($\tau \approx 1.0$). The decay rate of the downwind vortex is again faster than that of the upwind vortex, and also faster than for the case $R = 1$. The rebound of the upwind vortex is up to $z/b_0 \approx 0.7$; that of the downwind vortex is up to $z/b_0 \approx 1.0$: this is less than for the lower wind case; and is is expected due to the relatively more dominant effect of the wind on the wake vortices.

At late times, we observe some differences on the trajectories and circulations obtained from the two LES with cross-wind at $R = 1$. There is only a slight difference for the upwind vortex; but, for the downwind vortex, the two result curves separate after $\tau \approx 3.5$ (which is indeed already quite a long time). Further efforts could spent in order to identify the origin of these differences: further address the effect of the SGS modeling on the turbulence and associated dissipation rate (already partially done in the reporting by CENAERO/UCL, by investigating various SGS models), further address and separate the effects of different mesh sizes (CENAERO/UCL grid was finer than IMFT grid) along with different discretization orders (4th order finite difference for CENAERO/UCL instead of 2nd order for IMFT) leading to different levels of dispersive errors. Given the fact that the UCL/CENAERO code is fully “energy conserving” in absence of SGS modeling and molecular viscosity (i.e., no numerical dissipation), is higher order, and was used with a finer grid, it is likely that the obtained effective results (vortex trajectories and turbulent decay rates) of the 2VS IGE are closer to reality. It should also be mentioned that an twice larger LES of the cross-wind case with $R = 1$ was further carried by UCL (in the framework of the PhD thesis work of L. Bricteux, not funded by FAR-Wake): a LES with $L_y = 16b_0$, using the same code and another advance multiscale SGS model. The results are even better than the present run with $L_y = 8b_0$; yet, globally, they essentially confirm the present global results: both on obtained vortex trajectories and fast decay rates.

It could also be useful to further investigate the height of the computational domain (so far $L_z = 3b_0$). Based on the present results, the “blocking effect” is
likely quite small, except maybe at the end of the simulation, \( \tau = 5 - 6 \) (which indeed corresponds to a very long time), when the downwind vortex has rebounded quite high.

It should also be mentioned that the evaluation of the \( \Gamma_{5-15} \) circulations IGE can suffer of a significant amount of opposite sign vorticity close to the ground being accounted for in the integration, leading to an unclear physical interpretation of that diagnostic. A remedy to that is to use instead the \( \Gamma_{\text{max}} \) diagnostic: the maximum of the \( \Gamma(r) \) circulation profile as measured from the center of the primary vortex; indeed, that definition has the advantage that it only integrates the circulation of the primary vortex. This is why such diagnostic was also computed and reported.

The contributions of each partner, providing all the details about the numerical set-up and the time description of the flow, also using 3-D visualizations and 2-D longitudinally averaged flows, were also provided, as two technical reports (Appendices A and B to the deliverable).

2.4 Quantification of uncertainties in a 2-D vortex pair near the ground with and without cross-flow (D 3.1.1-4)

Stochastic 2D unsteady Navier-Stokes calculations (DNS) of a 2VS evolution IGE were carried and reported. The numerical procedure is based on the “polynomial chaos” representation of the stochastic process. The results include the uncertainty quantification of the 2D velocity field, originated from random perturbations in the initial condition, characterized by a uniform Beta pdf and a coefficient of variability equal to 10% in the initial vortex circulation and in the initial centroid position of one of the vortices. The coupled system of equations resulting from the application of the Polynomial Chaos Expansion Method of random variables to the NS equations requires several modes in the expansion series, yielding at least the solution of 8 systems of momentum and continuity equations comprising 24 strongly coupled differential equations. It is important to stress that “mean” variables here correspond to the ensemble average of a large number of events (each corresponding to a vortex decay with a certain value in the uncertainty range considered).

The output is the “mean” predicted (i.e., most probable) trajectory of the vortices, that can be usefully compared to the trajectory obtained by a deterministic simulation (i.e., that without variability in the initial condition). One also obtains the uncertainty (dispersion) along the most probable vortex trajectory using error bars for a chosen degree of probability (e.g., using confidence intervals for a a 90% degree of probability; one vortex core diameter of error bar being then typical).

