Abstract:

This report delineates operational scenarios that shall be investigated with WakeScene-D to contribute to the definition of safe separation distances for takeoff and departure and to the required quantitative safety assessment. For this purpose the report first recapitulates the findings obtained from the analysis of the measurement campaigns EDDF-1 and EDDF-2 and from preliminary Monte Carlo simulations conducted with WakeScene-D. The suggested scenarios can be split into (i) sensitivity analyses and validation cases that shall deepen the understanding of WakeScene-D and the confidence into the software package and into (ii) scenarios serving as a reference representing the current situation and the target scenarios for crosswind reduced separations and the related safety case. A ranking of the relevance of the various possible scenarios has been established with input from CREDOS partners.
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EXECUTIVE SUMMARY

This report delineates operational scenarios that shall be investigated with WakeScene-D to contribute to the definition of safe separation distances for takeoff and departure and to the required quantitative safety assessment. For this purpose the report first recapitulates the findings obtained from the analysis of the measurement campaigns EDDF-1 and EDDF-2 and from preliminary Monte Carlo simulations conducted with WakeScene-D. The suggested scenarios can be split into (i) sensitivity analyses and validation cases that shall deepen the understanding of WakeScene-D and the confidence into the software package and into (ii) scenarios serving as a reference representing the current situation and the target scenario for crosswind reduced separations and the related safety case. A ranking of the relevance of the various possible scenarios has been established with input from CREDOS partners.
INTRODUCTION

This report delineates operational scenarios that shall be investigated with WakeScene-D to contribute to the definition of safe separation distances for takeoff and departure and to the required quantitative safety assessment. The WakeScene-D software package (Wake Vortex Scenarios Simulation Package for Departure) has been developed for comprehensive airspace simulations of takeoff and departure (Holzäpfel et al., January 2008). WakeScene-D consists of modules that model traffic mix, aircraft trajectories, meteorological conditions, wake vortex evolution, and potential hazard area. The software package estimates the probability to encounter wake vortices in different traffic and crosswind scenarios using Monte Carlo simulation in a domain ranging from the runway to an altitude of 3000 ft above ground.

The current report first recapitulates the findings obtained from the analysis of the measurement campaigns EDDF-1 and EDDF-2. The measurement data were analysed by DFS, DLR and UCL employing different assumptions on the safety corridor definition and size, confidence levels, and crosswind measurement sources and definitions. Nevertheless, the analyses of the three institutions consistently yield crosswind thresholds on the order of 4 m/s to make sure that the wake vortices have escaped a safety corridor at a vortex age of 60 s. A quantification of the related risks is out of the scope of these investigations.

Next this report describes results of preliminary Monte Carlo simulations conducted with WakeScene-D. These simulations indicate an efficient reduction of encounter frequencies by strong crosswinds at low altitudes. However, for a 60 s aircraft separation the remaining encounters are on average more severe due to the reduced time for vortex decay compared to the ICAO 120 s separation. Also encounters at altitudes above 1200 ft gain importance with increasing crosswind velocities. Nevertheless, these preliminary investigations tentatively support the 4 m/s crosswind threshold derived from the analysis of measurements. However, further investigations with WakeScene-D are necessary to confirm that value. Basically, the quantification of the related risks is only possible with VESA (Vortex Encounter Severity Assessment) which allows determining the severity of the encounter situations found with WakeScene-D.

The report also includes a description of the context, the parameters, and the parameter ranges for which the different sub-models of WakeScene-D were validated. The established listings shall make sure that the simulation scenarios comprise only situations for which the employed sub-models are valid.

The departure scenarios suggested for investigation in this report can be split into four categories: (i) sensitivity analyses regarding the effects of the different models and parameters that shall deepen the understanding of WakeScene-D and, herewith, the confidence into the software package. (ii) A validation exercise employing statistics of the EDDF-2 measurement data. (ii) Reference scenarios representing the current situation to which CREDOS operations can be compared. (iv) The actual target scenarios for different crosswind thresholds and reduced departure separations.

The subsequent investigations with VESA will focus on determining the severity of encounters detected with WakeScene-D for the reference situation and the target crosswind thresholds and aircraft separations. Details of the set-up of VESA and the interface to WakeScene-D are not described in this report.

The current suggestions of scenarios result from discussion within WP3 and from a joint WP3/ WP4 meeting in Oberpfaffenhofen on 5 December 2008. The list of simulations that could be performed and analysed is quite long. Because it is not clear whether it will be possible to investigate all these scenarios and potentially additional scenarios, a ranking of the relevance of the various possible scenarios has been established with input from CREDOS partners. Even if finally all scenarios could be investigated, the ranking should be useful, because it provides guidance regarding the relevance of the different investigations.
1. THE CURRENT STATUS

In this section we briefly describe the results obtained from the analysis of the measurement campaigns EDDF-1 and EDDF-2 conducted at Frankfurt airport. Further we delineate the findings achieved so far with WakeScene-D. Note that some previous work has been conducted in order to identify the possible range of wake vortex encounter scenarios/encounter parameters during the takeoff phase (Schwarz and Holzäpfel 2007).

