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Aircraft Wake Vortex Scenarios Simulation Package for Takeoff and Departure

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I. Introduction

AIRCRAFT-GENERATED wake vortices pose a potential risk to following aircraft in various flight phases, whereas most wake-vortex encounters are reported for approach and landing and for takeoff and climb [1]. The wake-vortex aircraft separation standards [2] established in the 1970s increasingly degrade aviation efficiency when traffic congestion limits airport capacity during landing and takeoff. The most rapid growth scenario within a EUROCONTROL study [3] indicates that in the year 2025, 60 European airports could be congested, and as a result, 3.7 million flights per year could not be met.

Research has shown that the transport and persistence of wake vortices are highly dependent on meteorological conditions [4,5], so that in many cases the separation standards are overconservative. For single-runway operations, analyses [6–8] suggest that above a certain crosswind threshold, vortices are blown out of the flight corridor and pose no further threat to following aircraft. The European Union (EU) project CREDOS[¶] (Crosswind-Reduced Separations for Departure Operations) intends to demonstrate the operational feasibility of a concept of operations that uses measures of the prevailing crosswind component to allow temporary suspension of the need to apply wake turbulence separations between successive departing aircraft.

The focus on the combination of crosswind and departures has significant advantages:

1) The follower aircraft is still on the ground when the controller schedules the separation. So the controller always has the possibility to extend the separation without requiring the pilot to make a maneuver. This beneficial situation also reduces the time horizon for which crosswind conditions must be anticipated.

2) In contrast to arrival situations, the leader aircraft is generally faster and so the actual separations tend to increase.

This Note describes the WakeScene-D software package (Wake Vortex Scenarios Simulation Package for Departure) that has been developed for comprehensive airspace simulations of takeoff and departure and the related wake-vortex-induced risks at Frankfurt airport [9]. Within CREDOS, WakeScene-D is used for the following:

1) Support the definition of suitable crosswind criteria that allow reducing aircraft separations.

2) Identify critical parameter combinations.

3) Perform risk analyses, taking into account a broad range of variables that determine the probability and risk of a wake-vortex encounter.

WakeScene-D is an extension of WakeScene that has been developed for approach and landing and is described in detail in [10]. WakeScene-D 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. In cases with potential wake encounters, all relevant parameters can be provided to VESA (vortex encounter severity assessment) [10–12], which may subsequently perform detailed investigations of the severity of the encounter. WakeScene-D consists of elements that model traffic mix, aircraft trajectories, meteorological conditions, wake-vortex evolution, and potential hazard area. The process and data flows are controlled and evaluated by the MATLAB-based environment MOPS (Multi-Objective Parameter Synthesis) [13].

In the following a survey on the operating sequence of WakeScene-D is given and the employed submodels and databases are described. The determination of crosswind thresholds allowing for reduced aircraft separations is the subject of ongoing investigations that will be documented in a future publication. First-application examples of the software package can be found in [9].

II. Survey on Operating Sequence

The flowchart depicted in Fig. 1 sketches the operating sequence of WakeScene-D. Via simulation control (MOPS), the types of the generator aircraft and follower aircraft, the departure routes, and a number of aircraft and pilot parameters are selected. The trajectory model provides time, speed, position, attitude, lift, and mass of generator and follower aircraft along the flight paths. Wake-vortex evolution is predicted within control gates that are released along the flight path of the wake-vortex generator aircraft in predefined time increments (e.g., 5 s). The gates' orientations are perpendicular to the

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[¶] Data available online at http://www.eurocontrol.int/eec/credos/ (retrieved October 2008).