Another output is the “mean” predicted vorticity. That one cannot be compared to the vorticity field obtained by a deterministic simulation. Indeed, the ensemble of possible solutions (events) will form large clouds of vorticity related to clustered groups of events. This “mean” vorticity is not a physical field quantity; instead, it is a quantity that contains all possible solutions and displays, at each point, the most probable outcome value for that point.
The point of maximum mean vorticity is the location were it is most probable to find the vortex centroid. Consequently the mean trajectory is defined by these points. The error bar in the vortices trajectory is a measure of the variability along the mean trajectory and is calculated by considering the vortex centroid has a random variable.

A scenario with low level wind shear was also investigated. The crosswind was $1.8 V_0$ above $3.3 b_0$ and zero below $2.0 b_0$, with a linear profile in between. The vortices were generated at $5.0 b_0$. The Reynolds number was $4.4 \times 10^4$. A case where the viscosity of the fluid is randomized using a Gaussian distribution was first investigated, Deterministic and stochastic solutions were obtained and compared. Next, cases where the initial circulation of one vortex is considered to be a random variable (with Gaussian and Beta probability density functions) were considered. Deterministic and stochastic solutions were also obtained and compared. Finally, the shape of the transition profile was also varied, using an exponential type profile with stochastic parameter.

The uncertainty quantification originated from initial circulation, initial vortex position and cross wind velocity profiles were then revisited in a more systematic way. A variability of the random input of 10% was considered, with a uniform probability of occurrence.

First, a vortex pair evolution IGE without cross-wind was reconsidered. The initial height was $h_0 = b_0$. The computational domain was $L_y = 8 b_0$ and $L_z = 3 b_0$. The deterministic (symmetric) evolution was first computed. Stochastic evolutions were then performed: one with random initial circulation of one vortex (using a uniform (Beta) initial circulation for the left vortex, with a coefficient of variation equal to 10%), another one with random initial vertical position of one vortex (using a uniformly distributed random variable with 10% variation for the left vortex). The deterministic results were compared to the stochastic ones. The uncertainty in the prediction of the trajectories was found to be, in general, of the order of $2 r_c$.

Next, the case of the vortex pair evolution IGE with cross-wind was considered, using a mean (i.e., time-averaged) turbulent wind with log profile and having $U_w(h_0) = V_0$ (and wind uniform profile above $h_0$). The same cases as previously were computed: one with random initial circulation of the upwind vortex, one with random initial vertical position of the upwind vortex.

Finally, the case of a random crosswind velocity profile was considered, also with a 10%; this case is obtained by simply scaling locally the mean profile, which means that the uncertainty is proportional to the local velocity. It is found that the random input affecting most the results is the crosswind itself: its variation is able to here “destroy”, after some time, the obtained “mean vorticity” structures, meaning that a high dispersion of the vortex most probable position occurs.
2.5 Dynamics and decay of spatially-developing two- and four-vortex wakes near the ground (D 3.1.2)

That deliverable reports on the achievements of the work done in the second subtask, Subtask 3.1.2. It is made of four detailed technical reports. We here summarize the main outcomes.

2.5.1 Delivery of Airbus proprietary wake data measurements IGE (TR 3.1.2-1)

A CD-ROM with Airbus proprietary wake data from the B747 IGE measurements at Frankfurt airport was delivered. Its use is limited to work within FAR-Wake.

2.5.2 Towing tank PIV measurements on two- and four-vortex systems IGE (TR 3.1.2-2)

The spatial-temporal flow evolution of 2- and 4-vortex systems in ground proximity was investigated performing flow velocity field measurements in a towing tank. The F13 model consisting of one or two rectangular wings was used as vortex generator and is towed along an adjustable ground plate at specific heights of $h_0/b = 0.5, 0.25$ and $0.125$ with respect to the trailing edge of the main wing. Three different vortex configurations were investigated; i.e. a 2-vortex-system and two 4-vortex systems consisting of two co- and counter-rotating vortex pairs with a span width ratio of $b_2/b_1 = 0.3$ and circulation ratios of $\Gamma_2/\Gamma_1 = \pm 0.3$. A Stereo Particle Image Velocimetry setup was employed to determine the flow velocity fields in a cross plane through which the F13 model is moving.