1.1. EDDF-1 MEASUREMENT DATA

The EDDF-1 data base contains measurements of wake vortices of heavy aircraft that were mainly generated within a height range extending from 100 m (1.5 - 3 spans) to 400 m (6 - 12 spans) above ground. DLR has derived a safety corridor width of ± 74.3 m from the first vortex position measurements which were extrapolated to the time of vortex generation employing a 2σ (95.4%) confidence level (Dengler and Wiegele 2008). Winds at 10 m altitude were measured with an ultrasonic anemometer and winds at 100 m altitude were characterized with a SODAR. For 60 s old vortices the necessary crosswinds at 10 m (100 m) altitude amount to 3.9 m/s (4.0 m/s) in order that 95.4% of the vortices have left the safety corridor. For 120 s old vortices the necessary crosswinds at 10 m (100 m) altitude still amount to 3.2 m/s (3.0 m/s). The latter result demonstrates that criteria referring to the escape time from safety corridors are not directly related to the current situation enforced by ICAO.

1.2. EDDF-2 MEASUREMENT DATA

The EDDF-2 data base contains measurements of wake vortices that were generated by medium and heavy aircraft within a height range extending from the ground up to four wing spans (140 m). DFS has evaluated the crosswinds needed to transport 97.5% of the wake vortices measured with lidar out of runway centred safety corridors with dimensions of ± 50 m and ± 100 m for a range of vortex ages (Konopka and Fischer, 2008). The analysis discriminates between heavy and medium weight class vortex generators and four crosswind sources: surface winds measured by standard instrumentation at 10 m altitude, WTR/RASS averaged between 60 and 200 m, lidar averaged between 0 and 200 m, and lidar averaged over the altitude range in which the vortices evolved.

For the ± 50 m (± 100 m) corridor, medium generators, and 60 s old vortices the necessary crosswinds vary between 2 m/s and 4.5 m/s (2.8 m/s and 5.2 m/s) depending on the crosswind source. For the ± 50 m (± 100 m) corridor, heavy generators and 60 s old vortices the necessary crosswinds vary between 3.3 m/s and 5.6 m/s (4 m/s and > 6 m/s) depending on the crosswind source. The smallest crosswind thresholds are achieved based on lidar data which were averaged over the altitude range in which the vortices evolved, the highest crosswind thresholds result from the WTR/RASS data.

For the analysis of the same data set UCL employs five different crosswind definitions which are all based on lidar crosswind data but distinguish different heights and height ranges (De Visscher et al., 2008). They provide a framework which allows estimating crosswind thresholds needed to blow 90%, 95% or 99% of the vortices out of a safety corridor of arbitrary dimensions. For example, for the ±100 m corridor and a 99% confidence level, 4.4 m/s are needed for a 60 s aircraft separation time based on 10 m lidar crosswind, and 3.4 m/s for a 90 s separation.

Further, UCL estimates the impact of crosswind combined with different total wind magnitudes on circulation decay. As reference scenario (120 s aircraft separation) they choose wind speeds below 5 knots measured at 10 m. For example, a crosswind of 8 knots (4.1 m/s) combined with a wind magnitude of 14 knots is sufficient to reduce the observed circulation distributions below the reference scenario. Note however strong winds combined with high turbulence levels do not only reduce wake
vortex lifetimes but also the ability of the lidar to track wake vortices and estimate their circulation.

1.3. CONCLUSIONS FROM DATA ANALYSES

DFS, DLR and UCL employ different assumptions on the safety corridor definition and size, the employed confidence levels, and the crosswind measurement sources and definitions. Further, different height ranges are considered in the EDDF-1 and EDDF-2 campaigns. Nevertheless, the analyses of the three institutions consistently yield crosswind thresholds on the order of 4 m/s to make sure that the wake vortices have escaped a safety corridor at a vortex age of 60 s with a high probability based on good quality wind measurements (more or less within the observation plane of the vortices). Only UCL also considers the effect that on one hand 60 s old vortices have less time to decay but on the other hand the stronger wind supports the decay. None of the studies does attempt to quantify the related risks and to set the risks into relation to the ICAO reference scenario.

1.4. WAKESCENE-D SIMULATION DATA

The WakeScene-D software package (Holzäpfel et al., Jan 2008) was already used to perform Monte Carlo simulations of a number of different scenarios. Parts of these investigations are described in Holzäpfel et al. (Sep 2008). Even larger parts were introduced in CREDOS presentations with the same title given on 28.10.2008 at TU Berlin and on 5.12.2008 at DLR Oberpfaffenhofen.

In the selected reference scenario an aircraft separation of 120 s was used and all parameters including the meteorological data were varied randomly. 5.9% of departures result in encounters where encounters are defined by a distance of aircraft centre of gravity and vortex centre below 50 m and a vortex circulation above 100 m²/s. In this scenario 69% of encounters occur below 300 ft.

A reduction of the separation to 60 s roughly triples the encounter frequency to 18.1% where now even 84% of encounters occur below 300 ft. It is important to note that the frequency of strong encounters grows above average because the time available for vortex decay has been halved compared to the reference scenario.

A crosswind above 2 m/s at an altitude of 10 m almost halves the encounter frequency to 9.8%. The relative encounter probability below 300 ft is significantly reduced to 53%. Already a crosswind threshold of 3 m/s reduces the encounter frequency below the one of the reference scenario. However, the frequency of the strongest identified encounters (separation below 2 m and a vortex circulation above 350 m²/s) is with 0.020% still one order of magnitude higher than in the reference scenario with 0.0022%. Crosswinds above 4 m/s yield an encounter frequency of 0.012% of the most critical encounters which is still five times higher than in the reference scenario. Reducing the aircraft separations to 90 s for the 4 m/s crosswind still leads to an encounter frequency of 0.0047% of the strongest encounters. For encounters with circulations above 300 m²/s we find similar frequencies than in the reference case and for weaker encounters the frequencies are smaller compared to the reference case.