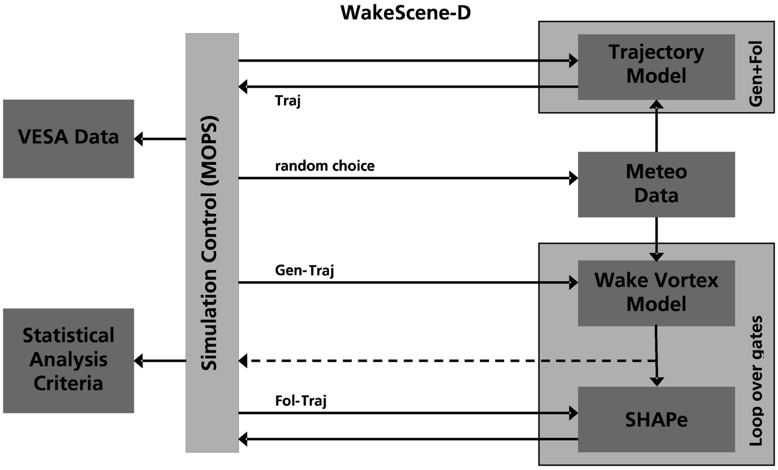

Fig. 1 WakeScene-D flowchart. Arrows denote the data flow.

aircraft true heading and perpendicular to the flight-path angle (see Fig. 2). Based on vertical profiles of wind speed and direction, air density, virtual potential temperature, turbulent kinetic energy, and eddy dissipation rate (meteorological database) and aircraft position, speed, attitude, lift, and span (trajectory model) at one gate, the wake-vortex model simulates the development of wake-vortex trajectories, circulation, vortex-core radius, and attitude of wake-vortex axes. The simplified hazard-area prediction model (SHAPE) computes the distance between wake vortex and follower aircraft within each gate and discriminates between potentially critical cases and cases in which safe and undisturbed flight is guaranteed. From all these data, MOPS computes defined criteria such as minimal distance between the wake vortex and follower aircraft and the respective vortex circulation and height, which are interpolated between the gates and statistically analyzed. Finally, data needed for further investigations with VESA are deduced and stored. The results are optionally visualized in graphs of the statistics, 2-D and 3-D views (see Fig. 2), or animations of the approaches of subsequent aircraft.

III. Employed Models and Databases

The submodels and databases that are employed by WakeScene-D are briefly introduced in the subsequent sections, followed by a brief estimation of the related uncertainties.

A. Meteorological Database

The variety of parameter combinations observed in the planetary boundary layer and their transformation on wake-vortex behavior 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 nonhydrostatic mesoscale weather-forecast model system NOWVIV (nowcasting wake-vortex impact variables [4]). 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 [14].

NOWVIV has previously been successfully employed for predictions of wake-vortex environmental parameters in five field campaigns [10]. The one-year meteorological database has been validated against a 30-year wind climatology, and a 40-day subset has been compared with ultrasonic anemometer, SODAR/RASS (sound detection and ranging/radio acoustic sounding system), and lidar (light detection and ranging) measurement data [15]. Assessments of wake prediction skill based on predictions of meteorological conditions with NOWVIV can be found in [8,16].

The database consists of about 1.3×10^6 vertical profiles of meteorological data at locations separated by 1 n mile and an output frequency of 10 min. The meteorological quantities comprise the three wind components, air density, virtual potential temperature, turbulent kinetic energy, eddy dissipation rate, and pressure.

B. Trajectory Model

The risk of encountering a wake vortex is strongly correlated with the actual flight paths of the vortex-generating aircraft and the encountering aircraft in space and time. Aircraft trajectories are modeled beginning on runway 25R along five different standard departure routes (TOBAK2F, BIBOS6F, SOBRA1F, ANEKI5F, and DKB2F) until 3000 ft above ground. The departure routes diverge at four waypoints leading from northwesterly up to southeasterly flight directions. Figure 2 shows exemplary aircraft trajectories for a southeasterly (leader) and a westerly (follower) route.

A large number of environmental- and aircraft-specific parameters influence an aircraft trajectory. The trajectory model (see [17] for details) simulates the impact of the most relevant parameters, which are the selected runway and the standard departure route; meteorological conditions, including air temperature, density, pressure, wind direction, and strength; aircraft type; aircraft takeoff weight; takeoff thrust that can be either takeoff go-around thrust or flex takeoff thrust (reduced thrust); start position on the runway; and pilot behavior that is described as a control model considering delayed pilot reaction time and a cross-track error.