The flow fields are analyzed with respect to flow separation at the ground, the generation of secondary vortices and the spatial-temporal development of the wing tip vortex trajectories and their circulation strengths. The Q-criterion is applied to the PIV data to identify the vortex core regions within the instantaneous velocity fields. The positions of the vorticity centroids are evaluated from the vortex core areas and are used as definition for the vortex center. The trajectories of the vortices are obtained by tracing the vortex centers in the wake vortex system evolving in time. The vortex circulation profile, $\Gamma(r)$, is evaluated by integrating the out-of-plane vorticity component in a circular area with radius $r$ centered at the core position. Adapting a common method to evaluate the circulation of wake vortices from field data, a mean value of the vortex circulation $\Gamma_{5-15}$ is then obtained from radially averaging over $1/12 \leq r/b \leq 1/4$.

When a counter-rotating vortex pair shedding from a wing producing positive lift approaches a ground their lateral spacing begin to spread. The lateral velocity of the vortices increases with decreasing altitude. Therewith, the width of the towing tank limits the maximum time frame up to which wall effects can be assumed to be negligible; i.e., the distance between the vortex core and the walls should be larger than $b$. This leads in the current case to a maximum observable vortex age of $\tau = \ldots$
$t/t_0 = 0.15$ to 0.9 depending on the initial altitude.

The interaction of the flow induced by the tip vortex with the ground was exemplarily described for the case of the 2-vortex system and $h_0/b = 0.25$. A flow separation and its re-attachment can be observed after the outboard directed flow having passed the vortex center. This flow structure enlarges in time, generating small scale vortices which are entrained by the vortex of opposite sense of rotation. The analysis of the vortex trajectories shows how the outboard directed lateral movement of the vortices depends on the vortex circulation and altitude. Also, the inner vortices of the 4-vortex systems are strongly influenced by the ground already at altitudes of $h_0/b = 0.5$. Without ground proximity, the inner vortices start to orbit around the tip vortices for the investigated case of $\Gamma_2/\Gamma_1 = 0.3$ and $-0.3$. This is no longer the case when the vortices come into ground proximity. The results for $h_0/b = 0.5$ show that the inner vortices are forced to reduce their separation distance according to their opposite sense of rotation. After some time, both inner vortices cancel out each other. Nevertheless, the inner vortices induce a higher decent speed of the outer vortices, which results in differences between the vortex trajectories of the 2- and 4-vortex systems. These differences vanish for lower values of $h_0/b$, also in the case of the 4-vortex system consisting of two co-rotating vortex pairs.

2.5.3 Towing tank visualizations of two-vortex systems IGE (TR 3.1.2-3)

The case of a space-developing wake vortex pair, generated by a generic rectangular wing model with a Wortmann FX63-137B-PT (F13) profile, was investigated in a towing tank, at a moderate, yet significant, Reynolds number ($cU_\infty/\nu \approx 40000$ and $\Gamma_0/\nu \approx 32000$). The wing span is $b = 24.8$ cm and the wing chord is $c = 4.0$ cm (aspect ratio $A_R = 6.2$). The configuration studied was a wake vortex pair generated by the wing model following a constant altitude track, at a constant velocity above the ground. Three different altitudes of wake generation IGE were investigated: $h_0 \approx 0.5b_0$, $0.25b_0$ and $0.125b_0$ (the reference length scale, $b_0$, being the vortex spacing as measured experimentally out of ground effect (OGE)). Laser Induced Fluorescence (LIF) visualizations were performed in order to study qualitatively the dynamics of both the primary vortices and the secondary vortices due to the separating boundary layer at the ground. Volume and two-dimensional visualizations were presented, as well as primary vortex trajectories.