The encounter frequency below 300 ft is effectively reduced from 4.1% in the reference scenario to 0.87% for a 60 s separation and crosswinds above 3 m/s and to 0.08% for a 60 s separation and crosswinds above 4 m/s. For the 4 m/s crosswind the majority of encounters occur at altitudes above 1200 ft and a large fraction of these is also combined with relatively large encounter angles. The estimation of the related risks in the reference scenario and the 4 m/s scenario with VESA could possibly support the suitability of the 4 m/s threshold which was also elaborated from the measurement data.

Finally, the simulations indicate that the height range within which the crosswind thresholds need to be

1 Note that in this section the term encounter denotes a situation of interest which might lead to an actual encounter. The thresholds of circulation and distance are set conservatively such that potential encounters may occur which only lead to negligible aircraft reactions.
exceeded have only a small effect on the encounter frequencies. The encounter frequency of 5.7% (for an encounter definition with encounter distances below 30 m and a vortex circulation above 100 m²/s) for crosswinds above 2 m/s at 10 m decreases to 5.3% if the crosswind threshold is exceeded up to 100 m and to 3.7% for a height range up to 3000 ft. Similarly small benefits for crosswinds extending over the full height range are found also for other crosswind magnitudes.
2. SUB-MODEL DESCRIPTIONS

This section describes the parameters and the context for which the different sub-models were validated. For each sub-model the ranges for which the respective parameters are valid are provided. Herewith, this documentation provides the basis to define and describe the simulation scenarios such that all the parameter values reside fully within their respective validated ranges.

2.1. METEOROLOGICAL DATA BASE

The variety of parameter combinations observed in the planetary boundary layer and their transformation on wake vortex behaviour lead to a significant manifold of situations. To capture this diversity an extensive one-year simulation of realistic meteorological conditions has been produced for the Frankfurt terminal area with the non-hydrostatic mesoscale weather forecast model system NOWVIV (NOwcasting Wake Vortex Impact Variables, Gerz et al., 2005). NOWVIV comprises a full physics package including boundary layer turbulence, surface energy and momentum balance, soil physics, radiation processes including cloud effects, cumulus convection, and cloud physics.

NOWVIV has previously been successfully employed for predictions of wake vortex environmental parameters in five field campaigns (Holzäpfel et al., 2009). The one-year meteorological data base has been validated against a 30-year wind climatology and a 40-days subset has been compared to ultrasonic anemometer, SODAR/RASS, and lidar measurement data (Frech et al., 2007). Assessments of wake prediction skill of P2P based on predictions of meteorological conditions with NOWVIV can be found in (Frech and Holzäpfel 2008, Holzäpfel and Robins 2004).

Initial and boundary data were taken from the numerical data assimilation model LM (Local Model) of DWD (German Weather Service). These data represent the best possible forcing of NOWVIV since actual observations (radio soundings, AMDAR (Aircraft Meteorological Data Relay), satellite data, surface observations, etc.) are used to analyse the state of the atmosphere. Detailed topography, land use and soil type data for the Frankfurt area were employed.

The data base consists of about $1.3 \times 10^6$ vertical profiles of meteorological data at locations along the glide slope separated by one nautical mile and an output frequency of 10 minutes. The vertical resolution varies between 8 m and 50 m. The meteorological quantities comprise the three wind components, air density, virtual potential temperature, turbulent kinetic energy, eddy dissipation rate (EDR), and pressure. Note that the spatiotemporal resolution of an mesoscale model implies that wind changes on the order of minutes or along distances on the order of 100 m are not resolved.

During the 40-days measurement campaign the following parameter ranges were predicted and observed (Frech et al., 2007). The measured and predicted ranges of the listed parameters were in good agreement. It can be assumed that the full one-year data base contains even higher ranges of the considered parameters.

\[
\begin{align*}
0 \leq & \text{ horizontal wind speed } \leq 16 \text{ m/s} \\
-13 \text{ m/s} \leq & \text{ cross wind speed } \leq 12 \text{ m/s} \\
0 \leq & \text{ wind shear } \leq 0.15 \text{ 1/s} \\
0 \leq & \text{ Brunt-Väisälä frequency, } N \leq 0.05 \text{ 1/s} \\
0 \leq & \text{ turbulent kinetic energy, TKE } \leq 6 \text{ m}^2\text{s}^{-2} \\
0 \leq & \text{ eddy dissipation rate, EDR } \leq 0.01 \text{ m}^2\text{s}^{-3}
\end{align*}
\]
2.2. AIRCRAFT TRAJECTORY MODEL

A trajectory model was developed, implemented, and verified with experimental data from a certified A330 full flight simulator and validated on the basis of recorded aircraft trajectories at Frankfurt airport. Aircraft trajectories can be modelled for takeoff and departure, beginning on the runway along a standard departure route until 3000 ft above ground level. The model is able to simulate sensitivities depending on parameters of main influence. Such parameters are:

- Different standard departure routes and runways;
- Meteorological conditions, including air temperature, density, pressure, wind direction and strength;
- Aircraft types;
- Aircraft takeoff weights;
- Takeoff thrust mode, takeoff go around (TOGA) thrust, or flex takeoff thrust (reduced thrust);
- Start position on the runway;
- Pilot behaviour.

Those parameters can be varied in between defined boundaries with given probability distribution in Monte Carlo Simulation (MCS) to generate a set of trajectories for different aircraft types and departure conditions. The table in Appendix A gives a detailed description of the listed parameters and their distribution ranges.