These factors are varied within defined boundaries and given probability distributions employing Monte Carlo simulation to generate a set of trajectories for different aircraft types and departure conditions. The aircraft trajectory is adequately described with the equations of motion for three translational degrees of freedom.

A deterministic verification has been accomplished by comparing results of the trajectory model with high-fidelity simulation data of departures that were simulated on the certified A330-300 full-flight simulator (A330-FFS) at Technische Universität Berlin. Furthermore, a statistical validation was performed by comparing Monte Carlo simulation results of the trajectory model with 20,000 measured departures at Frankfurt airport provided by DFS Deutsche Flugsicherung, GmbH.

Figure 3 shows exemplary results of 1000 simulated A320 departures. The simulations are based on variations of pilot behavior, aircraft weight, thrust mode, and wind conditions. In Fig. 3 the resulting mean trajectory and its standard deviations (black) are compared with the respective measurement data (gray). The agreement of the lateral flight path, the climb profile, and the speed profile is sound.

C. Wake-Vortex Prediction Models

WakeScene provides a choice between two different parametric wake-vortex prediction models. These are the deterministic two-phase wake-vortex decay model (D2P) and the deterministic wake-vortex model (DVM). Both vortex models have been validated for departing aircraft by evaluating statistics of the deviations between measured and predicted wake-vortex behavior employing data acquired during the two CREDOS field measurement campaigns at

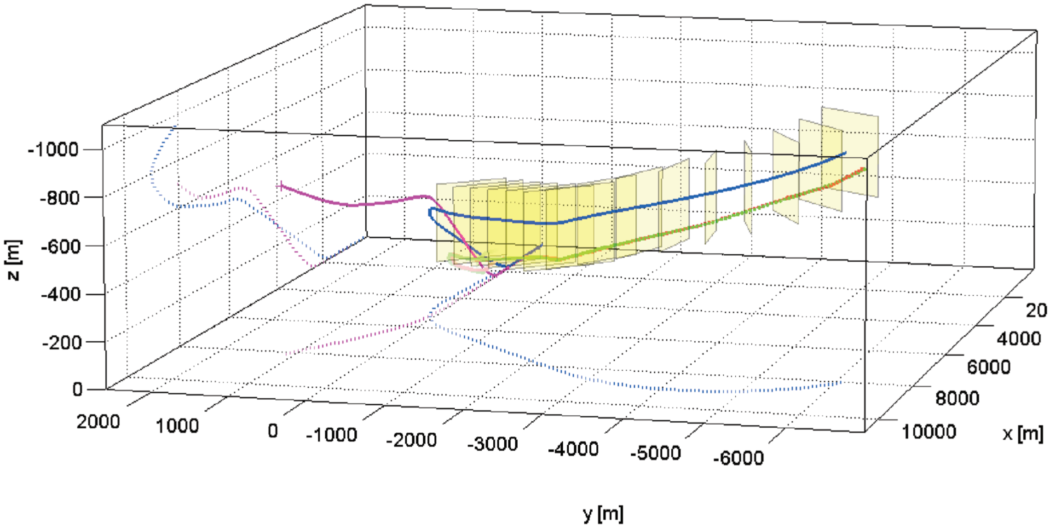

Fig. 2 Perspective view of trajectories of wake-generating aircraft (blue) and follower aircraft (magenta) together with wake-vortex positions (starboard vortex green, port vortex red). Projections of aircraft trajectories on vertical and horizontal planes and a number of gates used for wake-vortex prediction are displayed for convenience.