The mechanism of boundary layer separation with opposite sign vorticity, subsequently orbiting around the primary vortices and leading to vortex rebound and transition of the whole vortex system to turbulence, is clearly observed. The vortex trajectories also show the effect of the initial altitude on the vortex dynamics. For $h_0 \approx 0.5b_0$, a phase of vortex roll-up occurs, during which the primary vortex circulation increases and the observable vortex separation distance decreases. For $h_0 \approx 0.25b_0$ and $0.125b_0$, no clear roll-up phase is observed, showing that the process is affected by the ground: in that case, the primary vortices are transported away from each other as soon as they are generated, and they rebound higher than
their altitude of generation. These observations are in good agreement with results presented in D 3.1.1-1 “Span loading variations and wake roll-up in ground effect”.

A notable observation is the rapidity of the dynamics, leading to transition to turbulence (boundary layer separation, interaction of secondary vorticity with the primary vortices). These observations are also in good agreement with results presented in TR 3.1.1-2 “LES of two-vortex system in ground effect”. The level of turbulence observed in the secondary vorticity that separates from the ground and orbits around the primary vortex is however higher than in the LES (recall that these were spatially uniform LES, and with a low level amplitude initial perturbation). The primary vortex core is seen to remain coherent.

The dynamics IGE are also somewhat accelerated when the vortices are generated at the lower altitudes. In particular, a propagating perturbation, occurring much earlier than for typical “end-effects” as observed OGE, and leading to some “bursting” of the primary vortices is also observed. This can likely be explained by the space-developing nature of the flow: at any given time, the vortex wake being tilted with respect to the horizontal ground, its far part is interacting strongly with the ground before its near part is: there is thus a longitudinal perturbation that propagates along the primary vortex, following the wing at the same speed. These observations are in good general agreement with findings presented in TR 3.1.2-4 “LES calculations of spatially evolving wakes in ground effect”.

The space-developing wake dynamics IGE are thus found to be similar to the longitudinally uniform ones during the initial (essentially two-dimensional) phase, and then becomes rapidly quite different as three-dimensionality is developing, with some additional vortex bursting and a faster transition to turbulence.

### 2.5.4 LES calculations of spatially evolving wakes IGE (TR 3.1.2-4)

The case of a space-developing wake generated by an elliptical wing IGE was investigated at a moderate, yet significant, Reynolds number ($\Gamma_0/\nu \approx 10000$) using the large-eddy simulation (LES) approach with advanced subgrid-scale (SGS) modeling (a multiscale model where the effective subgrid viscosity only acts on the high frequency content of the local LES field: itself obtained using an efficient grid-based filter). The wing aspect ratio was $A_R = 6.0$ and the wing was flying at an altitude of $h_0 = 0.25b$. The span loading was obtained using the lifting line theory IGE, thus taking into account the image vorticity below the ground (procedure reported in D 3.1.1-1 “Span loading variation and wake rollup in ground effect”). The vortex sheet shed from the wing was obtained from that span loading, without axial velocity model added. The code is based on an efficient approach where the eulerian-lagrangian vortex-in-cell (VIC) method is used on a very compact grid (one that tightly contains the vorticity field), itself composed of multiple domains (i.e., a parallel domain decomposition method), and where the parallel fast multipole (PFM) method, which has a global view of the entire vorticity field, is used to efficiently obtain the exact boundary condition on each subdomain. The Poisson equation to obtain the streamfunction (and thus the velocity field) from the vorticity field is
solved using a fast Poisson solver and those boundary conditions. In the present case, the VIC-PFM method is further enhanced to take into account the ground, the inflow condition (vorticity of inflow vortex sheet and lifting line wing) and the outflow condition (vorticity downstream of the computational domain). The length of the computational domain was \( L_x = 12.5b \). The vortex sheet was regularized, using convolution with a gaussian regularization. The grid size was \( h = 0.010b \) and the total number of grid points was 50 million.

For comparisons, the exact same vortex wake was also investigated in a longitudinally uniform configuration (i.e., a temporal simulation with \( L_x = 4.0b \) and periodic boundary conditions; as opposed to inflow and outflow boundary conditions) using the same VIC-PFM code and SGS model. The two simulations were performed up to fully developed turbulence.