2.3. WAKE-VORTEX PREDICTION MODELS

The probabilistic vortex model P2P, which constitutes the basis of its deterministic version D2P, is described in detail in Holzäpfel (2003). Applications, assessments and further developments are reported in (Frech and Holzäpfel 2008, Holzäpfel and Robins 2004, Holzäpfel 2006, Holzäpfel and Steen 2007, Holzäpfel 2008). In total, P2P has been validated against data of over 10,000 cases gathered in two US and six European measurement campaigns. This includes cases for arrival, departure, level flight, and cruise; out of ground effect and in ground effect evolution of wake vortices; high-lift and clean configurations; heavy, medium, and even a few light aircraft. D2P accounts for the effects of wind, axial- and crosswind shear, turbulence, stable thermal stratification, and ground proximity. The ranges of meteorological parameters for which the model has been validated are:

- $-3 \text{ m/s} \leq \text{head wind speed} \leq 12 \text{ m/s}$
- $|\text{cross wind speed}| \leq 8 \text{ m/s}$
- $0 \leq \text{wind shear} \leq 0.11 \text{ 1/s}$
- Brunt-Väisälä frequency, $N \leq 0.056 \text{ 1/s}$
- Turbulent kinetic energy, $\text{TKE} \leq 3 \text{ m}^2/\text{s}^2$
- $0.0000004 \text{ m}^2/\text{s}^3 \leq \text{eddy dissipation rate, EDR} \leq 0.1 \text{ m}^2/\text{s}^3$

The comparison of the ranges of the meteorological parameters for which the wake vortex model has been validated with the ranges that occur in the meteorological data base (section 2.1) show that the data base naturally contains slightly larger ranges for most of the parameters. On the other hand, the underlying mechanisms for vortex behaviour are only expected to be somewhat more pronounced with these higher values but do not change in principle. Therefore, it can be assumed that the wake vortex model can be well applied for the full parameter ranges that do occur in the meteorological data base.

The Deterministic wake Vortex Model (DVM) is the new wake vortex predictor software developed by UCL. It accounts for the effects, on both transport and decay of the WV, of the wind profiles (headwind and crosswind), crosswind shear, turbulence profile, stable stratification profile and ground proximity.

The DVM is based on the Method of Discrete Vortices (MDV, a method of discrete vortex “particles”,...
see Winckelmans, 2004, Winckelmans et al, 2005). It integrates, in time, various physical models so as to predict 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. The DVM is based on the same numerical methodology and on some of the physical models of the Vortex Forecast System (VFS) that was originally developed by an international team (see Rennic et al., 1997, Winckelmans and Ploumhans, 1997, Winckelmans et al., 2000, Jackson et al, 2001, Winckelmans, 2001). The VFS then further improved and calibrated by UCL, also against US and EU databases and against LES, from 2001 to 2006 (e.g., improvement of the turbulence decay model, see Winckelmans and Jeanmart, 2001, Jeanmart and Winckelmans, 2002). Some of the improvement work was also done in the framework of EC funded projects: I-Wake, ATC-Wake (see Treve et al, 2004, Winckelmans et al, June 2005, Speiker et al., 2007), AWIATOR (see Winckelmans et al, Sept 2006), WakeNet2-Europe (see Gerz et al, 2005, Winckelmans and Holzäpfel, 2006). The description of the VFS models as of mid 2005 is also presented in details in Winckelmans et al, April 2005.

The DVM software integrates the previous VFS technology and most of its models (including all UCL improvements up to end 2006); yet it also includes new improved models, some having also been developed during EC projects such as FLYSAFE and FAR-Wake: e.g., improvement of the atmospheric profiles mathematical representation, improvement of the stratification model, improvement of the IGE model (see De Visscher et al, May 2008, Holzäpfel, De Visscher et al, May 2008, Winckelmans, Holzäpfel et al, May 2008) using the WakeFRA 2004 database and also new LES results (see Georges et al, 2007, Giovannini et al, 2007). The DVM was further assessed against the EDDF-1 and EDDF-2 campaigns in the framework of CREDOS WP2 (see De Visscher et al., Oct. 2008).

Upper software layers were also developed, for probabilistic modelling and assessment of wake vortices: first the Probabilistic VFS (P-VFS) based on a pseudo Monte-Carlo approach, using the VFS as sub-tool (see Winckelmans et al, June 2005, Winckelmans and Holzäpfel, 2006); then the Probabilistic wake Vortex Model (PVM) based on a true Monte-Carlo approach, and using the DVM as sub-tool. In WakeScene-D, only the DVM is used.

The DVM has been assessed against measurements of WV generated by heavy and medium aircraft, OGE and IGE. It has also been compared to the results of LES performed IGE without and with wind (cross wind and head wind cases) in FAR-Wake. The model was also used for comparative analysis of WV evolution in different scenarios (different meteorological conditions and different a/c trajectories) in the WAKE4D platform (3-D space + time simulation platform of UCL), also as part of simulations carried in support to the Time-Based Separation (TBS) project of EUROCONTROL.