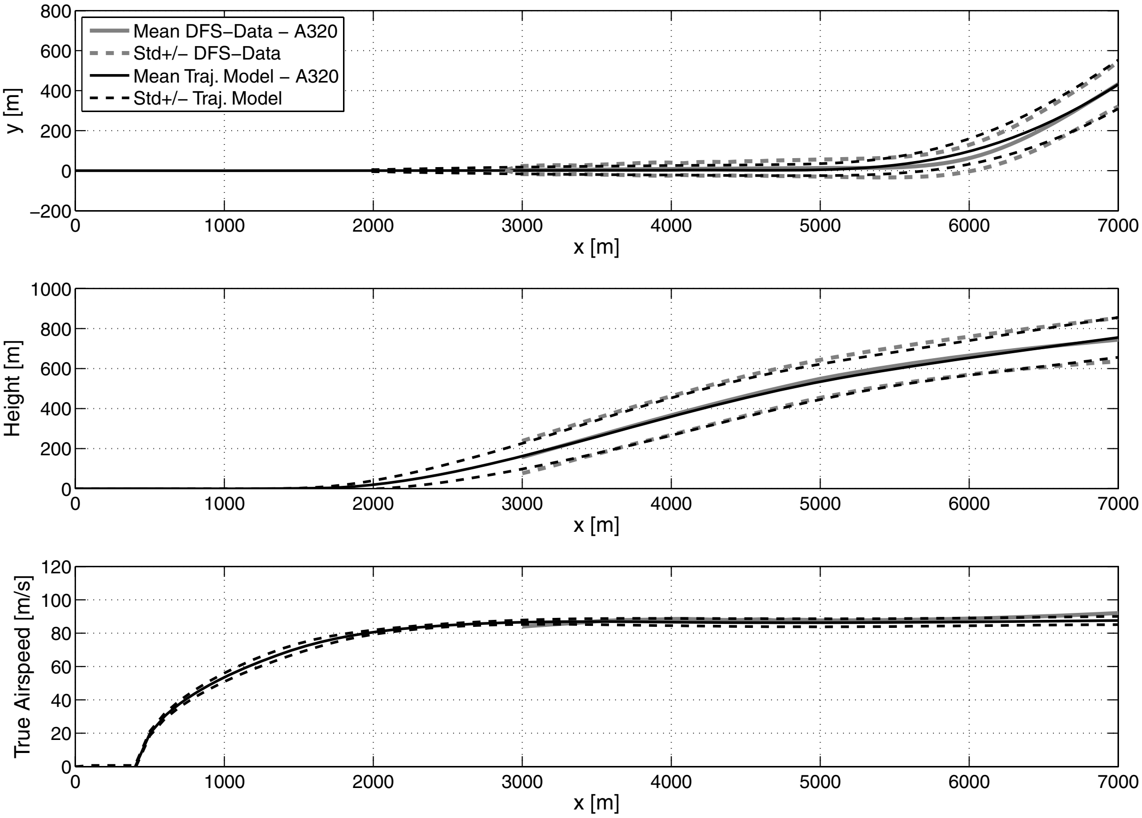

Fig. 3 Statistics of 1000 departures of A320 aircraft. Lateral and vertical positions as well as speed profile.

Frankfurt airport. The alternative application of two wake-vortex models allows assessing the sensitivity of WakeScene-D results on wake-vortex parameterizations.

A few adaptations were necessary to comply with the architecture devised for WakeScene-D. The control gates in which the vortices evolve (see Fig. 2) are inclined by the flight-path angle γ with respect to the vertical direction. For curved flight the vortices are initialized in positions rotated by the bank angle Φ such that the vortices descend in a direction tilted by Φ. The wake-vortex transport by headwind or tailwind is modeled by the respective transport of the gates. Because the gates have arbitrary orientations and move through the space, the determination of the closest distance between wake vortex and follower aircraft requires somewhat complex calculations.