It is important to stress that, in order to limit the required extent of the computational domain of the space-developing simulation to \( L_x = 12.5b \) (which already requires 50 million grid points!), we had to artificially increase the lift coefficient to \( C_L = 6.0 \). A more realistic simulation with \( C_L = 1.5 \) would require a four times longer computational domain, and thus a four times larger computational grid (something that was not affordable at the time, given the computational and human resources available; yet something that is doable with the VIC-PFM code). The wake is thus artificially more tilted with respect to the horizontal, as the ratio \( V_0/U_\infty \) is four times larger than the typical value. This means that the space-developing nature of the flow with respect to the ground is also artificially enhanced.

Finally, a 2-D direct numerical simulation (DNS, thus all scales resolved, no need for SGS modeling) of the same case was also performed, as a baseline, using a 2-D vortex particle method with flat ground.

For each configuration, the properly averaged vorticity field, vorticity fluctuation field, and axial velocity field were presented and discussed. The flow topology evolution was also analyzed for the 3-D configurations. Finally, the time evolution of diagnostics characterizing the wake dynamics were presented: trajectories, circulation, energy, etc.

The results show that, in the initial phase, the flow is essentially two-dimensional: during that phase, the 3-D results match very well with the 2-D reference configuration. One important feature, that is only present in the space-developing configuration, is the axial velocity defect obtained in the primary vortices, due to the fully 3-D nature of the rollup IGE. Moreover, as the vortex tubes are not parallel, this triggers some kind of “vortex system meandering” when the secondary (ground generated vortices) have completed about one turn around the primary vortices: this is clearly seen in animation of the 3-D vorticity field. Finally, the vortex wake being tilted with respect to the ground, its far part is interacting strongly with the ground before its near part is; hence the far part is getting turbulent before the near part is, and there are longitudinal perturbations that propagates along the primary and secondary vortices, following the wing at the same speed. These observations are in good general agreement with findings in TR 3.1.2-3 “Towing tank visualizations of two-vortex systems in ground effect”. The space-developing
wake is also seen to produce much more complex 3-D interactions with the ground than the longitudinally uniform wake. It therefore also exhibits an earlier and more violent transition to turbulence.

Some important features of wakes generated IGE and at low altitude can thus only be properly taken into account using a space-developing configuration. This is likely less required for wakes generated IGE but at higher altitude, as the wake non-horizontality then has relatively less importance. While the present results show some large differences between the space-developing and the longitudinally uniform configurations, one must remember that the investigated case is extreme (due to its artificially very high lift coefficient and to its close distance to the ground). Longitudinally uniform wake simulations IGE certainly remain a valid tool for investigating wakes generated at higher altitude (say \( h_0 \geq 0.5b \)). Note also that it simply would be near impossible to perform a space-developing simulation with realistic lift coefficient for such a wake. The space-developing simulation with realistic lift coefficient and \( h_0 = 0.25b \) is expensive but doable, using about 200 million grid points.
3 Dynamics and decay in real conditions (T 3.2)

Aircraft wake vortex field measurement data are analyzed, which were acquired by DLR in the WakeFRA campaign accomplished at Frankfurt airport during August and September 2004. The excellent support and work of the teams from Airbus, DFS Deutsche Flugsicherung GmbH, Fraport AG, and METEK GmbH during and after the measurement campaign is greatly acknowledged.

A total of 282 wake vortex pairs generated in ground proximity by aircraft during final approach to the closely spaced parallel runways 25L and 25R were analyzed in detail by DLR. Results have been published in the Journal of Aircraft and at an AIAA Conference. The nominal height of the aircraft passing the measurement plane of the pulsed LIDAR was 55 m (runway 25L) and 61 m (runway 25R). The data-set is quite unique since it also combines very nearby measurements of the DFS wind-line and a SODAR/RASS wind/temperature profiler. Together with runway-log information, this provides a high quality data-set for statistic wake vortex transport and decay analysis as well as for improved modeling of WV rebound in ground effect in the presence of cross-winds up to 5 m/s.

In good agreement with literature the vortices reach a minimum average height of 0.59 initial vortex spacings above ground. The analysis of wake vortex behavior in ground proximity reveals that the vortex decay rate is increased by the interaction with the ground at about 0.2 non-dimensional time units after the vortices have reached the minimum height.