The ranges of meteorological parameters for which the DVM model has been compared to measurements and/or LES are:

- **Head wind speed**: \(-3 \text{ m/s} \leq u \leq 12.5 \text{ m/s}\)
- **Cross wind speed**: \(|v| \leq 8 \text{ m/s}\)
- **Wind shear**: \(0 \leq Sh \leq 0.10 \text{ 1/s}\) (also higher values in some LES, see Winckelmans et al, 2000)
- **Brunt-Väisälä frequency**: \(N \leq 0.05 \text{ 1/s}\)
- **Turbulent kinetic energy**: \(0.01 \text{ m}^2/\text{s}^2 \leq \text{TKE} \leq 3 \text{ m}^2/\text{s}^2\) (higher values possible very close to the ground, due to the turbulence of the wind boundary layer; this is then modelled as no data are provided so close to the ground).
- **Eddy dissipation rate**: \(10^{-6} \text{ m}^2/\text{s}^3 \leq \text{EDR} \leq 0.01 \text{ m}^2/\text{s}^3\) (higher values possible very close to the ground, due to the turbulence of the wind boundary layer; this is then modelled as no data are provided so close to the ground).

Since the models in DVM are based on a physical modelling approach, and since they have been calibrated on measurements and LES results, they are expected to also provide adequate predictions outside of the above mentioned bounds.
3. OPERATIONAL SCENARIOS

This section provides a list of possible scenarios that could be investigated with WakeScene-D to contribute to the definition of safe separation distances for takeoff and departure and to the quantitative safety assessment. In sections 3.1 and 3.2 simulations are suggested that shall deepen the understanding of the sensitivity of the software package. This is also thought to increase confidence in the simulation results. Section 3.3 deals with the definition of a suitable reference scenario. Finally, section 3.4 describes the possible operational scenarios. Section 3.5 provides ratings of the CREDOS partners of the relevance of the different scenarios. The position of the respective scenarios within the ranking is provided after each scenario in brackets and bold letters.

3.1. SENSITIVITY ANALYSES

To gain deeper understanding of WakeScene-D and increase the confidence in the software package, the sensitivity of the simulation results on the different parameters should be worked out.

S1) First it would be interesting to see how the simulation results converge with increasing sample sizes. This study would be helpful to define a meaningful sample size that can be used with confidence for the large number of investigated situations. (4)

S2) The analysis of encounter frequencies for different aircraft combinations will allow for a better understanding of situations with high or low encounter frequencies which are probably strongly related to the different points of rotation. This will also shed some light on the importance of the used traffic mix and the transferability of the results to other airports. There might also be some evidence for concentrating on the chosen aircraft type combinations. Finally, because VESA is mainly modelling the A320, the comparison of A320 encounter statistics with other aircraft can be used to set the VESA investigations into perspective of encounter severities of a larger fleet. (5)

S3) Variations of aircraft weight and the impact on climb rate and the associated encounter probability. (5)

S4) Variations of take off thrust and the impact on climb rate and the associated encounter probability. (7)

S5) Evaluation of effects of brake release point / rotation point. Currently, brake release point varies between threshold and 1st intersect (0 – 750 m offset). (7)

S6) Evaluation of the effect of reducing the separation by 5 s from 60 s to 55 s. (8)

S7) The sensitivity of encounter frequencies on the standard departure routes will allow understanding the role of flight path diversions. SID (Standard Instrument Departure) combinations should be investigated dependent on crosswind direction. A comparison to a straight climb-out route scenario could show the influence of diverging departure routes. (2)

S8) The modelling of the flight path adherence (navigational precision) probably plays a significant role for the encounter frequencies. Therefore, the sensitivity of encounter frequencies to modifications of the flight path deviation model or its deactivation is worth analyzing. (P(recision))-RNAV defines European RNAV operations which satisfy a required track-keeping accuracy of ±1.0 NM for at least 95% of the flight time. The DFS radar data that were used to validate the aircraft trajectory model were presumably generated by aircraft that were flying on RNAV routes. However, this can not be verified by hindsight. The track-keeping accuracy found in the DFS radar data was clearly better than ± 0.3 NM for 95% of the departures (Amelsberg and Lenz, 2007.) (2)

S9) Regarding the meteorological situation it would be interesting to see differences between different wind directions (headwind, tailwind, winds from port or starboard direction), the seasons and the time of day. Further, it would be good to calculate the crosswinds with respect to Frankfurt runway 18 to see how the impact of synoptic situations and the local orography on the crosswind and its change of
sign with altitude influence the encounter frequencies (by default runway orientation 25 is investigated). Here the comparison of the reference simulation with a crosswind of 8 knots at 10 m height should already provide conclusive results. (5)

S10) Comparison of 24 h operations to operational hours of Frankfurt airport (6:00 – 23:00). (9)

S11) Clearly, wake vortex modelling constitutes a very important element of WakeScene-D. If both available wake vortex models (D2P and DVM) would lead to similar encounter statistics, this would indicate that details of the wake vortex model parameterizations do not impact strongly the conclusions drawn from the investigations. (3)

S12) In contrast to arrivals where a close-up effect on average reduces aircraft separations, an increase of average aircraft separations is expected for departures (pull away). It would be interesting to verify this increase of separations between subsequent aircraft which is postulated as a benefit of CREDOS. In the ICAO documents, there seems to be no specific description how "separation" has to be measured during takeoff on diverging routes. It is therefore recommended taking the point-to-point distance (x-y plane) between successive aircraft and additionally the vertical distance. (It is also important to verify that spatial ICAO separations are reached when the follower aircraft leaves the investigated height range of 3000 ft. However, the determination of this separation is out of the scope of WakeScene-D because the leading aircraft is only modelled until a height of 3000 ft.) (3)

S13) To be able to compare encounter probabilities for arrival and departure situations, a simulation with a B744 as leader and A320 and AT45 (replacing the VFW614) as followers should be performed. (6)

The employed encounter criterion “closest approach of aircraft to the vortices” largely affects the encounter statistics. Because the interaction of aircraft and wake vortices is not modelled within WakeScene-D, it is not possible to postulate a unique encounter criterion. Moreover, because we go for a relative safety assessment where reference and target case employ the same encounter criterion and because VESA is used to investigate the encounters in detail, no need appears to conduct additional investigations regarding alternative encounter criteria.