The probabilistic vortex model P2P, which constitutes the basis of its deterministic version D2P, is described in detail in [18]. Applications, assessments, and further developments are reported in [16,19,20]. In total, P2P has been validated against data of over 1400 cases gathered in two United States and five European measurement campaigns. D2P accounts for the effects of wind, axial, and crosswind shear; turbulence; stable thermal stratification; and ground proximity. Figure 4 delineates a comparison between measured wake-vortex positions and circulation and the predictions of the two wake-vortex models. Note the effective lateral transport of the

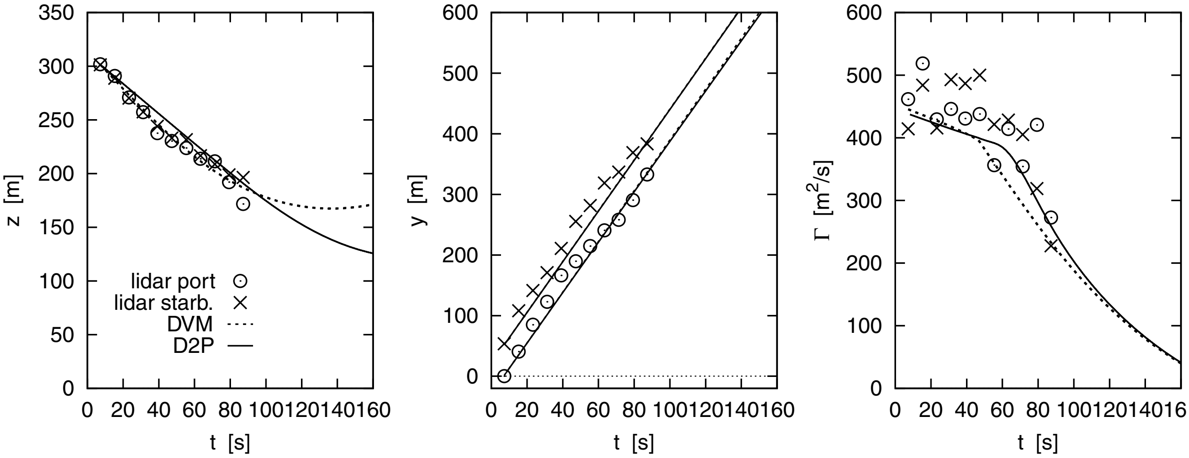

Fig. 4 Example for evolution of vertical and lateral positions and circulation in a case with a crosswind of about 4 m/s from CREDOS EDDF-1 campaign. Measurements by lidar (symbols) and predictions with D2P and DVM wake-vortex models (lines).

vortices in a case with a crosswind of about 4 m/s. Further output provided to VESA includes vortex-core radii and the interception angles between aircraft flight path and vortex axis: the so-called encounter angles.

The DVM is the new wake-vortex predictor software developed by the Université Catholique de Louvain, establishing a step forward in terms of robustness, modularity, and performance. It is based on the numerical methodology and the physical models of the Vortex Forecast System, originally developed by an international team [21] and further improved and calibrated (against two United States and two EU campaigns and against large eddy simulation) since 2002 in the framework of EU-funded projects (I-Wake, ATC-Wake [22], AWIATOR, WakeNet2-Europe [1], FLYSAFE, FAR-Wake, and CREDOS). The DVM accounts for the effects of wind transport (cross and axial), wind shear, decay due to turbulence, stratification, and ground proximity [23]. It also includes improvements regarding the evaluation of the vertical profiles of environmental conditions and of the in-ground-effect model. The probabilistic wake-vortex model is using the DVM in a Monte Carlo approach, taking into account the uncertainties and variations of the impact parameters from the aircraft and meteorological side and of some physical model coefficients of the DVM.

D. Hazards-Area Module

The hazards-area module computes the distance of the follower aircraft (center of gravity) to the vortex centers within each gate along the flight path. Then the closest distance between the follower aircraft and the vortex pair over all gates along the flight path is determined by interpolating aircraft trajectories and wake trajectories between the gates. This closest approach is used for further statistical analysis with WakeScene-D (e.g., vortex age and circulation for this point in time).

To estimate the severity of the potential wake-vortex encounter, an area of interest can optionally be defined around the vortices. If the trailing aircraft penetrates this area of interest, the wake-vortex encounter is classified as potentially hazardous. This is considered as a preliminary severity assessment. A corresponding concept called *simplified hazard areas* has been developed in [24] and adapted for takeoff and departure in [9]. Cases violating the area of interest can be subject to more detailed severity assessment, which is outside of the scope of WakeScene-D.