A clear correlation between ambient turbulence and vortex decay is found. Crosswind shear merely introduces a slight asymmetry in the decay rate. Both effects are weak and difficult to verify. On the other hand, the impact of crosswind shear on vortex rebound characteristics is very strong. Crosswind shear attenuates (intensifies) the formation of the luff (lee) secondary vortex which causes pronounced asymmetric rebound behavior. The impact of crosswind shear on wake vortex evolution can be characterized by crosswind measurements at altitudes of $z = 10 \text{ m}$, 0.6 vortex spacings, or even higher altitudes. Crosswind strength corresponding to the initial descent speed of the vortices is sufficient to trigger the observed asymmetry.

A conservative estimation of a threshold for runway clearance based on 10-min averaged crosswind magnitude measured between the runways at a standard height of 10 m amounts to 2.5 m/s for a 5 NM aircraft separation and 3.3 m/s for a 2 NM separation. Particular cases demonstrate that vortex interactions with jet-like shear layers situated above the vortices are likely to increase the rebound height. The maximum observed rebound height amounts to 2.6 initial vortex spacings. Also obstacles like parking aircraft or buildings may deflect wake vortices to higher rebound altitude. Here the maximum height reached is two vortex spacings.

In an accompanying study, using a sub-set (B747 wakes only) of the same dataset as used by DLR, NLR investigated the vortex transport and decay in relation to

crosswind, atmospheric turbulence and thermal stratification of the atmosphere. NLR entirely focussed on the data as such, without referring to correlation with a specific vortex prediction model. The following main conclusions are drawn:

- The vortices do rebound at an altitude (the lowest observed altitude before rising again) between about 17 and 40 m.
- Depending on crosswind magnitude the downwind vortex tends to rebound at a higher altitude than the upwind vortex.
- The rebound height difference between upwind and downwind vortex increases about linearly with crosswind magnitude (about 2.5 m height difference per m/s crosswind).
- The mean lateral displacement velocity of the vortices correlates quite well with the crosswind magnitude.
- Due to the ground effect, the downwind vortex travels faster than the upwind vortex.
- The effect of atmospheric turbulence and atmospheric stability on vortex decay seems to be rather weak in these NGE data.
- In a few cases with relatively small crosswind, very high rising vortices were observed (well above the ILS flight path). It remains unclear why in other cases with seemingly similar low wind conditions, the vortex trajectories can be very different.
- In a few cases, the downwind vortex created at runway 25L almost traveled to runway 25R. Based on the present data, vortices are expected to travel to the other runway (separated by 518 m), while still having a substantial circulation, when the crosswind becomes larger than about 5 m/s.

In addition an inventory was made with the much poorer quality selected data from Memphis database. This confirmed the asymmetric rebound behavior in crosswind, as observed in the Frankfurt data.

The studies of NLR and DLR provide complementary and fully consistent results of the dynamics and decay of wake vortices in real conditions.
4 Assessment and advanced real-time modeling (T 3.3)

Task 3.3 constitutes the logical “conclusion” process: assessment and advanced real-time modeling: assessment/evaluation of the findings of Task 3.1 and Task 3.2, and translation of the synthesized knowledge into the advanced models for real-time prediction of WV behavior (transport and decay) NGE and IGE.

First, it is worth stressing that the conclusions drawn in T 3.2 concerning wake vortex behavior IGE are in very good agreement with the conclusions drawn from the advanced LES studies carried in T 3.1 (see TR 3.1.1-2 and D 3.1.1-3). The differences between upwind and downwind wake vortex behavior when there is cross-wind is however more marked in the simulations (e.g., the slight difference in the rapid decay rate in case of low wind, the marked difference between vortex rebound height in case of low wind). This is as expected: indeed, since the wake vortices are more turbulent in reality than in the LES when they are at height $b_0$ (recall that the LES used, as initial condition analytical wake vortices, thus not turbulent, put in a turbulent wind at a height $b_0$), the differences in behavior, which are dominated by the additional turbulence generated IGE due to the interaction of the vortices with the ground and with the wind, are less marked.

The results of T 3.1 and of T 3.2 were thus used in a complementary, and also non-contradictory, way in T 3.3.