3.2. VALIDATION

Any software which may be employed to assess the safety of a wake-vortex advisory system must constitute a sufficiently accurate representation of the projected operation. However, for complex risk assessment tools one to one validation appears not feasible, because the significant manifold of parameters modelled in the various sub-models can not be measured simultaneously and reconstructed consistently in a simulation. For WakeScene-D the identification of the relevant processes and the definition of the appropriate degree of details with which they have to be modelled rely on thorough discussion and expert opinion. For the validation of the employed sub-models we refer to previous studies (Frech et al. 2007, Frech and Holzlüsphel 2008, Holzlüsphel and Robins 2004, Holzlüsphel 2006, Holzlüsphel and Steen 2007, Holzlüsphel et al. 2008, Jackson et al. 2001, Jeannart and Winckelmanns 2002, Winckelmanns et al. 2000, Winckelmanns and Holzlüsphel 2006, Winckelmanns et al. 2006) and the validation work performed within CREDOS (Amelsberg and Luckner 2007, Amelsberg and Lenz 2007, De Visscher et al. Oct. 2008, Holzlüsphel 2008).

V1) However, the wake vortex behaviour statistics achieved during the EDDF-2 campaign provide a good chance to validate WakeScene-D predictions within a single plane. For this purpose vortex evolution interpolated to the lidar observation plane can be analysed. (5)

Because we do not dispose of meteorological data for the time frame of the measurements that can be used by WakeScene-D on one hand and because the lidar measurements do not carry time stamps, it seems not to be possible to conduct one-to-one validations. However, it should be possible to obtain a picture whether the measured global vortex transport characteristics are met by the simulations. More insights might be gained by discriminating between the different aircraft types.
Note that extensive validation work of the wake vortex models based on EDDF-1 and -2 measurement data has been performed and documented in the deliverable D2-5.

3.3. REFERENCE SCENARIO

To establish crosswind dependent reduced aircraft separations a generally accepted definition of a reference scenario is mandatory.

RS1) So far for WakeScene-D investigations a reference scenario was selected which shall represent the real current situation. This reference scenario is based on an aircraft separation of 120 s and all parameters including the meteorological data are varied randomly. The working hypothesis assumes that the risk estimated for reduced separations under appropriate crosswind conditions shall not be higher than in the reference scenario. (1)

Note, that this approach, like any other approach, will increase the total risk, because aircraft separations are reduced compared to the status quo. Therefore, it is at present still unclear how to convince a regulator with a suitable safety argument. Note, on the other hand, that relative safety assessments for approaches which inherently increase the total risk have been accepted within other safety cases, e.g. for the HALS/DTOP safety case or the current FAA activities for departures from closely spaced parallel runways where the risks of reduced separations for parallel runway operations are compared to single runway operations (Lang and Tittsworth 2009).

There are alternative reference scenario definitions. One could assume that the current ICAO separations are safe under calm wind conditions, where vortex transport and vortex decay contribute less to the related encounter risks. Therefore, a reference scenario could be composed of the situations where the crosswind is below a certain threshold.

RS2) To see the potential of alternative reference scenarios, it is suggested to perform simulations for cases with crosswinds smaller than 4 knots and to compare the related risks of the different reference scenarios. (5)

The parameters used and varied in the reference scenario should be specified in a dedicated list. The reference scenario should exclude cases with tailwinds above 5 knots and be restricted to the operational hours of Frankfurt airport (6:00 – 23:00). These two constraints should also be applied as a baseline of all other investigated cases (sensitivity analyses, validation, and operational scenarios).

3.4. OPERATIONAL SCENARIOS

The simulations suggested in this section shall finally provide the target scenario for the crosswind dependent reduced separations. It is suggested to investigate cases with crosswind thresholds from 2 knots to 10 knots in 2 knots increments. The investigations should focus on 10 m winds, because this constitutes the operationally simplest situation and the benefit of larger height ranges appears limited.

The used temporal aircraft separations should be 60 s, 90 s, and 120 s. These separation times refer to the differences in times for start of roll between leader and follower aircraft. Additional separation times are possible in a refinement stage. An additional allowance which could account for the delay between the instant when the controller issues the clearance and the pilot starts to accelerate the aircraft shall not be considered, because this delay time will be similar for all temporal aircraft separations.

The analysis within WakeScene-D shall include statistics of the closest distance between aircraft and vortex, the respective vortex circulation, encounter altitude, and encounter angles.
In order to better understand the probability of encounters as a function of aircraft separation and crosswind a graphical representation as shown in Figure 1 is promising. Such histograms should be established from the simulations by evaluating encounter probabilities for crosswind slices.

**Figure 1:** Frequencies of encounters (distances below 50 m and vortex circulations above 100 m²/s) for three different aircraft separations as a function of the crosswind. Light blue bars denote the frequencies of the respective crosswind situations.
3.5. PARTNER RATINGS

The table below lists the ratings of the scenarios based on CREDOS partners’ inputs. Four categories were used: not needed, desirable, important, and mandatory corresponding to a scale of 0 to 3. The scenarios are ordered according to the achieved rank.