E. Estimation of Uncertainty

Any software that 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, straightforward validation appears to be infeasible, because the significant manifold of modeled parameters cannot 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 modeled rely on thorough discussion and expert opinion. For the validation of the employed submodels, we refer to the studies cited in the previous sections [8,10,15–17,19,20].

Here, we exemplarily perform a simple estimation of uncertainty for the most important parameter, which is lateral vortex transport, at a vortex generator height of about 50 m, which is within the most critical height range of 100 m above ground [1,9]. For B744 and A343 aircraft, the difference of predicted and measured standard deviations of lateral aircraft position amounts to $\sigma_{\mathrm{ac}} = 6.8$ m. For these aircraft types, the median RMS deviation of measured and predicted wake-vortex positions employing the D2P model has been estimated to $\sigma_{\mathrm{vort}} = 19.2$ m [20]. For our purposes here, the statistics only need to be accurate on average; that is, the predictions do not need to be correct in space *and* time. Because the vortex position uncertainty is dominated by spatial and temporal variations between the measured crosswind and the crosswind that is sensed by the vortices, the latter estimation is outmost conservative. Therefore, it can be understood that the vortex prediction uncertainty also implies uncertainties from numerical weather prediction. Assuming that these uncertainties are independent and statistically stationary, the overall uncertainty amounts to

$$\sigma_{\mathrm{tot}} = \sqrt{\sigma_{\mathrm{ac}}^2 + \sigma_{\mathrm{vort}}^2} = 20.3 \text{ m}$$

For this scenario and 120-s-old vortices, WakeScene-D determines a vortex spreading with $\sigma_{\mathrm{obs}} = 337.3$ m. Hence, a very conservative estimation of the relative uncertainty of lateral vortex positions in ground proximity can be estimated to 6.0%.

IV. Monte Carlo Simulation

Finally, we briefly describe the setup of a Monte Carlo simulation with a typical sample size of 500,000 aircraft pairings. A306, A310, A333, A343, B744, and B772 aircraft are used as vortex generators and A320, AT45, B733, and CRJ are used as followers. The traffic mix is modeled according to the statistics of Frankfurt airport in 2006 [25]. The following parameters of the generator and the follower aircraft are randomly distributed: start point, takeoff weight, thrust mode, departure-route combination, trajectory deviation, and pilot-delay parameter.

In the reference case, the follower aircraft obey the 120 s International Civil Aviation Organization separation and meteorological data of the full one-year database are employed. The baseline case may then be compared with situations with reduced temporal aircraft separations combined with different crosswind criteria. The determination of appropriate crosswind thresholds allowing for reduced aircraft separations is the subject of ongoing work that will be documented in a future publication. The first application examples of the software package can be found in [9].

V. Conclusions

WakeScene-D, a software package to determine wake vortex encounter probabilities for departures is described. The components of WakeScene-D that model traffic mix, aircraft trajectories, meteorological conditions, wake vortex evolution, and potential hazard area are specified together with the validation work accomplished thus far. Further, a brief estimation of related uncertainties is provided. WakeScene-D is an extension of WakeScene [10] that has been developed for approach and landing. Compared with this precursor version, major improvements have been achieved regarding realistic aircraft trajectory modeling on different standard departure routes. The developed trajectory model fully considers the impact of the most relevant parameters for 6 heavy vortex generator and 4 medium follower aircraft types. The comparison of simulated departures with full-flight simulator data and with 20,000 measured departures at Frankfurt airport yields good agreement. Another step ahead has been achieved by modeling the wake vortex behavior within inclined and moving gates. The gates that are oriented perpendicularly to the aircraft heading and flight-path angles are released in predefined time steps along the flight path and are advected through space by the prevailing headwind's respective tailwinds. The real target of WakeScene-D, the determination of appropriate crosswind thresholds allowing for reduced aircraft separations, is the subject of ongoing work and will be documented in a future publication. The first application examples of the software package can be found in [9].

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