DLR and UCL have each developed real-time tools to predict the wake vortex transport and decay, also NGE/IGE: respectively the Deterministic/Probabilistic Two-Phase wake vortex models (D2P/P2P) of DLR; and the Deterministic/Probabilistic wake Vortex Models (DVM/PVM) of UCL. These softwares aim to predict, in real-time, the transport and decay of the wake vortices in one computational gate (“i.e., one slice of space along the flight path”) generated by a given aircraft in given meteorological conditions.

In the Framework of the T 3.3, the ground proximity modeling of the two softwares has been improved. This improvement was supported by the data of the Airbus-funded measurement campaign performed by DLR (WakeFRA, 2004) of wake vortices generated by large aircraft close to the ground and respective environmental conditions, and analyzed in the framework of T 3.2; and by the results of Large Eddy Simulations (LES) of a two-vortex system IGE, with and without wind, performed by CENAERO/UCL and UPS-IMFT within T 3.1. Note that only the B747 cases of the WakeFRA 2004 database were made available to UCL. The database also enabled an assessment of the models, once improved and calibrated (also using a subset of the database).

4.1 Improvement of the D2P/P2P

The P2P of DLR considers all effects of the leading order impact parameters: aircraft configuration (span, weight, velocity and trajectory), wind (cross and head components), wind shear, turbulence, temperature stratification and proximity of
the ground. For the prediction of circulation, the concept of two-phase circulation decay is pursued. The turbulent diffusion phase is followed by a rapid decay phase. OGE, the onset time of rapid decay depends on ambient turbulence and stratification and the respective decay is adjusted by an “effective viscosity”.

To consider spatio-temporal variations of vortex position and strength, which are primarily caused by turbulent transport and deformation processes, the probabilistic wake-vortex model predicts the wake-vortex behavior within defined confidence intervals. For this purpose, the decay parameters are varied in consecutive model runs and various static and dynamic uncertainty allowances are added which consider the increased scatter in turbulent environments and modified trajectories caused by tilting and rebound in wind shear situations. The obtained probabilistic envelopes can be adjusted to represent selected degrees of probability. The respective envelopes are estimated based on a training procedure that relates the predicted envelopes to field measurement data. The deterministic model version D2P provides mean wake vortex evolutions employing intermediate decay parameters.

Based on the Frankfurt measurements, the dependence of decay parameters (onset time and effective viscosity) on ground proximity, crosswind and EDR have been studied and the model consequently adapted. Compared to wake vortex predictions out of ground effect, the rapid-decay phase appears to progress slower.

The effect of the ground on vortex trajectories in P2P is modeled using image vortices and counter-rotating ground effect vortices. The altitude and circulation of these secondary vortices have been related to the crosswind. A distinction has been made between the upwind and the downwind vortex to model the effect of the crosswind shear. The D2P model was also extended for the prediction of vortices generated at heights below one initial vortex spacing. The parameters for the generation of the secondary vortices (altitude and circulation) were adapted.

The performance of the suggested GE parameterizations has been evaluated using statistics of the deviations between LIDAR measurements and respective deterministic predictions. It evaluates the root mean square deviations of measurement and prediction of the lateral and vertical position and for the circulation for each overflight. From the distribution of rms values, the median and the 90th percentile are used to characterize the performance of the different parameterizations.

Comparison to wake predictions out of ground effect indicates that the rapid-decay phase progresses slower, in ground effect wake vortex evolution can be predicted with improved accuracy, and fair prediction skill requires only limited environmental data.

### 4.2 Improvement of the DVM/PVM

The DVM of UCL is based on the Method of Discrete Vortices (MDV): a method which uses discrete vortex “particles” (so-called vortex “blobs”) to represent the wake vorticity field. It integrates, in time, various physical models so as to forecast the transport and decay of the vortices. It also includes a time-to-demise evaluation
model (taking into account the atmosphere turbulence and stratification) and a two-phase decay model (various models available: EDR-based and TKE-based). The near-ground effects (NGE) are captured by using image vortices below the ground. The IGE model employs new (i.e., secondary) vortex particles that are generated close to the ground due to the no-slip condition (and, of course, their images below the ground) and that separate from the ground region at a dynamically computed location, modeling the separation of the wall boundary layer induced by the primary wake vortices IGE. It also includes a wind shear model that captures the effects of the non-uniform wind shear on the vortices (mainly a tilting effect). Finally, it includes a model for the stratification effects, using a two-equation model that acts on both the transport and the decay of the wake vortices.