<table>
<thead>
<tr>
<th>Topics Priorities</th>
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<td>sensitivity to</td>
<td>AD ECTL NLR DLR-PA DLR-RM DLR-FT FAA total ranking</td>
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<td>RS1 – all crosswinds</td>
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<tr>
<td>S7 – SID combinations</td>
<td>2 3 2 2 2 2 3 2</td>
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<td>S8 – flight path adherence</td>
<td>3 3 2 2 1 2 3 2</td>
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<td>S11 – wake vortex models</td>
<td>3 1 1 2 2 1 3 3</td>
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<tr>
<td>S12 – pull-away effect</td>
<td>2 3 3 1 1 1 2 3</td>
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<td>S1 – sample size</td>
<td>2 1 2 2 2 2 1 4</td>
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<td>RS2 – crosswinds &lt; 4 knots</td>
<td>2 2 3 1 0 1 2 5</td>
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<td>S2 – aircraft combinations</td>
<td>1 2 3 2 1 1 1 5</td>
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<td>S3 – aircraft weight</td>
<td>3 1 2 1 1 1 2 5</td>
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<tr>
<td>S9 – meteo situation</td>
<td>2 2 3 2 1 1 0 5</td>
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<td>V1 – EDDF-2 campaign</td>
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<td>S13 – departure – arrival situation</td>
<td>1 2 1 1 2 1 2 6</td>
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<td>S4 – takeoff thrust</td>
<td>3 1 2 0 0 1 2 7</td>
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<tr>
<td>S5 – brake release point</td>
<td>3 1 1 1 1 1 1 7</td>
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<tr>
<td>S6 – reduced separation by 5 s</td>
<td>1 2 1 0 0 0 2 8</td>
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<tr>
<td>S10 – operation times</td>
<td>1 0 1 1 2 0 0 9</td>
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</table>
4. CONCLUSIONS

This report delineates operational scenarios that shall be investigated with WakeScene-D to contribute to the definition of safe separation distances for takeoff and departure and to the required quantitative safety assessment. The current report first recapitulates the findings obtained from the analysis of the measurement campaigns EDDF-1 and EDDF-2. It further describes results of preliminary Monte Carlo simulations conducted with WakeScene-D. All these investigations indicate that for 60 s aircraft separations a crosswind threshold on the order of 4 m/s could be appropriate.

The report also includes a description of the context and the parameter ranges for which the different sub-models of WakeScene-D were validated. The established listings shall make sure that the simulation scenarios comprise only situations for which the employed sub-models are valid.

The departure scenarios suggested for investigation in this report can be split into four categories: (i) sensitivity analyses regarding the effects of the different models and parameters that shall deepen the understanding of WakeScene-D and, herewith, the confidence into the software package. (ii) A validation exercise employing statistics of the EDDF-2 measurement data. (iii) Reference scenarios representing the current situation to which CREDOS operations can be compared. (iv) The actual target scenarios for different crosswind thresholds and reduced departure separations. The final target scenario shall be derived based on scenarios with crosswind thresholds from 2 knots to 10 knots in 2 knots increments (winds at 10 m height) and temporal aircraft separations of 60 s, 90 s, and 120 s.

The subsequent investigations with VESA will focus on determining the severity of encounters detected with WakeScene-D for the reference situation and the target crosswind thresholds and aircraft separations.

A ranking of the relevance of the various possible scenarios has been established with input from CREDOS partners. Even if finally all scenarios could be investigated, the ranking should be useful, because it provides guidance regarding the relevance of the different investigations.

The ranking results clearly identify the most important scenarios based on a strong consensus between the inputs of the different specialists. Most important is obviously that the reference scenario against which the risks of the CREDOS operations shall be compared should be based on all crosswinds. Less conservative approaches based on weak crosswinds are seen quite critical. Also, effects of the respective flight paths on encounter probabilities (scenarios “SID combinations”, “flight path adherence”) appear to be essential. This is expected because compared to arrival situations the flight paths during departures are less constrained which excludes vortex descent as the primary mechanism to avoid encounters. WakeScene-D constitutes the tool within CREDOS which allows studying the implications of flight path variations.

The forthcoming investigations with WakeScene-D should first identify the sample size of the Monte Carlo simulations which is necessary to achieve converged results. Then the order of the investigations should follow the elaborated ranking.

The current suggestions of scenarios result from thorough discussion within WP3 and from a joint WP3/ WP4 meeting in Oberpfaffenhofen on 5 December 2008 followed by continued discussions. The devised scenarios clearly reflect the strategy of the CREDOS project and the resulting implications. The manifold of scenarios and their specific definitions combined with the guidance regarding the relevance of the different scenarios constitutes an excellent basis to deepen the understanding of the relevant mechanisms and to eventually find together with VESA a suitable definition of safe separation distances for takeoff and departure.
5. ACKNOWLEDGEMENTS

Contributions of CREDOS partners for the definition of the scenarios and the ranking of the scenarios are acknowledged. Our thanks are addressed to Andrew Harvey (ECTL), Sebastian Kauertz (AD), Jean-Pierre Nicolaon (FAA), Carsten Schwarz (DLR), Lennaert Speijker (NLR), and Anna Wennerberg (ECTL).
6. REFERENCES


Holzäpfel F., De Visscher I., Winckelmans G. and Lonfils T., Assessment of combined ground effects and meteorology on wake vortex transport and decay NGE and IGE, and improvement of the models D2P/P2P and DVM/PVM, including performance analysis, FAR-Wake Deliverable D 3.3-1 (made of Technical Reports by DLR and UCL), April 2008.

Winckelmans G., Duquesne T., Treve V., Desenfans O., Bricteux L., Summary description of the models used in the Vortex Forecast System (VFS), VFS version with added improvements done after completion of the Transport Canada funded project, Université catholique de Louvain (UCL) Internal Report, April 2005 (18 pages, also on http://www-mip.onera.fr/projets/WakeNet2-Europe ).


### 7. APPENDIX A

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Range</th>
<th>Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weather Conditions</td>
<td>See description in subchapter 2.1</td>
<td>NOWVIV</td>
<td>uniform (EDDF one year weather distribution)</td>
</tr>
<tr>
<td>SID Route</td>
<td>The Area Navigation (RNAV) Standard Instrument Departure Routes (SID) from the Jeppesen Navigation Database at Frankfurt/Main airport are used [2]. The SIDs are defined by a list of waypoints, speed and altitude restrictions. A set of five unique routes for each of the parallel runways, suitable for heavy and medium wake category aircraft, have been chosen. All other departure routes are either night routes, only for special aircraft types or differ only in the last one or two waypoints, where the aircraft has already reached the maximum simulation altitude of 3000 ft.</td>
<td>ANEK15F BIBOS6F DKB2F SOBRA1F TOBAK2F</td>
<td>Uniform</td>
</tr>
<tr>
<td>A/C Type</td>
<td>Type of aircraft. This parameter defines aircraft performance and geometric data i.e lift, drag, thrust, and fuel flow based on BADA (Base of Aircraft Data) [1]. According to D3-3, a selection of 6 aircraft types was validated. For the 4 further aircraft types listed below the respective parameters were derived in analogy from the validated aircraft types.</td>
<td>AIRBUS A300-600 (Heavy) AIRBUS A330-300 (Heavy) AIRBUS A340-300 (Heavy) BOEING 737-300 (Medium) BOEING 747-400 (Heavy) AIRBUS A320 (Medium) AIRBUS 310 (Heavy) BOEING 777-200 (Heavy) ATR 42-500 (Medium) CRJ-700 (Medium)</td>
<td>Aircraft mix is given in D3-3.</td>
</tr>
<tr>
<td>A/C Mass</td>
<td>Aircraft mass can be varied between the minimum and the maximum takeoff weight (MTOW), with a factor from zero to one. Zero defines the minimum takeoff weight and one stands for MTOW. The minimum takeoff weight is defined as 50% loaded. Mean aircraft weight for each type has been estimated using typical load factor information from flight plans of departing aircraft at Frankfurt airport.</td>
<td>0-1</td>
<td>Average aircraft weight is aircraft type specific, see D3-1, Appendix A and Addendum D3-1. A normal distribution is assumed around the mean weight (aircraft type specific) and limited between 0 and 1.</td>
</tr>
<tr>
<td>Thrust Mode</td>
<td>Different thrust settings change the aircraft acceleration characteristics and the final climb speed. The first recorded trajectory data is after lift-off, and the trajectory points and speed profile from takeoff until 3000 ft are available. For the acceleration phase on the runway from brakes-off until lift-off, there is no data available for validation. Validation sheets for several aircraft show that all aircraft types achieve climb speeds after lift-off, which are comparable to the respective validation data. The thrust mode can be either one, which gives the reduced takeoff (T/O) thrust or the so called “Flex T/O” thrust and zero, which stands for “Takeoff Go Around” (TOGA) thrust mode.</td>
<td>0-1</td>
<td>80% Flex TO (0), 20% TOGA (1)</td>
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<tr>
<td>Start Position</td>
<td>The start position can be varied between the beginning of the runway and the runway position where the aircraft line up via the first taxiway, changeable with a factor between zero and one (0= beginning of runway, 1= start at the first taxiway). The distance between threshold and first taxiway is approximately 750 m. For heavy aircraft the start position should only be varied inside a half Gauss distribution around zero; because heavy aircraft start without exception from the beginning of the runway. It has been assumed that 80 % of the medium categorized aircraft start from the beginning of the runway and 20 % from the runway entering position at the first taxiway; see Figure 1.</td>
<td>0-1</td>
<td>Figure 1: Assumed medium aircraft start position. Heavy aircraft start position is assumed to be half normal around zero, as it is shown at the left side of Figure 1. 80% of medium aircraft are assumed to start from the first taxiway.</td>
</tr>
<tr>
<td>Pilot Factor</td>
<td>The part of lateral trajectory variations caused by the pilot, is described with a combination of cross track deviation and pilot lag time on commanded tracks. The standard deviation for the cross track deviation varies between 40 m and 100 m. The standard deviation for the pilot lag time is expressed by a distance along the route and varies between $50 \text{ m} \pm 240 \text{ m}$ and $50 \text{ m} \pm 400 \text{ m}$. Both standard deviations result from the fits to the measured aircraft tracks and are different for the different aircraft types. A normal distribution was assumed for a pilot reaction time due to lateral deviations, see Figure 2. The validation data from Frankfurt airport show higher navigation performances than required by P-RNAV, because most departing aircraft are equipped with a flight management system.</td>
<td>0-1</td>
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<tr>
<td>Vertical profile</td>
<td>The vertical aircraft profile is strictly dependent on aircraft performance and airline procedure (beside the Airport Traffic Area (ATA) departure procedure) and cannot be modified by user, except indirectly through variation of a/c mass or takeoff thrust level.</td>
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</table>

![Figure 2: Assumed normal pilot behaviour](image)

[1] *BADA 3.6 User Manual; EUROCONTROL, 2003*