Because probabilistic modeling and assessment of wake vortices is what is operationally required, an upper software layer was also developed by UCL, i.e. the Probabilistic wake Vortex Model (PVM). It is based on a Monte-Carlo approach, using the DVM as a subtool. For each probabilistic run, several deterministic runs are computed, with variations on the impact parameters (i.e., met. conditions, aircraft characteristics and physical model coefficients). Using also resampling techniques, a statistical analysis (e.g., PDF, mean, variance, confidence interval) is then performed on the deterministic result samples. The PVM can thus provide, as a function of time, an envelope for the wake vortex characteristics (lateral and vertical position and circulation) corresponding to a certain degree of probability.

The previous version of the DVM already contained an IGE model, employing secondary vortex particles generated close to the ground, and that separate from the ground region at a dynamically computed location, modeling the separation of the wall boundary layer induced by the primary wake vortices IGE. These secondary vortices interact with the primary ones and induce the rebound. This model was however much improved in T 3.3. First, there was an improvement of the dynamically computed location for the separation of the secondary, ground-generated, vortex particles. Second, an improved modeling of the wind and of its associated turbulence in the region close to the ground was implemented, which allows to obtain a good estimation of the turbulent wind EDR (used in the EDR-based decay model) even when no measurement data are available. Third, a new model was developed to properly model the highly enhanced decay of the primary vortices after rebound, due to the strong turbulent interaction between the primary vortices, the secondary vortices (that also become turbulent), and the wind; that model was implemented using a new “Particle Strength Exchange” (PSE) approach. Fourth, and in order to represent more correctly the evolution of the secondary vortices interacting with the primary ones long after their generation, a further redistribution of the secondary particles around the primary vortices was also implemented. All these developments represent the new, improved, IGE model in the DVM: it is now capable of capturing accurately, and for long times, the transport of the wake vortices IGE together with the much enhanced decay of the vortices after rebound.

The analysis reported in D 3.1.1-1 showed that the wake roll-up process itself happens very fast compared to the global vortex-ground interaction, and is not really affected by the ground proximity, at least for $h_0/b > 0.25$. For those cases, one can replace the near wake vortex sheet by the already rolled-up vortex system as
if it were OGE, and obtain roughly the same dynamics. This is what is done in the
DVM: the primary vortices are then represented by one vortex particle (one vortex
blob), with an effective core radius typical of real aircraft (e.g., $r_c/b \approx 0.04$, this
can be changed). For wake generated at lower altitudes, it was shown in D 3.1.1-1
that part of the vortex sheet strongly interacts with the ground generated boundary
layer before being rolled-up into the primary vortex. That case can also be properly
modeled by the DVM: instead of using a roll-up vortex as initial condition, one uses
a vortex sheet discretized using multiple vortex blobs (e.g., typically 50). The sheet
then rolls up IGE, also interacting viscously with the ground, through its interaction
with the secondary vortex particles.

The new IGE model was first calibrated based on the LES results of D 3.1.1-2
without wind (specifically TR 3.1.1-2) and of D 3.1.1-3 with wind (two cross-wind
cases and one head wind case). It was then also calibrated on a subset of the
Frankfurt database LIDAR measurement results.

The new IGE model was then assessed on the whole database. The results re-
ported also provide, for the deterministic results, the rms of the “deviation” between
the LIDAR data (here assumed exact, which is not necessarily the case) and the
DVM results, as a function of time, for both vortex trajectories and vortex circu-
lations. The DVM results with the improved IGE modeling are seen to agree very
well with the database results, for the measured times (i.e., here up to 110 s; times
above being not considered for validation due to the too low number of available
cases). They are also seen to agree very well with the LES results up to the end of
the simulations (i.e., up to $\tau \approx 5 - 6$, which is quite long, typically something like
150 – 180 s).

Furthermore, in order to also highlight the good agreement of the probabilis-
tic results with the measurements, the percentage of measurement points inside
their corresponding 99.7% percentile envelope, as predicted by the PVM, were also
reported, as a function of time.